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# Robust test and trace strategies can prevent COVID-19 resurgences: a case study from New South Wales, Australia

RM Stuart<sup>1,2†</sup>, Romesh G. Abeysuriya<sup>2</sup>, Cliff C. Kerr<sup>3,4</sup>, Dina Mistry<sup>3</sup>, Daniel J. Klein<sup>3</sup>, Richard Gray<sup>5</sup>, Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>

1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark
2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia
3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation, Seattle, USA
4. School of Physics, University of Sydney, Sydney, New South Wales, Australia
5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia
6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia
7. University of Melbourne, Parkville, Victoria, Australia
8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne, Victoria, Australia
9. The School of Population and Global Health and the Peter Doherty Institute for Infection and Immunity, Melbourne, Victoria, Australia

† Corresponding author. E-mail: [robyn@math.ku.dk](mailto:robyn@math.ku.dk)

**Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, contact tracing, Australia

## Abstract

**Objectives:** The early stages of the COVID-19 pandemic illustrated that SARS-CoV-2, the virus that causes the disease, has the potential to spread exponentially. Therefore, as long as a substantial proportion of the population remains susceptible to infection, the potential for new epidemic waves persists even in settings with low numbers of active COVID-19 infections, unless sufficient countermeasures are in place. We aim to quantify vulnerability to resurgences in COVID-19 transmission under variations in the levels of testing, tracing, and mask usage.

**Setting:** The Australian state of New South Wales, a setting with prolonged low transmission, high mobility, non-universal mask usage, and a well-functioning test-and-trace system.

**Participants:** None (simulation study)

**Results:** We find that the relative impact of masks is greatest when testing and tracing rates are lower (and vice versa). With very high testing rates (90% of people with symptoms, plus 90% of people with a known history of contact with a confirmed case), we estimate that the epidemic would remain under control until at least the end of 2020, with as little as 70–110 new infections estimated over October 1 – December 31 under high mask uptake scenarios, or 340–1400 without masks, depending on the efficacy of community contact tracing. However, across comparable levels of mask uptake and contact tracing, the number of infections over this period would be up to 6 times higher if the testing rate was 80% instead of 90%, 17 times higher if the testing rate was 65%, or more than 100 times higher with a 50% testing rate.

**Conclusions:** Our work suggests that testing, tracing and masks can all be effective means of controlling transmission. A multifaceted strategy that combines all three, alongside continued hygiene and distancing protocols, is likely to be the most robust means of controlling transmission of SARS-CoV-2.

**Strengths and limitations of this study**

- A core strength of this study is that we are able to quantify the extent to which controlling COVID-19 transmission relies on the balance between testing, contact tracing, and mask usage.
- Our key result – that robust control is best facilitated by a multifaceted approach – has practical policy implications, both for the setting considered in this study and more broadly.
- These findings would be strengthened by more reliable data on the efficacy of contact tracing programs, including data on how many people were contacted for each confirmed index case of COVID-19.

## Introduction

Across the world, governmental responses to the ongoing COVID-19 pandemic have already profoundly curtailed the spread of SARS-CoV-2, the virus that causes the disease. As the pandemic unfolded during the second half of 2020, the nature of the governmental responses also evolved. An increasing number of countries moved from an initial crisis-management phase into a new phase centred around minimising transmission risk while allowing societal and economic activities to resume (1). In this paper, we focus on three key components of this phase: masks (either mandatory or recommended in certain settings), testing, and contact tracing, whereby those known to have been in contact with a confirmed case are required to test and/or quarantine. When used in combination with physical distancing and hand hygiene measures, all three strategies allow relatively high mobility: testing and contact tracing means that only those at greatest risk of transmitting the virus need to stay home, while masks mean that people with undiagnosed infections present less of a risk to others (2–4).

Given the complexities of COVID-19 transmission, including the duration of pre-symptomatic infection (5,6), the proportion of infections that are asymptomatic (7), and the possibility of transmission via surface contact (8), maintaining control of COVID-19 has proven challenging in many jurisdictions (9–13). The often-cited success stories of Taiwan, Vietnam, Thailand, and South Korea included high mask usage, high rates of testing, and fast, effective contact tracing (14–16). The benefits of a multi-pronged approach have also been illustrated in the literature; in the UK, for example, a recent study (17) found that mandating masks in secondary schools could achieve approximately the same reduction in resurgence risk as having an 8–11% increase in symptomatic testing.

In this work, we use an agent-based model to estimate the combination of testing, community-based contact tracing, and mask usage required to maintain epidemic control in a low-transmission, high-mobility setting. The context for our study is the Australian state of New South Wales (NSW), with a population of 7.5 million and just over 4000 diagnosed cases as of September 30, 2020. Over the period from June 1 – September 30, 2020, masks were recommended by the government for the general public and made mandatory for staff in various businesses including supermarkets. Across Australia, 58% of people reported wearing

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3 masks in mid-August, including all Victorians (18); the proportion of people in NSW wearing  
4 masks has not been reported, although CCTV footage from August registered ~30% of  
5 passengers on urban public transport wearing masks (19). At the same time, high levels of  
6 testing (~20,000 tests/day) and rapid contact tracing were in place, with notable focus on  
7 contact tracing. The state health department (NSW Health) required all businesses to have a  
8 COVID-19 Safety Plan, and for the majority of public-facing businesses this included a  
9 requirement for customers to register their details upon entry. Upon identifying a new case,  
10 NSW Health's contact tracers would then (a) conduct an extended interview to determine all  
11 possible venues in which transmission may have occurred, (b) place details of those venues  
12 on their website, on social media, and in newspapers, urging people who had been at the  
13 venue to self-isolate for 14 days, (c) attempt to contact all people who were registered to have  
14 been at venues within a given window of the time that the diagnosed case was known to have  
15 been there and instruct them to self-isolate for 14 days. Over the four months from June 1 –  
16 September 30, 2020 while this strategy was in place, approximately 900 new cases were  
17 identified, and only 45 (5%) of these were locally acquired and not linked to known clusters  
18 (20).  
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34 This paper builds on previous work in which we estimated the probability of epidemic rebound  
35 following a prolonged period of low, stable transmission and relatively high community mobility  
36 (21), assuming that 25% of contacts encountered in locations that require customer  
37 registration (including restaurants, cafes, bars, pubs, sports/leisure/fitness centres, arts  
38 venues, places of worship, and large events) could be traced within two weeks. However, in  
39 this study we consider a range of testing and contact tracing levels, and assess the balance  
40 between masks, testing and contact tracing as a means of controlling community-based  
41 transmission.  
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## 51 Methods

### 52 Transmission model

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54 As in our previous study (21), we used an open-source agent-based model, Covasim (22),  
55 developed by the Institute for Disease Modeling with source code and documentation available  
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at <https://covasim.org>. To simulate the epidemic and policy environment in New South Wales over March 1 – September 30, 2020, we include parameter changes that capture the testing, tracing, isolation, quarantine, and lockdown policies that were enacted over this time (summarised in Table S1), as well as the introduction of interstate cases in late June prior to the closure of the state border with neighbouring Victoria. We then calibrate the model by adjusting the per-contact transmission rate to fit data on the daily number of cases diagnosed, excluding cases acquired overseas or interstate, by performing an automated search for the values of the per-contact transmission risk and the number of seed infections that minimised the absolute differences between the model projections and the data (Figure 1). All data and code used in these analyses are available via Github ([https://github.com/optimamodel/covid\\_nsw](https://github.com/optimamodel/covid_nsw)).

## Model analysis

We run the model from October 1, 2020, until December 31, 2020, using a set of assumptions about future testing rates, the efficacy of contact tracing, and mask uptake. For testing rates, we distinguish between symptom-based testing and testing of asymptomatic contacts. NSW Health guidelines advise anyone with symptoms to get tested, as well as anyone identified as a contact regardless of symptoms (23). To reflect this, we use a baseline assumption that the testing rate for asymptomatic contacts is the same as for people with symptoms, and run a counterfactual set of scenarios in which it is assumed to be half the rate for those with symptoms (Table 1).

4x combinations of symptomatic testing	50%, 65%, 80%, 90% tested over the course of their symptoms
2x combinations of asymptomatic contact testing	1. Asymptomatic contact testing rate equal to symptomatic testing rate 2. Asymptomatic contact testing rate half of symptomatic testing rate
5x combinations of contact tracing for community	0%, 25%, 50%, 75%, 100% of

contacts	contacts traced within 1 week
4x combinations of mask uptake	0%, 25%, 50%, 75%

**Table 1:** overview of the 160 scenarios (4x2x5x4) analysed over Oct 1 – Dec 31, 2020.

To model the efficacy of contact tracing, we assume that 100% of household contacts will be traced and notified on the same day that test results are communicated, and that 95% of school contacts and 90% of workplace contacts will be notified on the following day. We then consider scenarios in which 0%, 25%, 50%, 75%, or 100% of all other contacts (which we refer to as community contacts) can be traced within a week of a case notification. For each scenario, the time to trace each contact is drawn from a scaled Poisson distribution with a mean of 1 day (Figure S1). We also assume that 0%, 25%, 50%, or 75% of the population will wear masks in dynamic community settings (i.e., settings in which people interact with strangers or random groups of people), which in the model includes arts venues, large events such as concerts, festivals, sports games, public parks and other outdoor settings, public transport, and all other community settings. We run ten simulations for each permutation of testing rates, mask usage and contact tracing efficacy.

For all simulations, we assume that masks will reduce the per-contact probability of transmission by 30%, in line with estimates from (24). We also assume that people who have been contact-traced will quarantine with 90% efficacy from their workplace, school, and community contacts. Test results are assumed to be communicated within 24 hours (25).

### **Role of the funding source**

The funders had no role in the design or execution of this study.

### **Patient and public involvement**

This is a modelling study; no personal data was used so patient/public involvement was not required.

## Results

Estimates of daily new infections under each scenario are presented in Figure 2. A key finding highlighted by Figure 2 is how effective high levels of testing are in maintaining epidemic control: all strategies in which there is at least some contact tracing in place and testing rates are very high (90% of people with symptoms and 90% of asymptomatic contacts of confirmed cases) lead to a robustly controlled epidemic, with as little as 70–110 new infections estimated over October 1 – December 31 under high mask uptake scenarios, or 340–1,400 without masks, depending on the efficacy of community contact tracing (Figure 2, bottom row). However, holding mask uptake and contact tracing constant, we estimate that the number of infections over October 1 – December 31, 2020, would be up to 6 times higher if the testing rate was 80% instead of 90%, 17 times higher if the testing rate was 65%, or more than 100 times higher with a 50% testing rate (Figure 2, third row).

A second key finding is that the lower the testing rate, the greater the impact of masks and contact tracing (and vice versa). With medium-lower testing rates of 50% or 65%, the marginal impact of both masks and contact tracing are considerable (Figure 2, top two rows). Under these scenarios, the most robust strategies consist of a combination of masks and community contact tracing. Assuming a 50% testing rate, a scenario with near-perfect tracing and no masks is approximately equivalent to a scenario with no tracing and high mask uptake. However, without community contact tracing, a reduction in mask usage from 75% to 50% would lead to a near-doubling in estimated infections (from 11,500 to 21,800), whereas even moderate levels of community contact tracing (25% traceable within a week) would increase the robustness of the response to lower mask usage (with 9,260 infections estimated under 75% mask usage and 13,700 under 50% mask usage). Similarly, masks strengthen the resilience of the epidemic outcome to decreases in contact tracing efficacy: without masks, a reduction in community contact tracing from 100% to 75% would lead to a 40% increase in total infections, whereas it would have no impact if 75% of the population were wearing masks.

If asymptomatic contacts only test at half the rate of people with symptoms, we estimate a more severe epidemic over the last quarter of 2020. In Figure 3 we highlight a particular set of scenarios corresponding to the most optimistic contact tracing assumptions, in which all

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community contacts are assumed to be traced within one week, with a mean time to trace of one day (the full set of scenarios are summarised in Figure S2). Within this set of scenarios, the total number of infections is estimated to be around 50% higher if asymptomatic contacts test at a lower rate than people with symptoms (averaged across all levels of mask usage).

## Discussion

In this work we present estimates illustrating the extent to which masks, community testing, and community contact tracing can reduce the spread of SARS-CoV-2 in New South Wales, Australia. We found that the relative impact of masks is greatest when testing and tracing rates are lower (and vice versa). With very high testing rates (90% of people with symptoms, plus 90% of people with a known history of contact with a confirmed case), we estimate that the epidemic in New South Wales would remain under control until at least the end of 2020, provided that fast and effective contact tracing is in place. If testing rates are lower, we estimate that mask use can play an important role in reducing the potential for epidemic resurgence.

Of the interventions considered, this study suggests that maintaining high levels of symptomatic testing, contact tracing, and testing of contacts is the most important. Longer term, there may be challenges associated with maintaining high levels of testing, mask use, and contact tracing. If daily case numbers remain low and the perceived threat of COVID-19 declines, community fatigue may influence testing behaviours, particularly for mild cases of COVID-19. There may also be a decline in mask use. Individuals may become less compliant with sign-in procedures, and venues may also become less vigilant in enforcing these procedures. This study suggests that having high levels of any two of mask use, testing and contact tracing can largely mitigate the need for the third; however practical challenges mean that this is unlikely to occur, and a more multifaceted approach of aiming for high coverage of all three and ending up with moderate coverage of all three may be an effective and more robust strategy.

Although various efforts have been made to synthesise the ever-expanding body of research regarding the efficacy of different interventions, each country's epidemic has distinct

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3 characteristics, and there are very few standardised, globally-applicable guidelines on what  
4 constitutes a best-practice public health strategy. As a result, jurisdictions have taken diverse  
5 approaches in terms of which interventions to prioritise, from a list that includes physical  
6 distancing, travel restrictions, wearing of masks or face coverings, isolation and/or testing of  
7 those with COVID-like symptoms, isolation of those who test positive, and tracing the contacts  
8 of confirmed cases for testing and/or quarantining. Although it may not always be articulated  
9 as such, numerous trade-offs are being made between different policy options in an attempt  
10 to allow the highest degree of societal activity commensurate with epidemic control. In New  
11 South Wales, mask use has been encouraged in particular settings since July, but not  
12 mandated; at the same time, there has been a strong focus on contact tracing. The results  
13 from this work suggest that the prioritisation of contact tracing may mitigate the relative  
14 importance of masks to some extent, but that this relies on continued high levels of community  
15 testing.  
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29 There are several limitations to this study. Firstly, the mathematical model that we use requires  
30 data on various aspects of SARS-CoV-2 transmission and prevention that are still not known  
31 exactly, including the effects of masks on preventing individual transmission and the proportion  
32 of infections that are asymptomatic. Whilst we have used the best available data and sampled  
33 from appropriate distributions where possible, this represents a source of uncertainty in all  
34 mathematical models of COVID-19. Secondly, we have constructed sets of scenarios that  
35 examine various combinations of parameters on mask uptake, contact tracing, testing of  
36 people with symptoms, and asymptomatic contact testing, but there are many more  
37 parameters that determine the dynamics of transmission, including the stringency of border  
38 control measures, people's adherence to quarantine and isolation policies, and the effect of  
39 ongoing distancing policies. Changes to any of these policies would affect the results  
40 presented here in ways that are not straightforward to predict or extrapolate. Third, we have  
41 not considered any outbreak risk associated with newly seeded cases in the community that  
42 may arise from international or interstate arrivals. Finally, the model used here does not  
43 contain a geospatial component, and we have not considered heterogeneities in incidence,  
44 behaviour, or contact patterns across different parts of the state in these analyses. This could  
45 be relevant for questions around mask uptake, as uptake of masks is generally higher in more  
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3 densely populated areas, so using a state-wide average for the proportion of the population  
4 wearing masks may underestimate their impact, especially since >90% of infections in NSW  
5 to date have occurred in the Sydney metropolitan area.  
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## 10 11 Conclusions

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14 Our work suggests that testing, tracing and masks can be effective means of controlling  
15 transmission in dynamic community settings, and higher compliance with one can offset lower  
16 compliance with the other to some extent. However, pursuing a strategy that combines  
17 aggressive testing, high mask usage, and effective contact tracing, alongside continued  
18 hygiene and distancing protocols, is likely to be the most robust means of controlling  
19 community-based transmission of SARS-CoV-2.  
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## 26 27 List of figures

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30 **Figure 1.** Calibration of the model to the NSW epidemic. Solid lines indicate the median model  
31 projections over 20 model runs; shaded areas indicate 95% projected intervals over different  
32 initialisations; blue diamonds indicate data on confirmed locally-acquired cases.  
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38 **Figure 2.** Trailing 14-day average of daily new infections under different assumptions about  
39 the testing rate (rows), proportion of community contacts that can be traced within one week  
40 (columns), and mask uptake (line colours). Projections represent the median of 20 simulations.  
41 Text boxes in each panel displays the cumulative number of infections over October 1 –  
42 December 31, 2020.  
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49 **Figure 3.** Estimated total infections over October 1 – December 31, 2020 under different  
50 assumptions about testing rates and mask uptake, assuming all community contacts can be  
51 traced within a week with a mean time to trace of 1 day. Projections represent the median of  
52 20 simulations.  
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## List of supplementary materials

- Figure S1: Assumed distribution of times required to find community contacts.
- Table S1: Effects of policies on transmission risk in New South Wales
- Figure S2: Estimated daily new infections assuming that asymptomatic contact-based testing rates are lower than symptomatic testing rates.

## Declarations

**Competing interests statement:** The authors declare that they have no competing interests.

**Data sharing statement:** All code and data analysed during this study are available in [https://github.com/optimamodel/covid\\_nsw](https://github.com/optimamodel/covid_nsw).

**Contributorship:** RMS wrote the manuscript and produced the results. The model parameters and calibration were agreed upon by RMS, RA, NS, and RG. The scenarios and analyses were agreed upon by NS, MH, and RMS. CK, RMS, RA, DM, and DJK led development of the model (along with numerous other contributors listed below).

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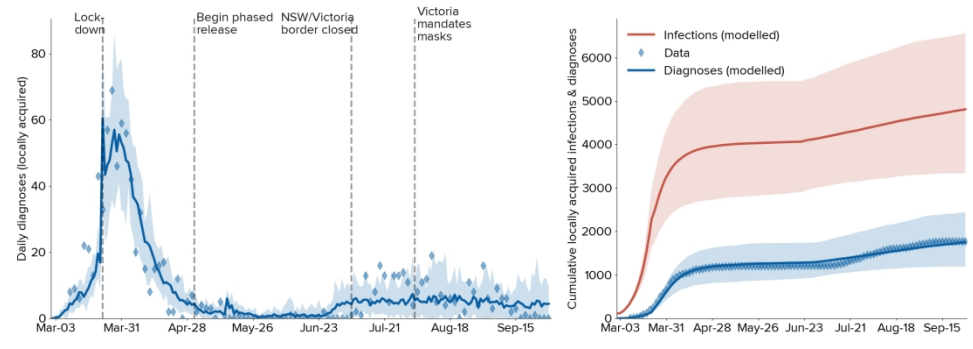


Figure 1. Calibration of the model to the NSW epidemic. Solid lines indicate the median model projections over 20 model runs; shaded areas indicate 95% projected intervals over different initialisations; blue diamonds indicate data on confirmed locally-acquired cases.

