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# Towards an instant structure-property prediction quality control tool for additive manufactured steel using a crystal plasticity trained deep learning surrogate

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RESEARCH ARTICLE

# The moderating effect of solar radiation on the association between human mobility and COVID-19 infection in Europe

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## Abstract
The novel coronavirus disease 2019 (COVID-19) has caused a global pandemic. Some studies have suggested a negative association between sunlight intensity and COVID-19 infection, alluding to the belief that it might be safe to go out on sunny days. This paper examined whether solar radiation mitigated the association between human mobility and COVID-19 infection in Europe using a dynamic panel data model to investigate the effect of human mobility, solar radiation, and their interaction on COVID-19 infection. The results revealed that outgoing mobility was positively correlated and solar radiation was negatively correlated with COVID-19 infection at lag levels of 1, 2, and 3 weeks. The coefficients of the interaction items indicated that solar radiation negatively moderated the relationship between outgoing mobility and the number of daily new confirmed cases at 2- and 3-week lag levels. However, the moderating effect was limited and unable to eliminate the positive effect of outgoing mobility on COVID-19 infection. Thus, these results suggested that solar radiation only weakly mitigated the relationship between human mobility and COVID-19 infection, providing policy implications that mobility should still be restricted on sunny days during the COVID-19 pandemic.

**Keywords** Solar radiation · Human mobility · COVID-19 · Moderating effect

## Introduction

Coronavirus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2, is a severe public health problem (Sohrabi et al., 2020). It first broke out in Wuhan City, China, in December 2019 (Lu et al. 2020). Despite local governments implementing consistent restriction measures, COVID-19 has become a global pandemic, and numerous countries are suffering from the contagion of COVID-19 (World Health Organization 2021).

Many studies (Kraemer et al. 2020; Xiong et al. 2020; Oztig and Askin 2020) have proven that the participation of people in outdoor activities plays an essential role in COVID-19 transmission. Furthermore, human mobility was identified as a critical variable in the spread of COVID-19 infections (Cartenì et al. 2020). Because increased human mobility is positively correlated with COVID-19 transmission, lockdown

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orders have been imposed by governments around the world during the outbreak (Cheng et al. 2020). However, these restrictions do not stop people from being more likely to go outside on sunny days (Paez et al. 2020; Azuma et al. 2020).

An increasing number of studies are investigating the association between sunlight and COVID-19 using a variety of measurements of sunlight, such as solar irradiance (Gupta et al. 2020; Bäcker 2020; Ahmadi et al. 2020), the ultraviolet index (Kalippurayil et al., 2020; Takagi et al. 2020), sunshine duration (Asyary and Veruswati 2020; Li et al. 2020a; Thangriyal et al. 2020), and latitude (Whittemore 2020). Although the results of these studies were somewhat inconsistent, most studies have shown that more sunlight is associated with reduced coronavirus infection (Carleton et al. 2021; Guasp et al. 2020; Thangriyal et al. 2020). Ultraviolet irradiation was reported to inactivate coronaviruses and reduce the viral load, thereby reducing coronavirus transmission (Bedell et al. 2016; Hamzavi et al. 2020). Additionally, sunlight exposure boosts the immune system by inducing vitamin D synthesis (Engelsen 2010; Wacker and Holick 2013; Holick 2017; Li et al. 2020b), which may help reduce the risk of COVID-19 infection (Grant et al. 2020; Ilie et al. 2020; Ebadi and Montano-Loza 2020; Xu et al. 2020). These findings could lead to some individuals and governments believing that it might be safe to go out on sunny days and thus tending to relax control measures when the local weather is sunny (The New York Times 2020; Matthews 2020; Robertson 2020; McGuinness 2021).

Although sunlight is negatively associated with COVID-19 transmission, it is unclear whether the association between human mobility and COVID-19 infection would be mitigated on sunny days. To this end, we investigated the moderating effect of sunlight on the association between human mobility and COVID-19 infection using data from 15 European countries. Our findings will contribute to address the misconception that it is safe to go outdoors on a sunny day, providing important implications for public health policymaking that weather conditions alone are insufficient to support lifting lockdown restrictions. Further contributing to the knowledge base of COVID-19 transmission, the study shows that in addition to a direct effect on viral transmission, solar radiation could also be helpful to control the pandemic by mitigating the association between human mobility and COVID-19 infection even if the moderating effect is limited.

