# Universal Masking is Urgent in the COVID-19 Pandemic: SEIR and Agent Based Models, Empirical Validation, Policy Recommendations

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## Abstract

We present two models for the COVID-19 pandemic predicting the impact of universal face mask wearing upon the spread of the SARS-CoV-2 virus—one employing a stochastic dynamic network based compartmental SEIR (susceptible-exposed-infectious-recovered) approach, and the other employing individual ABM (agent-based modelling) Monte Carlo simulation—indicating (1) significant impact under (near) universal masking when at least 80% of a population is wearing masks, versus minimal impact when only 50% or less of the population is wearing masks, and (2) significant impact when universal masking is adopted early, by Day 50 of a regional outbreak, versus minimal impact when universal masking is adopted late. These effects hold even at the lower filtering rates of homemade masks. To validate these theoretical models, we compare their predictions against a new empirical data set we have collected that includes whether regions have universal masking cultures or policies, their daily case growth rates, and their percentage reduction from peak daily case growth rates. Results show a near perfect correlation between early universal masking and successful suppression of daily case growth rates and/or reduction from peak daily case growth rates, as predicted by our theoretical simulations.

Taken in tandem, our theoretical models and empirical results argue for urgent implementation of universal masking in regions that have not yet adopted it as policy or as a broad cultural norm. As governments plan how to exit societal lockdowns, universal masking is emerging as one of the key NPIs (non-pharmaceutical interventions) for containing or slowing the spread of the pandemic. Combined with other NPIs including social distancing and mass contact tracing, a "mouth-and-nose lockdown" is far more sustainable than a "full body lockdown", from economic, social, and mental health standpoints. To provide both policy makers and the public with a more concrete feel for how masks impact the dynamics of virus spread, we are making an interactive visualization of the ABM simulation available online at http://dek.ai/masks4all. We recommend immediate mask wearing recommendations, official guidelines for correct use, and awareness campaigns to shift masking mindsets away from pure self-protection, towards aspirational goals of responsibly protecting one's community.


## 1 Introduction

With almost all of the world's countries having imposed measures of social distancing and restrictions on movement in March 2020 to combat the COVID-19 pandemic, governments now seek a sustainable pathway back towards eased social restrictions and a functioning economy. Mass testing for infection and serological tests for immunity, combined with mass contact tracing, quarantine of infected individuals, and social distancing, are rec-

*This collective work grew out of a Kinnernet discussion group about COVID-19 initiated by Guy-Philippe Goldstein. All authors contributed to the overall design and writing. Additionally, Goldstein formulated overall study goals and analysed policy data, Morgunov ran the SEIR simulation and collected policy data, De Kai created the online interactive ABM simulation, Nangalia contributed with medical expertise and to the model design, and Rotkirch and De Kai first drafted the report.

ommended by the WHO and have become widely acknowledged means of controlling spread of the SARS-CoV-2 virus until a vaccine is available.

Against this backdrop, a growing number of voices suggest that universal face mask wearing, as practiced effectively in most East Asian regions, is an additional, essential component in the mitigation toolkit for a sustainable exit from harsh lockdowns. The masks-for-all argument claims that 'test, trace, isolate' should be expanded to 'test, trace, isolate, mask'. This paper presents cross-disciplinary, multi-perspective arguments for the urgency of universal masking, via both new theoretical models and new empirical data analyses. Specifically, we aim to illustrate how different degrees of mass face wearing affects infection rates, and why the timing of introduction of universal masking is crucial.

In the first of two new theoretical models, we introduce an SEIR (susceptible-exposed-infectious-recovered) model of the effects of mass face mask wearing over time compared to effects of social distancing and lockdown. In the second of two new theoretical models, we introduce a new interactive individual ABM (agent-based modelling) Monte Carlo simulation showing how masking significantly lowers rates of transmission. Both models predict significant reduction in the daily growth of infections on average under universal masking (80-90% of the population) if instituted by day 50 of an outbreak, but not if only 50% of the population wear masks or if institution of universal masking is delayed.

We then compare the two new simulations presented here against a new empirical data set we have collected that includes whether regions have universal masking cultures or policies, their daily case growth rates, and their percentage reduction from peak daily case growth rates. Since little precise quantitative data is available on cultures where masking is prevalent, we explain in some depth the historical and sociological factors that support our classification of masking cultures. Results show a near perfect correlation between early universal masking and successful suppression of daily case growth rates and/or reduction from peak daily case growth rates, as predicted by our theoretical simulations.

Our analyses lead to the following key policy recommendations:

1. Masking should be mandatory or strongly recommended for the general public when in public transport and public spaces, for the duration of the pandemic.

2. Masking should be mandatory for individuals in essential functions (health care workers, social and family workers, the police and the military, the service sector, construction workers, etc.) and medical masks and gloves or equally safe protection should be provided to them by employers. Cloth masks should be used if medical masks are unavailable.

3. Countries should aim to eventually secure mass production and availability of appropriate medical masks (without exploratory valves) for the entire population during the pandemic.

4. Until supplies are sufficient, members of the general public should wear nonmedical fabric face masks when going out in public and medical masks should be reserved for essential functions.

5. The authorities should issue masking guidelines to residents and companies regarding the correct and optimal ways to make, wear and disinfect masks.

6. The introduction of mandatory masking will benefit from being rolled out together with campaigns, citizen initiatives, the media, NGOs, and influencers in order to avoid a public backlash in societies not culturally accustomed to masking. Public awareness is needed that "masking protects your community—not just you".

# 2 Background

Masks indisputably protect individuals against airborne transmission of respiratory diseases. A recent Cochrane meta-analysis found that masking, handwashing, and using gowns and/or gloves can reduce the spread of respiratory viruses, although evidence for any individual one of these measures is still of low certainty (Burch and Bunt, 2020). Currently, the lowest recorded daily growth rates in COVID-19 infections are found in countries with a culture of mass face mask wearing, most of whom have also made mask wearing in public mandatory during the epidemic, and most of whom are not currently locked down.

Outside of East Asia, support for universal masking is emerging elsewhere across the globe. The Czech Republic was the first non-Asian country to embrace and impose mandatory universal masking on March 11. The Czech policy swiftly inspired various initiatives from citizens, journalists and scientists—e.g., De Kai (2020), Howard and Fast.ai team (2020), Manjoo (2020), Abaluck *et al.* (2020), Feng *et al.* (2020), Fineberg (2020), Tufekci (2020)—and created global movements such as #masks4all and #wearafuckingmask. Their arguments build on the ability of the COVID-19 virus to spread from pre- and asymptomatic individuals who may not know that they are infected, and to linger in airborne droplets.

