

Effects of Face Mask Mandates on COVID-19 Transmission in 51 Countries: Retrospective Event-Study

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Table of Contents

Original Manuscript..... 5

Supplementary Files..... 26

 Figures 27

 Figure 0..... 28

 Figure 0..... 29

 Figure 1..... 30

 Figure 2..... 31

 Figure 3..... 32

 Figure 4..... 33

 Multimedia Appendixes 34

 Multimedia Appendix 1..... 35

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Abstract

Background: The question of the utility of face masks in preventing acute respiratory infections has received renewed attention in the context of the COVID-19 pandemic. However, given the inconclusive evidence of existing RCT, evidence based on real-world data with high external validity is missing.

Objective: This study evaluated whether face mask mandates in 53 countries increased public face mask use and reduced weekly Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases and deaths.

Methods: An event-study approach was applied to real-world data pooled from three different sources: country-level information on mask use was obtained from the COVID-19 Trends and Impact Survey. Data from the Oxford COVID-19 Government Response Tracker and the COVID-19 Our World in Data dataset provided information on face mask mandates and COVID-19 reproduction numbers and growth rates.

Results: Mandates lead to an average increase in mask use by 8.54 percent points (95%-CI 2.65 to 14.44) and Sars-CoV-2 reproduction numbers declined on average by -0.35 units (95%-CI -0.56 to -0.14). While an effect of mask mandates was observed for weekly growth rates of COVID-19 cases (-6.40 percent points, 95%-CI -14.58 to 1.78), no changes in growth rates of COVID-19-related deaths (-0.22 percent points, 95% -6.84 to -6.39) were found. Our results are robust to alternate model specifications that control for additional containment policies, as well as counterfactual linear trends. Further, recommendations for voluntary mask use had no effect on mask use, reproduction numbers and growth rates.

Conclusion: Mask mandates can be used as an effective measure to curb the spread of Sars-CoV-2. Our study adds external validity to existing RCTs on the effectiveness of face masks to reduce the spread of Sars-CoV-2.

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Original Manuscript

Original Paper

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Effects of Face Mask Mandates on COVID-19 Transmission in 51 Countries: Retrospective Event-Study

Abstract

Background: The question of the utility of face masks in preventing acute respiratory infections has received renewed attention in the context of the COVID-19 pandemic. However, given the inconclusive evidence of existing RCT, evidence based on real-world data with high external validity is missing.

Objective: To add real-world evidence, this study examined whether mask mandates in 51 countries and mask recommendations in 10 countries led to increased self-reported face mask use and reductions in Sars-CoV-2 reproduction numbers and COVID-19 case growth rates.

Methods: An event-study approach was applied to data pooled from four sources: country-level information on self-reported mask use was obtained from the COVID-19 Trends and Impact Survey. Data from the Oxford COVID-19 Government Response Tracker provided information on face mask mandates and recommendations as well as any other non-pharmacological interventions implemented during the observation period. Country-specific mobility indicators from Google's community mobility reports were also included. COVID-19 reproduction numbers and case growth rates were retrieved from the COVID-19 Our World in Data dataset.

Results: Mandates lead to an average increase in mask use by 8.81 percent points ($P=.006$) and Sars-CoV-2 reproduction numbers declined on average by -0.31 units ($P=.008$). While no significant average effect of mask mandates was observed for growth rates of COVID-19 cases (-0.98 percent points, $P=.56$), results indicate incremental effects at day 26 (-1.76 percent points, $P=.04$), 27 (-1.89 percent points, $P=.05$), 29 (-1.78 percent points, $P=.04$), and 30 (-2.14 percent points, $P=.02$) after mandate implementation. For self-reported face mask use and reproduction numbers, incremental effects are seen 6 and 12 days after mandate beginning. Both incremental effects persist for more than 30 days. Further, mask recommendations increased self-reported mask use on average (5.84

percent points, $P < .001$). However, there were no average effects of recommendations on reproduction numbers or growth rates (-0.06 units, $P = .70$ and -2.45 percent points, $P = .59$). Single incremental effects on self-reported mask use were observed on days 11 (3.96 percent points, $P = .04$), 13 (3.77 percent points, $P = .04$) and 25 to 27 (4.20 percent points, $P = .048$, and 5.91 percent points, $P = .01$) after recommendation. Recommendations also affected reproduction numbers at days 0 (-0.07 units, $P = 0.03$), and 1 (-0.07 units, $P = 0.03$), and between day 21 (-0.09 units, $P = .04$) and 28 (-0.11 units, $P = .05$) and case growth rates between day 1 and 4 (-1.60 percent points, $P = .03$ and -2.19 percent points, $P = .03$) and at day 23 (-2.83 percent points, $P = .05$) after publication.

Conclusion: Contrary to mask recommendations, mask mandates can be used as an effective measure to reduce Sars-CoV-2 reproduction numbers. Mandates alone, however, are not sufficient to reduce growth rates of COVID-19 cases. Our study adds external validity to existing RCTs on the effectiveness of face masks to reduce the spread of Sars-CoV-2.

Keywords: Non-Pharmacological Interventions, Face Masks, Infectious Diseases, COVID-19, Real-World Evidence

Introduction

Viral and bacterial acute respiratory infections (ARI) are among the leading causes of death worldwide. With a total of 3.8%, ARI contributed the fourth largest share to the global burden of disease in 2019 [1]. ARI thus pose a significant threat to global health. One measure to prevent ARI, which has also been discussed extensively in the context of the COVID-19 pandemic, is the wearing of face masks. At the heart of this discussion are the following two considerations: first, a large proportion of COVID-19 infections are transmitted by asymptomatic individuals [2,3]. Second, masks worn by infected individuals are thought to reduce transmission risks. Therefore, in the face of a potentially large number of undetected cases, it has been argued that wearing masks could contribute to a sustained decrease in the spread of COVID-19 [4]. In contrast, a recently updated Cochrane review did not reach a clear conclusion regarding the preventive efficacy of face masks for viral respiratory infections [5]. Based on a total of 78 randomized controlled trials (RCTs) conducted during influenza seasons as well as during the H1N1 and COVID-19 pandemics, the authors conclude that masks alone are not sufficient to reduce the spread of respiratory viruses. However,

given the results, it should be noted that interpretation is complicated by the fact that adherence was low, and outcome measures varied across a large proportion of RCTs. Furthermore, the observations of Jefferson et al. [5] are at odds with clinical trials demonstrating the efficacy of masks in protecting uninfected individuals from COVID-19 [6,7]. Clinical trials have also shown that masks reduce the risk of transmission of influenza or Sars-CoV-2 from previously infected individuals [8].

A key advantage of studies based on real-world data is their high external validity. As such, they can significantly complement the evidence from RCTs on the efficacy of face masks in protecting against ARI. ARI can be most effectively prevented at the population level when masks are worn by both susceptible and infectious individuals [8,9]. Following this line of reasoning, the World Health Organization issued a recommendation to publicly wear face masks to contain the spread of Sars-CoV-2 [10]. This recommendation has been adopted by countries around the world by implementing face mask mandates in 2020. As some countries and regions did not introduce any face mask policies, three studies used this fact to identify the causal effect of mandates on Sars-CoV-2 infections.: Lyu and Wehby [11] conducted a natural experiment with real-world data to show that mandates in 15 U.S. states and Washington, D.C., resulted in reductions in COVID-19 growth rates of up to 19%. Another study utilizing real-world data from the Global COVID-19 Trends and Impact Survey (CTIS) found mask mandates in the US to be related to decreases in daily new cases, daily new deaths, daily new hospital admissions, and increases in population shares wearing masks [12]. These findings are corroborated by Mitze et al. [13] who, using a synthetic control design, found a 47% reduction in daily COVID-19 case growth rates attributable to a local mask mandate in Jena, Germany. In addition, two other population-level studies found evidence for a direct association between wearing face masks and COVID-19 outcomes: controlling for time-constant unobserved heterogeneity, Rader et al. [14] report decreasing growth rates of COVID-19 cases with increasing state-specific proportions of face mask wearers at the US state level. Leffler et al. [15] employ a cross-sectional design across 196 countries and observe that longer durations of face mask usage are inversely associated with COVID-19 mortality.