## Materials and methods

### Data collection

We obtained our study data from Google Cloud Public Datasets (Wahltinez et al. 2020), including the numbers of daily new confirmed COVID-19 cases, mobility, and meteorological data (average temperature and rainfall) at the subregion level. Specifically, Google mobility data includes mobility information of individuals' visits to retail and recreation, groceries and pharmacies, parks, transit stations, workplaces, and residential. The data were constructed by Google by comparing visits and time spent in certain places to a baseline using information from Google Maps (Yilmazkuday 2021). Due to inconsistent trends, we excluded data on visits to parks and residences (Nouvellet et al. 2021). The start date of the mobility data was February 15, 2020. The moving average of the lag effect of human mobility for up to 21 days was calculated from data on COVID-19 cases collected after March 7, 2020. Then, we chose 3 months as the observation period (March 7–June 6, 2020) in this study.

Solar radiation data were obtained from the E-OBS daily gridded meteorological data (https://cds.climate.copernicus.eu/), which provides daily gridded weather variables at a resolution of 0.25° × 0.25° longitude in Europe. We linked the gridded weather data to the number of COVID-19 cases at the subregion level using BaiduMap SDK geocoder (https://lbsyun.baidu.com/index.php?title=webapi/guide/webservice-geocoding) to obtain the grids' locations and averaged the grid data of each region to capture climatic conditions.

After merging and excluding subregions (province, state, or the local equivalent) with incomplete data, the final dataset included 178 subregions in 15 European countries between March 7 and June 6, 2020 (Fig. 1). The number of subregions covered in each country is detailed in Table S1.

### Measuring outgoing mobility

Considering the high correlation between the four types of Google mobility (Table S2), we used principal component analysis to extract the common component as a new variable, named outgoing mobility to capture public outdoor mobility. The outgoing mobility of region $i$ on day $t$ was defined as follows:

$$mobout_{it} = 0.5159 \times mobrr_{it} + 0.4725 \times mobgp_{it} + 0.5148 \times mobts_{it} + 0.4955 \times mobw_{it} \quad (1)$$

where $mobout_{it}$ is the outgoing mobility of region $i$ on day $t$; $mobrr_{it}$, $mobgp_{it}$, $mobts_{it}$, and $mobw_{it}$ represent human mobility in retail and recreation, groceries and pharmacies, transit stations, and workplaces, respectively. All variables were standardized before input into Equation (1) (Singh and Harrison 1985). The weights of the four mobility variables in Equation (1) were obtained from the principal component analysis. $mobout_{it}$ explained 85.69% of the variance of the initial variables.

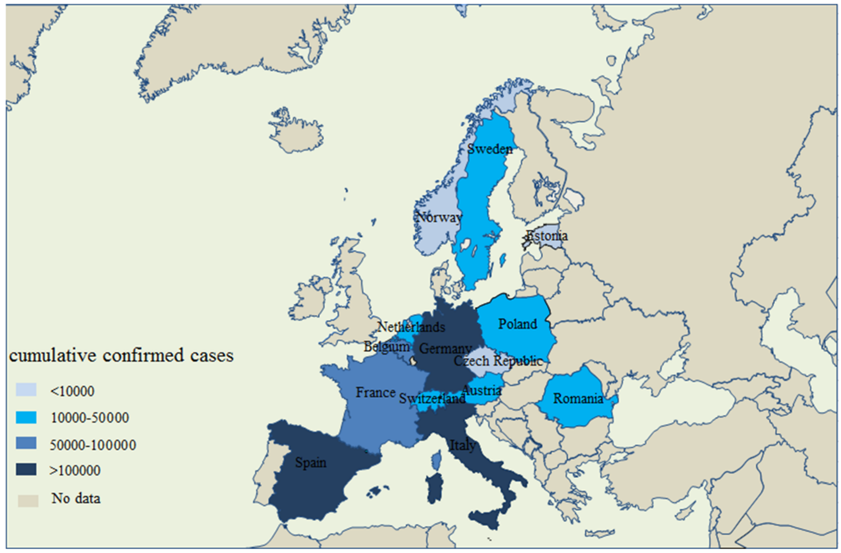


**Fig. 1.** Locations of 15 European countries and the cumulative number of confirmed new cases between 7 March and 6 June 2020 in the included subregions in each country.