Leading political and medical experts who early were advocated masking included Chinese CDC director-general Prof. George Fu Gao (Servick, 2020), former FDA commissioner Scott Gottlieb and Prof. Caitlin Rivers of Johns Hopkins (Gottlieb and Rivers, 2020), and the American Enterprise Institute's roadmap (Gottlieb *et al.*, 2020). In early April a rapidly increasing number of governments from countries without a previous culture of mask wearing require or recommend universal masking including the Czech Republic, Austria and Slovakia. Additionally, public health bodies in the USA, Germany, France (Académie nationale de médecine, 2020) and New Zealand have moved toward universal masking recommendations (Morgunov *et al.*, 2020), as shown below in Figure 6.

The World Health Organization (2019) previously issued guidelines discouraging the use of masks in the public. In early April the World Health Organization (2020) modified the guidelines, allowing self-made masks but rightly stressing the need to reserve medical masks for healthcare workers (Nebehay and Shalal, 2020), and to combine masking with the other main NPI needed to combat the pandemic. The policy shifts of the WHO and other CDCs reflect advances in our scientific understanding of this pandemic, and help legitimise the altruistic "mask resistance" of civil society in this global effort against COVID-19.

# 3 SEIR modelling of universal masking impact

In the first of our two new theoretical models, we employed stochastic dynamic network based compartmental SEIR modeling to forecast the relative impact of masking compared to the two main other societal non-pharmaceutical interventions, lockdown, and social distancing.

The SEIR simulations were fit to the current timeline in many Western countries, with a lockdown imposed March the 24th (day 1) and planned to be lifted on May 31st. Universal masking is introduced in April. The simulation continues for 500 days from day 0, or around 17 months.

The experimental results strongly support the need for universal masking as an alternative to continued lockdown scenarios. For this strategy to be most effective, the vast majority of the population must adopt mask wearing immediately, as most regions outside East Asia are rapidly approaching Day 50.

In a SEIR model, the population is divided into compartments which represent different states with respect to disease progression of an individual: susceptible ($S$), exposed ($E$), infectious ($I$) and recovered ($R$). A susceptible individual may become exposed if they interact with an infectious individual at rate $\beta$ (rate of transmission per $S$- $I$ contact per time). From $E$, the individual progresses to being infectious ($I$) and eventually recovered ($R$) with rates $\sigma$ (rate of progression) and $\gamma$ (rate of recovery), respectively. Additionally, individuals in $I$ are removed from the population (i.e., die of the disease) at rate $\mu_I$ (rate of mortality).

We used a SEIR model implemented[1] on a stochastic dynamical network that more closely mimics interactions between individuals in society, instead of assuming uniform mixing as is the case with deterministic SEIR models. Furthermore, such approach allows setting different model parameters for each individual, which we use to model masking. In a network model, a graph of society is built with nodes representing individuals and edges—their interactions. Each node has a state—$S$, $E$, $I$, $R$, or $F$ (the latter added to represent dead individuals). Adjacent nodes form close contact networks

[1] https://github.com/ryansmcgee/seirsplus

of an individual, while contacts made with an individual from anywhere in the network represent global contacts in the population. Varying the parameters affecting the two levels of interaction, as well as setting network properties such as the mean number of adjacent nodes (“close contacts”) allows us to model the degree of social distancing and lockdown measures.

Formally, each node $i$ is associated with a state $X_i$ which is updated based on the following probability transition rates:

$$\Pr(X_i = S \to E) = [p\frac{\beta I}{N} + (1-p)\frac{\beta \sum_{j \in C_G(i)} \delta_{X_j=i}}{|C_G(i)|}]\delta_{X_i=S} \quad (1)$$

$$\Pr(X_i = E \to I) = \sigma \delta_{X_i=E} \quad (2)$$

$$\Pr(X_i = I \to R) = \gamma \delta_{X_i=I} \quad (3)$$

$$\Pr(X_i = I \to F) = \mu_I \delta_{X_i=I} \quad (4)$$

where $\delta_{X_i=A} = 1$ if the state of $X_i$ is $A$, or $0$ if not, and where $C_G(i)$ denotes the set of close contacts of node $i$.

## 3.1 Experimental model

We implemented SEIR dynamics on a stochastic dynamic network with a heterogeneous population. We assumed an initial infected population of 1% and modelled the assumed effects of social distancing, lockdown, and universal masking over time on the rates of infection in the population.

All SEIR models were built using the SEIRS+ modelling tool[2], version 0.0.14. The baseline model parameters are fit to the empirical characteristics of COVID-19 spread, as documented in the SEIRS+ distributed COVID-19 notebooks. Specifically, we set $\beta = 0.155$, $\sigma = 1/5.2$ and $\gamma = 1/12.39$. This parameterisation describes a SEIR model with best estimates for COVID-19 dynamics.

The initial infected population (init$_i$) was set to 1%, and all others to 0%. The size of the total population was set to 67,000 (a representative typical case, that is a factor of 1,000 from the population of the UK).

[2] https://github.com/ryansmcgee/seirsplus

**Social distancing.** In the model, social distancing was defined as the degree distribution of the contact network of an individual. Default interaction networks were used, constructed as Barabasi-Albert graphs with $m = 9$ and processes using the package function custom_exponential_graph with different scale parameters. Normal graph (scale=100) with mean degree 13.2, distancing graph (scale=10) with mean degree 4.1 and lockdown graph (scale=5) with mean degree 2.2.

**Lockdown stringency.** Lockdown stringency was modelled considering no stringent lockdown (i.e. only social distancing) or stringent lockdown using the locality parameter p, which was set to 0.02 during lockdown and 0.2 during social distancing phases. This dictates the probability of individuals coming into contact with those outside of their immediate network. Assuming that individuals have around 13 contacts in normal everyday life, social distancing will reduce this to 4 and lockdown to only 2.

