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Supplementary appendix

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Supplementary material to

Determining the optimal strategy for reopening schools, the impact of test and trace interventions, and the risk of occurrence of a second COVID-19 epidemic wave in the UK: a modelling study

Jasmina Panovska-Griffiths[1,2,3,*], Cliff C. Kerr[4,5], Robyn M. Stuart[6,7], Dina Mistry[4], Daniel J. Klein[4], Russell M.Viner[8$], Chris Bonell[9$]

[1]Department of Applied Health Research, UCL, London, UK
[2]Institute for Global Health, UCL, London, UK
[3]The Queen's College, Oxford University
[4]Institute for Disease Modeling, Bellevue, WA, USA
[5]University of Sydney, Sydney, NSW, Australia
[6]University of Copenhagen, Copenhagen, Denmark
[7]Burnet Institute, Melbourne, VIC, Australia
[8]UCL Great Ormond St. Institute of Child Health, London
[9]Faculty of Public Health and Policy, London School of Hygiene and Tropical Medicine

*Corresponding author: j.panovska-griffiths@ucl.ac.uk
$=joint senior author

Methods

Adaptation of Covasim model for this analysis

In the simulations we used the Covasim model developed by the Institute of Disease Modelling, described in details in [1] with implementation material at http://docs.covasim.org. Covasim can be downloaded from https://github.com/InstituteforDiseaseModeling/covasim and the adaptation of Covasim for this study and the calibration parameter inference script are available at https://github.com/Jasminapg/Covid-19-Analysis.

Our adaptation involved parametrising Covasim to the UK context. We used demographic data to set the UK population to 67.86 million people with age distribution specific for the UK [2]. The model simulated a population of 100,000 with 1500[1] infectious individuals seeded on 21/01/2020, which we then rescaled to the UK population of 67.86 million. The model was ran between 21/02/2020 and 31/12/2021.

Covasim is an agent-based model where each individual is characterised as either susceptible, exposed to the virus but not infectious, infectious and can spread the virus, recovered from the virus (and assumed to be immune) and dead. Infectious people are also split into those that are asymptomatic, presymptomatic and within symptoms categorised as mild, severe and critical. Schematic of the model is shown in Figure 1 in the main manuscript. Publicly available data

[1] We explored this value together with the transmission probability and the % of symptomatic testing. We determined that the minimum number of infectious individuals we needed to seed on 21/01/2020 (10 days before the first reported case) was 1000 individuals so that an epidemic would occur. But in this case we were getting unrealistic values of R0 (between 3-6). We determined this value during the calibration process matching the simulated epidemic to the UK epidemic (i.e. matching reported cases and deaths associated with COVID-19 and R0 between 2-3 at the onset of the UK epidemic).

across a spectrum of parameters characterising SARS-CoV-2 virus were collated for parametrisation of Covasim and the core parameters used in the simulation are listed in tables S2 and S3[2].

Covasim has four available networks to describe the populations distribution and household, school, workplace sizes as reported in the UN Population Division, 2019. For the purposes of this study we used the hybrid network approach where each person in the population is assumed to have contacts in their household, school (for children), workplace (for adults) and community as described in [1]. With this approach, for each age group a population was drawn by Covasim according to an age distribution in the UK and each individual was randomly assigned to a household using data on household sizes. Specifically, children are assigned to school and adults to workplaces, and we specify the number of fixed daily contact. In this analysis we assumed Poisson-distributed daily contacts with means of 3 for households, and 20 for schools, workplace and within the community contacts.

Disease duration parameters, in days, used in simulations are listed in Table S2 while the age-linked disease parameters as odd ratios are listed in Table S3. In addition, the proportion of the infection that is symptomatic depends on the population age structure with more details in [1]. Using the baseline parameters we simulated the UK COVID-19 epidemic over the period 21/01/2020 and 31/12/2020 projecting the number of daily new infections, cumulative diagnosis and cumulative deaths.