Our main analysis used outgoing mobility data to explore the association between outgoing mobility and COVID-19 infection as well as the moderating effect of solar radiation. In the additional analysis, we used mobility data for retail and recreation, groceries and pharmacies, transit stations, and workplaces, respectively, to test the moderating effect of solar radiation.

## Statistical analysis

We used dynamic panel models to capture information on the partial adjustment mechanism of COVID-19 infections by adding lagged dependent variables to the model (Weinhold 1999; Leszczensky and Wolbring 2019). The most commonly used methods for estimating dynamic panel models are Arellano and Bond's (1991) difference generalized method of moments (GMM) and Blundell and Bond's (1998) system GMM. However, both perform poorly when the panel is characterized by a low number of individuals (Bogliacino et al. 2012). Thus, we used the least squares dummy variable corrected (LSDVC) estimator (Bruno 2005a), which performs well when the number of individuals is small and the panel is severely unbalanced (Bruno 2005b). Dang et al. (2015) found that the LSDVC estimator performs better for estimating dynamic panel data models in various experiments and empirical research when allowing for the presence of unobserved heterogeneity, endogeneity, and residual serial correlation. We also used the standard fixed effects estimation as a robustness check (Flannery and Hankins 2013).

Given the incubation period of COVID-19, we used a moving-average approach to account for the lag effect of solar radiation, human mobility, temperature, and rainfall (Xie and Zhu 2020; Duan et al. 2019). There were two parts to our analysis. Firstly, we examined the association of COVID-19 infection with human mobility and solar radiation (Model 1) as follows:

$$Y_{it} = \alpha_0 + \alpha_1 Y_{i,t-1} + \alpha_2 solar_{it_l} + \alpha_3 mobility_{it_l} + \alpha_4 tem_{it_l} + \alpha_5 rain_{it_l} + \eta_t + \mu_i + \varepsilon_{it} \quad (2)$$

where $t$ is the date and $i$ is the subregion; $Y_{it}$ is the daily number of new confirmed COVID-19 cases; $solar_{it_l}$ and $mobility_{it_l}$ represent the $(l+1)$-day moving average term (lag0–$l$) of solar radiation and human mobility in the region $i$ (we considered three lag levels: 1 week, $l$= 7; 2 weeks, $l$= 14; and 3 weeks, $l$= 21), respectively; $tem_{it_l}$ and $rain_{it_l}$ are the average temperature and rainfall during the same period, respectively; $\eta_t$ is the day fixed effects; $\mu_i$ is the unobserved subregion-specific effect; $\varepsilon_{it}$ is the regression residual; $\alpha_0$ is the intercept; and $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$ and $\alpha_5$ are the corresponding coefficients.

Next, we explored whether solar radiation moderates the relationship between human mobility and COVID-19 infection using Model 2 (Equation (3)). The variables were centered before the interaction term was calculated to avoid multicollinearity (Zheng et al. 2021). The model was expressed as follows:

$$Y_{it} = \beta_0 + \beta_1 Y_{i,t-1} + \beta_2 solar_{it_l} + \beta_3 mobility_{it_l} + \beta_4 solar_{it_l} \times mobility_{it_l} + \beta_5 tem_{it_l} + \beta_6 rain_{it_l} + \eta_t + \mu_i + \varepsilon_{it} \quad (3)$$

where $\beta_0$ is the intercept and $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, and $\beta_5$ are the corresponding coefficients.