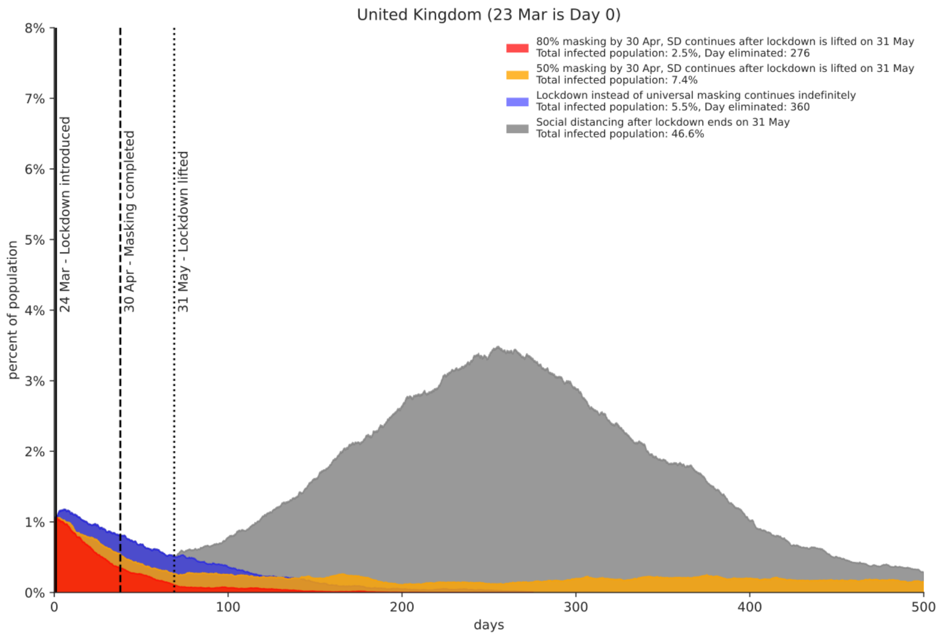
**Mask wearing.** A gradual increase in *mask wearing* was modelled using a linear increase in the proportion of individuals randomly allocated with a reduced rate of transmission. The factor by which $\beta$ was reduced was conservatively set to 2. The period of time over which the mask wearing went from 0 to maximum % was set to 10 days. 50% and 80% maximum values were considered.

**Date fitting.** The progression in the number of deaths was used to fit the model to an approximate calendar date representing Day 0. For the representative typical case of the UK, this corresponded to Mar 23.

## 3.2 Experimental results

Figure 1 shows the simulation results for a representative scenario: universal masking at 80% adoption (red) flattens the curve significantly more than maintaining a strict lockdown (blue). Masking at only 50% adoption (orange) is not sufficient to prevent continued spread. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

Our model suggests a substantial impact of universal masking. Without masking, but even with continued social distancing in place once the lockdown is lifted, the infection rate will increase and almost half of the population will become affected. This scenario, rendered in grey in Figure 1, would potentially lead to over a million deaths in a population the size of the UK. A continued lockdown, il-

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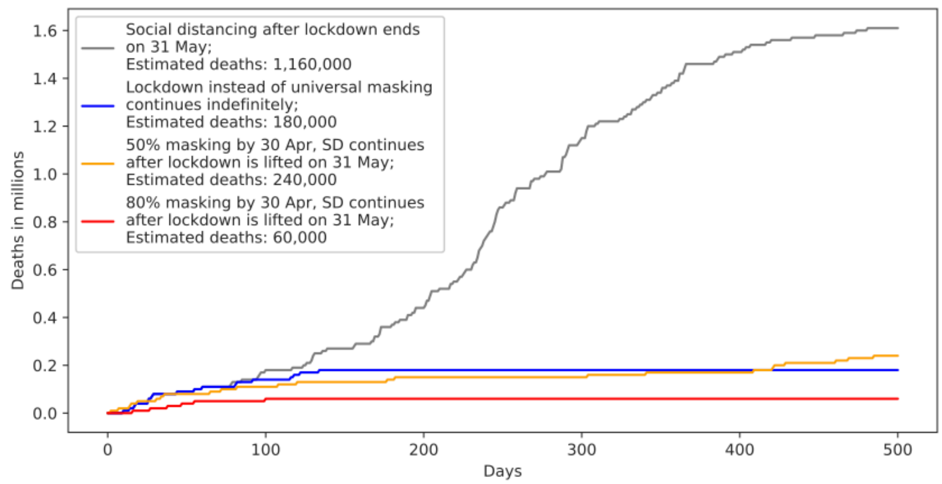
lustrated in blue colour, does eventually result in bringing the disease under control after around 6 months. However, the economic and social costs of a "full body lockdown" will be enormous, which strongly supports finding an alternative solution.

In the model, social distancing and masking at both 50% and 80% of the population—but no lockdown beyond the end of May—result in substantial reduction of infection, with 80% masking eventually eliminating the disease. Figure 2 shows the simulation results for a representative scenario: universal masking at 80% adoption (red) results in 60,000 deaths, compared to maintaining a strict lockdown (blue) which results in 180,000 deaths. Masking at only a 50% adoption rate (orange) is not sufficient to prevent continued spread and eventually results in 240,000 deaths. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

# 4 Agent based modelling of universal masking impact

In the second of our two new theoretical models, we employed stochastic individual agent based modelling (ABM) as an alternative Monte Carlo simulation technique for understanding the impact of universal masking. Agent based models have roots in various disciplines. A stochastic agent program can be defined as a agent function $f : \mathbf{p} \rightarrow \Pr(a)$ which maps possible *percept* vec-

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tors to a probabilistic distribution over possible *actions* (or to states that influence subsequent actions). In AI, Russell and Norvig (2009) summarise five classes of intelligent agents: simple reflex agents, model-based reflex agents, goal-based agents, utility-based agents, and learning agents; note, however, that agents may also be susceptible to *imperceptible* environmental factors such as viruses. Holland and Miller (1991) discuss artificial adaptive agents for modeling complex systems in economics. Bonabeau (2002) surveys agent based models for simulating human systems.

As in other disciplines, ABM approaches in epidemiology (see, e.g., Hunter *et al.* (2017). Tracy *et al.* (2018), or Hunter *et al.* (2018)) have several advantages compared to compartmental models which group undifferentiated individuals into large aggregates (like in the above SEIR simulation). First, because the behavior and characteristics of each agent is independent, they can simulate complex dynamic systems with less oversimplification of rich variation among individuals. Second, because agents can be simulated in physical two- or three-dimensional spaces, they can better simulate the geometry of contact between individuals, which is highly relevant in epidemiology. Third, the randomization on each run makes the statistical *variance* more apparent than in the SIR family of models, whose smooth curves often misleadingly convey more certainty than warranted. Fourth, ABMs lend themselves well to visualization, as seen in Figure 5, which helps convey the non-linear behavior of complex dynamic systems —an especially relevant advantage when the exponential effect of masking can be counterintuitive in many cultures due to pre-existing cultural biases (Leung, 2020) and unconscious cognitive biases (De Kai, 2020).

## 4.1 Mask characteristics

The ABM approach allows us to put masks on individual agents and to assign properties to those masks, to shed light on the question of how face masks—even nonmedical cloth masks—carry the promise to be so surprisingly effective. The objective is to examine how even a small barrier to individual infection transmission can multiply into a substantial effect on the level of communities and populations.

