

# 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.

J.Panovska-Griffiths<sup>1,2,3,\*</sup>, C.C. Kerr<sup>4,5</sup>, R.M. Stuart<sup>6,7</sup>, D. Mistry<sup>4</sup>, D.J. Klein<sup>4</sup>, R.M.Viner<sup>8§</sup>, C.Bonell<sup>9§</sup>

<sup>1</sup>Department of Applied Health Research, UCL, London, UK

<sup>2</sup>Institute for Global Health, UCL, London, UK

<sup>3</sup>The Queen's College, Oxford University

<sup>4</sup>Institute for Disease Modeling, Bellevue, WA, USA

<sup>5</sup>University of Sydney, Sydney, NSW, Australia

<sup>6</sup>University of Copenhagen, Copenhagen, Denmark

<sup>7</sup>Burnet Institute, Melbourne, VIC, Australia

<sup>8</sup>UCL Great Ormond St. Institute of Child Health, London

<sup>9</sup>Faculty of Public Health and Policy, London School of Hygiene and Tropical Medicine

\*Corresponding author: [j.panovska-griffiths@ucl.ac.uk](mailto:j.panovska-griffiths@ucl.ac.uk)

§=joint senior author

## Abstract

### Background

To slow down the spread of SARS-CoV-2, the virus causing COVID-19, the UK government has imposed strict physical distancing ('lockdown') measures including school 'dismissals' since 23 March 2020. As evidence is emerging that these measures have slowed the spread of the pandemic, it is important to assess the impact of any changes in strategy, including school reopening and broader relaxation of physical distancing measures. This work uses an individual-based model to predict the impact of two possible strategies for reopening schools to all students (full-time versus part-time rotas) in the UK from September 2020, in combination with different assumptions about the scale-up of testing.

### Methods

We use Covasim, a stochastic agent-based model for transmission of COVID-19, calibrated to the UK epidemic. The model describes individuals' contact networks stratified into household, school, workplace and community layers, and uses demographic and epidemiological data from the UK. We simulate six different scenarios, representing the combination of two school reopening strategies and three testing scenarios, and estimate the number of new infections, cases and deaths, as well as the effective reproduction number (R) under different strategies. To account for uncertainties within the stochastic simulation, we also simulated different levels of infectiousness of children and young adults under 20 years old compared to older ages.

### Findings

We found that with increased levels of testing (between 59% and 87% of symptomatic people tested at some point during an active COVID-19 infection, depending on the scenario), and effective contact tracing and isolation, an epidemic rebound may be prevented. Assuming 68%

of contacts could be traced, we estimate that 75% of those with symptomatic infection would need to be diagnosed and isolated if schools return full-time in September, or 65% if a part-time rota system were used. If only 40% of contacts could be traced, these figures would increase to 87% and 75%, respectively. However, without such measures, reopening of schools together with gradual relaxing of the lockdown measures are likely to induce a secondary wave that would peak in December 2020 if schools open full-time in September, and in February 2021 if a part-time rota system were adopted. In either case, the secondary wave would result in  $R$  rising above 1 and a resulting secondary wave of infections 2-2.3 times the size of the original COVID-19 wave. When infectiousness of <20 year olds was varied from 100% to 50% of that of older ages, we still find that comprehensive and effective TTI would be required to avoid a secondary COVID-19 wave.

### Interpretation

To prevent a secondary COVID-19 wave, relaxation of physical distancing including reopening schools in the UK must be accompanied by large-scale population-wide testing of symptomatic individuals and effective tracing of their contacts, followed by isolation of diagnosed individuals. Such combined measures have a greater likelihood of controlling the transmission of SARS-CoV-2 and preventing a large number of COVID-19 deaths than reopening schools and society with the current level of implementation of testing, tracing and isolation.

**Keywords:** COVID-19, reopening schools and society, test-trace-isolate strategies, mathematical modelling, agent-based model

## Research in Context

### *Evidence before this study*

Since the onset of the COVID-19 pandemic, mathematical modelling has been at the heart of informing decision-making, including the imposing of the lockdown in the UK. Although published studies have modelled the epidemic spread across different settings, no studies to date have used modelling to evaluate the impact of reopening schools and society specifically. We searched PubMed for modelling studies that have modelled different schools opening strategies in combination to testing interventions: ("SARS-CoV-2" OR "COVID-19") AND ("modelling" OR "model") AND ("testing") AND ("schools") on 10<sup>th</sup> May 2020. We did not find any published studies that met these criteria. As countries are now starting to ease lockdown measures, it is important to assess the impact of different lockdown exit strategies including whether and how to reopen schools and relax other physical distancing measures. Reopening of schools represents the first step of reopening society by allowing parents to return to work and hence increased community mixing.

### *Added value of this study*

Using mathematical modelling, we explored the impact of strategies to reopen schools and society in the UK, including the partial reopening of schools in June 2020. We assessed the impact of all school years going back in September (modelling full-time versus part-time rotas), accompanied by a society-wide relaxation of lockdown measures and in the presence of a different test-trace-isolate strategies. We projected the number of new COVID-19 infections, cumulative cases and deaths, as well as the temporal distribution in the effective reproduction number ( $R$ ) across different strategies and under different assumptions about the relative susceptibility of children. Our study is the first to provide quantification of the amount of testing and tracing that would be needed to prevent a second wave of COVID-19 in the UK under different school reopening scenarios.