To our knowledge, no real-world studies have been conducted to compare the effects of face mask mandates on Sars-CoV-2 infections internationally. Our study provides missing evidence. A prerequisite for mask mandates to be effective is that they encourage populations to wear masks [5,16]. Therefore, we exploited the longitudinal variation in COVID-19 outcomes to firstly evaluate the hypothesis that mask mandates increased mask use in 51 countries worldwide. We then used the

same design to test the hypothesis that mask mandates lead to a decrease in reproduction numbers and growth rates of COVID-19 related cases. In planning future non-pharmacological interventions, it is also important to be able to assess whether mandates are necessary to achieve the desired effect on health outcomes, or whether recommendations are sufficient. Thus, the hypothesis that recommendations for face masks would lead to an increase in self-reported face mask use and a reduction in reproduction numbers and case growth rates was also evaluated. COVID-19 is a specific type of ARI. With the exception of rhinovirus infections, ARI are comparable in terms of their transmission routes. The results of our study therefore not only provide an indication of the effectiveness of face mask interventions in the context of the COVID-19 pandemic but may also be indicative of how future ARI outbreak scenarios could potentially be addressed.

Methods

Measures

We gathered information on proportions of face mask wearers in 105 countries from the Covid-19 Trends and Impact Survey (CTIS), which is administered by the Carnegie Mellon University and the University of Maryland in partnership with Meta [17]. CTIS utilizes an administrative region-stratified random sample that was daily drawn from Facebook's active user base. Via Facebook's news feed, drawn individuals were invited to participate in the survey. After informed consent, users were provided a link to a web-based questionnaire on COVID-19-related attitudes, symptoms and behaviors. Daily population shares of self-reported face mask users were calculated from the responses of survey participants who stated that they had worn a face mask always or most of the time when in public. Prior to aggregation, individual-level observations were reweighted by means of survey weights provided by Meta. While no information collected by the survey is shared with Meta, Meta itself calculated weights that adjust for non-response and sampling frame mismatches with country-specific populations based on age, gender, and administrative regions [18]. Weights were made available to researchers without disclosing any user-related content.

In order to allow for linear model specifications, we chose two country-specific COVID-19 outcome measures: Sars-CoV-2 reproduction numbers and 3 day growth rates of COVID-19-associated cases per 100,000 inhabitants. To obtain information on the progression of reproduction numbers over time, we utilized the Our World in Data COVID-19 dataset [19]. The daily effective reproduction numbers included in the dataset were derived using Kalman filter estimates of weekly case growth rates as described in Arroyo-Marioli et al. [20].

Data on non-pharmacological interventions were obtained from the Oxford Covid-19 Government Response Tracker (OxCGRT) [21]. Between January 1, 2020, and December 31, 2022, the tracker collected starting and end dates of COVID-19-related policy interventions in 186 countries. The OxCGRT dataset also includes a measure that captures the scope of face mask-related policies on an ordinal scale from 1 to 4. 1 designates official face mask recommendations. Mandates are indicated by values from 2 to 4. Using this scale, we defined the levels of mandates according to the extent to which exemptions from the obligation to wear face masks in public were made: corresponding to a value of 2, level 1 applies to all mandates that required face masks to be worn in some public places where other people were present or where social distancing was not possible, such as certain shops or public transport. Level 2 is equivalent to a value of 3. Related mandates were more restrictive and generally required people to wear face masks in public places where other people were present or where social distancing was not possible. Level 2 mandates only allowed people not to wear masks in places such as less crowded streets or parks. Level 3 corresponds to a value of 4 and means that face masks had to be worn at all times outdoors, regardless of location or the presence of other people. We created dummy variables for each mandate level to indicate whether mandates at a particular level were enacted at a particular time. The OxCGRT data further include an item that differentiates between policies targeted at subgroups or at entire populations. A control variable for country-specific face mask mandates that applied only to subgroups was generated from this item and the indicators for level 1 face mask mandates. The variable takes the value one at dates when the corresponding subgroup mandates were active and otherwise it takes the value zero. This allows for the inclusion of all subgroup mandates. None of the countries included implemented subgroup mandates at a level higher than level 1. We furthermore added date-specific indicators of the following additional non-pharmacological interventions: school closures, bans on events and gatherings, international travel restrictions as well as curfews and measures to protect the elderly. Measures to protect the elderly include recommendations or restrictions on the number of visitors and on hygiene in nursing homes. At a given time, indicators for additional non-pharmacological interventions indicate whether the intervention is recommended or mandatory, as opposed to not recommended or mandatory. Country-level mobility indicators are also included in the analyses. The mobility indicator is calculated by Google from aggregated location data that users have agreed to share through their devices. The metric indicates daily relative changes in mobility as compared to the baseline period between January 3 and February 6, 2020 [22].

Observational Sample

For the analyses, we constructed a longitudinal dataset by merging daily repeated cross-sections of

the CTIS with the OxCGRT, Our World in Data and Google mobility datasets. Beginning in April 23, 2020, when first CTIS data became available, the observation period was restricted to October 31, 2020, yielding $T = 192$ observation dates in calendar time. 102 countries with national-level policy interventions targeted at general populations are commonly represented in all three datasets. Out of these, 80 enacted national mandates on the use of face masks in public. Because recording of CTIS data commenced only after interventions, effects of face mask policies could not be identified for 34 countries. These countries were excluded from the analysis. Another 3 countries were excluded because information on Sars-CoV-2 reproduction numbers was not available at the time when mask mandates became effective.

As can be inferred from Table 1, this resulted in a total of $N = 51$ observed countries worldwide, with 45 countries that implemented level 1 face mask interventions. CTIS Data and information on Sars-CoV-2 reproduction numbers and case growth rates were available for 8 countries that did not enact any face mask policies throughout the observation period. These countries served as the control group. The countries included were Albania, Azerbaijan, Belgium, Bangladesh, Belarus, Bolivia, Costa Rica, Germany, Denmark, Egypt, Finland, France, Ghana, Greece, Honduras, Croatia, Hungary, Ireland, Jordan, Japan, Kazakhstan, South Korea, Kuwait, Libya, Sri Lanka, Moldova, Myanmar, Nigeria, Nicaragua, Netherlands, Nepal, New Zealand, Oman, Panama, Philippines, Portugal, Paraguay, Palestine, Qatar, Romania, Saudi Arabia, Sudan, Serbia, Slovakia, Sweden, Tunisia, Turkey, Uruguay, Uzbekistan, Yemen, South Africa

Table 1. Observations and CTIS-respondents in mandate and non-mandate countries. Data sources: COVID-19 Trends and Impact Survey [17] & Oxford COVID-19 Government Response Tracker [21].