Face masks work in two ways: They can protect an infected person from spreading the virus (transmission), and they can limit how much the non-infected individual is exposed to the virus (absorption). Traditionally, masks are worn to protect the wearer from being infected by an ill person when in close and prolonged contact. In such classic situations, for instance in hospitals and elderly homes, only medical masks combined with other protective equipment provide protection. Comparing different mask materials, medical masks have been found to be up to three times more effective in blocking transmission compared to homemade masks (Davies *et al.*, 2013). Surgical masks most efficaciously reduce the emission of influenza virus particles into the environment in respiratory droplets. Still, although masks vary greatly in their ability to protect, using any type of face mask (without an exploratory valve) can help decrease viral transmission (Sande *et al.*, 2008).

However, the effect of universal masking does not require full protection from disease to be effective in lowering infection rates of COVID-19. Masks may be especially crucial for containing the COVID-19 pandemic, since many infections appear to come from people with no signs of illness. For instance, around 48% of COVID-19 transmissions were pre-symptomatic in Singapore and 62% in Tianjin, China (Ganyani *et al.*, 2020). This suggests that masking needs to be universal and not restricted to individuals who think they may be infected.

Furthermore, the SARS-CoV-2 virus is known to spread through airborne particles (Leung *et al.*, 2020) and quite possibly via aerosolised droplets as well according to Service (2020), van Doremalen *et al.* (2020), Santarpia *et al.* (2020), and Liu *et al.* (2020). It may linger in the air for and travel several meters, which is why social distancing rules require at least 2 meters between individuals to be effective.

## 4.2 Experimental model

As a contrastive baseline we employed a compartmental SEIR model with the same parameters as given for our SEIR experiments of section 3.

For the new agent based model, we implemented an environment consisting of a square wraparound two-dimensional space, within which a population of individual agents reside in four states: susceptible ($S$), exposed ($E$), infectious ($I$) and recovered ($R$). The wraparound space means that agents who move outside a border re-enter the square from the opposite side. As in our SEIR models, the initial infected population ($\text{init}_i$) was set to 1%, and all others to 0%. The size of the total population was set to 200, but the wraparound feature of the two-dimensional space in effect represents arbitrarily larger spaces that are approximated by replicated square tiles, thus giving more accurate dynamics without boundary effects from small spaces.

To best fit the same empirical characteristics of COVID-19 spread as our SEIR models, we again set $\sigma = 1/5.2$ and $\gamma = 1/12.39$. Note that $\beta$ is inapplicable in the ABM since infection transmission between individuals arises from physical proximity, which is more realistic than randomly infecting other individuals anywhere with some probability $\beta$ with no regard to their physical location. In the baseline Monte Carlo simulation, agents decide on a random destination location within a parameterised radius of their current point, then proceed at a parameterised speed to move there, and then repeat the process iteratively. We adjusted such ABM-specific parameters, as well as physical exposure distance, to optimise fit to the baseline SEIR model curves, assuming none of the population to be wearing masks. Again, this was done so as to best approximate known COVID-19 dynamics.

ABM runs were for 300 days from the onset of the outbreak since empirically, the emergent SEIR curves stabilise before the 300th day.

To model the impact of masking, the following masking parameters can be varied:

**Mask wearing.** Gradual increases (or decreases) in *mask wearing* can be modelled using parameterised rates of masking $M$ (or unmasking $U$) in the proportion of unmasked (or masked) individuals. The parameters $m_{min}$ and $m_{max}$ also allow modelling the minimum and maximum absolute numbers of masked agents. These masking parameters can be dynamically adjusted any time during any ABM run, to simulate varying policy decisions and cultural mindset shifts.

**Mask characteristics.** Varying degrees of mask effectiveness are modelled by the *mask transmission rate*$T$ and *mask absorption rate*$A$, which denote the proportion of viruses that are stopped by the mask during exhaling

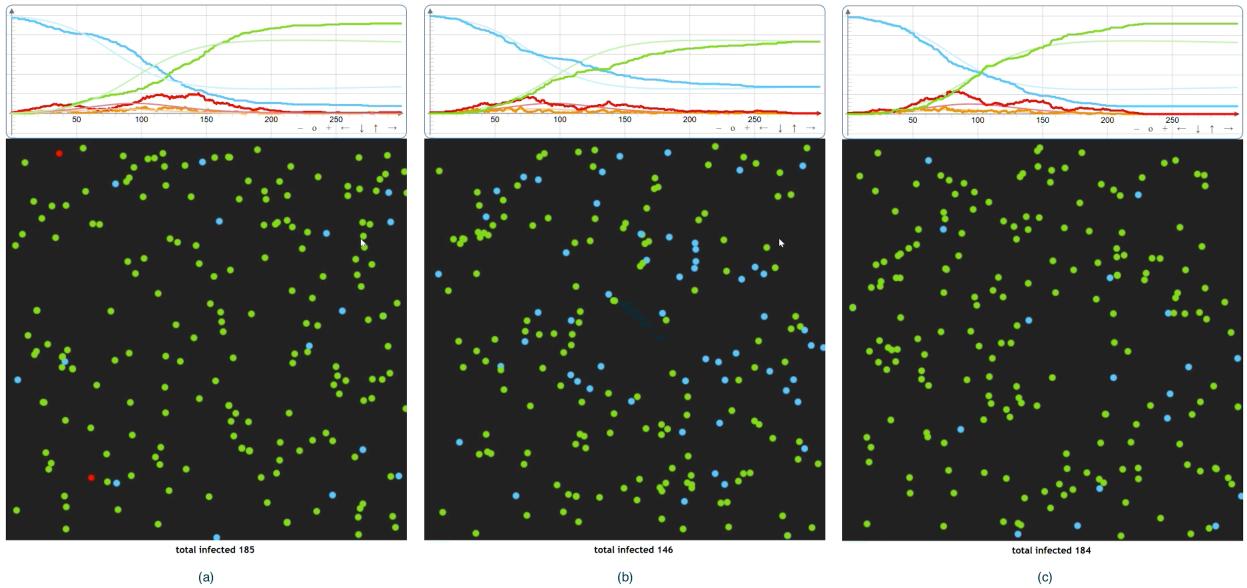


Figure 3: Three successive randomised runs of the agent based model for 300 days, with no mask wearing. Blue is susceptible, orange is exposed, red is infected, and green is recovered. The contrastive SEIR baseline model's predicted curves are shown in thinner, fainter lines. The ABM runs produce curves with a fine granularity of randomisation, centering on average around the ODE based SEIR curves.

(transmission) versus inhaling (absorption), respectively. We set $T = 0.7$ and $A = 0.7$ to model the use of inexpensive, widely available, and even nonmedical or homemade masks with only 70% effectiveness for universal masking, and not higher quality N95, N99, N100, FFP1, FFP2, or FFP3 masks which in many regions need to be reserved for medical staff.

### 4.3 Experimental results

ABM simulation shows that universal masking can significantly reduce virus spread if adopted sufficiently early, even if the masks are nonmedical or homemade.