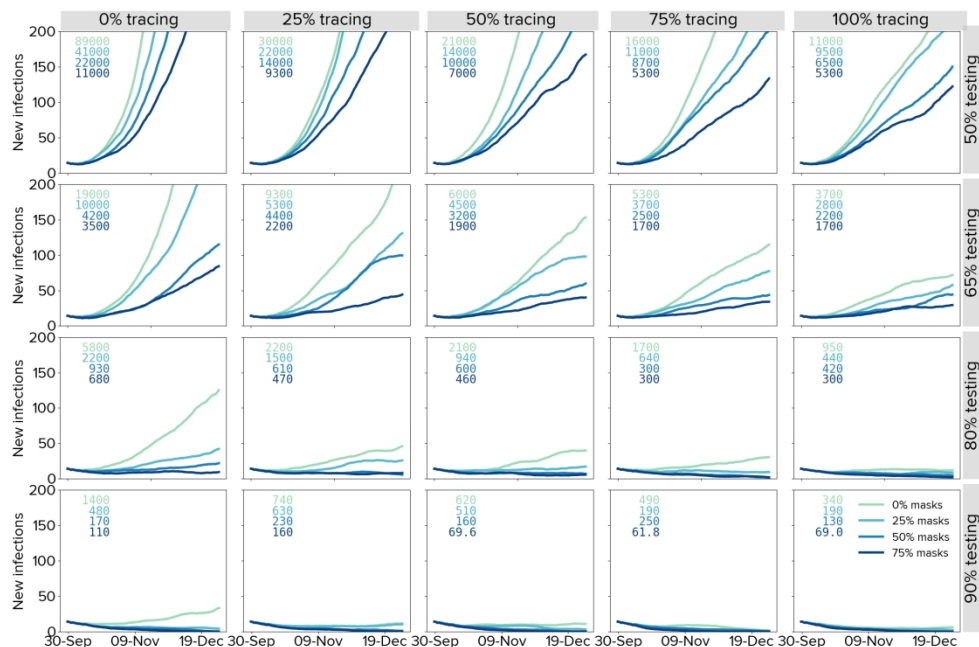


Figure 2. Trailing 14-day average of daily new infections under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours). Projections represent the median of 20 simulations. Text boxes in each panel displays the cumulative number of infections over October 1 – December 31, 2020.

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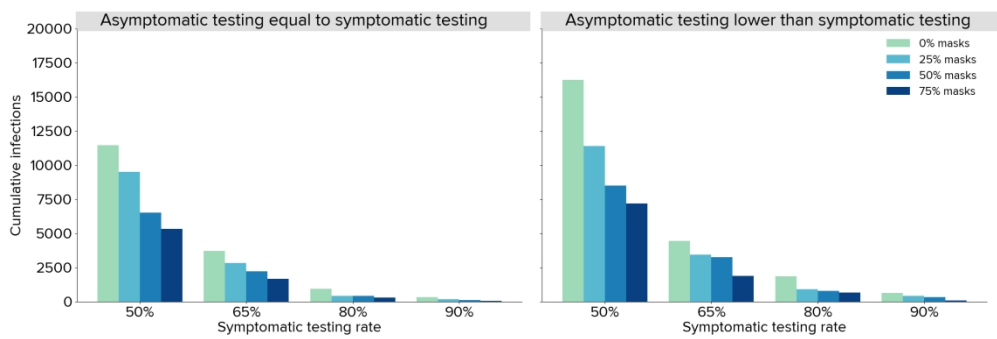


Figure 3. Estimated total infections over October 1 – December 31, 2020 under different assumptions about testing rates and mask uptake, assuming all community contacts can be traced within a week with a mean time to trace of 1 day. Projections represent the median of 20 simulations.

# Supplementary materials: Robust test and trace strategies can prevent COVID-19 resurgences: a case study from New South Wales, Australia

RM Stuart<sup>1,2†</sup>, Romesh G. Abeysuriya<sup>2</sup>, Cliff C. Kerr<sup>3,4</sup>, Dina Mistry<sup>3</sup>, Daniel J. Klein<sup>3</sup>, Richard Gray<sup>5</sup>, Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>

1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark

2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia

3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation, Seattle, USA

4. School of Physics, University of Sydney, Sydney, New South Wales, Australia

5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia

6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia

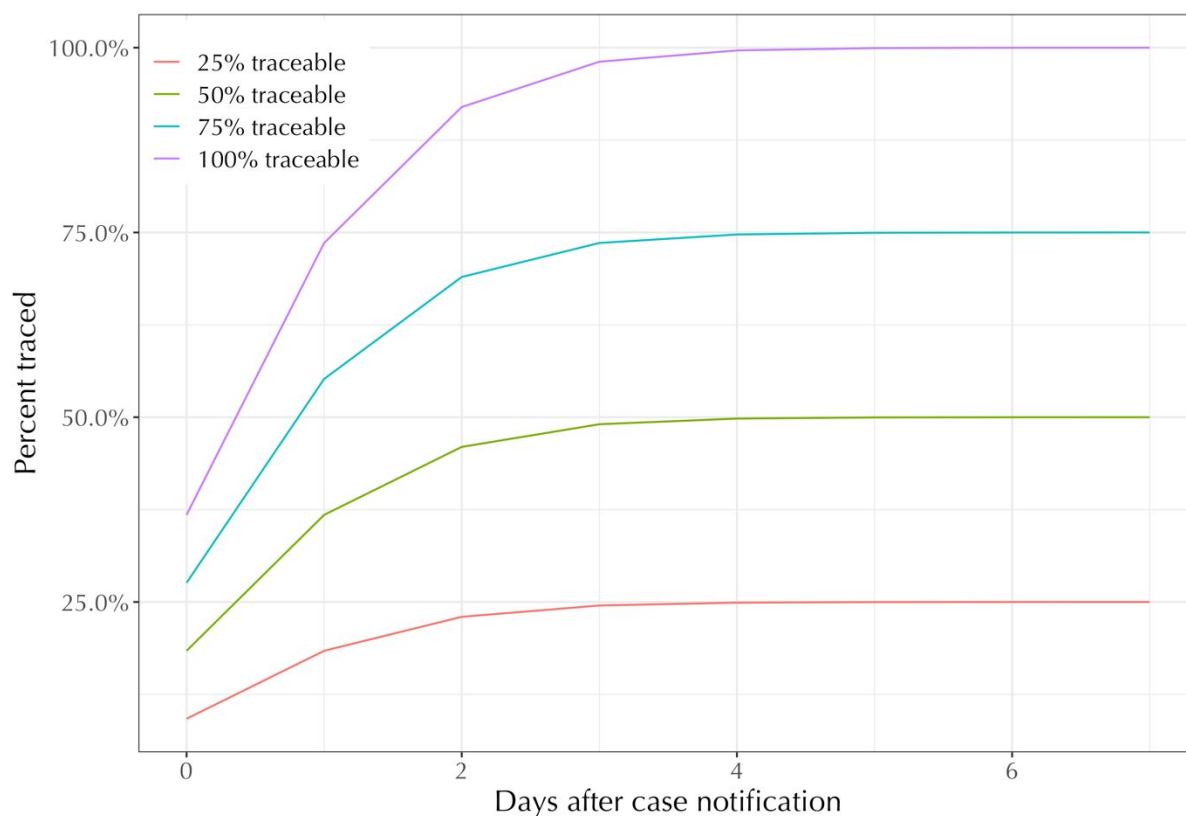
7. University of Melbourne, Parkville, Victoria, Australia

8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne, Victoria, Australia

9. The School of Population and Global Health and the Peter Doherty Institute for Infection and Immunity, Melbourne, Victoria, Australia

† Corresponding author. E-mail: [robyn@math.ku.dk](mailto:robyn@math.ku.dk)

**Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, contact tracing, Australia



**Figure S1.** Assumed distribution of times required to find venue-based contacts.

Setting	Description of policy changes and their effects
Schools	School attendance rates in NSW had already dropped by 25% by 15 March 2020 (1), and on 23 March 2020 the NSW Premier advised that although schools remained open, parents were encouraged to keep their children at home for online learning (2). School attendance rates subsequently dropped to 5% of their pre-COVID levels (3). However, attendance quickly returned to pre-COVID levels shortly after schools reopened in mid-May (4). To model this, we removed 95% of contacts between school children and then restored them again as schools opened, but with the relative transmission risk set to 80% of its pre-March levels to account for additional safety measures in place for school activities (5).

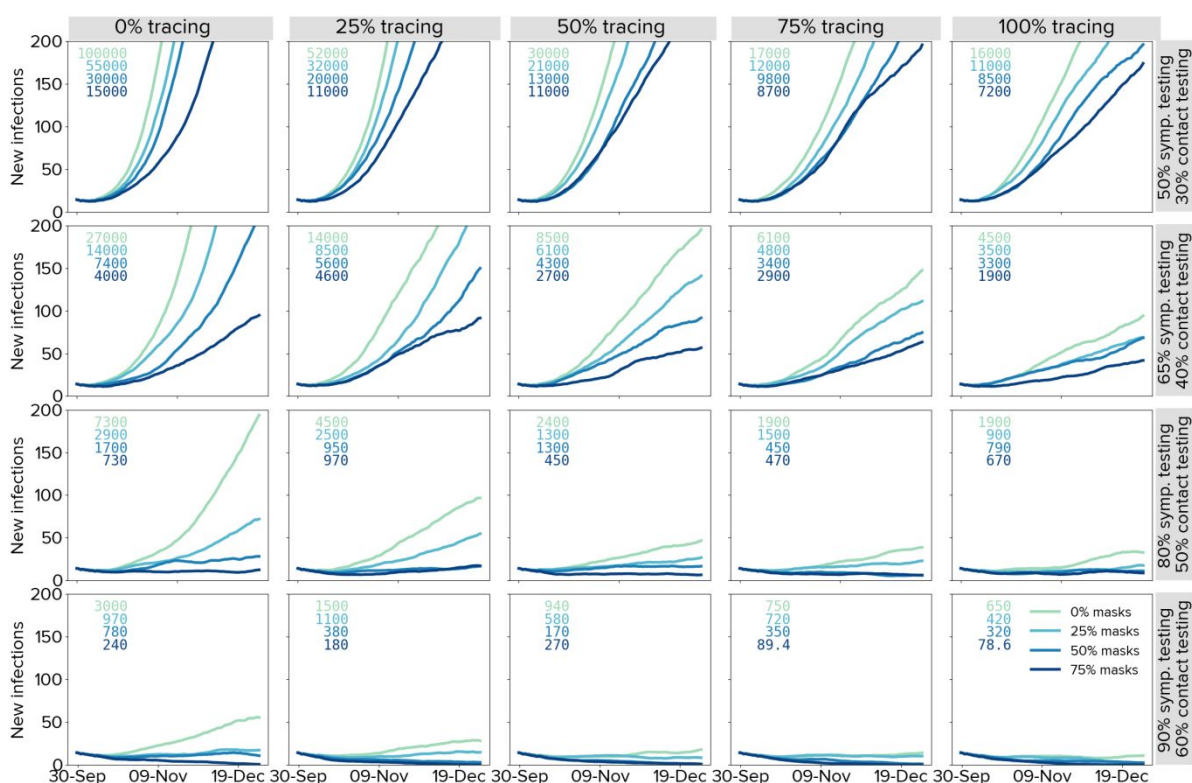
Workplaces	According to survey data from the Australian Bureau of Statistics, almost half of working Australians were working from home in late April/early May (6), which is roughly consistent with Google movement data indicating that 40% fewer people were at work over that period compared to baseline. Workplace-based activities increased as COVID restrictions eased, but remained 15% lower over June-July compared to baseline. In the model, we removed 50% of workplace contacts and then restored them so that the workplace network was back to 85% of its pre-COVID size by the beginning of July (Figure 1). As with schools, we set the relative transmission risk set to 80% of its pre-March levels to account for the presence of NPIs.
Static community	We assume that almost no contacts occurred over these networks from March 23 to May 1 with the exception of the limited contacts arising from permitted single-person visits., These networks were gradually restored over the period from May 1 to July 9 as restrictions eased.
Dynamic community networks over May-July (negligible mask usage)	Within New South Wales, arts venues such as museums, galleries, theatres, and cinemas, large events such as concerts, festivals, sports games, and pubs/bars were all closed over the period from March 23 to May 15, after which the networks were gradually restored. Cafes and restaurants, public parks and other outdoor settings, public transport, and all other community settings including essential retail remained open in some capacity throughout the year but with decreased demand and operational restrictions to reduce the likelihood of transmission (e.g., takeaway service only, closure of playgrounds, capacity limits on transport, and physical distancing/hygiene).
Dynamic community networks over August (increased)	From August 3, 2020, the use of masks was mandated in Victoria, which led to a marked increase in mask usage across the country. Only 13% of Australians wore a mask at least once over the month of June, but 58% reported wearing one at least once over August 7–17, 2020 (99% of Victorian residents compared to 44% of residents of other states) (7). Within New South Wales, media sources reported that 30% of people were wearing face



<p>mask usage)</p>	<p>masks on public transport in central Sydney in mid-August (8). To reflect the gradual increase in mask uptake in the model, we adjust the relative transmission risk assuming that the proportion of adults who wore masks while at work and in dynamic community settings increased over August to reach 30% by the end of the month.</p>
<p>Testing, tracing, and isolation</p>	<p>We assume that the daily testing probability for those with symptoms increased from 5% in April to 20% by the beginning of June. Assuming a symptomatic period of roughly 10 days, this implies that the proportion of symptomatic people who get tested increased from 40% to 90%. In addition to symptom-based testing, we also assume that 90% of people who are not symptomatic but have been told to quarantine as a result of having been in contact with a confirmed case will get tested.</p> <p>To model the efficacy of contact tracing over the period from June 1 – September 30, 2020, we assume that all household contacts were traced and notified on the same day that test results were communicated, that 95% of school contacts and 90% of workplace contacts were notified on the following day, and that 50% of all other contacts (which we refer to as community contacts) were traced within a week of a case notification, with a mean time to trace of one day (Figure S1). Note that these are more optimistic assumptions than were included in our previous study (9).</p> <p>We assume that confirmed cases will isolate with near-perfect effectiveness, meaning that the probability of them transmitting to school or workplace contacts is zero, and the probability of them transmitting to their household contacts is reduced by 80%. Similarly, we assume high levels of adherence to isolation policies imposed on those who have been notified that they were in contact with a confirmed case, with a 90% reduction in their probability of transmitting to school or workplace contacts.</p>

Quarantine, and border control measures	From early on in the epidemic, Australia imposed strict border control measures requiring all arrivals to quarantine for two weeks in a hotel. These policies are assumed to be maintained throughout the duration of the model simulations.
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**Table S1.** Effects of policies on transmission risk in New South Wales



**Figure S2.** Trailing 14-day average of daily new infections under different assumptions about the testing rate (rows), proportion of venue-based contacts that can be traced within one week (columns), and mask uptake (line colours). Projections represent the median of 20 simulations. Text boxes in each panel displays the cumulative number of infections over October 1 – December 31, 2020.

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# BMJ Open

## The role of masks, testing and contact tracing in preventing COVID-19 resurgences: a case study from New South Wales, Australia

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<b>Primary Subject Heading</b>:	Epidemiology
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Keywords:	Public health < INFECTIOUS DISEASES, EPIDEMIOLOGY, Health policy < HEALTH SERVICES ADMINISTRATION & MANAGEMENT

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16 6 Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>  
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18 7

- 19  
20 8 1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark  
21  
22 9 2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia  
23  
24 10 3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation,  
25  
26 11 Seattle, USA  
27  
28 12 4. School of Physics, University of Sydney, Sydney, New South Wales, Australia  
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30 13 5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia  
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32 14 6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria,  
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36 16 7. University of Melbourne, Parkville, Victoria, Australia  
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38 17 8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne,  
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40 18 Victoria, Australia  
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42 19 9. The School of Population and Global Health and the Peter Doherty Institute for Infection  
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44 20 and Immunity, Melbourne, Victoria, Australia

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46 21 † Corresponding author. E-mail: [robyn@math.ku.dk](mailto:robyn@math.ku.dk)  
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51 25 **Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, testing, contact tracing,  
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## Abstract

**Objectives:** The early stages of the COVID-19 pandemic illustrated that SARS-CoV-2, the virus that causes the disease, has the potential to spread exponentially. Therefore, as long as a substantial proportion of the population remains susceptible to infection, the potential for new epidemic waves persists even in settings with low numbers of active COVID-19 infections, unless sufficient countermeasures are in place. We aim to quantify vulnerability to resurgences in COVID-19 transmission under variations in the levels of testing, tracing, and mask usage.

**Setting:** The Australian state of New South Wales, a setting with prolonged low transmission, high mobility, non-universal mask usage, and a well-functioning test-and-trace system.

**Participants:** None (simulation study)

**Results:** We find that the relative impact of masks is greatest when testing and tracing rates are lower (and vice versa). Scenarios with very high testing rates (90% of people with symptoms, plus 90% of people with a known history of contact with a confirmed case) were estimated to lead to a robustly controlled epidemic, with a median of ~180 infections in total over October 1 – December 31 under high mask uptake scenarios, or 260–1,200 without masks, depending on the efficacy of community contact tracing. However, across comparable levels of mask uptake and contact tracing, the number of infections over this period were projected to be 2-3 times higher if the testing rate was 80% instead of 90%, 8-12 times higher if the testing rate was 65%, or 30-50 times higher with a 50% testing rate. In reality, NSW diagnosed 254 locally-acquired cases over this period, an outcome that had a low probability in the model (4-7%) under the best-case scenarios of extremely high testing (90%), near-perfect community contact tracing (75-100%), and high mask usage (50-75%), but a far higher probability if any of these were at lower levels.

**Conclusions:** Our work suggests that testing, tracing and masks can all be effective means of controlling transmission. A multifaceted strategy that combines all three, alongside continued hygiene and distancing protocols, is likely to be the most robust means of controlling transmission of SARS-CoV-2.

1

**Strengths and limitations of this study**

- A key methodological strength of this study is the level of detail in the model that we use, which allows us to capture many of the finer details of the extent to which controlling COVID-19 transmission relies on the balance between testing, contact tracing, and mask usage.
- Another key strength is that our model is stochastic, so we are able to quantify the probability of different epidemiological outcomes under different policy settings.
- A key limitation is the shortage of publicly-available data on the efficacy of contact tracing programs, including data on how many people were contacted for each confirmed index case of COVID-19.

2



# 1 Introduction

2 Across the world, governmental responses to the outbreak of the COVID-19 pandemic in the  
3 first half of 2020 profoundly curtailed the spread of SARS-CoV-2, the virus that causes the  
4 disease (1–4). By midway through the year, an increasing number of countries had moved  
5 from an initial crisis-management phase into a new phase centred around minimising  
6 transmission risk while allowing societal and economic activities to resume (5). However, by  
7 the end of 2020, many countries around the world had experienced epidemic resurgences  
8 necessitating further shutdowns (6). This was true even in settings that had come close to  
9 eliminating the virus, such as Vietnam (7), New Zealand (8), and Australia (9). In low- or zero-  
10 transmission contexts, new outbreaks can emerge if community transmission has not been  
11 eliminated, or if infected people arrive from abroad or interstate and interact with the local  
12 community (10). It is therefore essential to be able to quantify the risk of epidemic resurgence  
13 under different policy settings.

14  
15 Given the complexities of COVID-19 transmission, including the duration of pre-symptomatic  
16 infection (11,12), the proportion of infections that are asymptomatic (13), and the possibility of  
17 transmission via surface contact (14), maintaining control of COVID-19 has proven  
18 challenging in many jurisdictions (15–19). The often-cited success stories of Taiwan, Vietnam,  
19 Thailand, and South Korea included high mask usage, high rates of testing, and fast, effective  
20 contact tracing (20–22). The benefits of a multi-pronged approach have also been illustrated  
21 in the literature; in the UK, for example, a recent study (23) found that mandating masks in  
22 secondary schools could achieve approximately the same reduction in resurgence risk as  
23 having an 8-11% increase in symptomatic testing.