Data on number of reported COVID-19 cases in the UK

To compare with the model projections, we collated publicly available data on COVID-19 cases and associated deaths. The total number of confirmed cases of COVID-19 and COVID-19 associated deaths in the UK were collated between 21/02/2020 and 16/06/2020 from https://coronavirus.data.gov.uk.

School and society reopening scenarios

We model different scenarios of relaxing the lockdown in the UK by simulating reopening of schools, with some or all school years would go back to school at different times between June and September 2020, and proportional changes in work and community. Thus across scenarios we assume that increase in school transmission probability, workplace and community transmission probabilities would also increase respectively, to account for increased social mixing with reopening of schools.

Within Covasim this can be implemented as an increase in transmission due to contacts proportional to the % of school years going back under different scenarios. We thus simulate different strategies of reopening school, work and society by scaling the transmission probability within home (β_h), school (β_s), work (β_w) and community (β_c). For example, we accounted for reduced transmission probability across all contacts by 10% due to a hygiene campaign in the UK between 16/02/2020 and 23/03/2020 and a large reduction (98% in school transmission, 80% in work and community transmission) with the imposing of physical distancing measures in the UK from 23/03/2020. We then simulated an increase in the appropriate scaling for transmission probability layers, when we model schools reopening according to different scenarios with changes listed in Table 1 of the main text. We note that

[2] Variation of these tables was presented in [2] and here we have adapted them to what we used in this analysis.

within the scenarios design we accounted for school closures during the summer holidays, half-term and Christmas and Easter holidays. We assume during any school holidays, the transmission in schools will be 0%, while the transmission at home may increase.

We assumed that simultaneously to schools going back, there will be a society reopening with workplace and community contacts increased and hence probability of transmission due to contacts increased also. The exact percentages of change were chosen in discussion between co-authors. With uncertainty of what parts of society will reopen with schools reopen, it was a modelling assumption that reopening of society will be proportional to the increase in schools years going back when schools reopen. For example, with phased school reopening from 1st June, transmission at work and within community was assumed to be 40% (an increase of 20% to the situation during lockdown analogous to the increase in schools 3/13 schools years). Similarly, during term time after September 2020, the work transmission was assumed to be 70%, based on the assumption that 30% of the workforce will continue to work from home for the foreseeable future (personal communication with policy decision makers in the UK); while during school holidays we assumed the work transmission will be 50%. The community transmission probability was set to be 70% during school holidays and 90% during term.

We also assumed that the household contact rate and hence transmission probability would be reduced once schools reopen and remain as such during term-time. We made an assumption that this reduction would be around 29% using the information from Google movement data showing 29% increase in mobility trends for people's places of residence in the UK during the lock-down. We note that this modelling assumption represents the upper limit in this reduction. Exact details across scenarios are shown in the table of the main manuscript.

Testing, tracing and isolation scenarios

Testing in the model can be incorporated in two ways: (a) by assigning a daily number of tests assigned to the population, assigning test specificity and sensitivity and setting an odds ratio for testing symptomatic person or (b) by assigning probability of testing symptomatic, asymptomatic or quarantined people, assigning probability of true positive test, probability of the person being lost to follow up and days for test result to be known. In absence of exact number of daily tests, for this analysis we used the testing method that allows the user to specify the probabilities for different cohorts of people of receiving a test on each day.

Testing + isolation (TI) strategy between March 23, 2020 and May 31,2020

Until May 31, 2020 testing for COVID-19 in the UK was in people with severe symptoms and in hospital with some testing of essential key workers such as the NHS staff. (details in https://www.gov.uk/guidance/coronavirus-covid-19-information-for-the-public(accessed May 27, 2020). People who test positive were then asked to isolate. In addition people with symptoms were asked to self-isolate to prevent transmission. Based on this, we simulated the strategy between until May 31, 2020 to comprise of promoting self-isolation of people with symptoms, some testing of symptomatic people and isolation of positive diagnosis as well as testing a small number of people that are asymptomatic (e.g. NHS key workers).