**Table 1** Descriptive statistics of COVID-19 patients, meteorological variables, and outgoing mobility

| Variable | Mean | Std.Dev. | Min | Max |
|---|---|---|---|---|
| Daily new confirmed cases | 65.700 | 188.127 | 0 | 3251 |
| Solar radiation (W/m$^2$) | 235.410 | 65.770 | 15.925 | 415.9 |
| Average temperature (°C) | 11.235 | 5.117 | −9.844 | 26.104 |
| Rainfall (mm) | 1.409 | 3.377 | 0 | 47.171 |
| Outgoing mobility | −0.650 | 1.574 | −4.623 | 5.006 |

*Std.Dev.* standard deviation

## Results

### Descriptive analysis

Table 1 presents the descriptive statistics for meteorological variables, daily numbers of COVID-19 patients, and outgoing mobility. Over 923,000 confirmed COVID-19 cases were included in our study. The average daily number of new confirmed cases was 65.7 (maximum: 3,251). The average daily mean solar radiation level was 235.410 W/m$^2$ (minimum: 15.925 W/m$^2$). The average daily mean temperature and rainfall were 11.235 °C and 1.409 mm, respectively.

Table 2 shows the Spearman correlation coefficients between meteorological variables and mobility. Outgoing mobility was positively correlated with solar radiation, temperature, and rainfall.

### Estimation results of multivariate regression

Columns (1), (3), and (5) in Table 3 show the moving average lag effects (lag0–7, lag0–14, and lag0–21) of outgoing mobility and solar radiation on COVID-19 infection according to Equation (2). Outgoing mobility was positively associated with the number of daily new confirmed COVID-19 cases. A unit increase in outgoing mobility was associated with increases of 3.898 (95% confidence interval [CI]: 0.553–7.242), 6.922 (95% CI: 3.016–10.827), and 8.557 (4.736–12.378) in the number of daily new confirmed COVID-19 cases for lag0–7, lag0–14, and lag0–21, respectively.

Solar radiation was negatively correlated with the number of daily new confirmed COVID-19 cases at all three lag levels, indicating a negative association between solar radiation and COVID-19 transmission. The lag effect on COVID-19 infection of 1 W/m$^2$ of solar radiation was −0.065 (95% CI: −0.104 to −0.026) at lag0–7, −0.087 (95% CI: −0.133 to −0.041) at lag0–14, and −0.111 (95% CI: −0.162 to −0.059) at lag0–21. Thus, it was possible that high levels of solar radiation protected patients from COVID-19 infection.

Further analyses investigated the interactive impact of solar radiation and outgoing mobility. Interaction items of solar radiation and outgoing mobility were introduced in columns (2), (4), and (6) in Table 3. The interaction items were significantly and negatively correlated at the subregion level with new confirmed cases at lag0–14 and lag0–21. Fig. 2 depicts how solar radiation moderated the relationship between outgoing mobility and COVID-19 infection and suggests that high levels of solar radiation helped to mitigate the increased risk of outgoing mobility for COVID-19 infection. However, the interacting impact was too small to eliminate the risk of infection from going outside, and there was still a positive association between outgoing mobility and COVID-19 infection, even when exposed to high levels of solar radiation. The robustness checks showed similar results (Table S3).

Additional analyses using mobility data for retail and recreation, groceries and pharmacies, transit stations, and workplaces to separately test the moderating effect of solar radiation on the relationship between mobility and COVID-19 infection (Fig. S1–S4) also revealed a feeble association.

## Discussion

We explored the moderating effect of solar radiation on the relationship between human mobility and COVID-19 infection in Europe using data on new confirmed cases from 178 subregions (province, state, or local equivalent) in 15 countries from March 7–June 6, 2020.

We found a significant negative correlation between solar radiation and confirmed new COVID-19 at all three lag levels, which was consistent with most previous studies (Li et al. 2020a; Guasp et al. 2020; Thangriyal et al. 2020). Solar radiation might help to reduce the likelihood of transmission by

**Table 2** Spearman correlation coefficients among meteorological variables and outgoing mobility

| | Solar radiation | Average temperature | Rainfall | Outgoing mobility |
|---|---|---|---|---|
| Solar radiation | 1 | | | |
| Average temperature | 0.249*** | 1 | | |
| Rainfall | 0.050*** | −0.075*** | 1 | |
| Outgoing mobility | 0.048*** | 0.055*** | 0.046*** | 1 |

Level of significance: *** 1%, ** 5%, * 10%.