	Countries	Observations	CTIS-Respondents
No Mandate	8	1,536	2,158,083
Mandate	43	8,256	6,611,911
Total	51	9,792	8,769,994

Empirical Strategy

To evaluate face mask mandates, we follow the recommendations of Lison et al. [23] for effectiveness assessments of non-pharmaceutical interventions. A test of our hypotheses is provided by the following potential outcomes framework: Let $y_{1,ct}$ denote a potential outcome of interest in country c at calendar time t if a mandate is implemented. $y_{0,ct}$ designates the potential outcome of interest in the same country if no mandate has been implemented. The average treatment effect on

the outcome of interest in countries treated with mandates (ATT) is then defined as

$$\beta = \mathbb{E}[y_{1,ct} - y_{0,ct} | D_{ct} = 1], \quad (1)$$

where $D_{ct} = (0,1)$ is a mandate indicator switching on during mandate periods $s < T$. Because any given country is only observed for either $D_{ct} = 1$ or $D_{ct} = 0$, observed outcomes of interest y_{ct} can be written

$$y_{ct} = y_{0,ct} + [y_{1,ct} - y_{0,ct}] \times D_{ct} \quad (2)$$

When fitted to real-world data such as those generated with CTIS, models require additional identifying assumptions in order to provide causal interpretations of β : A first assumption that is being made is that, in absence of any mandates, outcomes would exhibit parallel trends for intervention and non-intervention countries. The parallel trends assumption ensures that estimates of the mandate effect are not biased by unobserved time-varying heterogeneity. Identification of the average treatment effect on countries with face mask mandates, β , further requires that country populations do not demonstrate any self-reported anticipatory uptake of face masks or decreases in reproduction numbers and growth rates prior to mandate introduction. In terms of Granger causality, a causal interpretation can be given to estimates $\hat{\beta}$ if mandate effects are observed after intervention, only. In addition, we assume face mask mandates to homogeneously affect all intervention countries in all time periods and countries. Note also that estimates $\hat{\beta}$ are unbiased only under strict exogeneity of D_{ct} . Furthermore, our empirical strategy aims to estimate changes in levels of self-reported face mask use, Sars-CoV-2 reproductions numbers as well as case growth rates. Countries with large differences in outcome baseline levels can therefore be included in the analysis without violating the underlying assumptions regarding the functional form of the model specifications outlined below. Based on the above assumptions, we estimate average mandate effects on treated countries β by

$$z_{ct} = \lambda_c + \varphi_t + \sum_{\substack{r=T_0, \\ r \neq -1}}^{r=T_1} \beta_{t+r} D_{ct+r} + \gamma X_{ct} + \varepsilon_{ct} \quad (3)$$

Whereby either

$$y_{ct} = \exp(z_{ct}) / 1 + \exp(z_{ct})$$

or $y_{ct} = z_{ct}$ designates Sars-CoV-2 reproduction numbers or case growth rates, respectively. Within this specification strategy, country and calendar time-specific fixed effects λ_c and ϕ_t provide full non-parametric control of any unobserved time- and country-constant heterogeneity [24]. X_{ct} represents a row vector of covariates containing subgroup treatment and treatment level indicators. Measures of COVID-19 outcomes depend on country-specific testing rates [25]. X_{ct} therefore also contains the number of country-specific COVID-19 tests per 100.000 inhabitants. Moreover, non-pharmacological interventions other than mask mandates as well as domestic mobility are a possible source of heterogeneity in Sars-CoV-2 reproduction numbers and case growth rates during the observation period. This may lead to biased estimates of mask mandate effects. For reproduction numbers and growth rates, X_{ct} thus includes indicators for both, for country-level mobility and non-pharmacological interventions other than mask mandates. γ is a column vector designating the corresponding parameters of interest. Assuming a quasi-binomial distribution of country proportions of self-reported face mask wearers, an error is given by $\varepsilon_{ct} \sim \text{Logistic}(\mu, \phi)$, with mean μ and dispersion parameter ϕ . $\varepsilon_{ct} \sim (0, \sigma^2)$ is assumed for linear models of Sars-CoV-2 reproduction numbers and growth rates. By specifying $r = T_0, \dots, T_1$ leads and lags of the mandate effect, with $T_0 < 0$ the lowest and $T_1 \geq 0$ the highest number of leads and lags considered, we employ a design that incorporates incremental mandate effects. This specification provides a test of the previously outlined assumption of no anticipatory mask uptake.

Since countries imposed face mask mandates at different calendar dates, utilizing already treated countries as control groups for yet to be treated countries is likely to induce heterogeneities of policy effects across treated units. Estimating equation (3) with conventional two-way fixed effects (TWFE) methods would therefore result in biased estimates $\hat{\beta}$. Hence, in order to relax the treatment homogeneity assumption made above, we group countries into cohorts depending on calendar dates of mandates becoming effective, as suggested by Sun and Abraham [26]. Countries without any face mask mandates during the entire observation period are combined into a single control group. Cohort outcomes at $r = -1$, i.e. the period before mandate implementation, are used as baseline outcomes. Estimates of average treatment effects are obtained thru weighing aggregated cohort-specific effects by cohort size.

Ethical Considerations

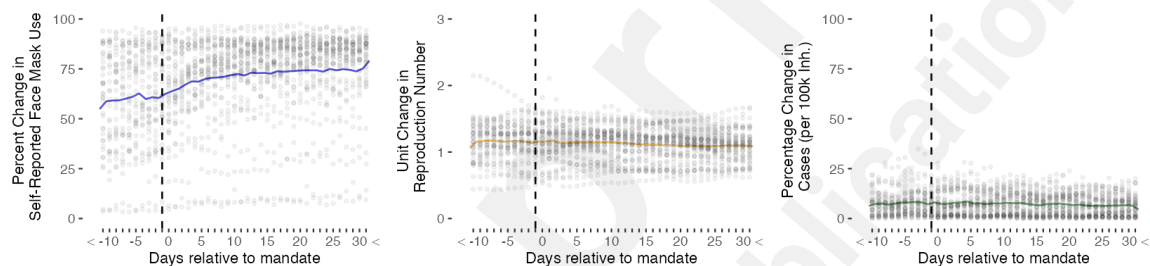
Only publicly available data, aggregated at country level, has been analyzed. This eliminates any re-identification risks of individuals. The study did not require any direct or indirect interaction with human subjects. This means that the regulatory requirements for research involving human subjects

are not met. This study is therefore exempt from institutional review board approval.