We implemented this in in the model by specifying the probability p_s with which symptomatic people receive a test each day and a probability p_{as} with which asymptomatic people receive a test each day. In the latter case, we used the estimate from https://www.gov.uk/guidance/coronavirus-covid-19-information-for-the-public (assessed

May 20, 2020) that around 50,000 key workers are tested daily, suggesting a daily probability of testing people without symptoms p_{as} of 0.00075. The daily probability of testing people with symptoms p_s was fitted during the calibration.

We assumed a delay of one day to receive the test result and once an individual tested positive, they were immediately isolated for 14 days. In the model, this isolation reduced their infectiousness by 90%.

Testing, contact-tracing +isolation (TTI) from June 2020

The UK Government started a large scale contact-tracing strategy from 1st June to coincide with reopening of schools, after initially trialling it on the Isle of Wight. We incorporated this on our analysis, and simulate two scenarios for the coverage of the tracing strategy. At the briefing by policy decision makers on 19th June 2020 it was suggested that 75% of those diagnosed positive are contacted [7] and 90% of their contacts are traced [8], implying a tracing level of 68%. We have simulated this as one scenario. In addition, we have also simulated a more pessimistic coverage of the tracing strategy and assumed this to be 40%. We feel these represent reasonable lower and upper bound, with the pessimistic scenario being based on preliminary results from tracing in the Isle of Wight[3], while the more optimistic 68% resembles the reported tracing coverage by policy decision makers. The time taken to identify and notify contacts was set to immediate for house contacts, 1 days for school and work contacts and 2 days for within the community contacts.

Aligned with the government strategy from June 2020, within the model, tracing is of contacts of people tested positive for infection i.e. of diagnosed people. From June 2020, we simulated daily probability of testing of symptomatic people, while continuing to test a small proportion of asymptomatic people (e.g. NHS workers or other essential workers) and isolate the positive cases in combination with tracing of contacts of those tested positive and asking them to self-isolate.

Model Calibration

The model comes with a set of default parameters derived from literature searches, but calibration was required to adjust these to the UK context. We used parameter inference with the Optuna framework (https://optuna.org) for automated parameter optimisation and optimised four models parameters to match the UK epidemic in terms of confirmed COVID-19 cases and deaths associated with COVID-19 between 21/01/2020 and 16/06/2020.

Specifically, the parameter inference was on the number of seeded infectious individuals in the model (pop_infected), the per-contact transmission risk (β) and the parameters describing the proportion of symptomatic people that are tested (p_s) in May and in June (until 16/06/2020 inclusive). We determined values of these parameters for which we could match the model's projections of cumulative deaths and cumulative diagnosis between 21/01/2020 and 16/06/2020 to the reported COVID-19 cases and deaths in the UK as described above. In Figure 1 we show the best fit calibration for cases and deaths when simulating the model until

[3] As of 14/05/20 there have been 52,250 unique downloads of the tracing app at the Isle of Wight by residents and population is 141,538, implying 36.9% coverage.

16/06/2020 and the calibration script is available in https://github.com/Jasminapg/Covid-19-Analysis .

Modelling different transmissibility level in under 20 years old

Given uncertainties about the role of different age groups in transmission, we explored how varying the transmission among children and young people compared to adults would alter our results. We did this by changing the infectiousness of anyone under 20 years old to be 50% or 100% of the infectiousness of adults.

To simulate this, we set the parameter p_{sus} in Table S2 for those aged 0-19 years old to be 0.5 instead of 1.0 and we recalibrated the model varying the values of β, and p_s for May and June and initial number of infectious people during calibration. We then repeated the analysis from the main manuscript, forecasting the number of new COVID-19 infections, deaths associated with COVID-19 and the effective reproduction number R over time.