### *Implications of all the available evidence*

Evidence to date points to the need for additional testing, contact tracing, and isolation of individuals who have either been diagnosed with COVID-19, or who are considered to be at high risk of carrying infection due to their contact history or symptoms. Our study supports these conclusions and provides additional quantification of the amount of testing and tracing that would be needed to prevent a second wave of COVID-19 in the UK under different lockdown exit strategies. Reopening schools and society alongside active testing of the symptomatic population (between 59% and 87% of people with symptomatic COVID-19 infection across different scenarios) and with an effective contact tracing and isolation strategies, will prevent a secondary pandemic wave and avert a large number of COVID-19 cases and deaths. However, in the absence of a large-scale testing, contact-tracing and isolation strategy, reopening schools partially in June 2020 and full time or in part-time rotas from September, alongside reopening society, is likely to induce a secondary pandemic wave of COVID-19 in the UK.

## Introduction (711 words)

The COVID-19 pandemic, caused by the SARS-CoV-2 virus, continues to spread globally with more than 9 million reported cases and over 473,000 deaths worldwide as of 24 June 2020<sup>1</sup>. In the UK, since the first two reported cases on 31 January 2020 and the first reported COVID-19-related death on 7 March 2020, the number of reported cases and deaths has increased steadily, with over 306,000 confirmed cases and over 42,900 deaths reported up to 24 June 2020.<sup>1</sup>

To slow down the virus spread, reduce the morbidity and mortality of the pandemic, and not overwhelm the National Health Service (NHS), the UK government imposed strict physical distancing ('lockdown') measures on 23 March 2020. Informed by mathematical modelling of the potential spread and mortality of this pandemic<sup>2</sup>, and following the example of the countries affected earlier<sup>3</sup>, schools closures have occurred worldwide as a key element of COVID-19 lockdown measures. On 19 March 2020, UNESCO estimated that 1.6 billion children and young people in over 180 countries had stopped attending school.<sup>3</sup> In the UK, schools for 4-18 years old remained open only for the children of key workers and children with defined health, education, or social needs, with estimated around 2% of school children attending during lockdown.

While closing schools does reduce the contact rate within the population and hence reduces onward transmission, considerable harms arise from school closures.<sup>4</sup> These include hampering healthcare and other key workers' ability to go to work<sup>4</sup>; reduced economic productivity<sup>5</sup>; and damage to children and young people's education, development, and physical and mental health<sup>6-8</sup> arising from social isolation<sup>9</sup>, reduced social support and possible increased exposure to violence at home.<sup>10</sup>

As the rate of increase in the number of COVID-19-related hospitalisations and deaths in the UK slowed down<sup>11</sup>, UK's lockdown has been slowly eased with partial reopening of English primary schools (reception, year one and year six) from 1 June 2020 and, secondary schools (years 10 and year 12) from 15 June 2020. These options are based on assumptions of lower transmission among primary school children and on findings from early population testing suggesting very low COVID-19 infection or asymptomatic carriage rates, particularly in those under 10 years.<sup>12</sup>

Under current plans, all primary and secondary school students will return to school in England in September, but the exact return-to-school policy is undecided. Return in other UK countries is also likely to be September 2020. Decisions will be based on an understanding of the likely impact of different policies, but this is particularly challenging because of the uncertainty about the importance of children and young people in COVID-19 transmission and the impact of school closures in COVID-19 control.<sup>7</sup> While previous modelling studies have suggested that school closures do reduce transmission when implemented alongside other physical distancing interventions<sup>2</sup>, this generally assumes that transmissibility among children and young people is equivalent to that among adults. Data on susceptibility to and transmission of COVID-19 among children and adolescents are sparse.<sup>5</sup> A population-based contact-tracing study on transmission in schools in Australia identified two likely secondary cases from 18 index cases and 863 contacts.<sup>6</sup> Yet others have suggested that the attack rate is similar to that in adults<sup>7</sup>, and much of the data on school transmission comes from periods when schools have been fully or partially closed. A recent meta-analysis suggested that susceptibility to SARS-CoV-2 amongst children and adolescents was around half of that amongst adults<sup>8</sup> but symptoms are

much less common in children than adults and the degree of asymptomatic transmission by children is unknown.

In this paper, we use modelling to explore the impact of two possible strategies to reopen all schools from September 2020 combined with society-wide relaxing of the physical distancing measures in the UK. Reopening of schools represents the first step of reopening society by allowing parents to return to work and hence increased community mixing. Specifically, we examine six core scenarios, representing the combination of two school reopening scenarios (schools reopen to all students from September with students either attending full-time or in a rota system) with three different TTI scenarios. We conduct sensitivity analyses to assess how our results would change if under 20 years old are less infectious than older ages. The strategies we have explored have been discussed with members of scientific advisory bodies in the UK.

## Methods (1553 words)

### *Transmission model*

We modelled the spread of COVID-19 using Covasim v1.4.7, a stochastic agent-based model of SARS-CoV-2 transmission. The model was developed by the Institute for Disease Modeling, with details at <http://docs.covasim.org> and model code available from <https://github.com/InstituteforDiseaseModeling/covasim>. Further details of the mathematical approach used for Covasim are contained in Kerr et al.<sup>13</sup> Briefly, within the model, individuals were modelled as either susceptible to the virus, exposed to it, infected, recovered or dead. In addition, infected and infectious individuals are categorised as either asymptomatic or in different symptomatic groups: pre-symptomatic (before viral shedding has begun), or with mild, severe or critical symptoms. A schematic of the model is given in Figure 1. For this study the model was adapted to the UK context and the code used to run all simulations contained in this paper is available from <https://github.com/Jasminapg/Covid-19-Analysis>.

Covasim's default parameters determine the ways in which people progress through the states depicted in Figure 1, including the probabilities associated with onward transmission and disease progression, duration of disease by acuity, and the effects of interventions; these were collated during Covasim's development over May<sup>13</sup> and are updated when new evidence becomes available. In addition, Covasim is pre-populated with demographic data on population age structures and household sizes by country, and uses these to generate population contact networks for the setting. By default, Covasim generates 4 different contact networks: schools, workplaces, households and community settings. The per-contact transmission probability ( $\beta$ ) that an infectious individual transmits the virus to a susceptible individual is assumed to depend on the contact network. Covasim accounts for testing strategies via parameters that determine the probabilities with which people with different symptoms receive a test each day. Further details can be found in the supplementary material.