Results

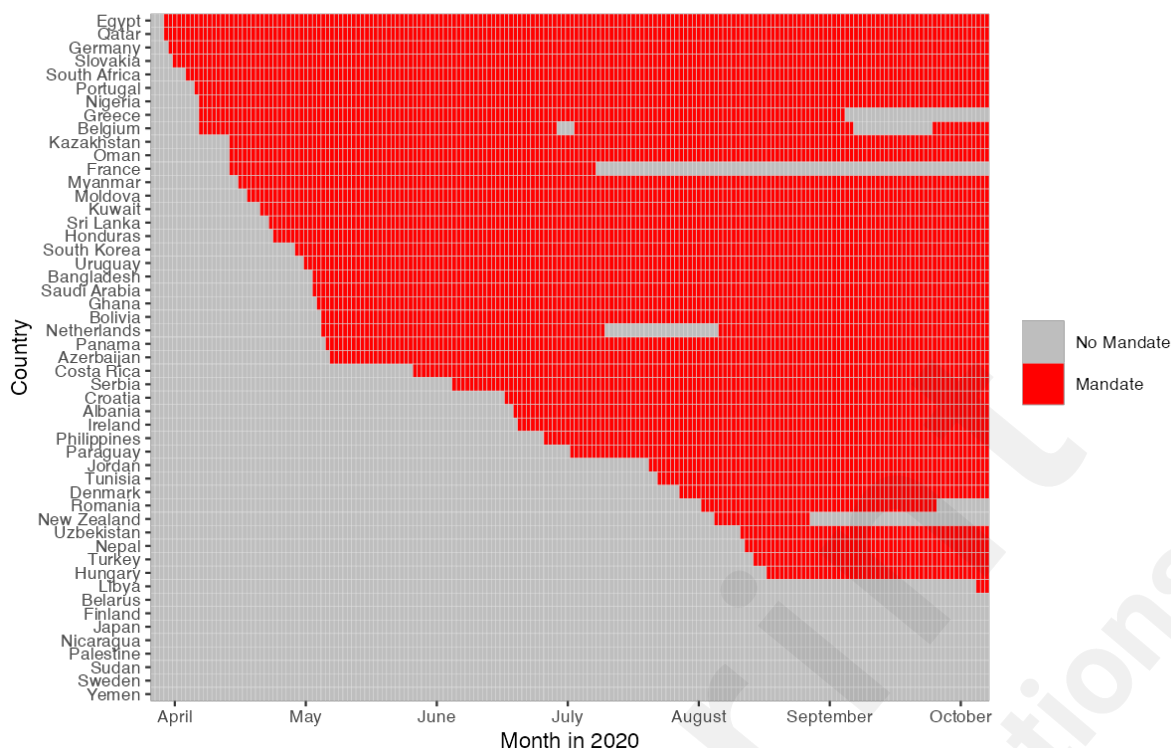
Figure 1 illustrates the daily average evolution of self-reported face mask use, Sars-CoV-2 reproduction numbers, and case growth rates in countries with mask mandates. Visual inspection of the left panel reveals a substantial increase in self-reported face mask wearers around the time the regulations came into effect in these countries. As further shown in the middle and right panels, no clear trends are visible for average Sars-CoV-2 reproduction numbers or growth rates of COVID-19 cases.

Figure 1. Daily average evolution of face mask usage, Sars-CoV-2 reproduction numbers, and growth rates of COVID-19 cases in mandate countries. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21] & Our World in Data – COVID-19 Dataset [19].



The timing of the introduction of face masks mandates in each country during the observation period is presented in Figure 2. There is a range of 186 days between the dates when mandates were introduced: while in Egypt and Qatar the wearing of masks in public was compulsory from 4 days after the start of the observation period, i.e. from 26 April 2020, in Libya it was only compulsory from 29 October 2020, i.e. three days before the end of the observation period.

Figure 2. Face mask mandate periods by country. Data source: Oxford COVID-19 Government Response Tracker [21].



We first estimated equation (3) for proportions of self-reported face mask users, Sars-CoV-2 reproduction numbers, as well as growth rates of COVID-19-related cases. All post-mandate period effects were aggregated to the total ATT of face mask mandates. As shown in Table 2, the results indicate that – on average – mandates are followed by an increase in self-reported face mask wearers of 8.81 percent points ($P=.006$). Likewise, an average decrease of -0.31 units ($P=.008$) was observed for Sars-CoV-2 reproduction numbers after face mask mandates became effective. No reduction of growth rates of COVID-19 cases was observed after mask mandates became effective (-0.98 percent points, $P=.56$).

Table 2. Event-study-regressions of self-reported face mask usage, Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases on face mask mandates. Percent point changes are shown for self-reported face mask use and growth rates of COVID-19 cases and unit changes are shown for reproduction numbers. S.E. (in parentheses) are clustered at the country level. The ATT (Average Treatment Effect on the Treated) is obtained by averaging Sun and Abraham interaction-weighted estimates of post-mandate period effects [26]. “Inh.” and “FE” are abbreviations from “Inhabitants” and “Fixed Effects”. Data sources: COVID-19 Trends

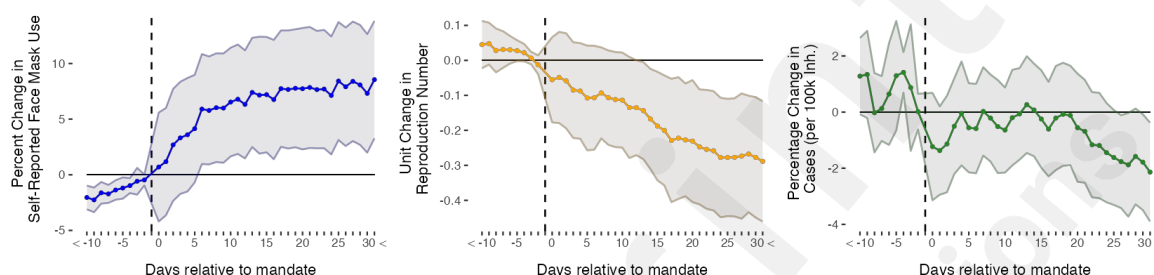
and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].

	Self-Reported Face Mask Usage	Reproduction Number	Growth in Cases
ATT	8.81 (3.08) P=.006	-0.31 (0.11) P=.008	-0.98 (1.66) P=.56
Subgroup Mandate	7.33 (4.76) P=.13	0.03 (0.09) P=.78	1.21 (1.54) P=.44
Level 2 - Mandate	4.49 (4.88) P=.36	0.16 (0.11) P=.14	1.06 (1.17) P=.37
Level 3 - Mandate	2.43 (4.62) P=.60	0.0006 (0.11) P=.995	1.39 (2.13) P=.52
School Closure	-	-0.02 (0.07) P=.74	0.64 (1.01) P=.53
Ban on Events	-	-0.11 (0.05) P=.05	0.23 (1.13) P=.84
Ban on Gatherings	-	-0.04 (0.04) P=.32	-1.89 (1.27) P=.14
Curfew	-	0.01 (0.06) P=.93	1.49 (1.21) P=.22
International Travel Restrictions	-	-0.13 (0.06) P=.05	-2.43 (1.17) P=.04
Protection of the Elderly	-	0.06 (0.09) P=.46	-0.84 (2.89) P=.77
Mobility	-	0.01 (0.00) P=.1	0.51 (0.14) P<.001
Tests per 100k Inh.	-	0.00 (0.00) P=.07	0.00 (0.00) P=.02
Country FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	8,867	6,078	5,960

The incremental effects of pre- and post-mandate implementation periods according to the event study specification of equation (3) are shown in Figure 3. As can be seen, incremental effects of face mask mandates are seen in an increase in the proportion of self-reported mask wearers at 6 days and decreases in reproduction numbers at 12 days after mandate beginning. For self-reported face mask use and reproduction numbers, the effects continuously persist for more than 30 days. Our estimations furthermore yield single mandate effects on case growth rates at days 26 (-1.76 percent points, P=.04), 27 (-1.89 percent points, P=.05), 29 (-1.78 percent points, P=.04) and 30 (-2.14 percent points, P=.02) after mandates were enacted. We observe pre-trends in self-reported face mask

use at up to 4 days and at day 4 in case growth rates prior to the beginning of mandate periods. Our identifying assumption of no anticipatory events is supported for the period of at least 4 days prior to the beginning of mandates for all outcomes.