Calibration of the model when kids' transmissibility is 100% that of adults	
Initial seeding of infectious persons on 21/02/2020	1500
β	0.005938
p_s in March	0.009
p_s in April	0.012
p_s in May	0.0198
p_s in June (01/06/2020-16/06/2020)	0.0198
p_{as} in May and June	0.00075
Calibration of the model when kids transmissibility is 50% that of adults	
Initial seeding of infectious persons on 21/02/2020	2200
β	0.00629
p_s in March	0.009
p_s in April	0.012
p_s in May	0.029
p_s in June (01/06/2020-16/06/2020)	0.029
p_{as} in May and June	0.00075

Table S1: Parameters fitted during the calibration.

Disease Duration Parameters

Parameter	Description	Distribution (mean, std)	Source
s	Length of time after exposure before an individual is infectious (i.e. has begun viral shedding)	$s \sim lognormal\,(4.6, 4.8)$	Lauer et al., 2020 [23], Du et al., 2020 [24], Nishiura et al., 2020 [19], Pung et al., 2020 [25]
i_1	Length of time after viral shedding has begun before an individual has symptoms	$i_1 \sim lognormal\,(1, 0.9)$	Linton et al., 2020 [26], Lauer et al., 2020 [23]
i_2	Length of time after symptoms appear before they become severe and the person requires critical care	$i_2 \sim lognormal\,(6.6, 4.9)$	Linton et al., 2020 [26]
i_3	Length of time after severe symptoms appear before the person requires critical care	$i_3 \sim lognormal\,(3, 7.4)$	Wang et al., 2020 [27]

r_a	Recovery time for asymptomatic cases	$r_a \sim lognormal\,(8, 2)$	Wölfel et al., 2020 [28]
r_m	Recovery time for mild cases	$r_m \sim lognormal\,(8, 2)$	Wölfel et al., 2020 [28]
r_s	Recovery time for severe cases	$r_s \sim lognormal\,(14, 2.4)$	Verity et al., 2020 [29]
r_c	Recovery time for critical cases	$r_c \sim lognormal\,(14, 2.4)$	Verity et al., 2020 [29]

Table S2: Disease duration parameters, in days, used in simulations. This table is modified from [1], which describes the Covasim model in more detail.

Age-linked Disease Parameters

Parameter	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
p_{sus}	0.34	0.67	1.00	1.00	1.00	1.00	1.00	1.24	1.47
p_{sym}	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
p_{sev}	0.0005	0.0065	0.0072	0.0208	0.03430	0.0765	0.1328	0.2066	0.2457
p_{cri}	0.00003	0.00008	0.00036	0.00104	0.00216	0.00933	0.03639	0.08923	0.1742
p_{death}	0.00002	0.00006	0.00030	0.00080	0.00150	0.00600	0.02200	0.05100	0.09300
β	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table S3: Age-linked disease parameters used in simulations. This table is borrowed from [1] describes the Covasim model in more detail. Key: p_{sus}: odds ratio of developing symptoms; p_{sym}: probability of developing symptoms; p_{sev}: probability of developing severe symptoms (i.e., sufficient to justify hospitalization); p_{cri}: probability of developing into a critical case (i.e., sufficient to require ICU); p_{death}: probability of death. Susceptibility values are derived from Zhang et al.[13]; all other values are derived from Verity et al.[29] and Ferguson et al.[2]. In the Supplementary Material, we explore variability in the transmissibility β of those under 20 by setting β to 0.50 for age groups 0-9 and 10-19.

Scenario	40% of contacts tracing		68% of contact tracing	
	p_s	% testing level	p_s	% testing level
Fully in September	0.18	87%	0.13	75%
Rota in September	0.13	75%	0.1	65%

Table S4: Parameters used to generate results in Figures 2-4 in the main text, showing the daily probability of symptomatic testing (p_s) to avoid secondary pandemic wave when transmissibility is the same across all ages.