24  
25 In this work, we use an agent-based model to estimate the combination of testing, community-  
26 based contact tracing, and mask usage required to maintain epidemic control in a low-  
27 transmission, high-mobility setting. These three non-pharmaceutical interventions (NPIs) were  
28 key components in reducing the probability of epidemic resurgences prior to the availability of  
29 a vaccine, and are likely to remain so for some time even after vaccination coverage increases  
30 (24). When used in combination with physical distancing and hand-washing/hygiene  
31 measures, all three strategies allow relatively high mobility: testing and contact tracing means

1 that only those at greatest risk of transmitting the virus need to stay home and have been  
2 shown to be effective in numerous settings (15,25–29), while masks mean that people with  
3 undiagnosed infections present less of a risk to others (30–34).

4  
5 The context for our study is the Australian state of New South Wales (NSW), with a population  
6 of 7.5 million and a cumulative total of just over 4700 diagnosed cases as of December 31,  
7 2020. After an initial wave of COVID-19 infections in March and subsequent lockdown in April,  
8 New South Wales began relaxing physical lockdown measures over May and was  
9 experiencing near-zero case counts by the start of June, with students back at school,  
10 businesses reopening and social/community activities resuming. In late June several clusters  
11 of new infections were detected, which subsequently led to a 4-month long period of low but  
12 steady case counts, with a mean of ~5 cases per day over July to October (excluding cases  
13 in quarantined travellers). However, NSW subsequently went on to record ~180 cases in the  
14 last two weeks of 2020, a result of a localised outbreak whose containment necessitated the  
15 introduction of stringent new restrictions on travel and gatherings that affected many over the  
16 holiday period (35).

17  
18 During the prolonged period of low transmission that NSW experienced in the second half of  
19 2020 prior to December 15, 2020, mobility remained high (36) and transmission was controlled  
20 via NPIs. Masks were recommended by the government for the general public and made  
21 mandatory for staff in various businesses including supermarkets, but were not universally  
22 adopted. In a survey undertaken in mid-September, 78% of the NSW population reported  
23 wearing a mask at some point in the previous week (37), although CCTV footage from August  
24 registered ~30% of passengers on urban public transport wearing masks (38). At the same  
25 time, high levels of testing were in place, with ~20,000 people tested per day over June–  
26 September (~2.7/day per 1,000 people), resulting in an average testing yield of 0.05%, one of  
27 the world's lowest (39). The state also had a strong focus on contact tracing, with all cases  
28 interviewed within one day of case notification (40). Over the four months from June 1 –  
29 September 30, 2020, ~900 new cases were identified, but only 45 (5%) of were classified as  
30 “source unknown”, meaning that they were neither acquired overseas/interstate nor linked to  
31 known clusters (41).

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2  
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4 1  
5 2 Relative to many other contact tracing programs across the world, the NSW contact tracing  
6  
7 3 program was differentiated by its extensive efforts to identify a person's community contacts  
8  
9 4 in addition to their household, social, school, and workplace contacts (42). The state's health  
10  
11 5 department (NSW Health) required all businesses to have a COVID-19 Safety Plan, and for  
12  
13 6 the majority of public-facing businesses this included a requirement for customers to register  
14  
15 7 their details upon entry. Upon identifying a new case, NSW Health's contact tracers would  
16  
17 8 then (a) conduct an extended interview to determine all possible venues in which transmission  
18  
19 9 may have occurred, (b) place details of those venues on their website, on social media, and  
20  
21 10 in newspapers, urging people who had been at the venue to self-isolate for 14 days, (c) attempt  
22  
23 11 to contact all people who were registered to have been at venues within a given window of the  
24  
25 12 time that the diagnosed case was known to have been there and instruct them to self-isolate  
26  
27 13 for 14 days (42).  
28  
29 14

30  
31 15 The dynamics of COVID-19 transmission are complex, and in low-transmission settings the  
32  
33 16 probability of maintaining epidemic control depends on numerous factors outside of policy  
34  
35 17 control, including the characteristics of people who get infected: the size of their households,  
36  
37 18 the type of work that they do, and a number of other socio-economic factors that may influence  
38  
39 19 their contact networks, access to testing and capacity to self-isolate. Several studies have  
40  
41 20 pointed to the role of superspreading events and overdispersion of infections in COVID-19  
42  
43 21 transmission (25,26,43,44). As a result, even with physical distancing, high levels of testing,  
44  
45 22 and rapid contact tracing, there is still a non-zero probability that a sustained outbreak could  
46  
47 23 occur depending on who gets infected and where. In this study, we consider a range of testing  
48  
49 24 and contact tracing levels, and assess the roles of masks, testing and contact tracing as a  
50  
51 25 means of controlling community-based transmission.  
52  
53 26

## 54 27 **Methods**

### 55 28 **Transmission model**

56  
57 29 We used an open-source agent-based model, Covasim (45), developed by the Institute for  
58  
59 30 Disease Modeling with source code and documentation available at <https://covasim.org>, and  
60

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4 1 previously adapted by our group to model the Victorian epidemic (10,46). Covasim contains  
5  
6 2 detailed descriptions of age-dependent disease acquisition and progression probabilities,  
7  
8 3 duration of disease by acuity, and the effects of interventions including symptomatic and  
9  
10 4 asymptomatic testing, isolation, contact tracing, and quarantine, as well as other NPIs such  
11  
12 5 as physical distancing, hygiene measures, and protective equipment such as masks.  
13  
14 6 Importantly, it also captures individual variability, with viral loads varying both between  
15  
16 7 individuals and over time.

16  
17 8  
18  
19 9 We began by simulating a population representative of New South Wales by taking data on  
20  
21 10 the age and sex composition of the population from the 2016 census (the latest available),  
22  
23 11 and using it to create a model population of agents with similar characteristics. The simulations  
24  
25 12 consist of 100,000 individual agents, who are dynamically scaled based on prevalence to  
26  
27 13 represent the total New South Wales population of 7.5 million. The dynamical scaling means  
28  
29 14 that whenever the proportion of susceptible agents falls below a threshold of 5%, the number  
30  
31 15 of agents in the model is increased; further implementation details can be found in Section  
32  
33 16 2.3.6 of Kerr et al (45).

33  
34 17  
35 18 Next, we created contact networks for these agents. The governmental response to COVID-  
36  
37 19 19 in New South Wales consisted of a set of highly context-specific policies covering  
38  
39 20 individuals, businesses, schools, and other types of organisations. To model these policies,  
40  
41 21 we allow agents in the model to interact over five types of contact network: households,  
42  
43 22 schools, workplaces, and static and dynamic community networks. The static community  
44  
45 23 network consists of interactions with friends, colleagues, or other known associates who come  
46  
47 24 together on a regular and predictable basis, and contains four sub-networks: professional  
48  
49 25 sports, community sports/fitness/leisure clubs, places of worship, and socialising with friends.  
50  
51 26 The dynamic community network consists of interactions in which people interact with  
52  
53 27 strangers or random groups of people, and contains seven separate sub-networks,  
54  
55 28 representing: (1) arts venues such as museums, galleries, theatres, and cinemas, (2) large  
56  
57 29 events such as concerts, festivals, sports games, (3) pubs and bars, (4) cafes and restaurants,  
58  
59 30 (5) public parks and other outdoor settings, (6) public transport, (7) all other community  
60  
31 settings. The method for constructing these networks is described in our previous study of the

1  
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4 1 Victorian epidemic (46) and is based on the methodology of the SynthPops Python package  
5 2 (47).  
6  
7 3  
8

9 4 Finally, to simulate the epidemic and policy environment in New South Wales over March 1 –  
10 5 September 30, 2020, we include parameter changes that capture the testing, tracing, isolation,  
11 6 quarantine, and lockdown policies that were enacted over this time. Figure 1 presents a  
12 7 summary of how contact networks and the relative risk of COVID-19 transmission in different  
13 8 settings changed as policies evolved. Some of these changes in transmission risk are derived  
14 9 from available data (48), while others are taken from a similar modelling exercise conducted  
15 10 in Victoria, in which a panel of Australia-based experts reviewed the likely effect of policies on  
16 11 transmission risks (46). Further details of all policies and how we model their effects on  
17 12 transmission risk are contained in Supplementary Table 1. We also model the introduction of  
18 13 interstate cases in late June prior to the closure of the state border with neighbouring Victoria.  
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## 30 15 Data and model fitting

31 16 We calibrate the model by adjusting the per-contact transmission risk to minimise the absolute  
32 17 differences between the model projections and data on the daily number of cases diagnosed,  
33 18 excluding cases acquired overseas or interstate from NSW Health (41). Specifically, we drew  
34 19 500 samples from a Gaussian prior distribution of values for the per-contact transmission risk  
35 20 ( $\sim N(0.025, 0.002)$ ). For each sample, we run  $N=20$  simulations for each to produce 10,000 trial  
36 21 simulations, and then retain the 1% of these with the minimum absolute differences between  
37 22 the model projections and the data.  
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## 48 24 Model analysis and timeframe

49 25 As described above, we fit the model using data up until September 30, 2020. We then run  
50 26 the model for three months (from October 1, 2020, until December 31, 2020), under a set of  
51 27 assumptions about future testing rates, the efficacy of contact tracing, and mask uptake. For  
52 28 each scenario (described below), we quantify the probability of the epidemic exceeding certain  
53 29 thresholds. We then compare these projections to the observed epidemic outcomes over the  
54 30 period from October 1 to December 31, 2020.  
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1  
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4 1 For testing rates, we distinguish between symptom-based testing and testing of asymptomatic  
5  
6 2 contacts. NSW Health guidelines advise anyone with symptoms to get tested, as well as  
7  
8 3 anyone identified as a contact regardless of symptoms (42). To reflect this, we use a baseline  
9  
10 4 assumption that the testing rate for asymptomatic contacts is the same as for people with  
11  
12 5 symptoms, and run a counterfactual set of scenarios in which it is assumed to be half the rate  
13  
14 6 for those with symptoms (Table 1). We modelled scenarios in which 50%, 65%, 80%, or 90%  
15  
16 7 of those with symptoms get tested. Test results are assumed to be communicated within 24  
17  
18 8 hours (49).

19  
20 10 We also considered variations on mask uptake and effectiveness. On uptake, we modelled  
21  
22 11 scenarios in which 0%, 25%, 50%, or 75% of the population will wear masks in dynamic  
23  
24 12 community settings (i.e., settings in which people interact with strangers or random groups of  
25  
26 13 people), which in the model includes arts venues, large events such as concerts, festivals,  
27  
28 14 sports games, public parks and other outdoor settings, public transport, and all other  
29  
30 15 community settings. We do not consider scenarios in which 100% of the population wear  
31  
32 16 masks across these settings, due to the infeasibility of wearing masks whilst eating or drinking.  
33  
34 17 On efficacy, we note that although the body of evidence supporting the effectiveness of masks  
35  
36 18 for protecting against transmission between individuals is now considerable, the size of the  
37  
38 19 effect is difficult to determine, with estimates in the range of 20–80% and varying depending  
39  
40 20 on whether one or both parties wear masks (31,50,51), or whether spillover behavioural  
41  
42 21 changes on people's attention to other NPIs are captured (52). To capture the uncertainty  
43  
44 22 regarding the effectiveness of masks, we assume that masks will reduce the per-contact  
45  
46 23 probability of transmission by 30%, in line with estimates from (53), but also consider 15% and  
47  
48 24 45% in a sensitivity analysis presented in the supplementary materials.

49  
50 26 To model the efficacy of contact tracing, we use publicly-available data from NSW Health (42).  
51  
52 27 We note that, although the program reports the proportion of known contacts that were  
53  
54 28 reached within defined timeframes, we would ideally like to know the proportion of all contacts  
55  
56 29 that were reached, which will be lower than the reported values since it will also include  
57  
58 30 contacts that the case did not recall or disclose. Thus, although NSW Health's published  
59  
60 31 reports (42) indicate that 100% of contacts are notified within 48 hours, we use slightly more

1 conservative values, namely that 100% of household contacts will be traced and notified on  
 2 the same day that test results are communicated, and that 95% of school contacts and 90%  
 3 of workplace contacts will be notified on the following day. We then consider scenarios in  
 4 which 0%, 25%, 50%, 75%, or 100% of all other contacts (which we refer to as community  
 5 contacts) can be traced within a week of a case notification. For each scenario, the time to  
 6 trace each contact is drawn from a scaled Poisson distribution with a mean of 1 day (Figure  
 7 S1). We run 100 simulations for each permutation of testing rates, mask usage and contact  
 8 tracing efficacy.

9  
 10 Finally, we assume that people who have been contact-traced will quarantine with 90%  
 11 compliance from their workplace, school, and community contacts. Whilst this assumption  
 12 may be optimistic in other global contexts, the lower case counts in NSW mean that contact  
 13 tracers have far greater capacity for rigorous ongoing follow-up of contacts, and breaches of  
 14 isolation are escalated with local authorities, as stipulated in national guideline documents  
 15 (50).  
 16

Core scenarios:	
4x combinations of symptomatic testing	50%, 65%, 80% 90% tested over the course of their symptoms
Asymptomatic contact testing	Asymptomatic contact testing rate equal to symptomatic testing rate
5x combinations of contact tracing for community contacts	0%, 25%, 50%, 100% of contacts traced within 1 week (Poisson distribution with a mean of 1 day)
4x combinations of mask uptake	0%, 25%, 50%, 75%
Mask efficacy	30%
Sensitivity analyses:	
Sensitivity to asymptomatic contact testing	We run the same 80 (4x5x4)

rate assumption	scenarios described above, but with the asymptomatic contact testing rate half of the symptomatic testing rate
Sensitivity to the mask efficacy assumption	We run the same 80 (4x5x4) scenarios described above, but with individual mask efficacy assumed to be 15% or 45% instead of 30%

**Table 1:** overview of the scenarios analysed over Oct 1 – Dec 31, 2020.

### Role of the funding source

The funders had no role in the design or execution of this study.

### Patient and public involvement

This is a modelling study; no personal data was used so patient/public involvement was not required.

## Results

According to our modelled estimates, 4,550 (95% projected interval: 3,700–6,660) people had acquired COVID-19 in NSW by the end of September 2020 (excluding cases acquired overseas or interstate), of which 39% (27–48%) had been diagnosed (Figure 2). The majority of undiagnosed infections occurred during the March-April wave; since the beginning of June, we estimate that 65% of all locally-acquired infections have been diagnosed, with the remaining 35% being primarily comprised of asymptomatic infections (65%). We further estimate that 79,330 (60,100–129,020) people had been required to self-isolate at some point by September 30, 2020 as a result of having potentially been in contact with a confirmed case.

Estimates of daily new infections under each combination of testing, community contact tracing, and mask usage are presented in Figure 3. A key finding highlighted by Figure 3 is how effective high levels of testing are in maintaining epidemic control: all strategies in which there is at least some contact tracing in place and testing rates are very high (90% of people



1  
2  
3  
4 1 with symptoms and 90% of asymptomatic contacts of confirmed cases) lead to a robustly  
5  
6 2 controlled epidemic, with a median of ~180 infections in total estimated over October 1 –  
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8 3 December 31 under high mask uptake scenarios, or 260–1,200 without masks, depending on  
9  
10 4 the efficacy of community contact tracing (Figure 3, bottom row). However, holding mask  
11  
12 5 uptake and contact tracing constant, we estimate that the number of infections over October  
13  
14 6 1 – December 31, 2020, would be 2-3 times higher if the testing rate was 80% instead of 90%,  
15  
16 7 8-12 times higher if the testing rate was 65%, or 30-50 times higher with a 50% testing rate  
17  
18 8 (Figure 3, third row).  
19

20 10 A second key finding is that the lower the testing rate, the greater the impact of masks and  
21  
22 11 contact tracing (and vice versa). With medium-lower testing rates of 50% or 65%, the marginal  
23  
24 12 impact of both masks and contact tracing are considerable (Figure 3, top two rows). Under  
25  
26 13 these scenarios, the most robust strategies consist of a combination of masks and community  
27  
28 14 contact tracing. Assuming a 50% testing rate, a scenario with near-perfect tracing and no  
29  
30 15 masks is approximately equivalent to a scenario with no tracing and high mask uptake.  
31  
32 16 However, without community contact tracing, a reduction in mask usage from 75% to 50%  
33  
34 17 would lead to a near-doubling in estimated infections (from 7,900 to 17,000), whereas even  
35  
36 18 moderate levels of community contact tracing (25% traceable within a week) would increase  
37  
38 19 the robustness of the response to lower mask usage (with 6,400 infections estimated under  
39  
40 20 75% mask usage and 9,700 under 50% mask usage). Similarly, masks strengthen the  
41  
42 21 resilience of the epidemic outcome to decreases in contact tracing efficacy: without masks, a  
43  
44 22 reduction in community contact tracing from 75% to 50% would lead to a 70% increase in total  
45  
46 23 infections, whereas it would have no impact if 75% of the population were wearing masks.  
47

48 24  
49 25 Figure 4 captures the risks associated with different strategies, quantified in terms of the  
50  
51 26 probability of the 14-day average of daily diagnoses exceeding a given number by December  
52  
53 27 31, 2020. With no community tracing and a 50% testing rate, the probability of exceeding 100  
54  
55 28 diagnoses/day by the end of 2020 was calculated to be 98% without masks, and to remain  
56  
57 29 greater than 50% even under the most optimistic mask uptake scenario (Figure 4, top left  
58  
59 30 panel). However, higher levels of community tracing reduce these risks considerably: even  
60  
31 without any mask usage, the probability of exceeding 100 cases/day is estimated to be half

1 as high with perfect community tracing (Figure 4, top right panel) compared to the same  
2 scenario without community tracing (48% vs 98%), and the addition of mask usage in  
3 community settings is estimated to reduce this even further, to ~10%.

## 4 5 Comparison with actual outcomes

6 The text boxes on Figure 4 display the probability of observing the outcome that was seen in  
7 NSW, in which the two-week average of daily diagnoses exceeded 12 by December 31. We  
8 calculate that this outcome would have been assigned a low probability (4-7%) under the best-  
9 case scenarios of extremely high testing (90%), near-perfect community contact tracing (75-  
10 100%), and high mask usage (50-75%), but that it would have been considered a far more  
11 likely outcome if any of these were assumed to be at lower levels.

## 12 13 Sensitivity analyses

14 If asymptomatic contacts only test at half the rate of people with symptoms, we estimate a  
15 more severe epidemic over the last quarter of 2020, but the key results regarding the roles of  
16 community contact tracing and masks do not change (Figure S2). Since our core analyses  
17 already assume high compliance with recommended self-isolation policies for known contacts  
18 of confirmed cases, the marginal benefit of high asymptomatic contact tracing is primarily to  
19 further bolster the efficacy of contact tracing, since it allows for the identification of chains of  
20 transmission even in the absence of symptoms. To highlight the role of testing asymptomatic  
21 contacts, in Figure 5 we highlight a particular set of scenarios corresponding to the most  
22 optimistic contact tracing assumptions, in which all community contacts are assumed to be  
23 traced within one week, with a mean time to trace of one day (the full set of scenarios are  
24 summarised in Figure S2). Within this set of scenarios, the total number of infections is  
25 estimated to be around 50% higher if asymptomatic contacts test at a lower rate than people  
26 with symptoms (averaged across all levels of mask usage).

27  
28 We also find that, if masks are assumed to be more or less effective, this would change the  
29 risks associated with diagnosing more than a given number of cases per day under the  
30 different mask scenarios, but would not qualitatively change the results (Figure S3-S4).