Figure 3. Incremental effects of face mask mandates on self-reported face mask use, Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases. Colored points depict Sun and Abraham interaction-weighted estimates of relative period effects [26]. 95%-CI are indicated by colored areas. S.E. are clustered at the country level. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].



To assess the parsimony of models of reproduction numbers and growth rates, equation (3) was re-estimated restricting the parameters of mobility and containment measures other than mask mandates to jointly equal zero. Restricted models yielded a lower mandate ATT for Sars-CoV-2 reproduction numbers (-0.32 units, $P=.01$). In line with the original specification, the results do not demonstrate any relationship between mask mandates and growth rates of COVID-19 cases (-1.21 percent points, $P=.43$). In post-mandate periods, the restricted specification also reveals no changes in terms of incremental decreases in Sars-CoV-2 reproduction numbers: our findings demonstrate a negative effect of mask mandates on reproduction numbers at 12 days after mandate beginning. The observed incremental effects last longer than 30 days. A single incremental effect of mandates on COVID-19 case growth rates is observed at day 30 after mandate implementation (-1.84 percent points, $P=.03$). A Wald test was employed to test the null hypothesis that parameters of mobility and containment measures other than mask mandates jointly equal zero. The hypothesis was not rejected for both models of mask mandate effects on reproduction numbers (2.67, $P=.01$) and case growth rates (6.13, $P<.001$). We therefore retained the initial model specification including indicators of mobility and non-pharmacological interventions other than mask mandates.

Equation (3) was also re-estimated with counterfactual linear trends in order to evaluate the robustness of the initial results. Compared to the baseline specification, the observed mandate ATTs

are lower for self-reported face mask use (8.66 percent points, $P=.01$) and remain unchanged for Sars CoV-2 reproduction numbers (-0.31 units, $P=.01$). As in the original specification, no ATT is found for the growth rates of COVID-19-related cases (-0.97 percent points, $P=.56$). Incremental increases in self-reported mask use are observed at 6 days after mandate implementation. In addition, incremental decreases in COVID-19 reproduction numbers are demonstrated at 12 days. The incremental effects persist for more than 30 days for both models. Both results are consistent with the original specification. Significant incremental effects of mandates on COVID-19 case growth rates are found between 26 and 30 days (-1.76 percent points, $P=.04$, and -2.13 percent points, $P=.02$) after the mandates take effect.

As a final sensitivity check, we have taken into account that selection into mandate policies must be strictly exogenous for our specification to yield unbiased estimates of mandate effects. However, the possibility that countries enacted mask mandates depending on the course of the pandemic cannot be ruled out. To rule out bias, mandate indicators D_{ct} were regressed on reproduction numbers and growth rates of COVID-19 cases, controlling for country-specific fixed effects. No significant effects were observed. In conclusion, the results of the sensitivity analyses confirm the baseline estimation results. See the appendix for an overview of all results from above sensitivity analyses.

The mask mandates evaluated required populations of the countries under study to wear masks. However, in 25 of the 102 countries represented in the data underlying our analysis, recommendations for voluntary mask use were issued first. Therefore, the final step was to investigate whether these recommendations might have been sufficient to prevent COVID-19 transmission. Accordingly, the baseline specification of equation (3) was re-estimated with cohorts defined depending on calendar dates of recommendations becoming effective. 12 countries were excluded from the evaluation because they demonstrated non-parallel outcome trends in preliminary analyses. This resulted in a total of 80 countries included in the analysis: information on self-reported mask use, COVID-19 reproduction numbers, and case growth rates was available for 10 countries at the time of face mask recommendations. The control group consisted of a total of 70 countries, of which 3 did not implement any face mask policies while 67 enacted mask mandates, only.

As can be seen from Table 3, no significant ATTs of mask recommendations were found for reproduction numbers and case growth rates (-0.06 units, $P=.70$ and -2.45 percent points, $P=.59$). However, an ATT of 5.84 percentage points ($P<.001$) was shown for mask use. In addition, increases of mask use by 11.70 percent points ($P = .001$) and 13.60 percent points ($P = .002$) are observed for

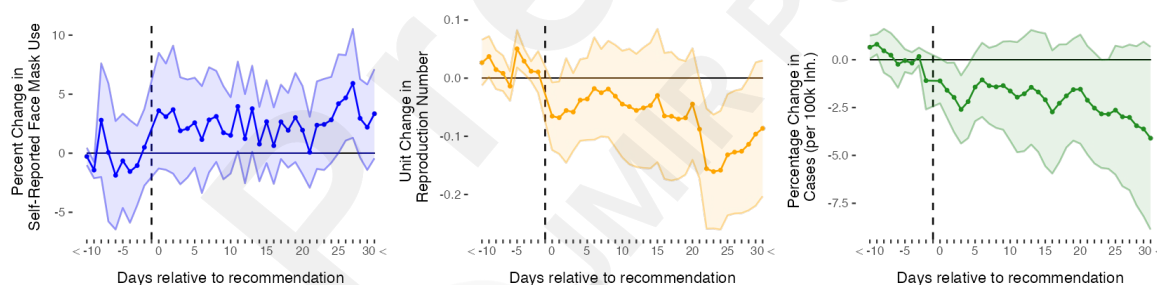
mask mandates and subgroup mandates, respectively. Our findings also demonstrate mandate effects on reproduction numbers (-0.19 units, $P=.04$).

Table 3. Event-study-regressions of self-reported face mask use, Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases on face mask recommendations. The table reports percent point changes of self-reported face mask use and growth rates of COVID-19 cases and unit changes of reproduction numbers. S.E. (in parentheses) are clustered at the country level. The ATT (Average Treatment Effect on the Treated) is obtained by averaging Sun and Abraham interaction-weighted estimates of post-recommendation period effects [26]. “Inh.” and “FE” are abbreviations from “Inhabitants” and “Fixed Effects”. Data Sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].

	Self-Reported Face Mask Usage	Reproduction Number	Growth in Cases
ATT	5.84 (1.60) $P<.001$	-0.06 (0.16) $P=.70$	-2.45 (4.54) $P=.59$
Mask Mandate	11.70 (3.44) $P=.001$	-0.19 (0.09) $P=.04$	-2.01 (1.36) $P=.15$
Subgroup Mandate	13.60 (4.34) $P=.002$	-0.18 (0.12) $P=.16$	-3.18 (2.22) $P=.16$
Level 2 – Mandate	1.16 (3.20) $P=.72$	0.05 (0.08) $P=.54$	2.22 (1.38) $P=.11$
Level 3 – Mandate	-1.27 (3.88) $P=.74$	-0.08 (0.10) $P=.42$	0.76 (1.99) $P=.70$
School Closure	-	0.07 (0.05) $P=.12$	1.13 (0.92) $P=.22$
Ban on Events	-	-0.12 (0.05) $P=.02$	-0.38 (0.77) $P=.62$
Ban on Gatherings	-	-0.02 (0.05) $P=.70$	-0.70 (1.02) $P=.50$
Curfew	-	-0.09 (0.04) $P=.02$	-0.81 (0.66) $P=.23$
International Travel Restrictions	-	-0.09 (0.06) $P=.15$	-1.58 (1.41) $P=.27$
Protection of the Elderly	-	0.04 (0.05) $P=.42$	-0.78 (1.50) $P=.61$
Mobility	-	-0.01 (0.01) $P=.26$	0.37 (0.098) $P<.001$
Tests per 100k Inh.	-	0.00 (0.00) $P=.20$	0.00 (0.00) $P=.02$
Country-FE	Yes	Yes	Yes
Time-FE	Yes	Yes	Yes
Observations	13,159	8,500	8,325