### *Data sources and calibration*

We used Covasim's defaults to generate a population of 100,000 agents who interact over the 4 networks described above. This approach is similar to that in Ferguson et al.,<sup>2</sup> one of the studies that directly influenced the imposition of lockdown measures in the UK. To fit the model to the UK epidemic, we performed an automated search for the optimal values of the number of infected people on 21 January 2020, the per-contact layer-dependent transmission probabilities, and the daily testing probabilities for symptomatic individuals ( $p_s$ ) during May

and June that minimised the sum of squared differences between the model's estimates of confirmed cases and deaths, and data on these same two indicators between 21 January 2020 and 17 June 2020 collated from the UK government's COVID-19 dashboard (<https://coronavirus.data.gov.uk>). These particular parameters were selected as the most important to estimate because the considerable uncertainties around them – in particular, about whether  $\beta$  is age-dependent<sup>14</sup> or differs across asymptomatic and symptomatic cases – translate to uncertainties around the true number of infections in the population and the proportion of those that have been detected. We accounted for effect of the lockdown by reducing the per-contact transmission probabilities from 23 March 2020, to 2% of their pre-lockdown values within schools, and to 20% of their pre-lockdown values within workplace and community settings.

The calibrated model estimated that between 21 January 2020-17 June 2020, the daily probabilities of testing people with symptoms were 1.98% corresponding to ~18% of people with symptomatic infections being tested at some point during their illness (assuming an average symptomatic period of roughly 10 days). The model also assumed the daily probabilities of testing people without symptoms were 0.075% corresponding to ~0.75% of people with asymptomatic COVID-19 infections being tested at some point during their illness (assuming an average symptomatic period of roughly 10 days). In addition we determined there were 1500 infected people in the UK on 21 January 2020, and that the per-contact transmission probability was 0.59%. These calibrated parameters are summarised in Table S1, and Figure S1 shows the model projections alongside data.

### *School and society reopening scenarios*

As the first step of the phased easing of the lockdown measures, the UK government reopened schools in a phased manner from 1 June 2020, with students in reception (aged 4-5), year one (aged 5-6) and year six (aged 10-11) in English primary schools returning to school on 1 June 2020, followed by secondary school students in years 10 and 12 from 15 June 2020. Under current plans, all school students will return in September either full time or part time depending on the state of the epidemic. Therefore, a second plausible scenario is that returning to school in September may include a rota system with students attending school on alternate weeks, with half of the students attending school one week and the other half the following week. We explore these two scenarios of schools returning from September together with phased reopening from June, with details of the scenarios contained in Table 1.

The phased reopening of schools was implemented by setting the per-contact transmission probabilities within schools  $3/13=23\%$  on 1 June 2020 (representing 3 of 13 school years returning to school), and then to  $5/13=38\%$  on 15 June 2020 (representing 2 additional school years), 90% of its pre-lockdown value for the full-reopening scenario (to account for protective measures assumed to be in place) and 50% for the rota scenario from 1<sup>st</sup> September. In both cases, we accounted for holiday periods by assuming no transmission in schools and higher transmission in households (by 29%, based on Google movement data over the lockdown period) over holiday periods.

We also assumed that reopening schools would also correspond to increases in workplace and community transmission probabilities, to account for a) increased social mixing with reopening of schools and b) relaxation of the physical distancing restrictions that have applied to work, leisure and community activities. To simulate this, we assume that if schools were to reopen full time or in a part-time rota system, the transmission probability in community settings

would be respectively 90% or 70% of its pre-lockdown value when schools are in session and 70% during school holiday periods, while workplace transmission would be 70% of its pre-lockdown value during school terms (under the assumption that 30% remain working from home for foreseeable future; personal communication with policy decision makers) and 50% during school holidays. In addition we assumed that if school reopen in a part time rota this would be for one school term (autumn term 2020) only and then schools will go back full time from 1 January 2021. These scenarios are summarised in Table 1.

### *Testing, tracing and isolation strategies*

In line with current policy in the UK, we also modelled the implementation of TTI strategies to test those in the population presenting with COVID-19-like symptoms, isolate those testing positive and trace their contacts. Since 23 March 2020 the strategy in the UK has been to test people presenting with COVID-19 symptoms and isolate them, and starting on 1 June 2020, this has been complemented by a strategy to trace contacts of those people who test positive to infection. The tracing strategy was simulated in Covasim by introducing two coverage levels of tracing beginning on 1 June 2020. Firstly, to resemble the current scenario of tracing contacts we assumed that 75%<sup>15</sup> of those testing positive are contacted and that 90%<sup>16</sup> of their contacts are traced and asked to isolate, which results in a contact tracing level of 68%. We also simulate a more pessimistic scenario for tracing capability, which could arise if there were problems in scaling up TTI, of a contact tracing level of 40%.

We used the model to derive the testing levels necessary to avoid the secondary pandemic wave with these two tracing strategies. 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%. In addition, with both strategies, symptomatic people were also isolated with their infectiousness reduced by 50%. More details are available in the supplementary material.

### *Analysis*

Given uncertainties about the role of different age groups in transmission,<sup>5</sup> we explored how varying the infectiousness of anyone under 20 years old to be 50%<sup>17</sup> or 100% of the infectiousness of adults changes the results. To run the sensitivity analysis (50%), we needed to re-calibrate the model to the UK epidemic; the calibrated parameters are summarised in Table S1, and Figure S2 shows the model projections alongside data.