## Discussion

In this work we presented estimates illustrating the extent to which masks, community testing, and community contact tracing could reduce the spread of SARS-CoV-2 in New South Wales, Australia in the absence of widespread vaccination. We found that the relative impact of masks is greatest when testing and tracing rates are lower (and vice versa). With very high testing rates (90% of people with symptoms, plus 90% of people with a known history of contact with a confirmed case), we estimate that epidemic control would be possible even without widespread mask uptake, provided that fast and effective contact tracing is in place. However, under any scenario where testing rates are lower, we estimate that mask use can play an important role in reducing the potential for epidemic resurgence.

Our findings have relevance for assessing the outbreak that occurred in the state towards the end of December 2020, which saw an average of ~12 diagnoses/day over two weeks. According to our estimates, this outcome would have been assigned a relatively low probability (4-7%) if it was assumed that compliance with the state's testing guidelines, venue registration protocols, and non-mandatory mask recommendations would be at very high levels, but that it would have been evaluated as a far more likely outcome if compliance with any of these NPIs was assumed to be lower. As a result of the December 2020 outbreak, the NSW government made masks mandatory in all indoor community settings from January 4, 2021 (54), a decision which will likely increase the robustness of the overall response to decreases in testing or contact tracing rates, but will still require ongoing commitment to ensure these remain at high levels, at least until vaccination coverage is sufficiently high. According to Australia's vaccination schedule, half the population may be vaccinated by mid-2021, and NPIs will feature as part of the COVID-19 control strategy until well beyond this point (55).

Of the interventions considered, this study suggests that maintaining high levels of symptomatic testing, contact tracing, and testing of contacts are all important. We also quantified the importance of testing asymptomatic contacts as a strategy that further strengthens the power of contact tracing programs, since it allows the tracing and quarantining of their contacts in turn. Longer term, 'pandemic fatigue' may bring about challenges in maintaining high levels of testing, mask use, and contact tracing (56). This study suggests that

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4 1 having high levels of any two of mask use, testing and contact tracing can largely mitigate the  
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6 2 need for the third; however practical challenges mean that this is unlikely to occur, and a more  
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8 3 multifaceted approach of aiming for high coverage of all three and ending up with moderate  
9  
10 4 coverage of all three may be an effective and more robust strategy. Various studies have  
11  
12 5 shown that the roll-out of vaccination plans is unlikely to mitigate the need for NPIs such as  
13  
14 6 these for some time (24,57–59), so these finding are likely to remain relevant for a  
15  
16 7 considerable portion of 2021.

16 8  
17  
18 9 Although various efforts have been made to synthesise the ever-expanding body of research  
19  
20 10 regarding the efficacy of different interventions (1–4,60), each country's epidemic has distinct  
21  
22 11 characteristics and there are very few standardised, globally-applicable guidelines on what  
23  
24 12 constitutes a best-practice public health strategy (61,62). As a result, jurisdictions have taken  
25  
26 13 diverse approaches in terms of which interventions to prioritise, from a list that includes  
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28 14 physical distancing, travel restrictions, wearing of masks or face coverings, isolation and/or  
29  
30 15 testing of those with COVID-like symptoms, isolation of those who test positive, and tracing  
31  
32 16 the contacts of confirmed cases for testing and/or quarantining. Although it may not always be  
33  
34 17 articulated as such, numerous trade-offs are being made between different policy options in  
35  
36 18 an attempt to allow the highest degree of societal activity commensurate with epidemic control.  
37  
38 19 In New South Wales, mask use was encouraged in particular settings since July 2020, but not  
39  
40 20 mandated until January 2021; at the same time, there was a strong focus on contact tracing.  
41  
42 21 The results from this work suggest that the prioritisation of contact tracing may mitigate the  
43  
44 22 relative importance of masks to some extent, but that this relies on continued high levels of  
45  
46 23 community testing.

46 24  
47  
48 25 There are several limitations to this study. Firstly, the mathematical model that we use requires  
49  
50 26 data on various aspects of SARS-CoV-2 transmission and prevention that are still not known  
51  
52 27 exactly, including the effects of masks on preventing individual transmission and the proportion  
53  
54 28 of infections that are asymptomatic. Whilst we have used the best available data and sampled  
55  
56 29 from appropriate distributions where possible, this represents a source of uncertainty in all  
57  
58 30 mathematical models of COVID-19. Additional uncertainties are introduced by the evolution of  
59  
60 31 new strains of SARS-CoV-2 with increased transmissibility and/or severity. Secondly, we have

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4 1 constructed sets of scenarios that examine various combinations of parameters on mask  
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6 2 uptake, contact tracing, testing of people with symptoms, and asymptomatic contact testing,  
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8 3 but there are many more parameters that determine the dynamics of transmission, including  
9  
10 4 the stringency of border control measures, people's adherence to quarantine and isolation  
11  
12 5 policies, and the effect of ongoing distancing policies. Changes to any of these policies would  
13  
14 6 affect the results presented here in ways that are not straightforward to predict or extrapolate.  
15  
16 7 Third, we have not considered any outbreak risk associated with newly seeded cases in the  
17  
18 8 community that may arise from international or interstate arrivals. Another limitation is the  
19  
20 9 relatively simplistic way that we have modelled mask usage, whereby we have not included  
21  
22 10 variation in (a) adherence to mask usage across different types of venue, or (b) individual  
23  
24 11 compliance. Assuming that mask-wearing reduces everyone's transmission risk by a certain  
25  
26 12 percentage disregards the individual behavioural changes that may adjust individual-level  
27  
28 13 transmission risk by varying amounts. Furthermore, it is very likely that mask usage would be  
29  
30 14 higher in certain settings (e.g., public transport) than others, especially restaurants which are  
31  
32 15 suspected to be important for transmission. Finally, the model used here does not contain a  
33  
34 16 geospatial component, and we have not considered heterogeneities in incidence, behaviour,  
35  
36 17 or contact patterns across different parts of the state in these analyses. This could be relevant  
37  
38 18 for questions around mask uptake, as uptake of masks is generally higher in more densely  
39  
40 19 populated areas, so using a state-wide average for the proportion of the population wearing  
41  
42 20 masks may underestimate their impact, especially since >90% of infections in NSW to date  
43  
44 21 have occurred in the Sydney metropolitan area.  
45  
46 22

## 23 Conclusions

24 Our work suggests that testing, tracing and masks can be effective means of controlling  
25  
26 25 transmission in dynamic community settings, and higher compliance with one can offset lower  
27  
28 26 compliance with the other to some extent. However, pursuing a strategy that combines  
29  
30 27 aggressive testing, high mask usage, and effective contact tracing, alongside continued  
31  
32 28 hygiene and distancing protocols, is likely to be the most robust means of controlling  
33  
34 29 community-based transmission of SARS-CoV-2.  
35  
36 30

## List of figures

**Figure 1.** Relative changes in network structure and transmission risk across different settings in New South Wales over March–August. The absolute transmission risk varies by setting and is highest in household and lowest in outdoor settings (see (46) for details).

**Figure 2.** Calibration of the model to the NSW epidemic. Solid lines indicate the median model projections over 100 model runs; shaded areas indicate 95% projected intervals over different initialisations; blue diamonds indicate data on confirmed locally-acquired cases.

**Figure 3.** Trailing 14-day average of daily locally-acquired infections under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours). Projections represent the median of 100 simulations. Text boxes in each panel displays the cumulative number of infections over October 1 – December 31, 2020.

**Figure 4.** Quantifying the likelihood of epidemic resurgence in New South Wales: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).

**Figure 5.** Estimated total infections over October 1 – December 31, 2020 under different assumptions about testing rates and mask uptake, assuming all community contacts can be traced within a week with a mean time to trace of 1 day. Projections represent the median of 100 simulations.

## List of supplementary materials

- Figure S1: Assumed distribution of times required to find community contacts.
- Table S1: Parameter values and effects of policies on transmission risk in New South Wales.

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- 1 • Figure S2: Sensitivity to asymptomatic testing assumption: the probability of the trailing  
2 14-day average of locally-acquired cases exceeding a given number by December 31,  
3 2020 with individual-level mask efficacy set to 15%, under different assumptions about  
4 the testing rate (rows), proportion of community contacts that can be traced within one  
5 week (columns), and mask uptake (line colours).
- 6 • Figure S3: Sensitivity to mask efficacy assumption: the probability of the trailing 14-  
7 day average of locally-acquired cases exceeding a given number by December 31,  
8 2020 with individual-level mask efficacy set to 15%, under different assumptions about  
9 the testing rate (rows), proportion of community contacts that can be traced within one  
10 week (columns), and mask uptake (line colours).
- 11 • Figure S4: Sensitivity to mask efficacy assumption: the probability of the trailing 14-  
12 day average of locally-acquired cases exceeding a given number by December 31,  
13 2020 with individual-level mask efficacy set to 45%, under different assumptions about  
14 the testing rate (rows), proportion of community contacts that can be traced within one  
15 week (columns), and mask uptake (line colours).

## 1        1    Declarations

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8        3    **Competing interests statement:** The authors declare that they have no competing interests.  
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13       6    public, commercial or not-for-profit sectors.  
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17       8    **Data sharing statement:** All code and data analysed during this study are available in  
18       9    [https://github.com/optimamodel/covid\\_nsw](https://github.com/optimamodel/covid_nsw).  
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22       11    **Contributorship:** RMS wrote the manuscript and produced the results. The model parameters  
23       12    and calibration were agreed upon by RMS, RA, NS, and RG. The scenarios and analyses  
24       13    were agreed upon by NS, MH, and RMS. CK, RMS, RA, DM, and DJK led development of the  
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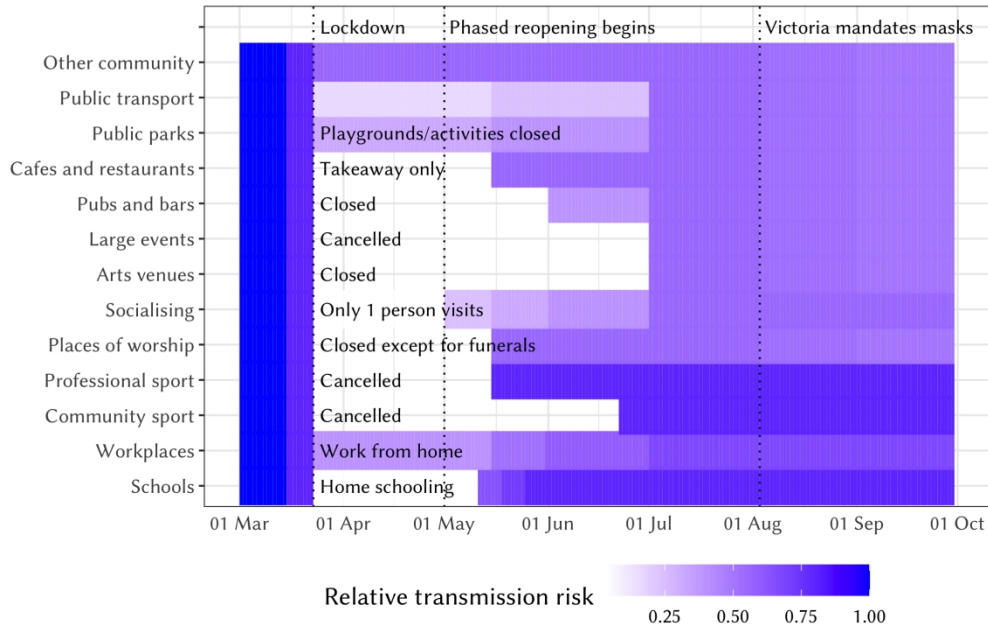


Figure 1. Relative changes in network structure and transmission risk across different settings in New South Wales over March–August. The absolute transmission risk varies by setting and is highest in household and lowest in outdoor settings (see (46) for details).

805x524mm (72 x 72 DPI)

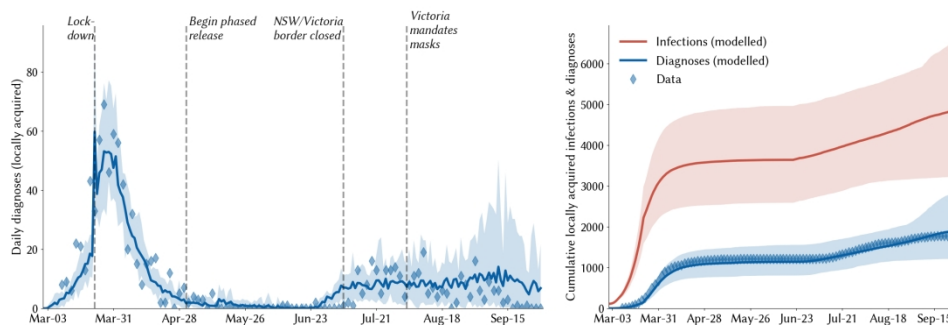


Figure 2. Calibration of the model to the NSW epidemic. Solid lines indicate the median model projections over 100 model runs; shaded areas indicate 95% projected intervals over different initialisations; blue diamonds indicate data on confirmed locally-acquired cases.



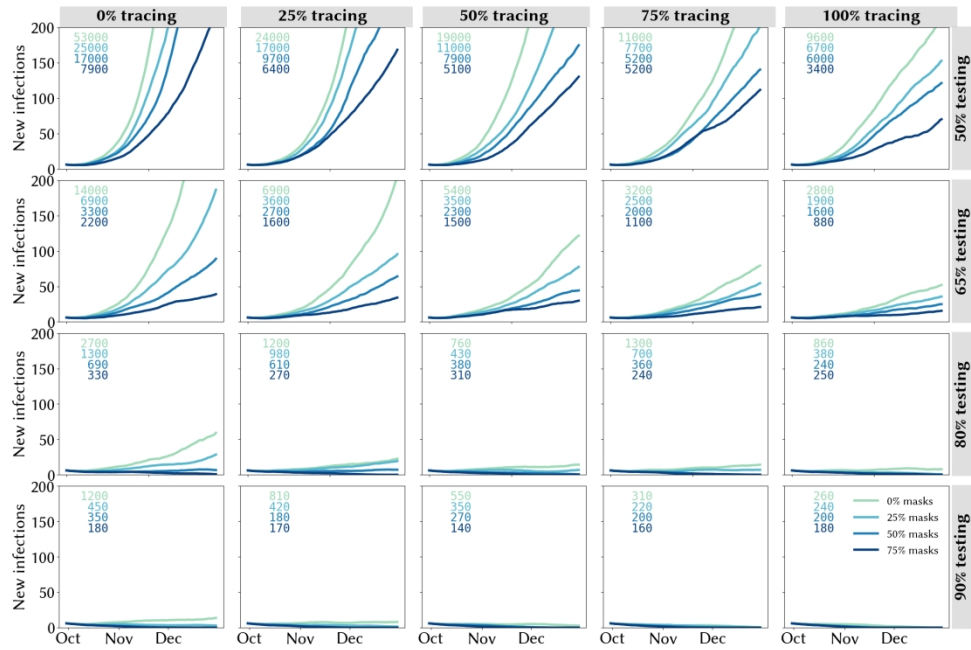


Figure 3. Trailing 14-day average of daily locally-acquired infections under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours). Projections represent the median of 100 simulations. Text boxes in each panel displays the cumulative number of infections over October 1 – December 31, 2020.

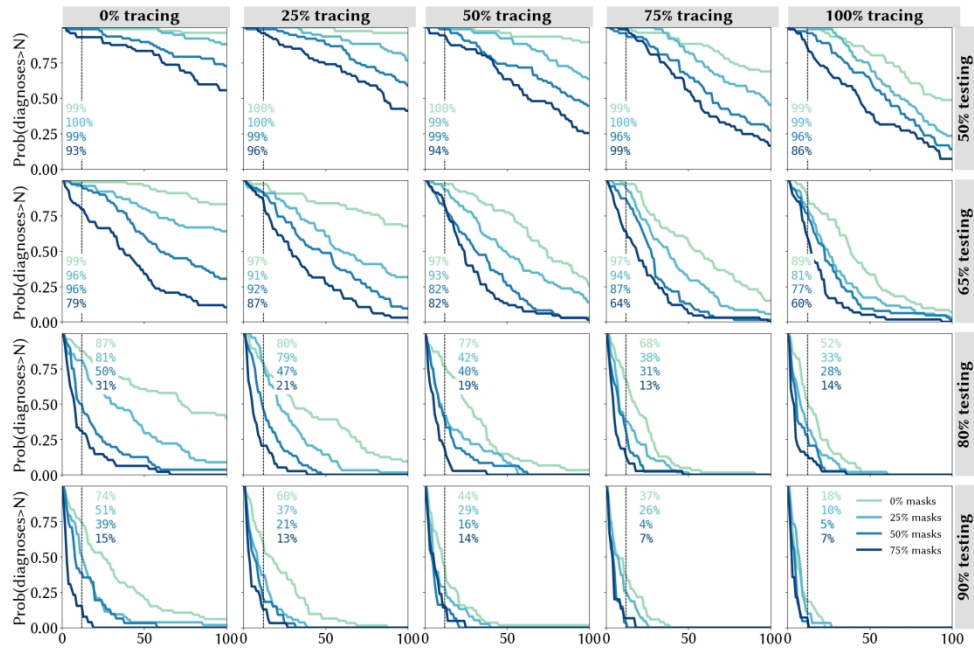


Figure 4. Quantifying the likelihood of epidemic resurgence in New South Wales: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).

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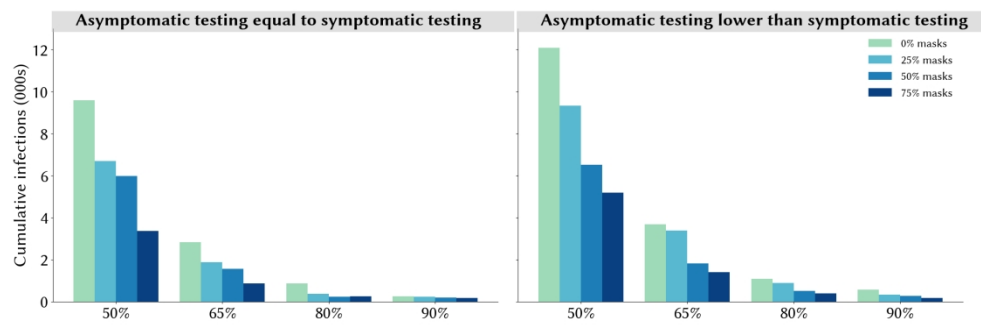


Figure 5. Estimated total infections over October 1 – December 31, 2020 under different assumptions about testing rates and mask uptake, assuming all community contacts can be traced within a week with a mean time to trace of 1 day. Projections represent the median of 100 simulations.