Figure 3 shows three successive runs for the baseline $m = 0$ case with zero mask adoption. Each dot (which is in motion during simulation runs) represents an individual agent, who may become exposed to the virus through proximity to other agents who are infectious. Blue dots are healthy susceptible agents, orange dots are exposed agents, red dots are infected agents, and green dots are recovered agents. A dot with a white rectangle on it represents an agent who is wearing a mask.

The three baseline ABM runs show how chance plays a significant role in the dynamics of virus spread. Since each simulation run is randomised, to decrease variance requires observation over multiple runs. On average, the baseline case with zero mask adoption adheres to the simpler SEIR model's predicted curves.

Figure 4 compares typical runs for four scenarios that simulate how COVID-19 spreads among individual agents under different masking scenarios, with the contrastive baseline SEIR model curves shown in thin lines as a reference: (a) $m_0 = 100\%$ meaning that the entire population adopts mask at the onset of the outbreak on day 0; (b) $m_0 = 0\%, m_{50} = 90\%$ meaning that none of the population is wearing masks at the onset but that nearly universal masking is instituted on day 50; and (c) $m_0 = 0\%$,$m_{50} = 50\%$ meaning that none of the population is wearing masks at the onset but that half of the population adopts masks on day 50, and (d) $m_0 = 0\%, m_{75} = 90\%$ meaning that

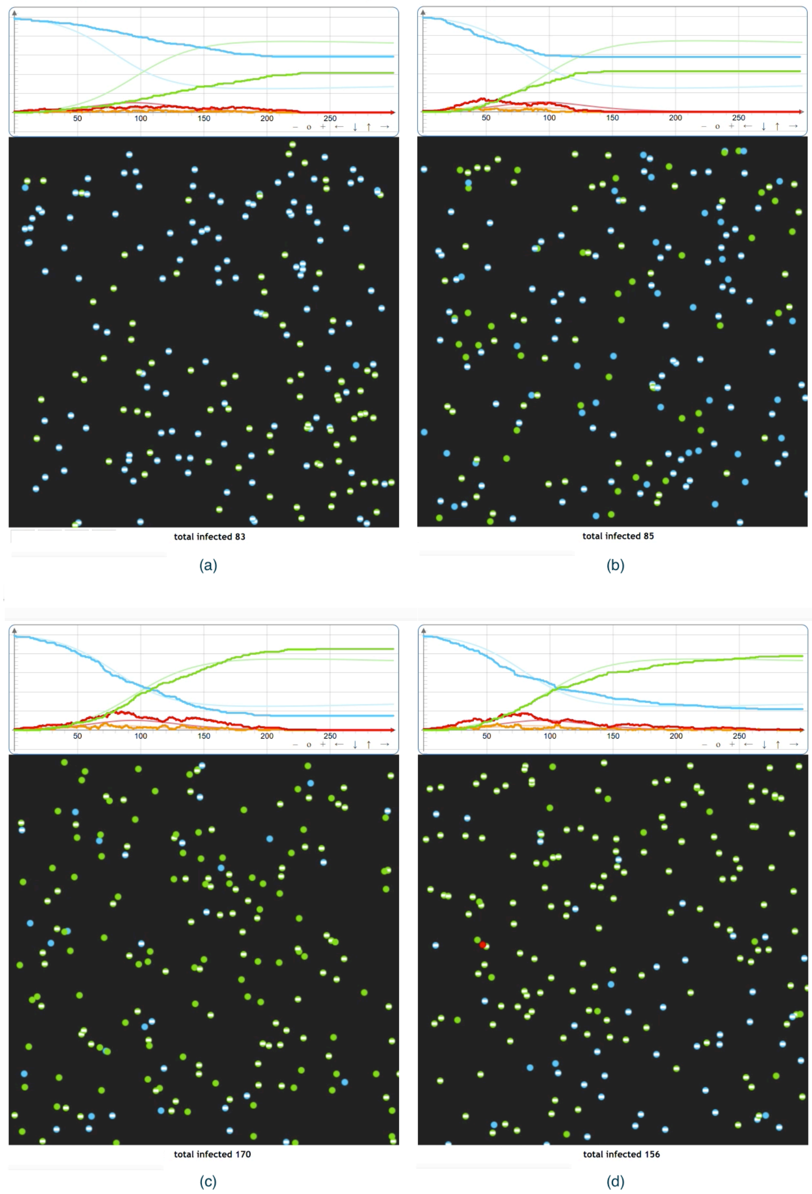


Figure 4: Four ABM runs under varying masking scenarios. (a) 100% of the population wearing masks from the onset of the outbreak, with excellent suppression of infection spread. (b) 0% of the population initially wearing masks, but instituting near universal masking of 90% of the population at day 50, still with significant suppression of infection spread. (c) 0% of the population initially wearing masks, and instituting some masking of 50% of the population at day 50, with not much impact on infection spread. (d) 0% of the population initially wearing masks, but instituting near universal masking of 90% of the population at day 75 with not much impact on infection spread.

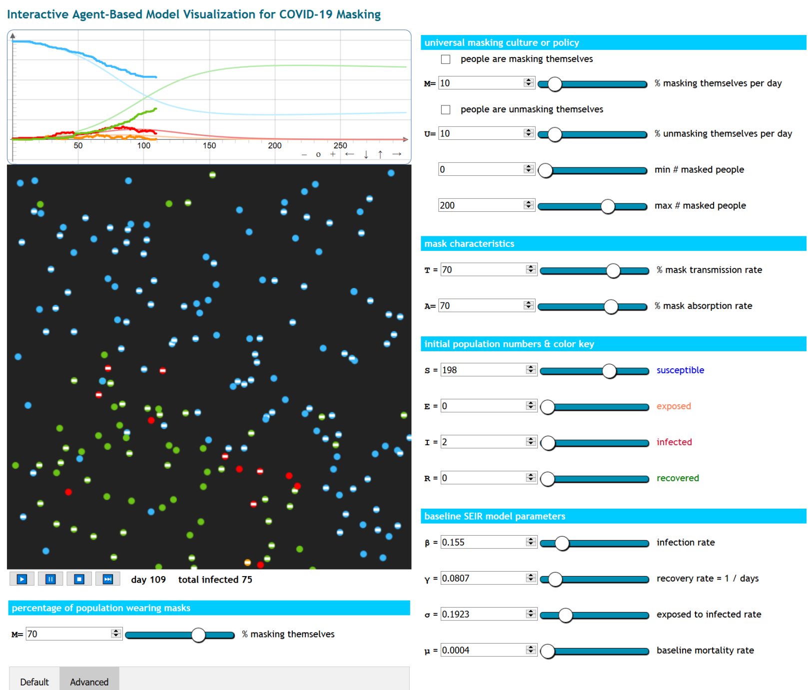


Figure 5: Interactive visualisation tool for the ABM simulation model to help policy makers and the general public gain a more concrete feel for how masks impact the dynamics of virus spread, available online at http://dek.ai/masks4all.

none of the population is wearing masks at the onset but that nearly universal masking is instituted on day 75.