Scenario	40% of contacts tracing		68% of contact tracing	
	p_a	% testing level	p_{as}	% testing level
Fully in September	0.143	78%	0.09	61%
Rota in September	0.115	70%	0.085	59%

Table S5: Parameters used to generate results in Figures S2-S4 in the main text, showing the daily probability of asymptomatic testing (p_s) to avoid secondary pandemic wave when under 20 years old transmissibility is 50% that of other ages

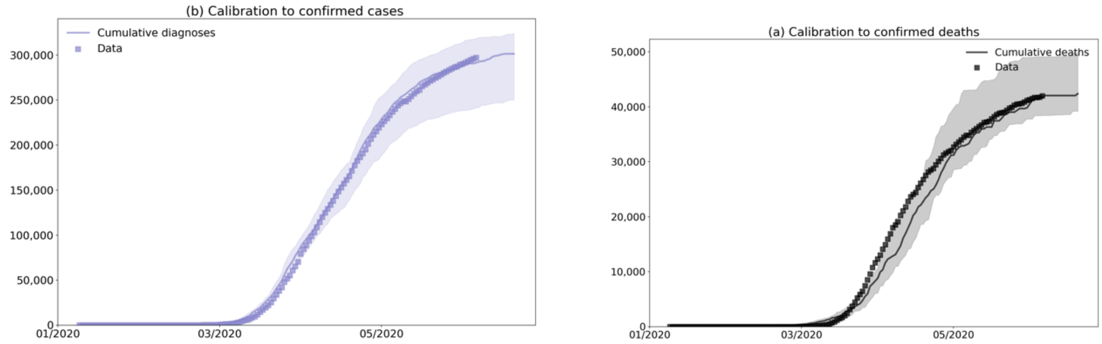

Figure S1: Model calibration when children's transmissibility is the same as that of adults.

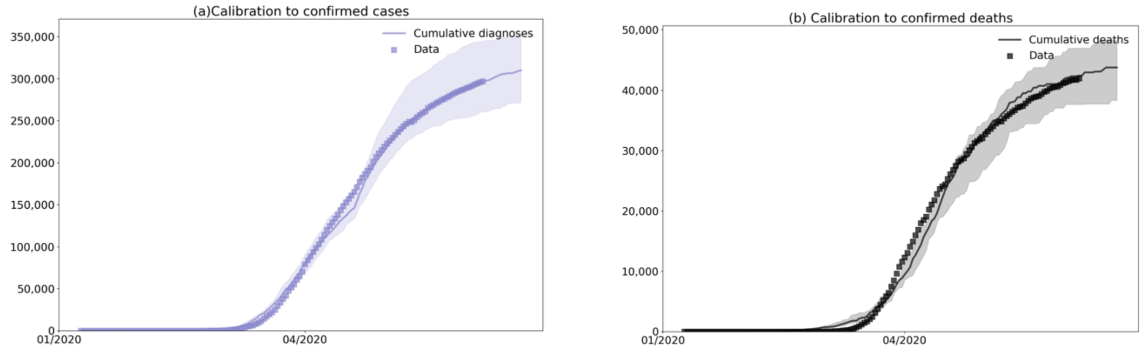

Figure S2: Model calibration when under 20 years old transmissibility is half that of other ages.