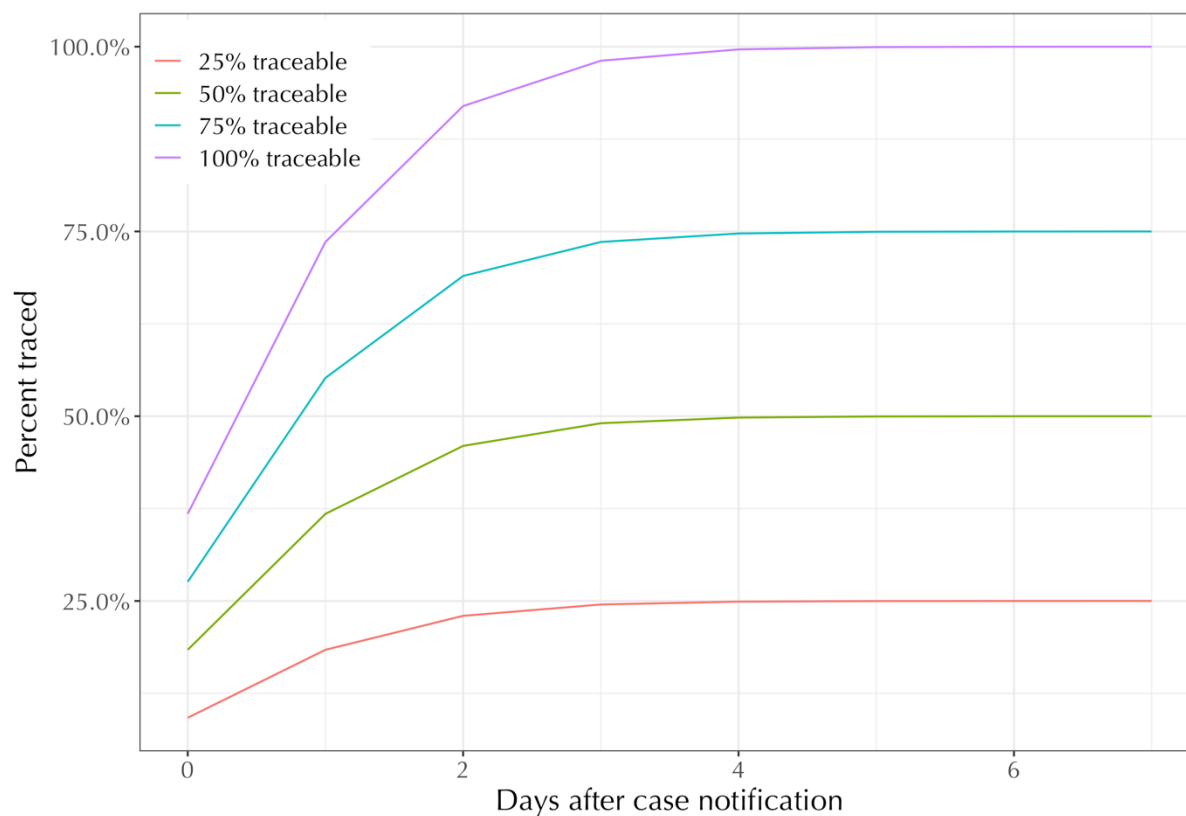
# Supplementary materials: The role of masks, testing and contact tracing in preventing COVID-19 resurgences: a case study from New South Wales, Australia

RM Stuart<sup>1,2†</sup>, Romesh G. Abey Suriya<sup>2</sup>, Cliff C. Kerr<sup>3,4</sup>, Dina Mistry<sup>3</sup>, Daniel J. Klein<sup>3</sup>, Richard Gray<sup>5</sup>, Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>

1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark
2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia
3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation, Seattle, USA
4. School of Physics, University of Sydney, Sydney, New South Wales, Australia
5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia
6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia
7. University of Melbourne, Parkville, Victoria, Australia
8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne, Victoria, Australia
9. The School of Population and Global Health and the Peter Doherty Institute for Infection and Immunity, Melbourne, Victoria, Australia

† Corresponding author. E-mail: robyn@math.ku.dk

**Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, contact tracing, Australia



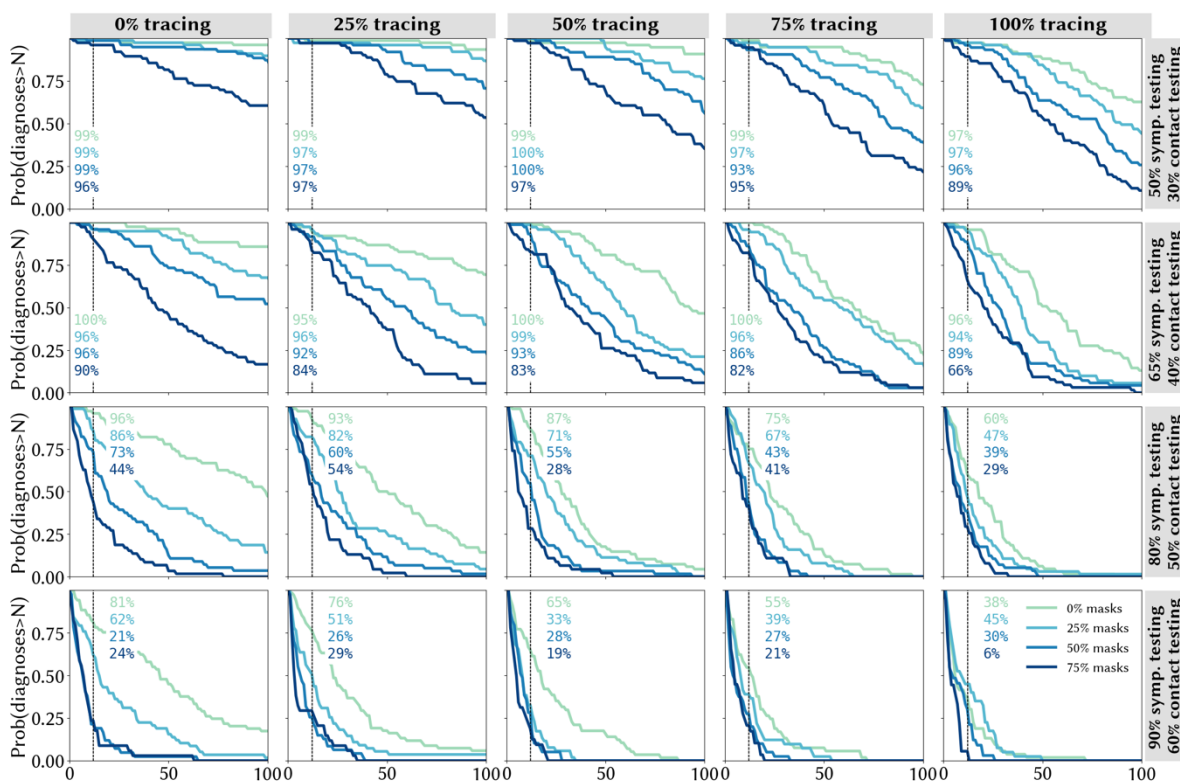
**Figure S1.** Assumed distribution of times required to find venue-based contacts.

Setting	Description of policy changes and their effects
Schools	School attendance rates in NSW had already dropped by 25% by 15 March 2020 (1), and on 23 March 2020 the NSW Premier advised that although schools remained open, parents were encouraged to keep their children at home for online learning (2). School attendance rates subsequently dropped to 5% of their pre-COVID levels (3). However, attendance quickly returned to pre-COVID levels shortly after schools reopened in mid-May (4). To model this, we removed 95% of contacts between school children and then restored them again as schools opened, but with the relative transmission risk set to 80% of its pre-March levels to account for additional safety measures in place for school activities (5).
Workplaces	According to survey data from the Australian Bureau of Statistics, almost half of working Australians were working from home in late April/early May (6), which is roughly consistent with Google movement data indicating that 40% fewer people were at work over that period compared to baseline. Workplace-based activities increased as COVID restrictions eased, but remained 15% lower over June-July compared to baseline. In the model, we removed 50% of workplace contacts and then restored them so that the workplace network was back to 85% of its pre-COVID size by the beginning of July (Figure 1). As with schools, we set the relative transmission risk set to 80% of its pre-March levels to account for the presence of NPIs.

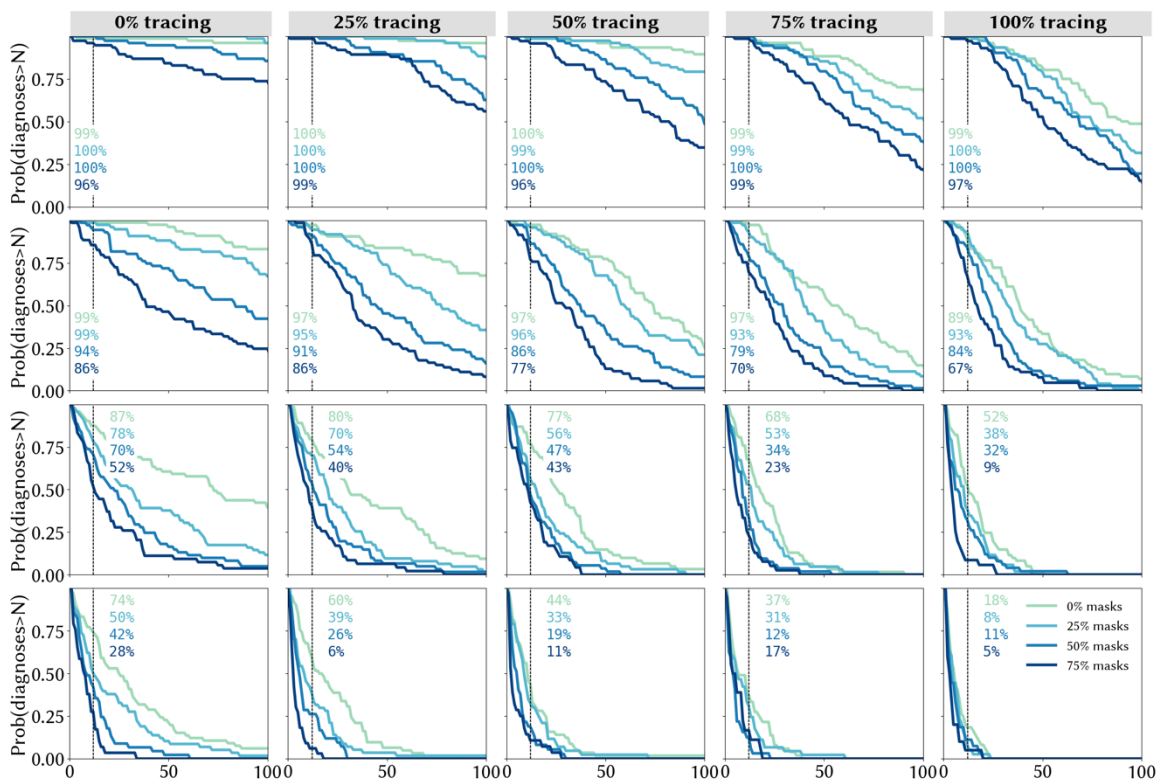
Static community	We assume that almost no contacts occurred over these networks from March 23 to May 1 with the exception of the limited contacts arising from permitted single-person visits. These networks were gradually restored over the period from May 1 to July 9 as restrictions eased.
Dynamic community networks over May-July (negligible mask usage)	Within New South Wales, arts venues such as museums, galleries, theatres, and cinemas, large events such as concerts, festivals, sports games, and pubs/bars were all closed over the period from March 23 to May 15, after which the networks were gradually restored. Cafes and restaurants, public parks and other outdoor settings, public transport, and all other community settings including essential retail remained open in some capacity throughout the year but with decreased demand and operational restrictions to reduce the likelihood of transmission (e.g., takeaway service only, closure of playgrounds, capacity limits on transport, and physical distancing/hygiene).
Dynamic community networks over August (increased mask usage)	From August 3, 2020, the use of masks was mandated in Victoria, which led to a marked increase in mask usage across the country. Only 13% of Australians wore a mask at least once over the month of June, but 58% reported wearing one at least once over August 7–17, 2020 (99% of Victorian residents compared to 44% of residents of other states) (7). Within New South Wales, media sources reported that 30% of people were wearing face masks on public transport in central Sydney in mid-August (8). To reflect the gradual increase in mask uptake in the model, we adjust the relative transmission risk assuming that the proportion of adults who wore masks while at work and in dynamic community settings increased over August to reach 30% by the end of the month.
Testing, tracing, and isolation	<p>We assume that the daily testing probability for those with symptoms increased from 5% in April to 20% by the beginning of June. Assuming a symptomatic period of roughly 10 days, this implies that the proportion of symptomatic people who get tested increased from 40% to 90%. In addition to symptom-based testing, we also assume that 90% of people who are not symptomatic but have been told to quarantine as a result of having been in contact with a confirmed case will get tested. Our assumptions around test sensitivity coupled with our modelling of viral load kinetics are specified such that the probability of identifying a true positive increases and then decreases over the course of an infection, following a similar profile to that reported in the literature (9–10).</p> <p>To model the efficacy of contact tracing over the period from June 1 – September 30, 2020, we assume that all household contacts were traced and notified on the same day that test results were communicated, that 95% of school contacts and 90% of workplace contacts were notified on the following day, and that 50% of all other contacts (which we refer to as community contacts) were traced within a week of a case notification, with a mean time to trace of one day (Figure S1).</p> <p>We assume that confirmed cases will isolate with near-perfect effectiveness, meaning that the probability of them transmitting to school or workplace contacts is zero, and the probability of them transmitting to their household contacts is reduced by 80%. Similarly, we assume high levels of adherence to isolation policies</p>

	imposed on those who have been notified that they were in contact with a confirmed case, with a 90% reduction in their probability of transmitting to school or workplace contacts.
Quarantine, and border control measures	From early on in the epidemic, Australia imposed strict border control measures requiring all arrivals to quarantine for two weeks in a hotel. These policies are assumed to be maintained throughout the duration of the model simulations.

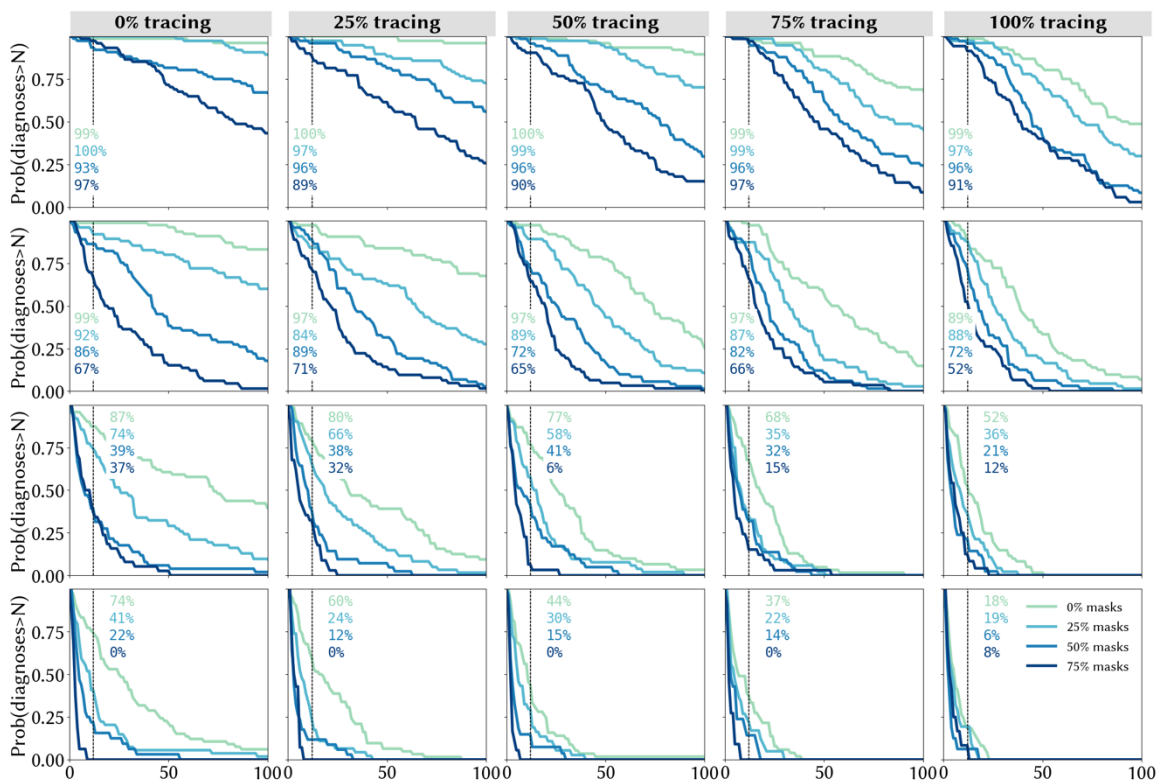
**Table S1.** Effects of policies on transmission risk in New South Wales



**Figure S2.** Sensitivity to asymptomatic testing assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 15%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).



**Figure S3.** Sensitivity to mask efficacy assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 15%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).





**Figure S4.** Sensitivity to mask efficacy assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 45%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).

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# BMJ Open

## The role of masks, testing and contact tracing in preventing COVID-19 resurgences: a case study from New South Wales, Australia

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7 2 preventing COVID-19 resurgences: a case study from  
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10 3 New South Wales, Australia  
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14 5 RM Stuart<sup>1,2†</sup>, Romesh G. Abeysuriya<sup>2</sup>, Cliff C. Kerr<sup>3,4</sup>, Dina Mistry<sup>3</sup>, Dan Klein<sup>3</sup>, Richard Gray<sup>5</sup>,  
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16 6 Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>  
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19  
20 8 1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark

21 9 2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia

22  
23 10 3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation,  
24  
25 11 Seattle, USA

26  
27 12 4. School of Physics, University of Sydney, Sydney, New South Wales, Australia

28  
29 13 5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia

30  
31 14 6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria,  
32  
33 15 Australia

34  
35 16 7. University of Melbourne, Parkville, Victoria, Australia

36  
37 17 8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne,  
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39 18 Victoria, Australia

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41 19 9. The School of Population and Global Health and the Peter Doherty Institute for Infection  
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43 20 and Immunity, Melbourne, Victoria, Australia

44 21 † Corresponding author. E-mail: [robyn@math.ku.dk](mailto:robyn@math.ku.dk)  
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51 25 **Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, testing, contact tracing,

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# Abstract

**Objectives:** The early stages of the COVID-19 pandemic illustrated that SARS-CoV-2, the virus that causes the disease, has the potential to spread exponentially. Therefore, as long as a substantial proportion of the population remains susceptible to infection, the potential for new epidemic waves persists even in settings with low numbers of active COVID-19 infections, unless sufficient countermeasures are in place. We aim to quantify vulnerability to resurgences in COVID-19 transmission under variations in the levels of testing, tracing, and mask usage.

**Setting:** The Australian state of New South Wales, a setting with prolonged low transmission, high mobility, non-universal mask usage, and a well-functioning test-and-trace system.

**Participants:** None (simulation study)

**Results:** We find that the relative impact of masks is greatest when testing and tracing rates are lower and vice versa. Scenarios with very high testing rates (90% of people with symptoms, plus 90% of people with a known history of contact with a confirmed case) were estimated to lead to a robustly controlled epidemic. However, across comparable levels of mask uptake and contact tracing, the number of infections over this period were projected to be 2-3 times higher if the testing rate was 80% instead of 90%, 8-12 times higher if the testing rate was 65%, or 30-50 times higher with a 50% testing rate. In reality, NSW diagnosed 254 locally-acquired cases over this period, an outcome that had a moderate probability in the model (10-18%) assuming low mask uptake (0-25%), even in the presence of extremely high testing (90%) and near-perfect community contact tracing (75-100%), and a considerably higher probability if testing or tracing were at lower levels.

**Conclusions:** Our work suggests that testing, tracing and masks can all be effective means of controlling transmission. A multifaceted strategy that combines all three, alongside continued hygiene and distancing protocols, is likely to be the most robust means of controlling transmission of SARS-CoV-2.

### Strengths and limitations of this study

- A key methodological strength of this study is the level of detail in the model that we use, which allows us to capture many of the finer details of the extent to which controlling COVID-19 transmission relies on the balance between testing, contact tracing, and mask usage.
- Another key strength is that our model is stochastic, so we are able to estimate the probability of different epidemiological outcomes under different policy settings.
- A key limitation is the shortage of publicly-available data on the efficacy of contact tracing programs, including data on how many people were contacted for each confirmed index case of COVID-19.