**Table 3** Effects of solar radiation, outgoing mobility, and their interaction on daily new confirmed cases

| Variables | lag0-7 | | lag0-14 | | lag0-21 | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Outgoing mobility | 3.898*** (0.553, 7.242) | 3.985** (0.641, 7.329) | 6.922*** (3.016, 10.827) | 6.884*** (2.942, 10.827) | 8.557*** (4.736, 12.378) | 8.215*** (4.382, 12.048) |
| Solar radiation | −0.065*** (−0.104, −0.026) | −0.067*** (−0.106, −0.029) | −0.087*** (−0.133, −0.041) | −0.096*** (−0.143, −0.048) | −0.111*** (−0.162, −0.059) | −0.126*** (−0.180, −0.071) |
| Solar * outgoing mobility | | −0.015 (−0.034, 0.005) | | −0.027** (−0.049, −0.005) | | −0.032** (−0.057, −0.006) |
| Control variables | YES | YES | YES | YES | YES | YES |
| Observations | 13,964 | 13,964 | 13,964 | 13,964 | 13,964 | 13,964 |

Level of significance: *** 1%, ** 5%, * 10%.

inactivating viruses (Carvalho et al. 2021; Sagripanti and Lytle 2020; Biasin et al. 2021). Additionally, exposure to solar radiation, mainly through outdoor activities, plays another protective role via vitamin D synthesis in the skin (Adams et al. 1982; Kimlin 2008; Engelsen 2010). Recent clinical studies have confirmed the association between vitamin D deficiency and COVID-19 incidence (Meltzer et al. 2020; Ali 2020; Luo et al. 2021). However, some studies also reported that sunshine duration (Asyary and Veruswati 2020) or solar radiation (Yao et al. 2020; Ahmadi et al. 2020) was not associated with the incidence of COVID-19 infection. Notably, because the inactivating effect of sunlight on COVID-19 may not be immediate, the lag effect of sunlight might have been overlooked in these studies. We found that outgoing mobility was positively correlated with the number of new confirmed cases at all three lag levels, consistent with previous studies (Kraemer et al. 2020; Xiong et al. 2020; Oztig and Askin 2020; Cartenì et al. 2020) and our conjecture.

Our results also demonstrated the negative moderating effect of solar radiation at 2- and 3-week lag levels, providing evidence that solar radiation could mitigate the relationship between human mobility and COVID-19 infection in Europe. This was probably because high levels of solar radiation would be more conducive to inactivating coronaviruses and reducing the viral load, thereby weakening coronavirus transmission (Ratnesar-Shumate et al. 2020) and reducing the likelihood of COVID-19 infection caused by outgoing mobility. However, coronavirus replication is exceptionally rapid (Chu et al. 2020), and most viruses spread under conditions where they are not typically exposed to sunlight or where they receive insufficient sunlight exposure to result in inactivation. Therefore, we concluded that the moderating effect of solar radiation was too weak to eliminate the correlation between outgoing mobility and COVID-19 infection. These findings contribute to the literature on the association of environmental factors and COVID-19 transmission, such as temperature (Xie and Zhu 2020; Ma et al. 2020; Shahzad et al. 2020a, b; Iqbal et al. 2020; Doğan et al. 2020), humidity (Liu et al. 2020; Fareed et al. 2020; Doğan et al. 2020), and air pollution (Zhu et al., 2020; Shakoor et al. 2020; Fareed et al. 2020; Shahzad et al. 2020b; Doğan et al. 2020). We have provided new evidence that besides the direct effect on virus transmission, solar radiation could also be helpful to control the pandemic by mitigating the association between human mobility and COVID-19 infection.