Overall, we simulated a total of 6 core scenarios, comprising 2 different school reopening strategies (students return fulltime in September vs students return part-time in a rota system in September) and 3 TTI strategies:

1. 68% of contacts are traced with no scale-up in testing i.e. 18% of people with symptomatic infection and ~0.75% of those with asymptomatic infection are tested;
2. 40% of contacts are traced and symptomatic testing is scaled up sufficiently to avoid a secondary COVID-19 wave;
3. 68% of contacts are traced and testing scaled up sufficiently to avoid a secondary COVID-19 wave).

For each scenario, we estimated the daily and cumulative numbers of infections and deaths, as well as time series of the effective reproduction number  $R$ , until 31 December 2021. Since Covasim is stochastic, we simulated each scenario under 10 different random number seeds,

and we present the median estimates along with ranges corresponding to the upper and lower bounds generated by these 10 seeds. We also simulated these same scenarios again for our sensitivity analysis, this time with transmissibility for people <20 years old assumed to be half that of people >20, again using 10 random number seeds.

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

The funders had no role in the study design, data collection, analysis or interpretation of the data or writing of the report. The corresponding author had full access to all of the data and the final responsibility to submit for publication.

### **Results (566 words)**

The results of the six core scenarios are shown in Figures 2-4. Figures 2-3 show projections of the daily counts of COVID-19 infections (Fig 2) and deaths (Fig 3), and Figure 4 shows the effective reproduction number R.

Reopening schools either full-time or in a part-time rota system from 1 September 2020 alongside relaxation of other social distancing measures will induce a secondary COVID-19 wave in the absence of a scaled-up testing program (Figure 2-4, first column). This secondary wave would peak in December 2020 if schools open full-time in September, and in February 2021 if a part-time rota system were adopted. In either case, the secondary wave would be 2-2.3 times larger than the first COVID-19 wave in the UK.

Our findings suggest that it may be possible to avoid a secondary pandemic wave across both school reopening scenarios if enough people with symptomatic infection can be diagnosed, their contacts traced and effectively isolated (Figure 2-4, 2<sup>nd</sup> column and 3<sup>rd</sup> column). Assuming 68% of contacts could be traced, we estimate that 75% of those with symptomatic infection would need to be diagnosed and isolated if schools return full-time in September, or 65% if a part-time rota system were used (Table 4). If only 40% of contacts could be traced, these figures would increase to 87% and 75%, respectively.

The temporal profiles of the effective reproduction number R follow the trend of the time series of new infections (comparing respective tiles across Figure 2 and 4). R evidently increases over the threshold of 1, suggesting an increase in the number of new infections, when a secondary COVID-19 wave occurs (1<sup>st</sup> column in Figures 2 and 4). Across both scenarios of school and society reopening and different tracing levels, the TTI strategy would need to test a sufficiently large proportion of the population with COVID-19 symptomatic infection and trace their contacts with sufficiently large coverage, for R to diminish below 1 (Figures 2-3 2<sup>nd</sup> and 3<sup>rd</sup> column). Specifically, our simulations suggest that the time when R diminishes depends on the level of implemented TTI and the combination of testing and tracing; the exact relationship between timing of R diminishment at different levels of TTI from June 2020 will be explored in subsequent analyses.

When we reran the six core scenarios with infectiousness amongst under 20 years old assumed to be 50% of that among older ages, the main messages from our results remained largely unchanged. We still found that it is possible to avoid a secondary COVID-19 wave across all scenarios of school and society reopening and different tracing levels, if the TTI strategy tests a sufficiently large proportion of the population with COVID-19 symptomatic infection and



traces their contacts with sufficiently large coverage. Assuming 68% of contacts could be traced, we estimate that 61% of those with symptomatic infection would need to be diagnosed and isolated if schools return full-time in September (compared to 75% if children transmit equally to adults), or 59% if a part-time rota system were used (Table S5). If only 40% of contacts could be traced, these figures would increase to 78% and 70%, respectively. These results are summarised in the supplementary materials; Table S5 presents the testing levels required to prevent a secondary wave (analogous to Table S4 for the main analysis) and Figures S3-S5 show projections of daily infections, cumulative deaths, and the effective reproductive number (analogous to Figures 2-4).

## Discussion (1415 words)

Our modelling results suggest that if schools and society reopened full-time or in a part-time rota system in September with sufficiently broad TTI coverage, a secondary COVID-19 wave could be prevented in the UK. In addition, such measures would markedly reduce cumulative numbers of new infections and deaths, and contribute to keeping  $R$  below 1. This is the case both in the main analyses assuming infectivity of under 20 years old is 100% of adults and when we assume that infectivity of under 20 years old is 50% that of adults (Figure S3 in supplementary material). We note that depending on the overall population prevalence of COVID-19-like illness, achieving this level of coverage with a TTI strategy would likely require testing a large number of people.

However, we also predict that in the absence of sufficiently broad TTI coverage, reopening schools combined with accompanied reopening of the society across all scenarios can induce a secondary COVID-19 wave. For example, our modelling results suggest that full reopening in September without effective TTI would result in  $R$  rising above 1 and a resulting secondary wave of infections 2.3 times the size of the original COVID-19 wave.

Evidence from countries like South Korea<sup>23,24</sup> where large-scale testing and contact-tracing have been able to control the spread of COVID-19, points to the need for additional testing, effective contact tracing, and isolation of individuals who have either been diagnosed with COVID-19, or who are considered to be at high risk of carrying infection due to their contact history or symptoms, to control the virus spread. Our study supports these conclusions and provides additional quantification of the amount of testing and tracing that would be needed to prevent a second wave of COVID-19 in the UK under different strategies to reopen schools and society from June 2020. To our knowledge, this is the first study to give such quantitative measures for the UK.