1

# 1 Introduction

2 Across the world, governmental responses to the outbreak of the COVID-19 pandemic in the  
3 first half of 2020 profoundly curtailed the spread of SARS-CoV-2, the virus that causes the  
4 disease (1–4). By midway through the year, an increasing number of countries had moved  
5 from an initial crisis-management phase into a new phase centred around minimising  
6 transmission risk while allowing societal and economic activities to resume (5). However, by  
7 the end of 2020, many countries around the world had experienced epidemic resurgences  
8 necessitating further shutdowns (6). This was true even in settings that had come close to  
9 eliminating the virus, such as Vietnam (7), New Zealand (8), and Australia (9). In low- or zero-  
10 transmission contexts, new outbreaks can emerge if community transmission has not been  
11 eliminated, or if infected people arrive from abroad or interstate and interact with the local  
12 community (10). It is therefore essential to be able to quantify the risk of epidemic resurgence  
13 under different policy contexts.

14  
15 Given the complexities of COVID-19 transmission, including the duration of pre-symptomatic  
16 infection (11,12), the proportion of infections that are asymptomatic (13), and the possibility of  
17 transmission via surface contact (14), maintaining control of COVID-19 has proven  
18 challenging in many jurisdictions (15–19). The often-cited success stories of Taiwan, Vietnam,  
19 Thailand, and South Korea included high mask usage, high rates of testing, and fast, effective  
20 contact tracing (20–22). The benefits of a multi-pronged approach have also been illustrated  
21 in the literature; in the UK, for example, a recent study (23) found that mandating masks in  
22 secondary schools could achieve approximately the same reduction in resurgence risk as  
23 having an 8-11% increase in symptomatic testing.

24  
25 In this work, we use an agent-based model to estimate the combination of testing, community-  
26 based contact tracing, and mask usage required to maintain epidemic control in a low-  
27 transmission, high-mobility setting. These three non-pharmaceutical interventions (NPIs) were  
28 key components in reducing the probability of epidemic resurgences prior to the availability of  
29 a vaccine, and are likely to remain so for some time even after vaccination coverage increases  
30 (24). When used in combination with physical distancing and hand-washing/hygiene  
31 measures, these three strategies together can allow relatively high mobility: testing and

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4 1 contact tracing means that only those at greatest risk of transmitting the virus need to stay  
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6 2 home and have been shown to be effective in numerous settings (15,25–29), while masks  
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8 3 mean that people with undiagnosed infections present less of a risk to others (30–34).  
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11 5 The context for our study is the Australian state of New South Wales (NSW), with a population  
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13 6 of 7.5 million and a cumulative total of just over 4700 diagnosed cases as of December 31,  
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15 7 2020, of which the majority (~57%) were acquired overseas. After an initial wave of COVID-  
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17 8 19 infections in March and subsequent lockdown in April, New South Wales began relaxing  
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19 9 physical lockdown measures over May and was experiencing near-zero case counts by the  
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21 10 start of June, with students back at school, businesses reopening and social/community  
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23 11 activities resuming. In late June several clusters of new infections were detected, which  
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25 12 subsequently led to a 4-month long period of low but steady case counts, with a mean of ~5  
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27 13 cases per day over July to October (excluding cases in quarantined travellers). However, NSW  
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29 14 subsequently went on to record ~180 cases in the last two weeks of 2020, a result of a  
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31 15 localised outbreak whose containment necessitated the introduction of stringent new  
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33 16 restrictions on travel and gatherings that affected many over the holiday period (35).  
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36 18 During the prolonged period of low transmission that NSW experienced in the second half of  
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38 19 2020 prior to December 15, 2020, mobility remained high (36) and transmission was controlled  
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40 20 via NPIs. Masks were recommended by the government for the general public and made  
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42 21 mandatory for staff in various businesses including supermarkets, but were not universally  
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44 22 adopted. In a survey undertaken in mid-September, 78% of the NSW population reported  
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46 23 wearing a mask at some point in the previous week (37), although CCTV footage from August  
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48 24 registered ~30% of passengers on urban public transport wearing masks (38). At the same  
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50 25 time, high levels of testing were in place, with ~20,000 people tested per day over June–  
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52 26 September (~2.7/day per 1,000 people), resulting in an average testing yield of 0.05%, one of  
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54 27 the world's lowest (39). The state also had a strong focus on contact tracing, with all cases  
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56 28 interviewed within one day of case notification (40). Over the four months from June 1 –  
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58 29 September 30, 2020, ~900 new cases were identified, but only 45 (5%) of were classified as  
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60 30 “source unknown”, meaning that they were neither acquired overseas/interstate nor linked to  
31 known clusters (41).



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5 2 Relative to many other contact tracing programs across the world, the NSW contact tracing  
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7 3 program was differentiated by its extensive efforts to identify a person's community contacts  
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9 4 in addition to their household, social, school, and workplace contacts (42). The state's health  
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11 5 department (NSW Health) required all businesses to have a COVID-19 Safety Plan, and for  
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13 6 the majority of public-facing businesses this included a requirement for customers to register  
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15 7 their details upon entry. Upon identifying a new case, NSW Health's contact tracers would  
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17 8 then (a) conduct an extended interview to determine all possible venues in which transmission  
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19 9 may have occurred, (b) place details of those venues on their website, on social media, and  
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21 10 in newspapers, urging people who had been at the venue to self-isolate for 14 days, (c) attempt  
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23 11 to contact all people who were registered to have been at venues within a given window of the  
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25 12 time that the diagnosed case was known to have been there and instruct them to self-isolate  
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27 13 for 14 days (42).  
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31 15 The dynamics of COVID-19 transmission are complex, and in low-transmission settings the  
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33 16 probability of maintaining epidemic control depends on numerous factors outside of policy  
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35 17 control, including the characteristics of people who get infected: the size of their households,  
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37 18 the type of work that they do, and a number of other socio-economic factors that may influence  
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39 19 their contact networks. Several studies have pointed to the role of superspreading events and  
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41 20 overdispersion of infections in COVID-19 transmission (25,26,43,44). As a result, even with  
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43 21 physical distancing, high levels of testing, and rapid contact tracing, there is still a non-zero  
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45 22 probability that a sustained outbreak could occur depending on who gets infected and where.  
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47 23 In this study, we consider a range of testing and contact tracing levels, and assess the  
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49 24 interacting roles of masks, testing and contact tracing as a means of controlling community-  
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51 25 based transmission.  
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## 54 27 **Methods**

### 55 28 **Transmission model**

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57 29 We used an open-source agent-based model, Covasim (45), developed by the Institute for  
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59 30 Disease Modeling with source code and documentation available at <https://covasim.org>, and  
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3 1 previously adapted by our group to model the Victorian epidemic (10,46). Covasim contains  
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5 2 detailed descriptions of age-dependent disease acquisition and progression probabilities and  
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7 3 the duration of disease by acuity (see Tables 1-2 in reference (45)), as well as the effects of  
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9 4 interventions including symptomatic and asymptomatic testing, isolation, contact tracing, and  
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11 5 quarantine, as well as other NPIs such as physical distancing, hygiene measures, and  
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13 6 protective equipment such as masks. Importantly, it also captures individual variability, with  
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15 7 viral loads varying both between individuals and over time.  
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18 9 We began by simulating a population representative of New South Wales by taking data on  
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20 10 the age and sex composition of the population from the 2016 census (the latest available),  
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22 11 and using it to create a model population of agents with similar characteristics. The simulations  
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24 12 consist of 100,000 individual agents, who are dynamically scaled based on prevalence to  
25  
26 13 represent the total New South Wales population of 7.5 million. The dynamical scaling means  
27  
28 14 that whenever the proportion of susceptible agents falls below a threshold of 5%, the number  
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30 15 of agents in the model is increased; further implementation details can be found in Section  
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32 16 2.3.6 of Kerr et al (45).  
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35 18 Next, we created contact networks for these agents. The governmental response to COVID-  
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37 19 19 in New South Wales consisted of a set of highly context-specific policies covering  
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39 20 individuals, businesses, schools, and other types of organisations. To model these policies,  
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41 21 we allow agents in the model to interact over five types of contact network: households,  
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43 22 schools, workplaces, and static and dynamic community networks. The static community  
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45 23 network consists of interactions with friends, colleagues, or other known associates who come  
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47 24 together on a regular and predictable basis, and contains four sub-networks: professional  
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49 25 sports, community sports/fitness/leisure clubs, places of worship, and socialising with friends.  
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51 26 The dynamic community network consists of interactions in which people interact with  
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53 27 strangers or random groups of people, and contains seven separate sub-networks,  
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55 28 representing: (1) arts venues such as museums, galleries, theatres, and cinemas, (2) large  
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57 29 events such as concerts, festivals, sports games, (3) pubs and bars, (4) cafes and restaurants,  
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59 30 (5) public parks and other outdoor settings, (6) public transport, (7) all other community  
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31 settings. The method for constructing these networks is described in our previous study of the

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4 1 Victorian epidemic (46) and is based on the methodology of the SynthPops Python package  
5 2 (47).  
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9 4 Finally, to simulate the epidemic and policy environment in New South Wales over March 1 –  
10 5 September 30, 2020, we include parameter changes that capture the testing, tracing, isolation,  
11 6 quarantine, and lockdown policies that were enacted over this time. Figure 1 presents a  
12 7 summary of how contact networks and the relative risk of COVID-19 transmission in different  
13 8 settings changed as policies evolved. Some of these changes in transmission risk are derived  
14 9 from available data (48), while others are taken from a similar modelling exercise conducted  
15 10 in Victoria, in which a panel of Australia-based experts reviewed the likely effect of policies on  
16 11 transmission risks (46). Further details of all policies and how we model their effects on  
17 12 transmission risk are contained in Supplementary Table 1. We also model the introduction of  
18 13 interstate cases in late June prior to the closure of the state border with neighbouring Victoria.  
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## 30 15 Data and model fitting

31 16 We calibrate the model by adjusting the per-contact transmission risk to minimise the absolute  
32 17 differences between the model projections and data on the daily number of cases diagnosed,  
33 18 excluding cases acquired overseas or interstate from NSW Health (41). Specifically, we drew  
34 19 500 samples from a Gaussian prior distribution of values for the per-contact transmission risk  
35 20 ( $\sim N(0.025, 0.002)$ ). For each sample, we run  $N=20$  simulations for each to produce 10,000 trial  
36 21 simulations, and then retain the 1% of these with the minimum absolute differences between  
37 22 the model projections and the data.  
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## 48 24 Model analysis and timeframe

49 25 As described above, we fit the model using data up until September 30, 2020. We then run  
50 26 the model for three months (from October 1, 2020, until December 31, 2020), under a set of  
51 27 assumptions about future testing rates, the efficacy of contact tracing, and mask uptake. For  
52 28 each scenario (described below), we quantify the probability of the epidemic exceeding certain  
53 29 thresholds. We then compare these projections to the observed epidemic outcomes over the  
54 30 period from October 1 to December 31, 2020.  
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4 1 For testing rates, we distinguish between symptom-based testing and testing of asymptomatic  
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6 2 contacts. NSW Health guidelines advise anyone with symptoms to get tested, as well as  
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8 3 anyone identified as a contact regardless of symptoms (42). To reflect this, we use a baseline  
9  
10 4 assumption that the testing rate for asymptomatic contacts is the same as for people with  
11  
12 5 symptoms, and run a counterfactual set of scenarios in which it is assumed to be half the rate  
13  
14 6 for those with symptoms (Table 1). We modelled scenarios in which 50%, 65%, 80%, or 90%  
15  
16 7 of those with symptoms get tested. Test results are assumed to be communicated within 24  
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18 8 hours (49).

19  
20 10 We also considered variations on mask uptake and effectiveness. On uptake, we modelled  
21  
22 11 scenarios in which 0%, 25%, 50%, or 75% of the population will wear masks in dynamic  
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24 12 community settings (i.e., settings in which people interact with strangers or random groups of  
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26 13 people), which in the model includes arts venues, large events such as concerts, festivals,  
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28 14 sports games, public parks and other outdoor settings, public transport, and all other  
29  
30 15 community settings. We do not consider scenarios in which 100% of the population wear  
31  
32 16 masks across these settings, due to the infeasibility of wearing masks whilst eating or drinking.  
33  
34 17 On efficacy, we note that although the body of evidence supporting the effectiveness of masks  
35  
36 18 for protecting against transmission between individuals is now considerable, the size of the  
37  
38 19 effect is difficult to determine, with estimates in the range of 20–80% and varying depending  
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40 20 on whether one or both parties wear masks (31,50,51), or whether spillover behavioural  
41  
42 21 changes on people's attention to other NPIs are captured (52). To capture the uncertainty  
43  
44 22 regarding the effectiveness of masks, we assume that masks will reduce the per-contact  
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46 23 probability of transmission by 30%, in line with estimates from (53), but also consider 15% and  
47  
48 24 45% in a sensitivity analysis presented in the supplementary materials. We do not model the  
49  
50 25 differences between both people wearing masks vs source-only vs target only, so the  
51  
52 26 estimates we use here should be considered as averages across these different possibilities.

53  
54 28 To model the efficacy of contact tracing, we use publicly-available data from NSW Health (42).  
55  
56 29 We note that, although the program reports the proportion of known contacts that were  
57  
58 30 reached within defined timeframes, we would ideally like to know the proportion of all contacts  
59  
60 31 that were reached, which will be lower than the reported values since it will also include

1 contacts that the case did not recall or disclose. Thus, although NSW Health's published  
 2 reports (42) indicate that 100% of contacts are notified within 48 hours, we use slightly more  
 3 conservative values, namely that 100% of household contacts will be traced and notified on  
 4 the same day that test results are communicated, and that 95% of school contacts and 90%  
 5 of workplace contacts will be notified on the following day. We then consider scenarios in  
 6 which 0%, 25%, 50%, 75%, or 100% of all other contacts (which we refer to as community  
 7 contacts) can be traced within a week of a case notification. For each scenario, the time to  
 8 trace each contact is drawn from a scaled Poisson distribution with a mean of 1 day (Figure  
 9 S1). We run 100 simulations for each permutation of testing rates, mask usage and contact  
 10 tracing efficacy.

11  
 12 Finally, we assume that people who have been contact-traced will quarantine with 90%  
 13 compliance from their workplace, school, and community contacts. Whilst this assumption  
 14 may be optimistic in other global contexts, the lower case counts in NSW mean that contact  
 15 tracers have far greater capacity for rigorous ongoing follow-up of contacts, and breaches of  
 16 isolation are escalated with local authorities, as stipulated in national guideline documents  
 17 (50).

Core scenarios:	
4x combinations of symptomatic testing	50%, 65%, 80% 90% tested over the course of their symptoms
Asymptomatic testing of known contacts	Asymptomatic contact testing rate equal to symptomatic testing rate
5x combinations of contact tracing for community contacts	0%, 25%, 50%, 100% of contacts traced within 1 week (Poisson distribution with a mean of 1 day)
4x combinations of mask uptake	0%, 25%, 50%, 75%
Mask efficacy	30%

Sensitivity analyses:	
Sensitivity to asymptomatic contact testing rate assumption	We run the same 80 (4x5x4) scenarios described above, but with the asymptomatic contact testing rate half of the symptomatic testing rate
Sensitivity to the mask efficacy assumption	We run the same 80 (4x5x4) scenarios described above, but with individual mask efficacy assumed to be 15% or 45% instead of 30%

**Table 1:** overview of the scenarios analysed over Oct 1 – Dec 31, 2020.

### Role of the funding source

The funders had no role in the design or execution of this study.

### Patient and public involvement

This is a modelling study; no personal data was used and patient/public involvement was not required.

## Results

According to our modelled estimates, 4,550 (95% projected interval: 3,700–6,660) people had acquired COVID-19 in NSW by the end of September 2020 (excluding cases acquired overseas or interstate), of which 39% (27–48%) had been diagnosed (Figure 2). The majority of undiagnosed infections occurred during the March-April wave; since the beginning of June, we estimate that 65% of all locally-acquired infections have been diagnosed, with the remaining 35% being primarily comprised of asymptomatic infections (65%). We further estimate that 79,330 (60,100–129,020) people had been required to self-isolate at some point by September 30, 2020 as a result of having potentially been in contact with a confirmed case.

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4 1 Estimates of daily new infections under each combination of testing, community contact  
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6 2 tracing, and mask usage are presented in Figure 3. A key finding highlighted by Figure 3 is  
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8 3 how effective high levels of testing are in maintaining epidemic control: all strategies in which  
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10 4 there is at least some contact tracing in place and testing rates are very high (90% of people  
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12 5 with symptoms and 90% of asymptomatic contacts of confirmed cases) lead to a robustly  
13  
14 6 controlled epidemic, with a median of ~180 infections in total estimated over October 1 –  
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16 7 December 31 under high mask uptake scenarios, or 260–1,200 without masks, depending on  
17  
18 8 the efficacy of community contact tracing (Figure 3, bottom row). However, holding mask  
19  
20 9 uptake and contact tracing constant, we estimate that the number of infections over October  
21  
22 10 1 – December 31, 2020, would be 2-3 times higher if the testing rate was 80% instead of 90%,  
23  
24 11 8-12 times higher if the testing rate was 65%, or 30-50 times higher with a 50% testing rate  
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26 12 (Figure 3, third row).

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28 14 A second key finding is that the lower the testing rate, the greater the impact of masks and  
29  
30 15 contact tracing (and vice versa). With medium-lower testing rates of 50% or 65%, the marginal  
31  
32 16 impact of both masks and contact tracing are considerable (Figure 3, top two rows). Under  
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34 17 these scenarios, the most robust strategies consist of a combination of masks and community  
35  
36 18 contact tracing. Assuming a 50% testing rate, a scenario with near-perfect tracing and no  
37  
38 19 masks is approximately equivalent to a scenario with no tracing and high mask uptake.  
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40 20 However, without community contact tracing, a reduction in mask usage from 75% to 50%  
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42 21 would lead to a near-doubling in estimated infections (from 7,900 to 17,000), whereas even  
43  
44 22 moderate levels of community contact tracing (25% traceable within a week) would increase  
45  
46 23 the robustness of the response to lower mask usage (with 6,400 infections estimated under  
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48 24 75% mask usage and 9,700 under 50% mask usage). Similarly, masks strengthen the  
49  
50 25 resilience of the epidemic outcome to decreases in contact tracing efficacy: without masks, a  
51  
52 26 reduction in community contact tracing from 75% to 50% would lead to a 70% increase in total  
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54 27 infections, whereas it would have no impact if 75% of the population were wearing masks.

55  
56 29 Figure 4 captures the risks associated with different strategies, quantified in terms of the  
57  
58 30 probability of the 14-day average of daily diagnoses exceeding a given number by December  
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60 31 31, 2020. With no community tracing and a 50% testing rate, the probability of exceeding 100

1 diagnoses/day by the end of 2020 was calculated to be 98% without masks, and to remain  
2 greater than 50% even under the most optimistic mask uptake scenario (Figure 4, top left  
3 panel). However, higher levels of community tracing reduce these risks considerably: even  
4 without any mask usage, the probability of exceeding 100 cases/day is estimated to be half  
5 as high with perfect community tracing (Figure 4, top right panel) compared to the same  
6 scenario without community tracing (48% vs 98%), and the addition of mask usage in  
7 community settings is estimated to reduce this even further, to ~10%.

## 8 9 **Comparison with actual outcomes**

10 The text boxes on Figure 4 display the probability of observing the outcome that was seen in  
11 NSW, in which the two-week average of daily diagnoses exceeded 12 by December 31. We  
12 calculate that this outcome would have been assigned a low probability (4-7%) under the best-  
13 case scenarios of extremely high testing (90%), near-perfect community contact tracing (75-  
14 100%), and high mask usage (50-75%), but that it would have been considered a far more  
15 likely outcome if any of these were assumed to be at lower levels.