Figure 4 presents the effects of face mask recommendations in 10 countries. As can be inferred, recommendations had an isolated incremental effect on self-reported use face masks use on days 11 (3.96 percent points, $P=.04$), 13 (3.77 percent points, $P=.04$) and 25 to 27 (4.20 percent points, $P=.048$, and 5.91 percent points, $P=.01$) after publication. Single incremental effects of mask recommendations are also observed for reproduction numbers at days 0 (-0.07 units, $P=0.03$), and 1 (-0.07 units, $P=0.03$), and between day 21 (-0.09 units, $P=.04$) and 28 (-0.11 units, $P=.05$) after publication. Case growth rates decrease incrementally between day 1 and 4 (-1.60 percent points, $P=.03$ and -2.19 percent points, $P=.03$) and at day 23 (-2.83 percent points, $P=.05$) after recommendations were published. Pre-trends are shown for more than 10 days and at 9 days prior to recommendation for self-reported face mask use, at 9, 5 and 4 days for reproduction numbers, and at 10 and 9 days for growth rates of COVID-19-related cases. These findings support the assumption of no anticipatory events for at least 3 days prior to face mask recommendations.

Figure 4. Incremental effects of face mask recommendations on self-reported face mask use, Sars-CoV-2 reproduction numbers and growth Rates of COVID-19 cases. Colored points depict Sun and Abraham interaction-weighted estimates of relative period effects [26]. 95%-CI are indicated by colored areas. S.E. are clustered at the country level. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].



Discussion

According to the above results, the introduction of face mask mandates was associated with an increase in self-reported face mask use and a decrease in Sars-CoV-2 reproduction numbers. The sustainability of face mask mandates is demonstrated by the fact that the observed effects persist for more than thirty days after the mandates come into effect. Our results are robust to different sensitivity analyses. Thus, during our observation period, face mask mandates proved to be an effective non-pharmacological measure to reduce Sars-CoV2 reproduction numbers.

The effectiveness of mask use has occasionally been questioned in public debate [9]. This is particularly true in light of the inconclusive findings of Jefferson et al [5]. According to the authors, a key problem with the existing RCTs is that they have a wide variation in outcome measures, making it difficult to compare results. By using real-world data, our study allows comparison of Sars-CoV-2 reproduction numbers and case growth rates across 51 countries. This increases the external validity of previous findings, which are largely based on RCTs. Furthermore, our results support the findings of Ueki et al. [27] and Cheng et al. [28]. Based on aerosol and droplet transmission models, both papers show that face masks are effective in reducing the risk of transmission in low virus load environments such as public spaces.

In addition, our observations suggest inconclusive evidence on the effect of mask mandates on growth rates of COVID-19 cases. While Chernozhukov et al. [29] demonstrate that mask mandates have contributed to a reduction in case growth rates at the US state level, we found no differences in COVID-19 cases between mandate and non-mandate countries. The lack of mask mandate effects in our study may be, at least in part, due to the high infectiousness of the Sars-CoV-2 virus. With such high infectiousness, implementation of mask mandates may not be sufficient to prevent clusters of COVID-19 cases in the most vulnerable populations, such as the elderly or immunosuppressed. This may be particularly true for facilities such as old peoples' or care homes, where most of the cases occurred. Inadequate compliance with mask mandates or improper use of face masks by infectious individuals in contact with these populations is hardly always avoidable. The occurrence of such clusters is therefore difficult to prevent. Stricter additional containment measures may have been required to protect the most vulnerable populations.

For masks to have a preventive effect, they must be worn by the public. Accordingly, Jefferson et al [5] discuss lack of mask adherence as a possible cause of the inconclusive results of RCTs on the effectiveness of face masks in preventing ARIs. To increase the willingness to wear masks, public health authorities used social media to educate the public during the COVID-19 pandemic [30] or distributed masks free of charge [31]. In addition to these interventions, governments have introduced more drastic initiatives, such as mandatory masks, which penalize people who do not wear masks. Adding to the existing evidence from RCTs, our study shows that the self-reported use of masks is significantly increased as a result of such regulations. While this is consistent with a previous study that found high compliance with mandatory mask use [12], our results further indicate

that mandates rather than recommendations are required to ensure self-reported mask adherence.

Limitations

It cannot be completely ruled out that the estimates of self-reported face mask use are biased due to the employed sampling method. The data on self-reported face mask use come from country-specific samples of Facebook users. The distribution of these samples may not reflect the composition of each country's population. The survey weights calculated by Meta, which are based on population- and region-specific gender and age distributions, may only partially compensate for such biases. Another possible limitation is that it can be assumed that the course of infection is determined by individual behavior. No micro-level data were available for the present study that would have allowed us to test this assumption and accurately estimate behavioral effects on the effectiveness of mask mandates. A third complication is that the available data do not allow to distinguish between the type of mask worn (surgical vs. N95 mask). Depending on mask type, the effects of mandates on reproduction numbers may differ. Such differences cannot be estimated within the framework of the present study.

Conclusions

Our results suggest that mask mandates encourage self-reported mask use and reduced Sars-CoV-2 reproduction numbers. They may be a simple measure in a non-pharmacological strategy to control epidemics caused by respiratory-transmissible pathogens. When implementing mask mandates, special care should be taken to ensure compliance with respect to the most vulnerable individuals. Given the lack of mandate effects on growth rates of COVID-19 cases, additional containment measures may be required to ensure adequate protection of the most vulnerable populations.

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Data Availability

The dataset generated and analyzed as part of this study are available on request.

Authors' Contributions

AFN, MSA and MK selected, cleaned, and merged the datasets for analysis. The statistical models for the analysis were specified by AFN and implemented by AFN and MSA. All authors, AFN, FB, MSA, MK and FPM, contributed to the interpretation of results. Literature research was conducted

by MK. MK and AFN visualized Data and Results. All authors, AFN, FB, MSA, MK and FPM, contributed to the writing of the manuscript. FB provided the required resources.

Conflicts of Interest

The authors declare no competing interests.