In scenario (a), a dramatic decrease in the number of infections is evident as a result of universal masking at the onset of the outbreak. Unfortunately, most regions outside East Asia missed the time window for scenario (a).

In scenario (b), even though the population is not initially wearing masks, if universal masking is instituted by day 50, good chances of dramatic suppression of infection rates can still be achieved. Fortunately, this option is within reach of most regions at the time of writing.

In scenario (c), again the population is not initially wearing masks. On day 50, half the population dons masks, but unlike scenario (b) which succeeds with 90% universal masking, unfortunately 50% is an insufficient level of mask adoption to suppress infection rates to a significant degree.

In scenario (d), the population again is not initially wearing masks, but unlike scenario (b) the 90% universal masking is not instituted until day 75, instead of day 50. Waiting too long unfortunately greatly decreases the degree to which infection rates can be suppressed.

To help policy makers and the general public gain a more concrete feel for how masks impact the dynamics of virus spread, we have made available online[3] an interactive visualisation tool for the ABM simulation model, as shown in Figure 5. The default view allows direct adjustment in real time of the percentage of masked individual agents through a slider control. Optional advanced controls allow playing with various scenarios: whether masking is used, the adoption rate of masking, virus transmission and absorption rates through masks of varying quality, as well as other modelling parameters such as the initial numbers of susceptible, exposed, infected, or recovered agents, and the contrastive baseline SEIR model parameters.

[3] http://dek.ai/masks4all

# 5 Evaluation against empirical data on universal masking impact

## 5.1 Management of COVID-19 by countries or provinces segmented by the enforcement of universal masking

For validation of the SEIR and ABM predictions, we compare against macro scale empirical data, since precise numbers for masking rates, mask transmission and absorption rates, and infectious but asymptomatic cases are not yet known. We collected a new data set @De Kai FIXME finish framing the narrative as empirical evaluation of theoretical models

Figure 6 shows the daily growth of confirmed cases, reduction from peak of new cases, and masking & lockdown policies in 38 selected countries.

In order to evaluate if the above experimental results from the models would be infirmed or not by actual country data or provinces in the context of the Covid-19 pandemic, we have run an empirical data analysis. This analysis based on (i) a selection of 38 countries or provinces in Asia, Europe and North America based on similar, highest level of economic development (based on World Bank GDP PP per capita ); (ii) detected cases from Jan 23 to April 10, 2020; (iii) review of universal masking culture and/or universal masking orders or recommendations by governments.

The management of the epidemic outbreak is measured by (i) slower daily growth after the number of detected cases reached 30, ideally below 12.5% daily growth (equivalent to number of cases doubling at the slower pace of 6 days or more) or (ii) a recent, significant (>60%) reduction of new cases calculated as the average of the last 5 days to April 10, 2020 compared to the average of the 3 highest number of daily new cases since the number of detected cases reached 30 till April 10, 2020. These measures help to highlight both situations of suppressing growth from the start (ex: Taiwan) or managing the epidemy by reducing the number of new cases after a peak (ex: South Korea).

"Masking culture" is defined as an established practice by a significant section of the general population to wear face masks prior to the start of the Covid-19 pandemic. A cursory review of the scientific literature and

| Country or region | Daily growth | Reduction from peak | Masking culture? | Universal masking (date made mandatory or recommended) | Strict lockdown (mass home quarantine) |
|---|---|---|---|---|---|
| Macau | 2.4% | 96.0% | yes | Feb 19 | |
| Beijing | 3.6% | 98.5% | yes | Feb 8 | partial |
| Shanghai | 3.7% | 83.6% | yes | Feb 8 | partial |
| Guangdong | 5.0% | 95.8% | yes | Feb 8 | partial |
| Hong Kong | 5.5% | 69.8% | yes | Jan 15 | |
| Taiwan | 5.6% | 85.0% | yes | Jan 27 | |
| Singapore | 6.8% | 23.5% | yes | Jan 30 (sick) Apr 5 (all) | partial |
| Japan | 9.1% | 24.5% | yes | Mar 4 | partial |
| Estonia | 10.0% | 69.4% | | | |
| Slovakia | 11.3% | 29.9% | | Mar 24 | |
| S Korea | 11.6% | 94.4% | yes | Feb 27 | |
| Slovenia | 12.0% | 46.0% | | Mar 19 | |
| Malaysia | 13.1% | 38.2% | | | Mar 18 |
| Australia | 13.9% | 77.7% | | | Mar 23 |
| Finland | 14.2% | 27.3% | | | Mar 27 |
| Hungary | 14.3% | 26.5% | | | Mar 28 |
| Norway | 14.5% | 61.0% | | | Mar 12 |
| Lithuania | 15.5% | 46.0% | | | Mar 16 |
| Sweden | 15.9% | 17.2% | | | |
| Denmark | 16.2% | 20.3% | | | Mar 11 |
| CZ | 16.6% | 36.8% | | Mar 18 | Mar 16 |
| Israel | 17.0% | 54.9% | | | |
| Austria | 17.0% | 70.3% | | Mar 31 | Mar 16 |
| Lux | 17.0% | 63.2% | | | |
| IT | 17.2% | 40.4% | | | Mar 9 |
| NZ | 17.2% | 44.3% | | | Mar 26 |
| CH | 17.3% | 45.8% | | | |
| ND | 18.4% | 16.6% | | | Mar 16 |
| Pol | 18.5% | 17.5% | | | Mar 13 |
| Belgium | 18.5% | 20.1% | | | Mar 18 |
| Ire | 18.6% | 23.9% | | | Mar 12 |
| Canada | 18.7% | 37.1% | | | |
| Germany | 19.6% | 36.0% | | | (only Bavaria) |
| France | 20.2% | 56.6% | | | Mar 17 |
| Portugal | 20.4% | 27.1% | | | Mar 19 |
| UK | 20.4% | 22.4% | | | Mar 24 |
| US | 21.6% | 5.5% | | | Mar 19-24 (CA, NV, CT, IL, KS, MA, MI, NY, OR, WI) |
| Spain | 21.9% | 38.8% | | | Mar 14 |

Figure 6: Epidemic daily growth and reduction from peak daily growth, together with masking and lockdown policies, from January 23 to April 10, 2020 for selected list of countries or provinces with high GDP PPP per capita in Asia, Europe and North America. Universal masking was employed in every region that handled COVID-19 well. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