## 16 17 **Sensitivity analyses**

18 If asymptomatic contacts only test at half the rate of people with symptoms, we estimate a  
19 more severe epidemic over the last quarter of 2020, but the key results regarding the roles of  
20 community contact tracing and masks do not change (Figure S2). Since our core analyses  
21 already assume high compliance with recommended self-isolation policies for known contacts  
22 of confirmed cases, the marginal benefit of high asymptomatic contact tracing is primarily to  
23 further bolster the efficacy of contact tracing, since it allows for the identification of chains of  
24 transmission even in the absence of symptoms. To highlight the role of testing asymptomatic  
25 contacts, in Figure 5 we highlight a particular set of scenarios corresponding to the most  
26 optimistic contact tracing assumptions, in which all community contacts are assumed to be  
27 traced within one week, with a mean time to trace of one day (the full set of scenarios are  
28 summarised in Figure S2). Within this set of scenarios, the total number of infections is  
29 estimated to be around 50% higher if asymptomatic contacts test at a lower rate than people  
30 with symptoms (averaged across all levels of mask usage).



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4 1 We also find that, if masks are assumed to be more or less effective, this would change the  
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6 2 risks associated with diagnosing more than a given number of cases per day under the  
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8 3 different mask scenarios, but would not qualitatively change the results (Figure S3-S4). For  
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10 4 example, we estimate 1500 infections over the three-month period assuming 50% tracing,  
11  
12 5 65% symptomatic testing and 75% mask uptake if masks have an efficacy of 30% (Figure 3,  
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14 6 central panel), compared to 1800 infections if masks had 15% efficacy or 1300 infections if  
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16 7 masks had 45% efficacy.  
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## 9 Discussion

10 In this work we presented estimates illustrating the extent to which masks, community testing,  
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12 11 and community contact tracing could reduce the spread of SARS-CoV-2 in New South Wales,  
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14 12 Australia in the absence of widespread vaccination. We found that the relative impact of masks  
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16 13 is greatest when testing and tracing rates are lower (and vice versa). With very high testing  
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18 14 rates (90% of people with symptoms, plus 90% of people with a known history of contact with  
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20 15 a confirmed case), we estimate that epidemic control would be possible even without  
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22 16 widespread mask uptake, provided that fast and effective contact tracing is in place. However,  
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24 17 under any scenario where testing rates are lower, we estimate that mask use can play an  
25  
26 18 important role in reducing the potential for epidemic resurgence.  
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30 20 Our findings have relevance for assessing the outbreak that occurred in the state towards the  
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32 21 end of December 2020, which saw an average of ~12 diagnoses/day over two weeks.  
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34 22 According to our estimates, this outcome would have been assigned a relatively low probability  
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36 23 (4-7%) if it was assumed that compliance with the state's testing guidelines, venue registration  
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38 24 protocols, and non-mandatory mask recommendations would be at very high levels, but that  
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40 25 it would have been evaluated as a far more likely outcome if compliance with any of these  
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42 26 NPIs was assumed to be lower. As a result of the December 2020 outbreak, the NSW  
43  
44 27 government made masks mandatory in all indoor community settings from January 4, 2021  
45  
46 28 (54), a decision which will likely increase the robustness of the overall response to decreases  
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48 29 in testing or contact tracing rates, but will still require ongoing commitment to ensure these  
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50 30 remain at high levels, at least until vaccination coverage is sufficiently high. According to  
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4 1 Australia's vaccination schedule, half the population may be vaccinated by mid-2021, and  
5 2 NPIs will feature as part of the COVID-19 control strategy until well beyond this point (55).  
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9 4 Of the interventions considered, this study suggests that maintaining high levels of  
10 5 symptomatic testing, contact tracing, and testing of contacts are all important. We quantified  
11 6 the importance of testing asymptomatic contacts as a strategy that further strengthens the  
12 7 power of contact tracing programs, since it allows the tracing and quarantining of their contacts  
13 8 in turn. The interdependencies between different arms of testing and tracing strategies are  
14 9 complex, as testing of asymptomatic contacts is only feasible if contact tracing is effective  
15 10 enough to identify them. Longer term, 'pandemic fatigue' may bring about challenges in  
16 11 maintaining high levels of testing, mask use, and contact tracing (56). This study suggests that  
17 12 having high levels of any two of mask use, testing and contact tracing can largely mitigate the  
18 13 need for the third; however practical challenges mean that this is unlikely to occur, and a more  
19 14 multifaceted approach of aiming for high coverage of all three and ending up with moderate  
20 15 coverage of all three may be an effective and more robust strategy. Various studies have  
21 16 shown that the roll-out of vaccination plans is unlikely to mitigate the need for NPIs such as  
22 17 these for some time (24,57–59), so these finding are likely to remain relevant for a  
23 18 considerable portion of 2021.  
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20 Although various efforts have been made to synthesise the ever-expanding body of research  
21 regarding the efficacy of different interventions (1–4,60), each country's epidemic has distinct  
22 characteristics and there are very few standardised, globally-applicable guidelines on what  
23 constitutes a best-practice public health strategy (61,62). As a result, jurisdictions have taken  
24 diverse approaches in terms of which interventions to prioritise, from a list that includes  
25 physical distancing, travel restrictions, wearing of masks or face coverings, isolation and/or  
26 testing of those with COVID-like symptoms, isolation of those who test positive, and tracing  
27 the contacts of confirmed cases for testing and/or quarantining. Although it may not always be  
28 articulated as such, numerous trade-offs are being made between different policy options in  
29 an attempt to allow the highest degree of societal activity commensurate with epidemic control.  
30 In New South Wales, mask use was encouraged in particular settings since July 2020, but not  
31 mandated until January 2021; at the same time, there was a strong focus on contact tracing.

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4 1 The results from this work suggest that the prioritisation of contact tracing may mitigate the  
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6 2 relative importance of masks to some extent, but that this relies on continued high levels of  
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8 3 community testing.  
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11 5 There are several limitations to this study. Firstly, the mathematical model that we use requires  
12  
13 6 data on various aspects of SARS-CoV-2 transmission and prevention that are still not known  
14  
15 7 exactly, including the effects of masks on preventing individual transmission and the proportion  
16  
17 8 of infections that are asymptomatic. Whilst we have used the best available data and sampled  
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19 9 from appropriate distributions where possible, this represents a source of uncertainty in all  
20  
21 10 mathematical models of COVID-19. Additional uncertainties are introduced by the evolution of  
22  
23 11 new strains of SARS-CoV-2 with increased transmissibility and/or severity. Secondly, we have  
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25 12 constructed sets of scenarios that examine various combinations of parameters on mask  
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27 13 uptake, contact tracing, testing of people with symptoms, and asymptomatic contact testing,  
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29 14 but there are many more parameters that determine the dynamics of transmission, including  
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31 15 the stringency of border control measures, people's adherence to quarantine and isolation  
32  
33 16 policies, and the effect of ongoing distancing policies. Changes to any of these policies would  
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35 17 affect the results presented here in ways that are not straightforward to predict or extrapolate.  
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37 18 Third, we have not considered any outbreak risk associated with newly seeded cases in the  
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39 19 community that may arise from international or interstate arrivals. Another limitation is the  
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41 20 relatively simplistic way that we have modelled mask usage, whereby we have not included  
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43 21 variation in (a) adherence to mask usage across different types of venue, or (b) individual  
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45 22 compliance. Assuming that mask-wearing reduces everyone's transmission risk by a certain  
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47 23 percentage disregards the individual behavioural changes that may adjust individual-level  
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49 24 transmission risk by varying amounts. Furthermore, it is very likely that mask usage would be  
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51 25 higher in certain settings (e.g., public transport) than others, especially restaurants which are  
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53 26 suspected to be important for transmission. Finally, the model used here does not contain a  
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55 27 geospatial component, and we have not considered heterogeneities in incidence, behaviour,  
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57 28 or contact patterns across different parts of the state in these analyses. This could be relevant  
58  
59 29 for questions around mask uptake, as uptake of masks is generally higher in more densely  
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30 populated areas, so using a state-wide average for the proportion of the population wearing

1 masks may underestimate their impact, especially since >90% of infections in NSW to date  
2 have occurred in the Sydney metropolitan area.

## 3 4 Conclusions

5 Our work suggests that testing, tracing and masks can be effective means of controlling  
6 transmission in dynamic community settings, and higher compliance with one can offset lower  
7 compliance with the other to some extent. However, pursuing a strategy that combines  
8 aggressive testing, high mask usage, and effective contact tracing, alongside continued  
9 hygiene and distancing protocols, is likely to be the most robust means of controlling  
10 community-based transmission of SARS-CoV-2.

## 11 12 List of figures

13 **Figure 1.** Relative changes in network structure and transmission risk across different settings  
14 in New South Wales over March–August. The absolute transmission risk varies by setting and  
15 is highest in household and lowest in outdoor settings (see (46) for details).

16  
17 **Figure 2.** Calibration of the model to the NSW epidemic. Solid lines indicate the median model  
18 projections over 100 model runs; shaded areas indicate 95% projected intervals over different  
19 initialisations; blue diamonds indicate data on confirmed locally-acquired cases.

20  
21 **Figure 3.** Trailing 14-day average of daily locally-acquired infections under different  
22 assumptions about the testing rate (rows), proportion of community contacts that can be traced  
23 within one week (columns), and mask uptake (line colours). Projections represent the median  
24 of 100 simulations. Text boxes in each panel displays the cumulative number of infections  
25 over October 1 – December 31, 2020.

26  
27 **Figure 4.** Quantifying the likelihood of epidemic resurgence in New South Wales: the  
28 probability of the trailing 14-day average of locally-acquired cases exceeding a given number  
29 by December 31, 2020 under different assumptions about the testing rate (rows), proportion

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4 1 of community contacts that can be traced within one week (columns), and mask uptake (line  
5 2 colours).

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9 4 **Figure 5.** Estimated total infections over October 1 – December 31, 2020 under different  
10 5 assumptions about testing rates and mask uptake, assuming all community contacts can be  
11 6 traced within a week with a mean time to trace of 1 day. Projections represent the median of  
12 7 100 simulations.

## 13 8 14 9 **List of supplementary materials**

- 15 10 • Figure S1: Assumed distribution of times required to find community contacts.
- 16 11 • Table S1: Parameter values and effects of policies on transmission risk in New South  
17 12 Wales.
- 18 13 • Figure S2: Sensitivity to asymptomatic testing assumption: the probability of the trailing  
19 14 14-day average of locally-acquired cases exceeding a given number by December 31,  
20 15 2020 with individual-level mask efficacy set to 15%, under different assumptions about  
21 16 the testing rate (rows), proportion of community contacts that can be traced within one  
22 17 week (columns), and mask uptake (line colours).
- 23 18 • Figure S3: Sensitivity to mask efficacy assumption: the probability of the trailing 14-  
24 19 day average of locally-acquired cases exceeding a given number by December 31,  
25 20 2020 with individual-level mask efficacy set to 15%, under different assumptions about  
26 21 the testing rate (rows), proportion of community contacts that can be traced within one  
27 22 week (columns), and mask uptake (line colours).
- 28 23 • Figure S4: Sensitivity to mask efficacy assumption: the probability of the trailing 14-  
29 24 day average of locally-acquired cases exceeding a given number by December 31,  
30 25 2020 with individual-level mask efficacy set to 45%, under different assumptions about  
31 26 the testing rate (rows), proportion of community contacts that can be traced within one  
32 27 week (columns), and mask uptake (line colours).

## 1        1    Declarations

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8        3    **Competing interests statement:** The authors declare that they have no competing interests.  
9  
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12       5    **Ethics statement:** Ethical approval was not required for this study.  
13  
14       6

15       7    **Funding statement:** This research received no specific grant from any funding agency in the  
16  
17       8    public, commercial or not-for-profit sectors.  
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20  
21       10   **Data sharing statement:** All code and data analysed during this study are available in  
22  
23       11   [https://github.com/optimamodel/covid\\_nsw](https://github.com/optimamodel/covid_nsw).  
24  
25       12

26       13   **Contributorship:** RMS wrote the manuscript and produced the results. The model parameters  
27  
28       14   and calibration were agreed upon by RMS, RA, NS, and RG. The scenarios and analyses  
29  
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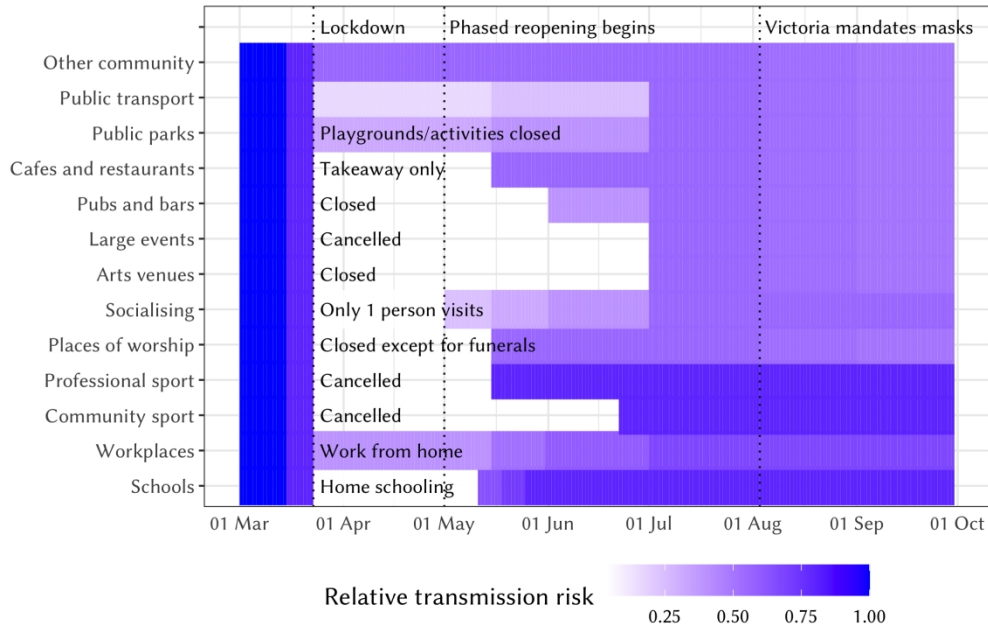


Figure 1. Relative changes in network structure and transmission risk across different settings in New South Wales over March–August. The absolute transmission risk varies by setting and is highest in household and lowest in outdoor settings (see (46) for details).

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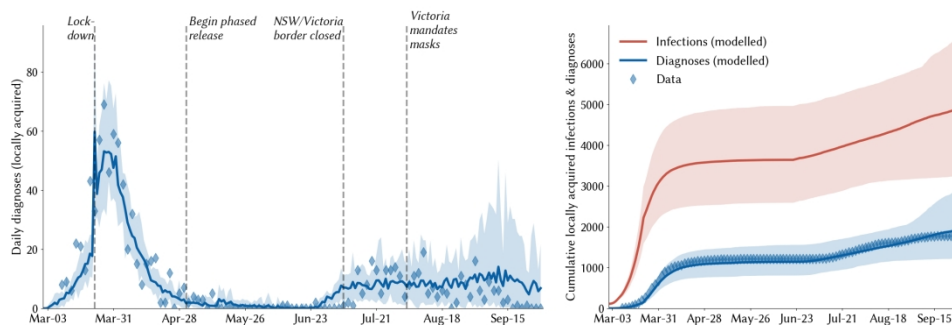


Figure 2. Calibration of the model to the NSW epidemic. Solid lines indicate the median model projections over 100 model runs; shaded areas indicate 95% projected intervals over different initialisations; blue diamonds indicate data on confirmed locally-acquired cases.

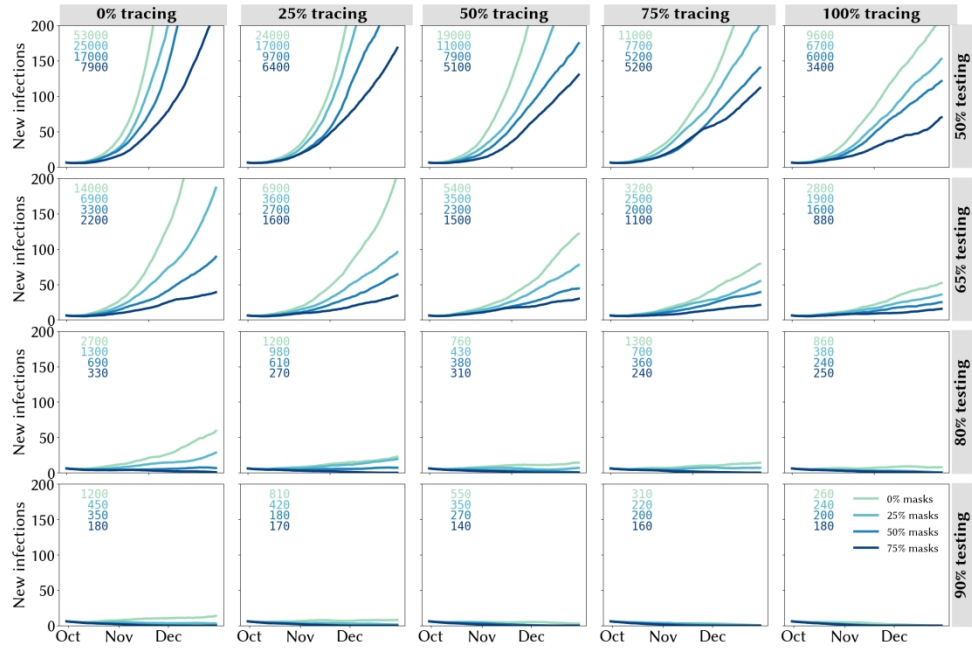


Figure 3. Trailing 14-day average of daily locally-acquired infections under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours). Projections represent the median of 100 simulations. Text boxes in each panel displays the cumulative number of infections over October 1 – December 31, 2020.

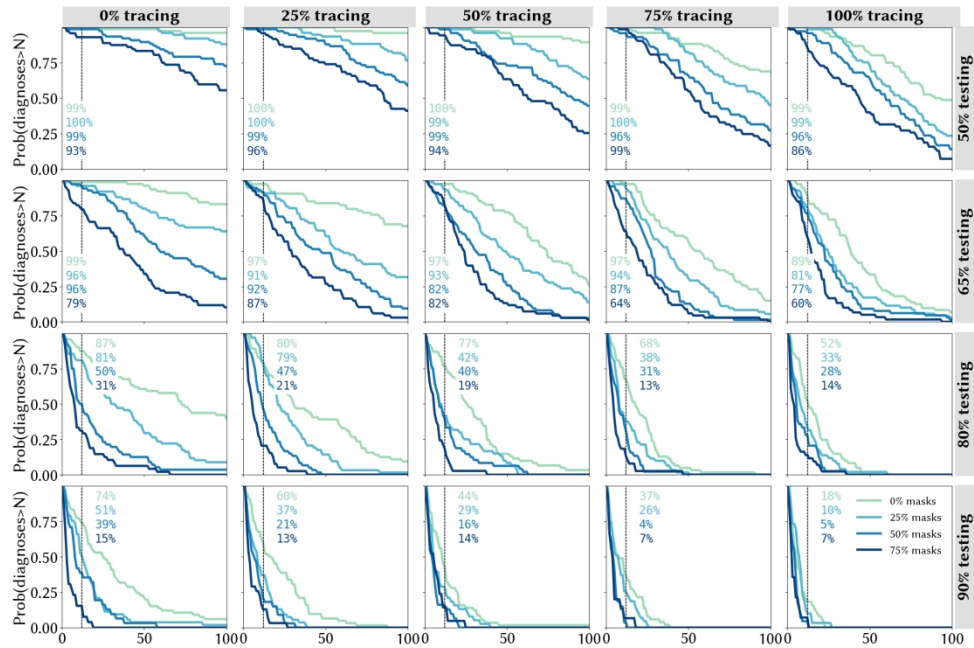


Figure 4. Quantifying the likelihood of epidemic resurgence in New South Wales: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).