Abbreviations

ARI: Acute Respiratory Infections

ATT: Average Treatment Effect on the Treated

CTIS: Global COVID-19 Trends and Impact Survey

COVID-19: Coronavirus Disease 2019

OxCGRT: Oxford Covid-19 Government Response Tracker

RCT: Randomized Controlled Trial

Sars-CoV-2: Severe Acute Respiratory Syndrome Coronavirus Type 2

TWFE: Two-Way Fixed Effects

US: United States

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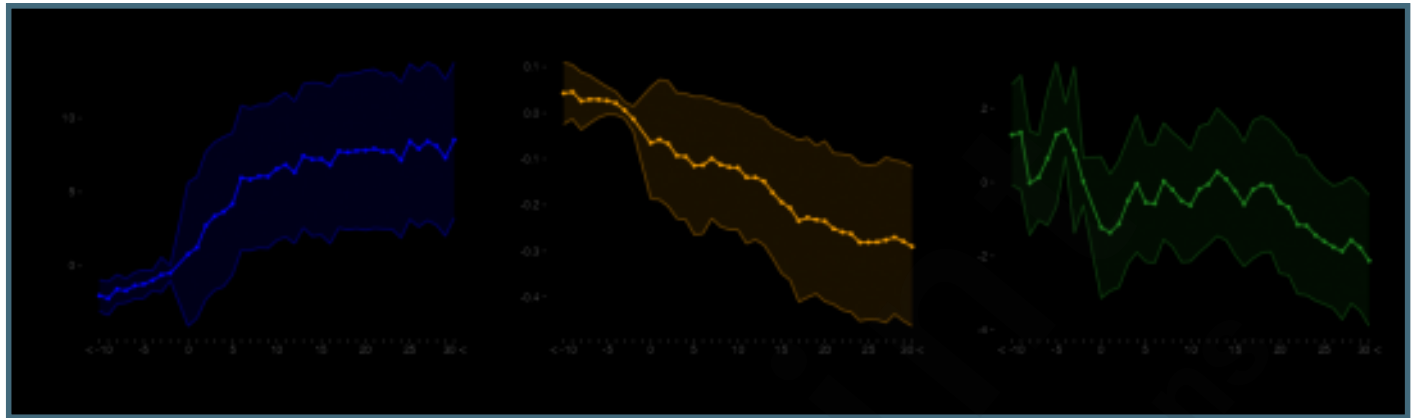
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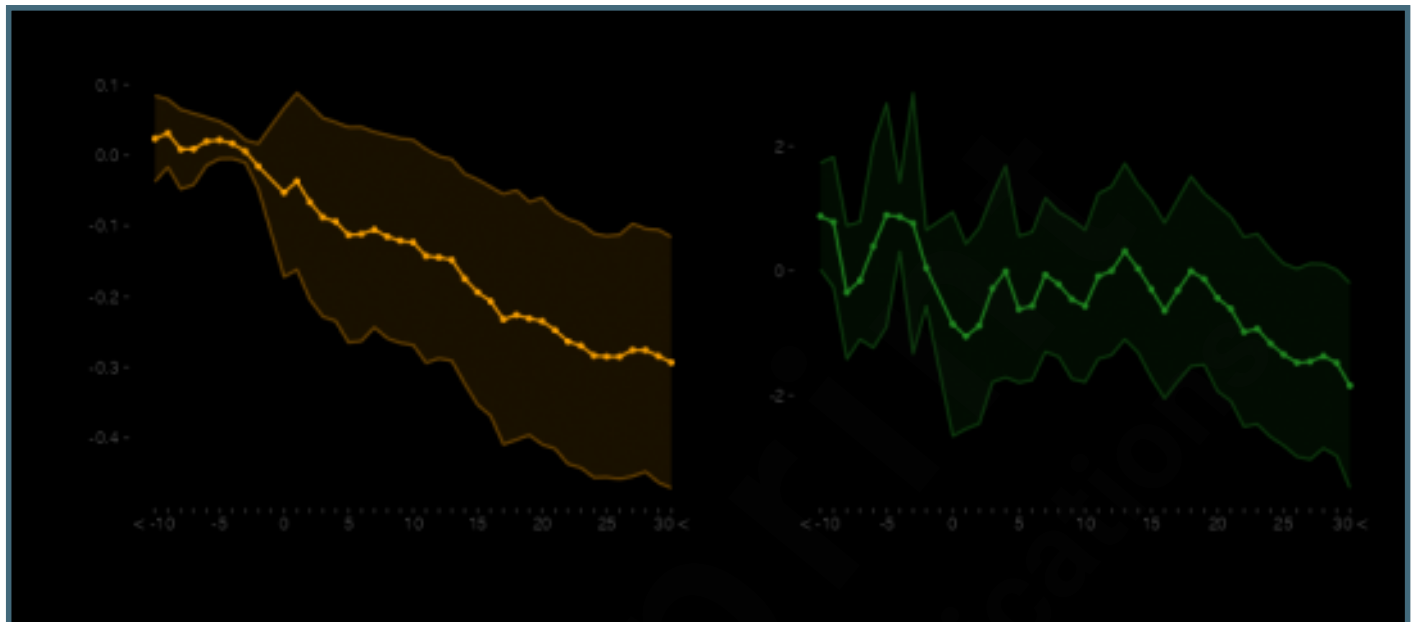
Supplementary Files

Figures

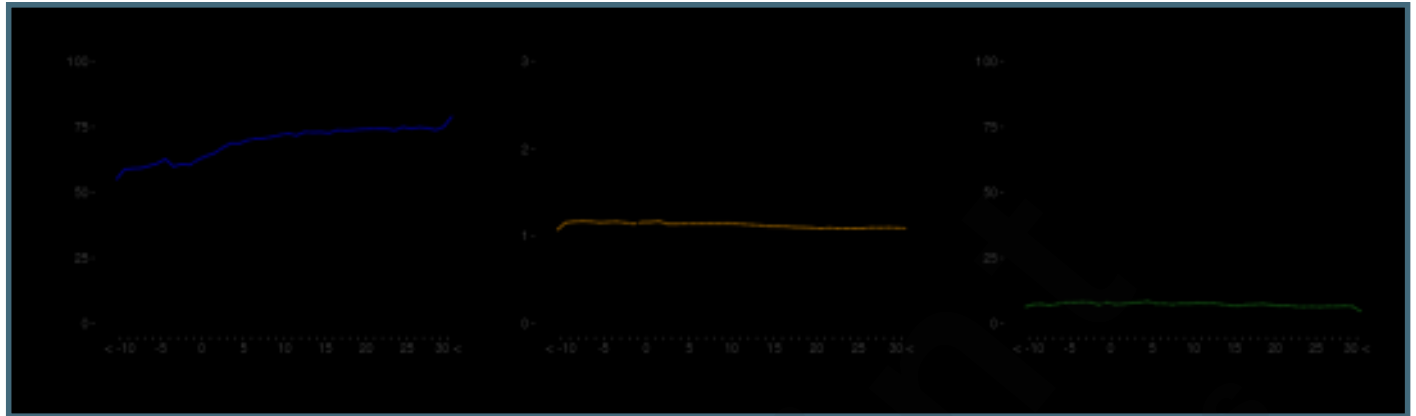
Incremental effects of face mask mandates on self-reported face mask usage, Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases. Estimations include counterfactual linear trends. Colored points depict Sun and Abraham interaction-weighted estimates of relative period effects [26]. S.E. are clustered at the country level. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].