The analyses presented here have a number of limitations. First, while we have made an effort to characterise the pandemic to resemble that of the UK, some of the parameters we have used are from a variety of sources across different settings.<sup>13</sup> However, the main aspect we have focused on changing to illustrate different scenarios, is the transmission probability of social (household, school, workplace and community) contacts and the primary source for this was UK based.<sup>18</sup> The changes we have simulated across scenarios reflect our understanding of possible options for school reopening as discussed in the UK. They are therefore fit for purpose within this analysis. Secondly, as with any modelling study, we have made a series of assumptions within the modelling framework. In particular, we made assumptions about the proportion of COVID-19 infections that are symptomatic, as in the literature, there is a mixed evidence on this. While the World Health Organisation suggests that 80% of infections show mild symptoms<sup>19</sup> and a recent study from the Italian city of Vo' Euganeo at the epicentre of

the European pandemic confirms that a large proportion, 50%-75%, of COVID-19 infections do not result in symptoms, other studies suggest this number is smaller: e.g. 10% among children,<sup>20</sup> 18% among passengers on the Diamond Princess cruise ship<sup>21</sup> and 42% among Japanese people returning from Wuhan.<sup>22</sup> There is currently a large level of uncertainty around the proportion of asymptomatic infection with recent evidence<sup>25</sup> suggesting that asymptomatic incidence is 2-57%. We note, however, that many studies do not differentiate between presymptomatic and asymptomatic infection; instead the number reported is the percent exhibiting symptoms at the time of testing positive. Instead in our model, we have assumed that asymptomatic infections account for 30% of onward-transmitted infections and that development of symptoms is age-dependent. The assumption in this study, as in Covasim, is that 70% of infection is symptomatic and guided by the findings by Davies et al.<sup>17</sup> that the probability of developing clinical symptoms raises from around 20% in under 10s to over 70% in older adults. Future analyses will explore how changing the proportion of asymptomatic COVID-19 infections influences the impact of a TTI strategy, but this was beyond the remit of this study.

Some of our assumptions about the implementation of TTI are likely to be optimistic in the UK context, so our finding should be interpreted as the minimal amount of testing that would need to be done. In particular, we assume a one-day delay after a test is conducted before results are communicated, that diagnosed individuals immediately isolate for 14 days with 90% efficacy, and that individuals displaying COVID-19-like symptoms will self-isolate with 50% efficacy until symptoms clear.

Furthermore, in the absence of robust data, we made assumptions (varied in the sensitivity analysis) about the infectiousness among children and young adults under 20 years old. Future analysis may suggest that infectiousness among children is even lower than 50%, although there are no data suggesting higher transmission than in adults.<sup>5</sup> Our model can be rerun when further evidence becomes available. Finally, we note that in addition to simulating the current TTI policy for the UK, we also simulated an additional level of tracing chosen to resemble a more pessimistic tracing level. We have chosen this to be 40% as a modelling assumption. For both levels of tracing, 40% and 68%, simulated here, we determined the testing level required to avoid a secondary COVID-19 wave in the UK during 2020 and 2021. We note that we have not swept the entire testing/tracing level parameter space to explore regimes within the phase plane where  $R < 1$  at all time and hence secondary wave is avoided, as this is beyond the scope of this work. Indeed, follow on work on this is currently ongoing both for the UK and the USA.

Our model and analyses caution against school and society reopening in the absence of a fully implemented TTI strategy. We show that school and society reopening in combination with TTI strategies is able to reduce  $R$  to below 1, and hence likely to prevent a secondary pandemic wave of COVID-19, control the transmission of SARS-CoV-2, and prevent a large number of COVID-19 deaths. This is true both of analyses assuming children transmit COVID-19 similarly to adults and those assuming a lower infectivity amongst children. In our modelling we have assumed that reopening schools is not a binary off-on switch, but instead that reopening schools would be accompanied by broader changes. School reopening would allow parents to go back to work, as part of reopening a proportion of businesses that are anticipated to be an important step in restarting the economic activity within the society. Specifically, we simulated increasing not only the school transmission, but also increased transmission within workplaces and the community that would arise as a result of reopening of school and society. The exact numbers representing these changes in this analysis are based on modelling assumptions, and the model can be rerun if more reliable numbers are available in future.

There are differences in policies relating to school re-opening across the four UK countries but these findings are likely to be generalisable to each country. We anticipate that rerunning the analysis separately for England, Scotland, Wales, and Northern Ireland would highlight the need for comprehensive TTI to avoid secondary COVID-19 peak, but possibly the minimum testing levels at 40% and 68% tracing level will differ across the four UK countries. While this work was beyond the scope of this paper, we are planning to explore this further in future work.

We also have not modelled in this study the behavior of young people who are not in school and specifically, we have not assumed an increased social mixing outside of schools. Including this is possible within our framework, and currently this is difficult to quantify. We can rerun the model when reliable estimates are available in future.

In summary, our findings suggest that reopening schools can form part of the next step of gradual relaxing of lockdown if combined with a high-coverage TTI strategy. It is currently unclear when the UK TTI strategy will achieve sufficient coverage. Such a strategy, to prevent onward transmission, could possibly comprise of virus testing for active infection in symptomatic individuals (i.e. RT-PCR tests for SARS-CoV-2) and possibly as part of primary care, followed by contact-tracing of individuals within the network of the infected person and isolation of individuals, including those showing symptoms or diagnosed positive for infection. This would be an alternative to intermittent lockdown measures including further school closures while we await an effective vaccine against SARS-CoV-2.