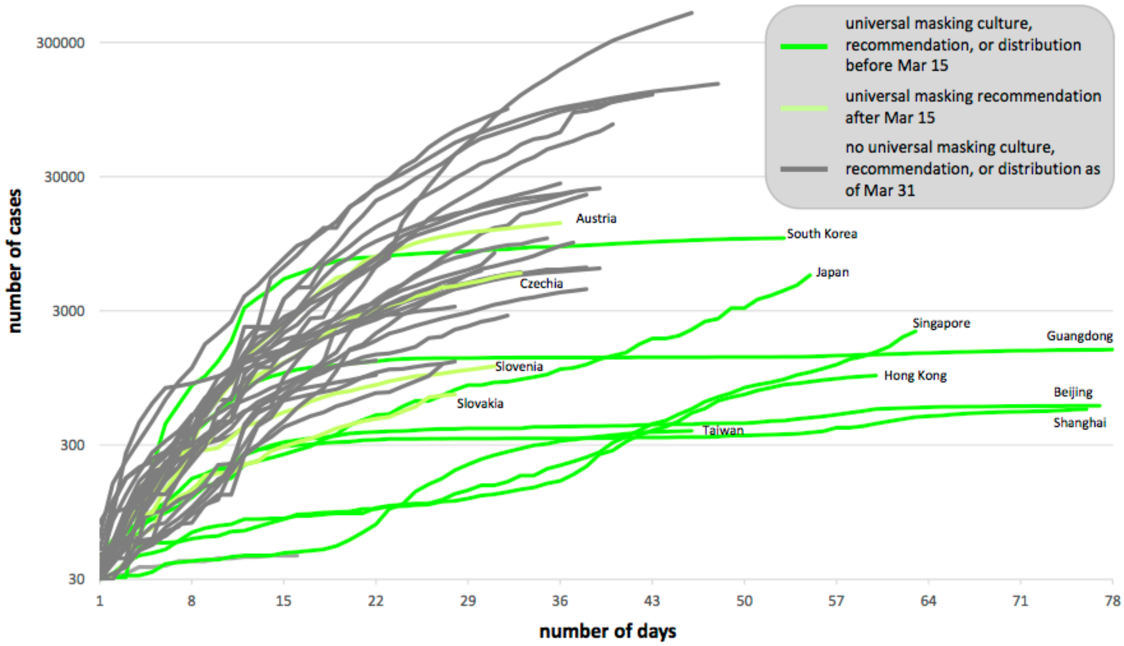


Figure 7: Daily growth curves showing the impact of universal masking on epidemic control: epidemic trajectory after 30 detected cases in universal masking selected countries and provinces (green) vs. others (grey). Masking is nearly perfectly correlated with lower daily growth or strong reduction from peak growth of COVID-19. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

the general press has identified Japan, Thailand, Vietnam (Burgess and Horii, 2012), China's urban centers (Kuo, 2014), Hong Kong (Cowling *et al.*, 2020), Taiwan, Singapore and South Korea (Yang (2014), Jennings (2020)) as countries with such a consistent practice, at least in the decade predating the Covid-19 pandemic. Nevertheless, the notion of "culture" should not imply that the practice of facemask wearing has been extensive and consistent throughout time. For example, though this practice may have fit with preexisting Taoist and health precepts of Chinese traditional medicine, its actual emergence may be relatively recent, starting with the industrialization of Japan at the start of the XXth century and both the flu pandemics of the XXth century as well as the rise of particle pollution (Yang, 2014). The rest of the above-listed east Asian countries has followed the same course in the second half of the XXth century, including China as it was confronting a severe particle pollution crisis in the first part of the 2010s (Kuo (2014), Li (2014), Hansstein and Echegaray (2018)). Beyond price, availability and government recommendation, the actual practice of masking in the Asian general population may be mediated by factors such as social norms or peer-pressure, perception of one's competence, past behaviors or perception of the danger (Hansstein and Echegaray, 2018). As an example of the latter, in Hong Kong, masking was practiced by 79% of the general population during the 2003 SARS outbreak, but by only a maximum of 10% of the general population during the Influenza A pandemic in 2009 (Cowling *et al.*, 2020).

Additionally, to the extent that government recommendations or mandatory orders may shape perceptions and assist in masks availability, it may amplify the masking practice in the general population. It can thus be assumed that the maximum potency of universal masking in the context of epidemics may be reached when a government issues a mandatory or highly recommended order to the general population, issued at an early date, supported by the availability of face masks and amplified by a pre-existing "masking culture". In that case, it can be hypothesised that such national situations may be compared to the experimental results achieved in the models in the above section for maximum values (ex: 80%) in terms of percentage of the general population wearing masks.

Indeed, as of April 10, 2020, the majority of countries or provinces that have best-managed epidemic outbreaks were countries or provinces with either (1) established universal masking cultures or (2) mandatory orders or government recommendations supported by significant and early mask production destined to the general population. These countries or provinces include Taiwan, South Korea, Hong Kong, Singapore, Japan and Chinese provinces or special administrative regions such as Beijing, Shanghai, Guangdong or Macau. In effect, masking in public has been required in Taiwan, metropolitan areas in China such as Shanghai and Beijing (as well as Guangzhou, Shenzhen, Tianjin, Hangzhou, and Chengdu), Japan, South Korea, and other countries (Morgunov *et al.*, 2020). On the other hand, most of the countries which have adopted mass testing, tracking and quarantining, but lack a universal masking culture and clear recommendations and availability for universal masking, have not achieved an equivalent level of Covid-19 epidemic control as of April 10, 2020. These empirical data seem to support the experimental results from the models in the above section. Figure 7 shows daily growth curves revealing the impact of universal masking on epidemic control. Masking is nearly perfectly correlated with lower daily growth of COVID-19 cases. Similarly, Figure 8 shows daily growth versus percentage reduction from peak daily daily growth in quadrants revealing the impact of universal masking on epidemic control. Again, masking is nearly perfectly correlated with strong reduction from peak growth of COVID-19 cases

This empirical data highlights the gradual nature of the protection against Covid-19 achieved with a higher fraction of the population practicing masking, as observed in the experimental results from the models when comparing situations with 80% masking or 50% masking or none. In countries or provinces with masking culture and universal masking orders or recommendations before March 15, 2020, the average daily growth was 5.9% and the reduction from peak was 74.6%. In the countries without masking culture and universal masking orders or recommendations after March 15, 2020, the average daily growth was 14.2% and the reduction from peak was 45.8%. Finally, for the rest of the other countries, the average daily growth was 17.2% and the reduction from peak was 37.4%, the lowest results of the sample. The latter group includes countries that have gone into "strict lockdown" (or mass home quarantine) for 20 out of 27 countries (74%). This is much higher than for the intermediate group of countries without masking culture and "late" universal masking orders (2 out 4, or 50% of the sample), or the first group of countries and provinces with masking culture and "early" universal masking orders. In that first group, no countries or provinces had to endure "strict lockdown".