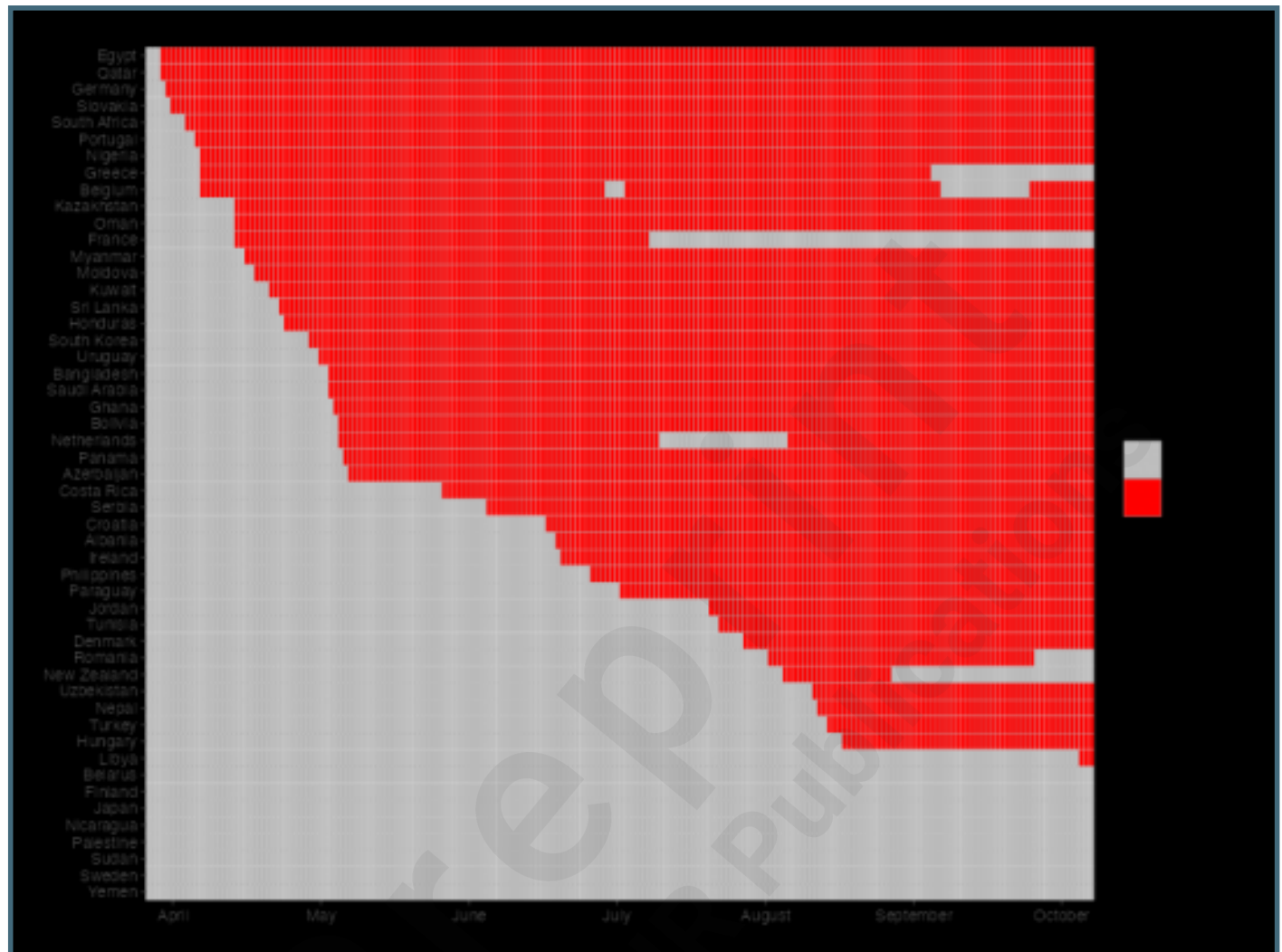
Incremental effects of face mask mandates on Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases. Estimations exclude indicators of mobility and non-pharmacological interventions other than mask mandates. Colored points depict Sun and Abraham interaction-weighted estimates of relative period effects [26]. S.E. are clustered at the country level. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].



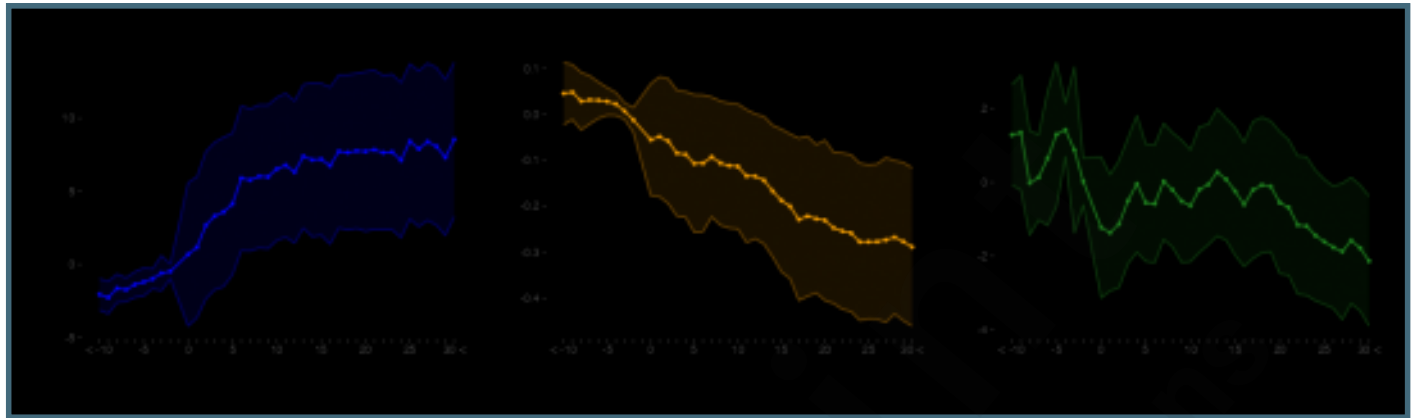
Daily average evolution of face mask usage, Sars-CoV-2 reproduction numbers, and growth rates of COVID-19 cases in mandate countries. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21] & Our World in Data – COVID-19 Dataset [19].



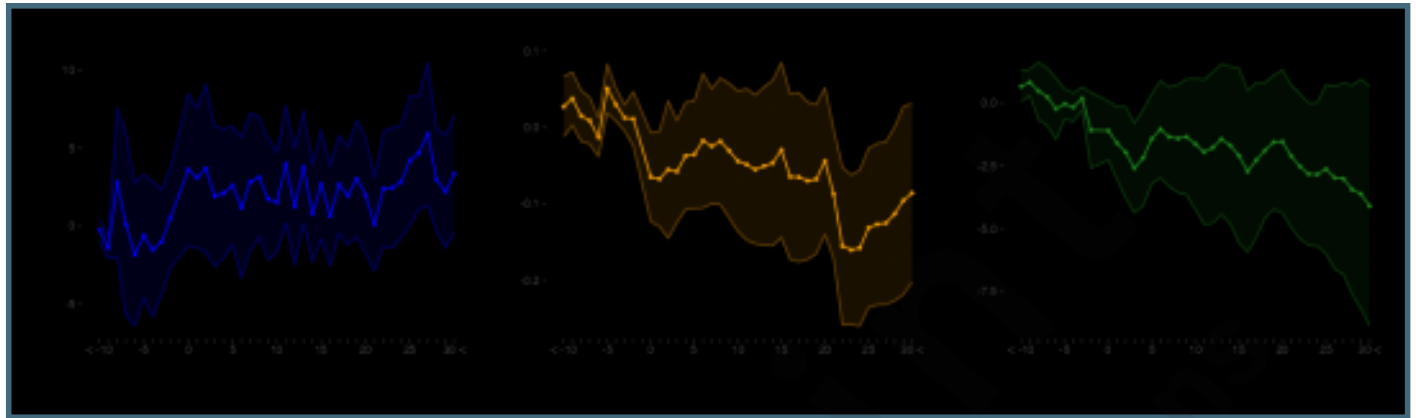
Face mask mandate periods by country. Data source: Oxford COVID-19 Government Response Tracker [21].



Incremental effects of face mask mandates on self-reported face mask use, Sars-CoV-2 reproduction numbers and growth rates of COVID-19 cases. Colored points depict Sun and Abraham interaction-weighted estimates of relative period effects [26]. 95%-CI are indicated by colored areas. S.E. are clustered at the country level. Data sources: COVID-19 Trends and Impact Survey [17], Oxford COVID-19 Government Response Tracker [21], Our World in Data – COVID-19 Dataset [19] & Google COVID-19 Community Mobility Reports [22].



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Multimedia Appendixes

Additional results from sensitivity analyses.

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