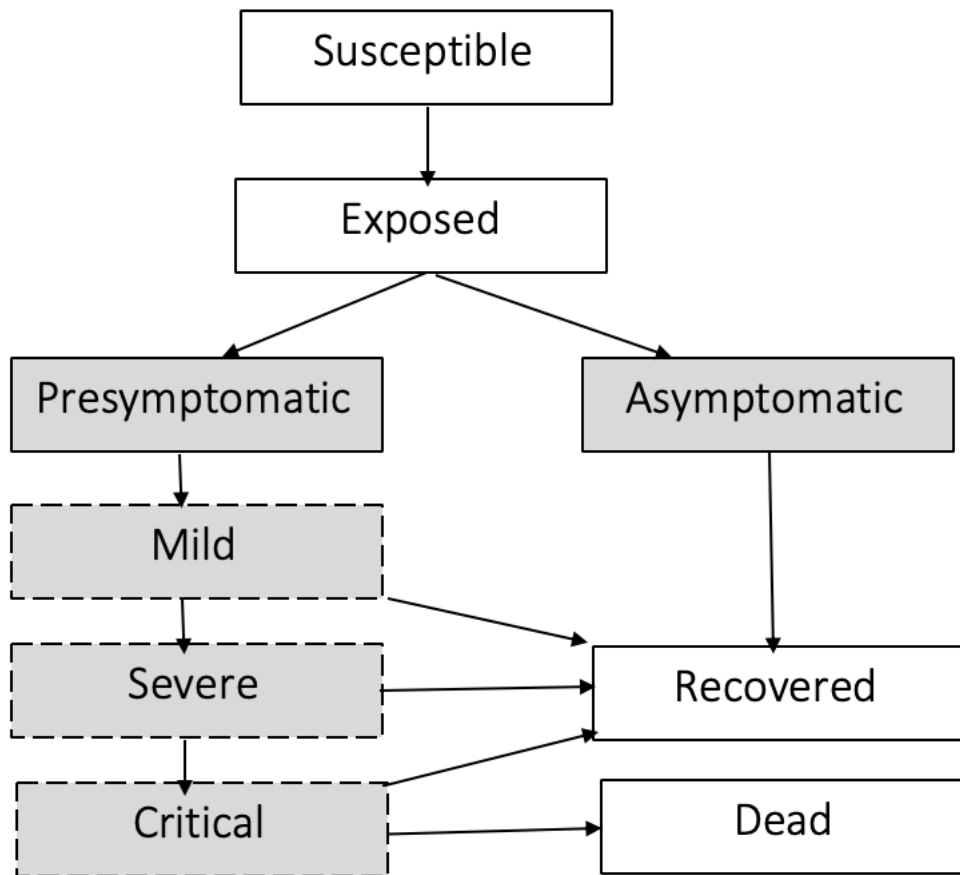
## Tables

### Schools and Society reopening

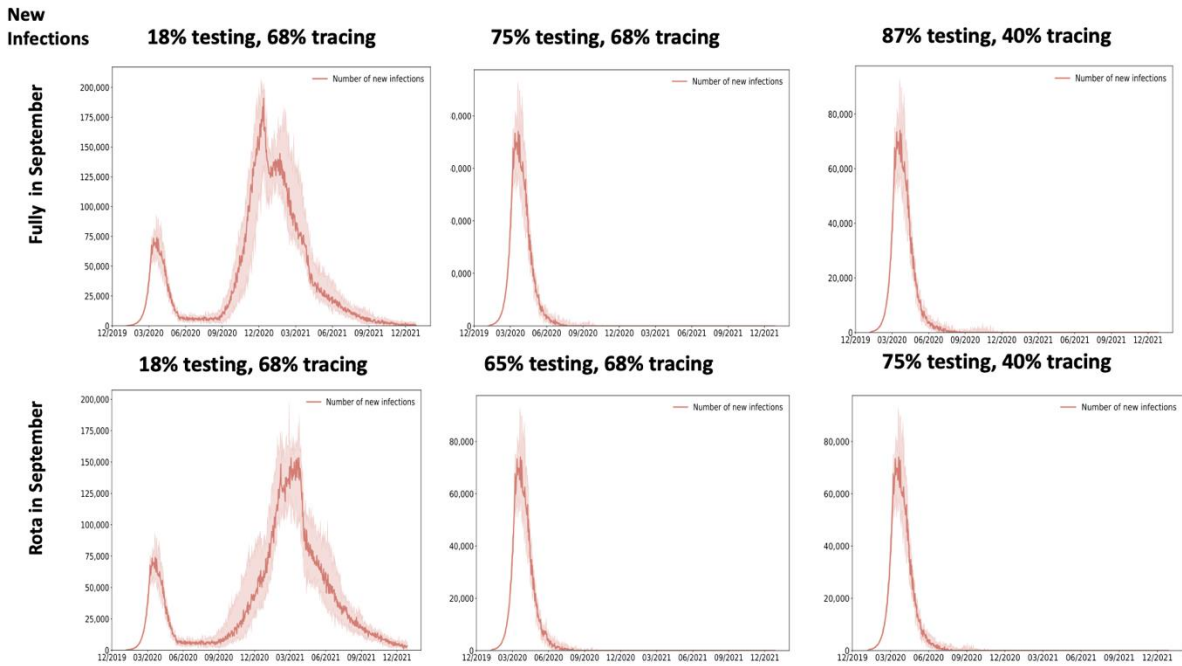
School opening strategy	Home contacts	School contacts	Work contacts	Community contacts
<i>Phased schools opening in June, July and fully September (Phased from June; Fully in September)</i>	100%	3/13= <b>23%</b> on 1 <sup>st</sup> June, 5/13= <b>38%</b> on 15 <sup>th</sup> June 13/13-10%= <b>90%</b> on 1 <sup>st</sup> September	<b>40%</b> on 1 <sup>st</sup> June, <b>50%</b> on 15 <sup>th</sup> June <b>70%</b> on 1 <sup>st</sup> September	<b>40%</b> on 1 <sup>st</sup> June, <b>50%</b> on 15 <sup>th</sup> June <b>90%</b> on 1 <sup>st</sup> September
<i>Phased schools opening in June, July and fully September (Phased from June, Rota in September)</i>	100%	3/13= <b>23%</b> on 1 <sup>st</sup> June, 5/13= <b>38%</b> on 15 <sup>th</sup> June 13/13 -10%=100% but only half of school years present at one time= <b>50%</b> on 1 <sup>st</sup> September 13/13 -10%=90% on 1 <sup>st</sup> January 2021	<b>40%</b> on 1 <sup>st</sup> June, <b>50%</b> on 15 <sup>th</sup> June <b>70%</b> on 1 <sup>st</sup> September	<b>40%</b> on 1 <sup>st</sup> June, <b>50%</b> on 15 <sup>th</sup> June <b>70%</b> on 1 <sup>st</sup> September <b>90%</b> on 1 <sup>st</sup> January 2021