This study provides several policy implications for governments and the public. First, governments should not relax human mobility restrictions based solely on weather conditions (e.g., moving into summer) because solar radiation only weakly mitigates the relationship between human mobility and COVID-19 infection. For citizens, although the exposure to more sunlight boosts the immune system, public mobility outdoors carries a risk of infection, even on sunny days.

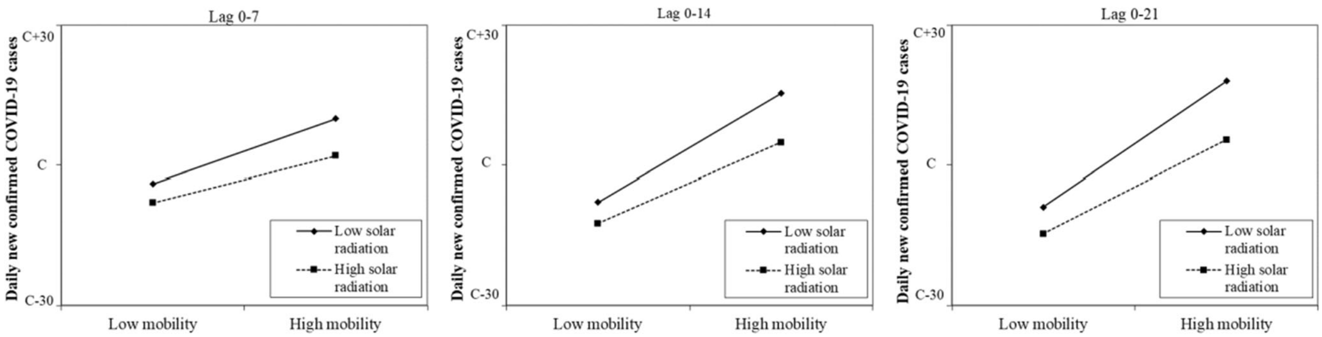


**Fig. 2.** The moderating effect of solar radiation on the relationship between outgoing mobility and COVID-19 infection. *C* represents the constant term in Equation (3). High (low) solar radiation/mobility represents one standard deviation above (below) the mean.

Overall, we recommended that people are exposed to more sunlight without increasing outdoor mobility, such as on their balconies or in their gardens. Recently, the relative control of the COVID-19 pandemic with increasing levels of vaccinations has resulted in many countries gradually lifting their lockdown restrictions. We recommend that outdoor activities are opened first and the reopening of some indoor activities, such as restaurants, be moved outside during the daytime as much as possible.

There are several limitations to our study. Firstly, we analyzed the number of daily reported new cases, which might differ from the actual numbers. Secondly, the human mobility data were only obtained from Google. Although it might well approximate the overall mobility level in each region, the numbers could be biased because Google could not capture all the mobility. Thirdly, we only focused on the association, not the causal effect, and there could be endogeneity issues caused by unidentified confounders associated with this observational study.

## Conclusion

We found a positive correlation between outgoing mobility and COVID-19 infection and a negative correlation between solar radiation and COVID-19 infection. Additionally, the influence of outgoing mobility on COVID-19 transmission decreased with increased levels of solar radiation at 2- and 3-week lag levels. However, such a moderating effect was unable to eliminate the association of outgoing mobility with COVID-19 infection. Our findings correct the misconception that it is safe to go out on a sunny day, providing policy implications that lifting lockdown measures on sunny days is inappropriate. However, considering that the pandemic has been relatively controlled with vaccinations and many countries have relaxed lockdown restrictions, it is recommended that some indoor activities, such as reopening restaurants, be moved outside during the daytime as much as possible.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-15738-w.

**Availability of data and materials** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Author contribution** Wenyu Zhao: data curation, writing (original draft preparation), visualization, and investigation.

Yongjian Zhu: validation and writing—reviewing and editing.

Jingui Xie: conceptualization, reviewing, and supervision.

Zhichao Zheng: methodology, supervision, and writing—reviewing and editing.

Haidong Luo: supervision, reviewing, and validation.

Oon Cheong Ooi: supervision, reviewing, and validation.

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## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interests** The authors declare no competing interests.

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