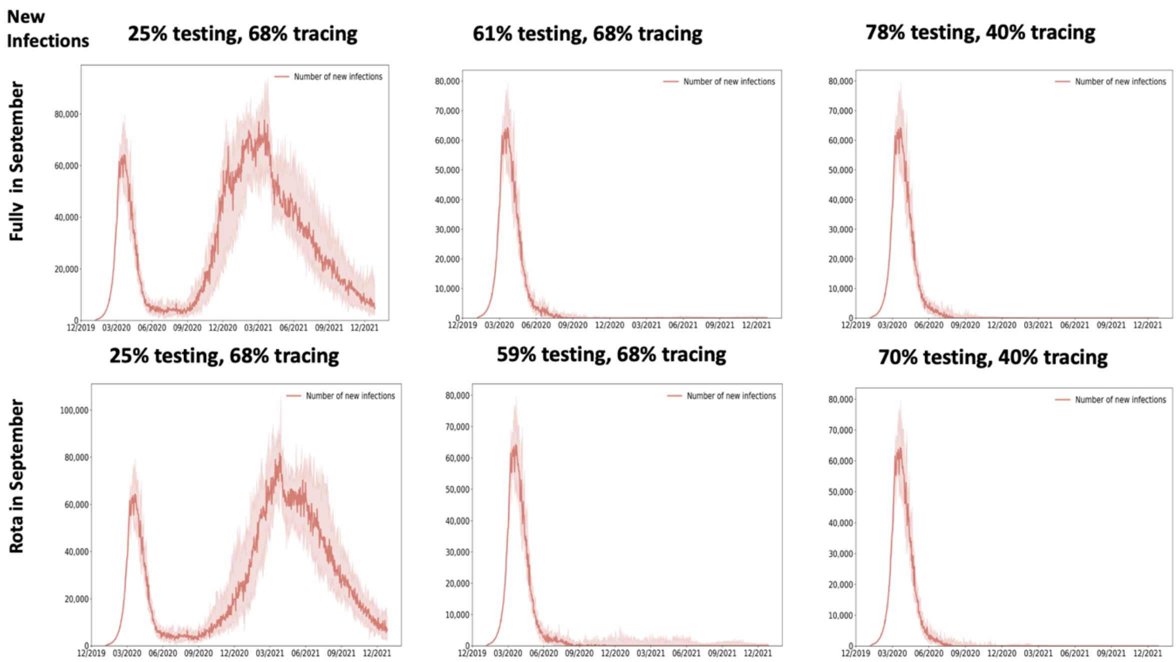

Figure S3: Model estimates of daily new COVID-19 infections over 21 January 2020 and 31 December 2021 across different school and society reopening scenarios in the presence of different test-trace-isolate (TTI) strategies, with infectiousness of under 20 years old set to 50%

of that of older ages. Medians across ten simulations are indicated by solid red lines and 10% and 90% quantiles by red shading.