**Table 1:** Description of strategies to reopen schools, workplace and society simulated in the model. Each intervention is simulated by altering the daily transmission probability due to home, school, workplace and/or community contact with details presented in the supplementary material. We assume that transmission within schools is proportional to schools years going back and that allows parents to go back to work. We thus assume that workplaces going back is proportional to reopening schools. Furthermore we assume that 30% of the workforce will remain working from home for the foreseeable future.

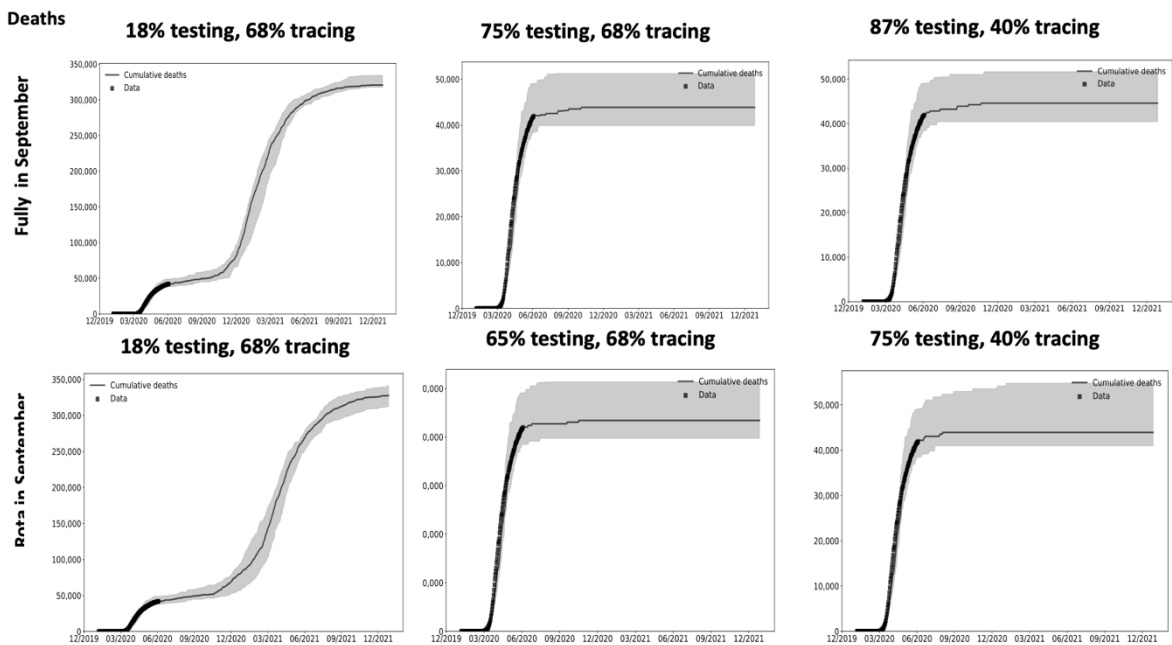
**Figures caption**



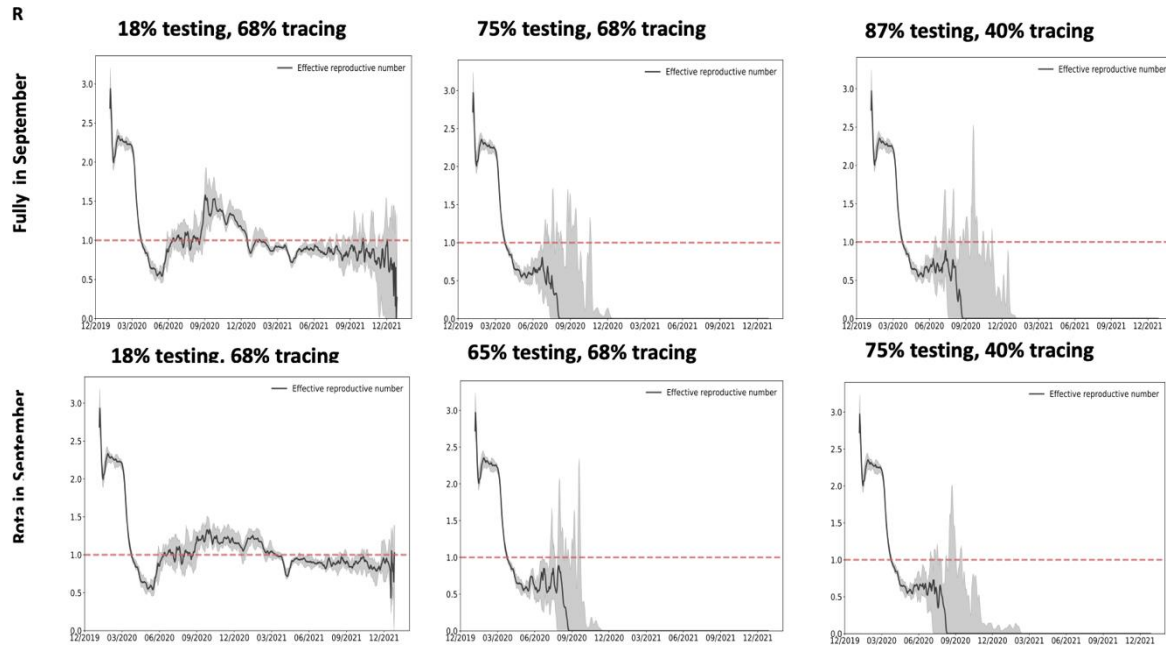
**Figure 1.** Modelled disease states. Grey shading indicates that an individual is infectious and can transmit the disease to other susceptible individuals. States with a dashed border are considered to be symptomatic for the purpose of testing eligibility. This schematic is reproduced from existing work from members of this group.<sup>12</sup>