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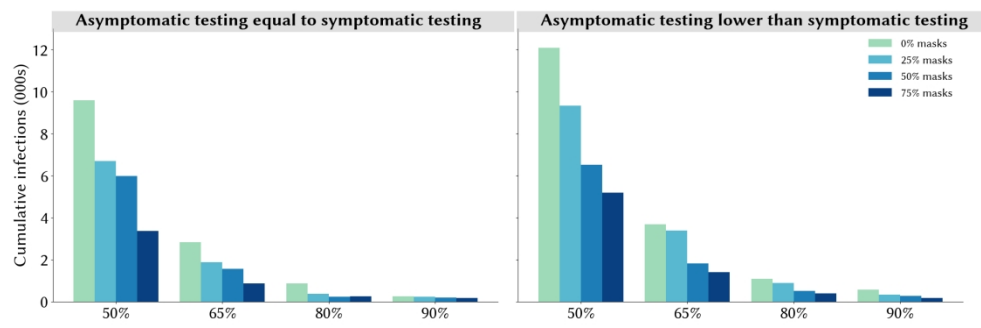


Figure 5. Estimated total infections over October 1 – December 31, 2020 under different assumptions about testing rates and mask uptake, assuming all community contacts can be traced within a week with a mean time to trace of 1 day. Projections represent the median of 100 simulations.

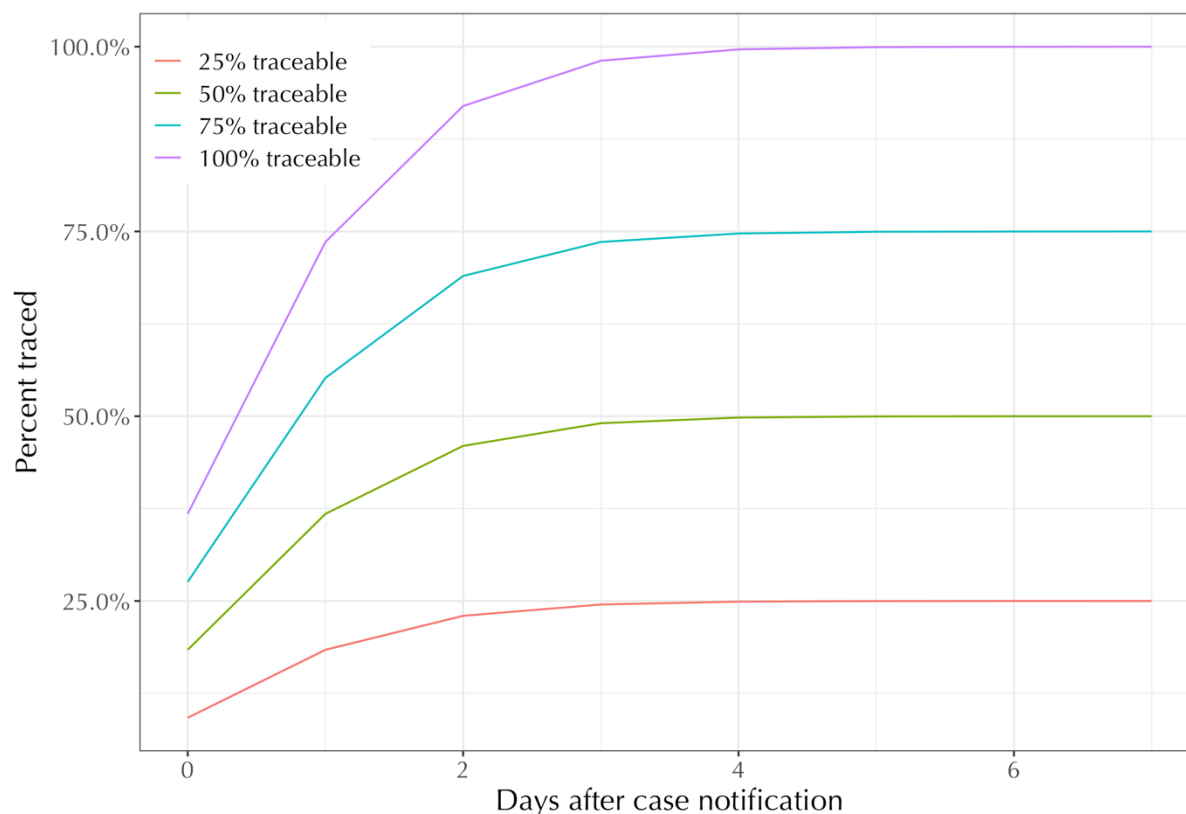
# Supplementary materials: The role of masks, testing and contact tracing in preventing COVID-19 resurgences: a case study from New South Wales, Australia

RM Stuart<sup>1,2†</sup>, Romesh G. Abey Suriya<sup>2</sup>, Cliff C. Kerr<sup>3,4</sup>, Dina Mistry<sup>3</sup>, Daniel J. Klein<sup>3</sup>, Richard Gray<sup>5</sup>, Margaret Hellard<sup>2,6,7,8,9</sup>, Nick Scott<sup>2,6</sup>

1. Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark
2. Disease Elimination Program, Burnet Institute, Melbourne, Victoria, Australia
3. Institute for Disease Modeling, Global Health Division, Bill & Melinda Gates Foundation, Seattle, USA
4. School of Physics, University of Sydney, Sydney, New South Wales, Australia
5. The Kirby Institute, UNSW Sydney, Sydney, New South Wales, Australia
6. School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia
7. University of Melbourne, Parkville, Victoria, Australia
8. Department of Infectious Diseases, The Alfred Hospital and Monash University, Melbourne, Victoria, Australia
9. The School of Population and Global Health and the Peter Doherty Institute for Infection and Immunity, Melbourne, Victoria, Australia

† Corresponding author. E-mail: robyn@math.ku.dk

**Key words:** COVID-19, coronavirus, SARS-CoV-2, modelling, masks, contact tracing, Australia



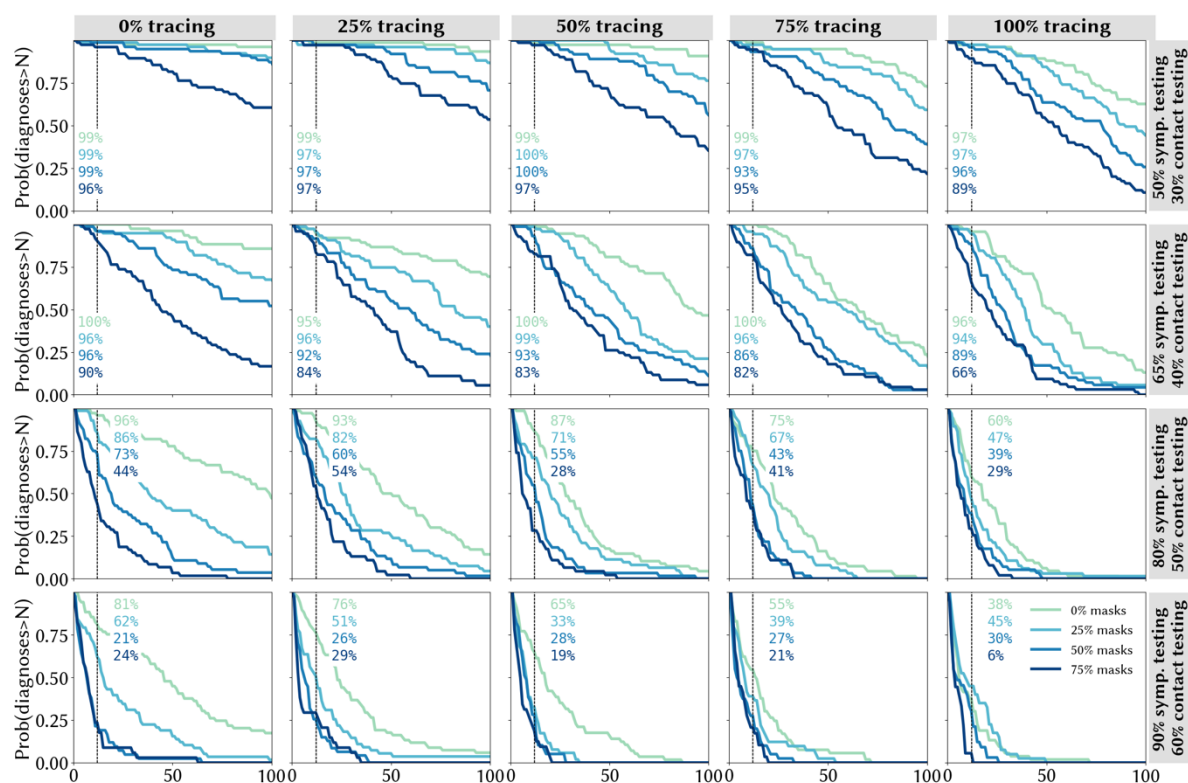
**Figure S1.** Assumed distribution of times required to find venue-based contacts.

Setting	Description of policy changes and their effects
Schools	School attendance rates in NSW had already dropped by 25% by 15 March 2020 (1), and on 23 March 2020 the NSW Premier advised that although schools remained open, parents were encouraged to keep their children at home for online learning (2). School attendance rates subsequently dropped to 5% of their pre-COVID levels (3). However, attendance quickly returned to pre-COVID levels shortly after schools reopened in mid-May (4). To model this, we removed 95% of contacts between school children and then restored them again as schools opened, but with the relative transmission risk set to 80% of its pre-March levels to account for additional safety measures in place for school activities (5).
Workplaces	According to survey data from the Australian Bureau of Statistics, almost half of working Australians were working from home in late April/early May (6), which is roughly consistent with Google movement data indicating that 40% fewer people were at work over that period compared to baseline. Workplace-based activities increased as COVID restrictions eased, but remained 15% lower over June-July compared to baseline. In the model, we removed 50% of workplace contacts and then restored them so that the workplace network was back to 85% of its pre-COVID size by the beginning of July (Figure 1). As with schools, we set the relative transmission risk set to 80% of its pre-March levels to account for the presence of NPIs.

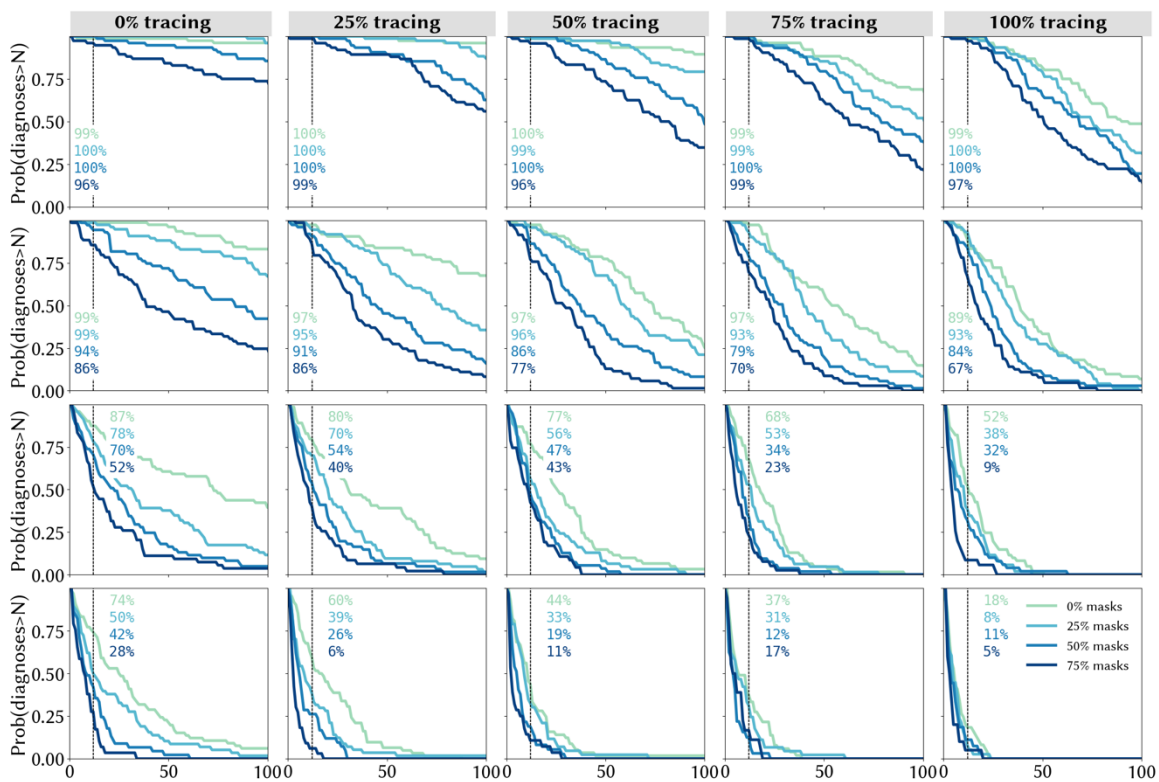
Static community	We assume that almost no contacts occurred over these networks from March 23 to May 1 with the exception of the limited contacts arising from permitted single-person visits. These networks were gradually restored over the period from May 1 to July 9 as restrictions eased.
Dynamic community networks over May-July (negligible mask usage)	Within New South Wales, arts venues such as museums, galleries, theatres, and cinemas, large events such as concerts, festivals, sports games, and pubs/bars were all closed over the period from March 23 to May 15, after which the networks were gradually restored. Cafes and restaurants, public parks and other outdoor settings, public transport, and all other community settings including essential retail remained open in some capacity throughout the year but with decreased demand and operational restrictions to reduce the likelihood of transmission (e.g., takeaway service only, closure of playgrounds, capacity limits on transport, and physical distancing/hygiene).
Dynamic community networks over August (increased mask usage)	From August 3, 2020, the use of masks was mandated in Victoria, which led to a marked increase in mask usage across the country. Only 13% of Australians wore a mask at least once over the month of June, but 58% reported wearing one at least once over August 7–17, 2020 (99% of Victorian residents compared to 44% of residents of other states) (7). Within New South Wales, media sources reported that 30% of people were wearing face masks on public transport in central Sydney in mid-August (8). To reflect the gradual increase in mask uptake in the model, we adjust the relative transmission risk assuming that the proportion of adults who wore masks while at work and in dynamic community settings increased over August to reach 30% by the end of the month.
Testing, tracing, and isolation	<p>We assume that the daily testing probability for those with symptoms increased from 5% in April to 20% by the beginning of June. Assuming a symptomatic period of roughly 10 days, this implies that the proportion of symptomatic people who get tested increased from 40% to 90%. In addition to symptom-based testing, we also assume that 90% of people who are not symptomatic but have been told to quarantine as a result of having been in contact with a confirmed case will get tested. Our assumptions around test sensitivity coupled with our modelling of viral load kinetics are specified such that the probability of identifying a true positive increases and then decreases over the course of an infection, following a similar profile to that reported in the literature (9–10).</p> <p>To model the efficacy of contact tracing over the period from June 1 – September 30, 2020, we assume that all household contacts were traced and notified on the same day that test results were communicated, that 95% of school contacts and 90% of workplace contacts were notified on the following day, and that 50% of all other contacts (which we refer to as community contacts) were traced within a week of a case notification, with a mean time to trace of one day (Figure S1).</p> <p>We assume that confirmed cases will isolate with near-perfect effectiveness, meaning that the probability of them transmitting to school or workplace contacts is zero, and the probability of them transmitting to their household contacts is reduced by 80%. Similarly, we assume high levels of adherence to isolation policies</p>

	imposed on those who have been notified that they were in contact with a confirmed case, with a 90% reduction in their probability of transmitting to school or workplace contacts.
Quarantine, and border control measures	From early on in the epidemic, Australia imposed strict border control measures requiring all arrivals to quarantine for two weeks in a hotel. These policies are assumed to be maintained throughout the duration of the model simulations.

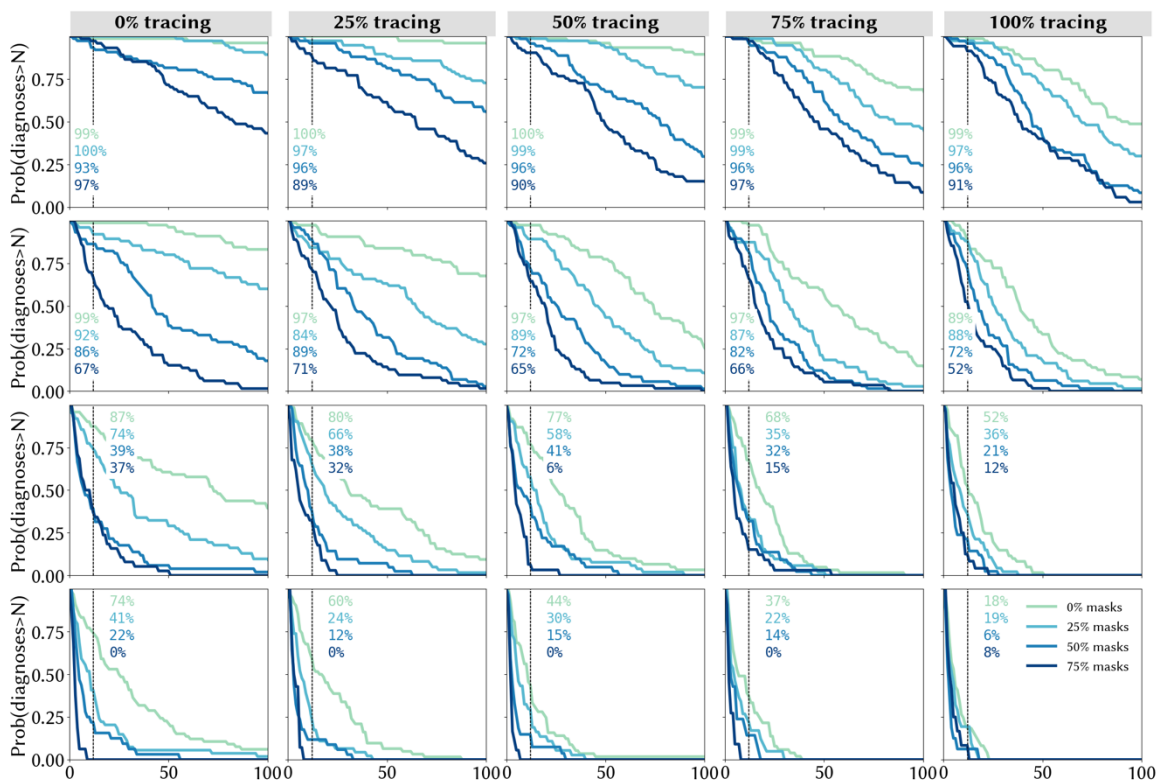
**Table S1.** Effects of policies on transmission risk in New South Wales



**Figure S2.** Sensitivity to asymptomatic testing assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 15%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).



**Figure S3.** Sensitivity to mask efficacy assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 15%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).



**Figure S4.** Sensitivity to mask efficacy assumption: the probability of the trailing 14-day average of locally-acquired cases exceeding a given number by December 31, 2020 with individual-level mask efficacy set to 45%, under different assumptions about the testing rate (rows), proportion of community contacts that can be traced within one week (columns), and mask uptake (line colours).

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