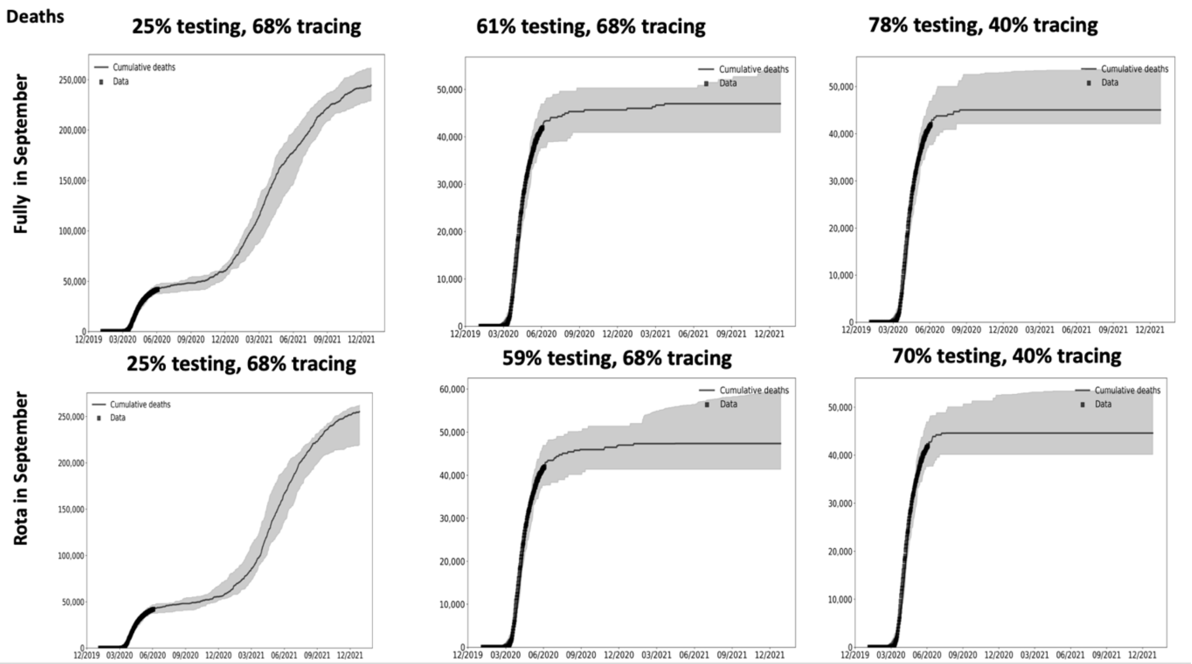

Figure S4: Model estimates of cumulative COVID-19 deaths over 21 January 2020 and 31 December 2021 across different school and society reopening scenarios in the presence of different test-trace-isolate (TTI) strategies, with infectiousness of under 20 years old set to 50% of that of older ages. Medians across ten simulations are indicated by solid black lines and 10% and 90% quantiles by grey shading.

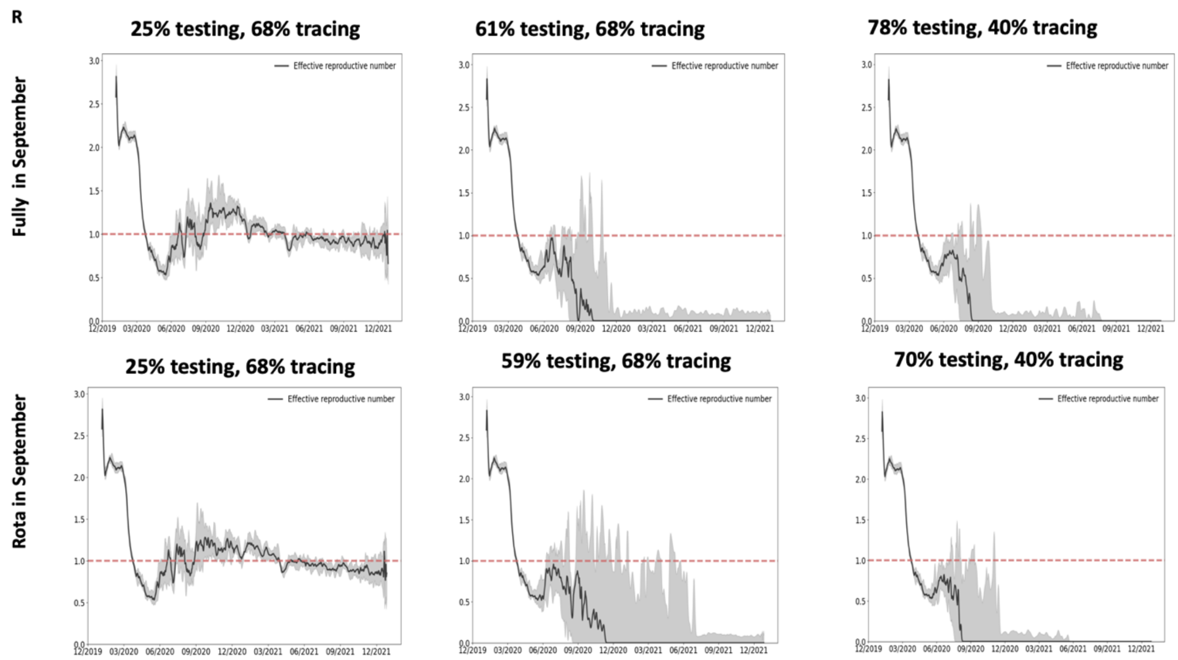

Figure S5: Model estimates of the effective reproduction number R over 21 January 2020 and 31 December 2021 across different school and society reopening scenarios in the presence of different test-trace-isolate (TTI) strategies, with infectiousness of under 20 years old set to 50% of that of older ages. Medians across ten simulations are indicated by solid black lines and 10% and 90% quantiles by grey shading.

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