Yet, even within this first group, the strength of the universal masking recommendations from the government may impact the proportion of the general population actually wearing masks and thus the level of epidemic control, as hypothesised in the above models. For example, Singapore initially encouraged people to wear masks only when feeling unwell. Then, on April, 5, the government changed policy and decided to distribute reusable face-masks to all households (Cheong, 2020). On the other end, Hong Kong decided by January 24, 2020 to advise the general population to wear surgical masks in crowded places and public transports (Hong Kong Department of Health, 2020). As can be observed from the maskingdata table, as of April 10, 2020, the characteristics for epidemic control in terms of daily growth and peak from reduction are better for Hong Kong than for Singapore. These variations may be related to levels of adherence to masking by the general population. Though there are no available data as of April 10, 2020 as per adherence to universal masking in Singapore, telephone surveys in Hong Kong done in February 11-14, 2020 and then in March 10-13, 2020, both after DoH public advice, have shown declared masking adherence at the very high levels of resp. 97.5% and 98.8% when going out (Cowling *et al.*, 2020). Provided the adherence level to masking were lower in Singapore since the general population order came much later, this would support the experimental results from the models.

Although these correlations may be due to underlying unobserved factors, they call for further enquiry into the effects of masking. These results confirm other previous findings. A recent macro-level regression analysis by


Figure 8: Visual representation of epidemic daily growth versus percentage reduction from peak daily daily growth in quadrants showing the impact of universal masking on epidemic control: and reduction from peak, from January 23 to April 10, 2020 for selected list of countries or provinces with high GDP PPP per capita in Asia, Europe and North America. Masking is nearly perfectly correlated with lower daily growth or strong reduction from peak growth of COVID-19. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

economists at Yale University, taking into account masking cultures and times of country COVID-19 policy responses, estimated that growth of COVID-19 rates only half that of mask wearing countries —the growth rate of confirmed cases is 18% in countries with no pre-existing mask norms and 10% in countries with such norms, while the growth rate of deaths is 21% in countries with no mask norms and 11% in countries with such norms. The authors note that such a 10% reduction in transmission probabilities could correspond to a per capita gain of $3,000-6,000 per each additional cloth mask, and that the economic benefits of each medical mask for healthcare personnel could be substantially larger (Abaluck *et al.*, 2020).

## 6 Conclusion: Universal masking needs broad support and clear guidelines

Our SEIR and ABM models suggests a substantial impact of universal masking. Without masking, but even with continued social distancing in place once the lockdown is lifted, the infection rate will increase and almost half of the population will become affected. This scenario would potentially lead to over a million deaths in a population the size of the UK. Social distancing and masking at both 50% and 80% of the population —but no lockdown beyond the end of May —result in substantial reduction of infection, with 80% masking eventually eliminating the disease.

Without masking, lifting lockdown after nine weeks while keeping social distancing measures will risk a major second wave of the epidemic in 4-5 months' time. However, if four out of five citizens would start wearing cloth masks in public before the lockdown is lifted, the number of new COVID-19 cases could decline enough to exit lockdown and still avoid a second wave of the epidemic. If only every second person starts wearing a mask, infection rates would also decline substantially, if not fully enough to prevent the second wave.

Combined with the correlational empirical evidence, our results highlight the need for mass masking as an alternative to a continued lockdown scenario. For this strategy to be most effective, the vast majority of the population needs to adopt mask wearing immediately. When a well-timed "mouth-and-nose lockdown" accompanies the current "full body lockdown", both the human and economic costs of the COVID-19 pandemic can be significantly lowered.

Our results are in line with previous studies suggesting that a high rate of masking may be needed in a population to provide efficient protection from influenza (Yan *et al.*, 2019) and masking can be an effective intervention strategy in reducing the spread of a pandemic (Tracht *et al.*, 2010).

Furthermore, universal masking can reduce stigmatization of ethnic groups, risk groups, or the sick and contribute to public solidarity (Feng *et al.*, 2020).

We urge governments and international bodies who have not yet done so to consider masking as one of the key tools in population policy after the COVID-19 lockdowns and until the virus is under control. The analysis presented here supports recent studies (Abaluck *et al.*, 2020), suggesting that the effectiveness of universal masking is comparable to that of social distancing or a societal lockdown with closed workplaces, schools, and public spaces and limited geographical mobility. The results from our simulation help explain the dynamics behind the perplexing advantage in the Asian experience of tackling COVID-19 compared to the situation elsewhere.

Our analyses lead to the following key policy recommendations:

1. Masking should be mandatory or strongly recommended for the general public when in public transport and public spaces, for the duration of the pandemic.

2. Masking should be mandatory for individuals in essential functions (health care workers, social and family workers, the police and the military, the service sector, construction workers, etc) and medical masks and gloves or equally safe protection should be provided to them by employers. Cloth masks should be used if medical masks are unavailable.

3. Countries should aim to eventually secure mass production and availability of appropriate medical masks (without exploratory valves) for the entire population during the pandemic.

4. Until supplies are sufficient, members of the general public should wear nonmedical fabric face masks when going out in public and medical masks should be reserved for essential functions.

5. The authorities should issue masking guidelines to residents and companies regarding the correct and optimal ways to make, wear and disinfect masks.

6. The introduction of mandatory masking will benefit from being rolled out together with campaigns, citizen initiatives, the media, NGOs, and influencers in order to avoid a public backlash in societies not culturally accustomed to masking. Public awareness is needed that "masking protects your community—not just you".

The effectiveness of universal masking in a given population is likely to depend on the type of masks used, the acceptance of masking in the population, the level of contagion of the virus, and what other interventions have been applied. From this perspective, the Central European experience will be highly informative, since it represents the first major shift to universal masking in a formerly non-masking culture. The effects of this pioneering intervention on infection rates and fatalities will appear only in the forthcoming weeks, although Slovakia and Slovenia are currently showing early indications of progress (see Figure 7). In any case, they illustrate that a country with no prior history of mask wearing in public may rapidly change course, and quickly adopt masks as a non-stigmatised —even street smart —way to express caring and solidarity in the community.

The medical and social risks of increased infections need to be countered by proper advice in the public domain. Some studies do indicate negative effects of cloth mass use, for instance, higher risks of infection due to moisture retention, reuse of cloth masks and poor filtration, in comparison to medical masks (MacIntyre *et al.*, 2015). There are also concerns that lay individuals may use both medical and/or cloth and paper masks incorrectly. Masking techniques and norms need to be taught with targeted information to different demographics, just as proper handwashing and social distancing techniques have been taught.

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