**Figure 2:** 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. Medians across ten simulations are indicated by solid red lines and 10% and 90% quantiles by red shading. The results do not change if we run a larger number of simulations and we tested 1,3,6,8, 10 and 20 simulations. The difference is that the noise in the simulations increases with increased size of simulations and this is why we chose ten simulations for the figures here.



**Figure 3:** Model estimates of cumulative COVID-19 deaths over 21 January 2020 and 31 December 2021 across different school and society reopening scenarios in presence of different test-trace-isolate (TTI) strategies. Medians across ten simulations are indicated by solid black lines and the 10% and 90% quantiles by grey shading.



**Figure 4:** Model estimates of effective reproduction number  $R$  over 21 January 2020 and 31 December 2021 across different school and society reopening scenarios in presence of different test-trace-isolate (TTI) strategies. Medians across ten simulations are indicated by solid black lines and the 10% and 90% quantiles by grey shading.

### Statement on data quality

Publicly available data was collated and used for modelling purposes.

### Funding statement

JPG was supported by the National Institute for Health Research (NIHR) Applied Health Research and Care North Thames at Bart's Health NHS Trust (NIHR ARC North Thames). CCK, DM, and DJK were supported by Bill and Melinda Gates through the Global Good Fund. The funders had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The views expressed in this article are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health and Social Care.

### Contribution

JPG and RV came up with the idea of the study. JPG, CCK, RMS and DM developed the specific modelling framework, based on the Covasim model developed by CCK, RMS, DM and DK. CCK, RMS, DM, RK and JPG collated data for the parameters used. JPG ran the modelling analysis with input from CCK, RMS and DM. JPG, RV and CB defined the different scenarios in the UK context following conversations with Scientific Pandemic Influenza Modelling Group which gives expert advice to the UK Department of Health and Social Care and wider UK Government. JPG wrote the manuscript with input from CB, RV, CCK, RMS, DM and DK. All authors approved the final version.

### Acknowledgments

We would like to acknowledge Prof Graham Medley (LSHTM) on helpful discussions around the modelling scenarios, Dr Edwin van Leeuwen (Public Health England), Dr Tim Colbourn (UCL) and Dr William Waites (University of Edinburgh) for their helpful conversations about different modelling approaches and Prof. Ruth Gilbert (UCL) for reading an earlier version of the paper.

## References

1. World Health Organisation Situation report 156 . [https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200624-covid-19-sitrep-156.pdf?sfvrsn=af42e480\\_2](https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200624-covid-19-sitrep-156.pdf?sfvrsn=af42e480_2) (accessed 25 June 2020).
2. Ferguson NM, Laydon D, Nedjati-Gilani G, et al. Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. London: Imperial College, 2020.
3. COVID-19 educational disruption and response. 2020. <https://en.unesco.org/themes/education-emergencies/coronavirus-school-closures> (accessed 19 March 2020).
4. Viner RM, Russell SJ, Croker H, et al. School closure and management practices during coronavirus outbreaks including COVID-19: a rapid systematic review. *Lancet Child Adolesc Health* 2020.
5. Brurberg KD. The role of children in the transmission of SARS-CoV-2 (COVID-19), 1st update– a rapid review. Oslo: Norwegian Institute of Public Health; 2020.
6. (NCIRS) NCFIRaS. COVID-19 in schools - the experience in NSW. Sydney: NSW Government, 2020.
7. Bi Q, Wu Y, Mei S, et al. Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: a retrospective cohort study. *Lancet Infect Dis* 2020.
8. Viner RM, Mytton O, Bonell C, al. e. Susceptibility to COVID-19 amongst children and adolescents compared with adults: a systematic review and meta-analysis. *medRxiv preprint server* 2020.
9. Jones TC, Muhlemann B, Veith T, et al. An analysis of SARS-CoV-2 viral load by patient age. Berlin: Charité - Universitätsmedizin, 2020.
10. How COVID-19 may increase domestic violence and child abuse <https://www.apa.org/topics/covid-19/domestic-violence-child-abuse> (assessed 20 May 2020)
11. Coronavirus (COVID-19) in the UK: Update 6 May 2020. 6 May 2020 2020. [https://coronavirus.data.gov.uk/?\\_ga=2.41681382.554770926.1588844302-1722033634.1588620867](https://coronavirus.data.gov.uk/?_ga=2.41681382.554770926.1588844302-1722033634.1588620867) (accessed 6 May 2020)
12. Ministry of Education standards for suspension. 2020. <https://cpd.moe.gov.tw/articleInfo.php?id=2568> (accessed 25 April 2020)
13. Kerr CC, et al. Covasim: an agent-based model for COVID-9 dynamics and suppression scenarios. *medRxiv preprint server* 2020.
14. Zhang J, Litvinova M, Liang Y, et al. Changes in contact patterns shape the dynamics of the COVID-19 outbreak in China. *Science* 2020.
15. 75% of people tested positive are contacted in the UK, <https://www.theguardian.com/world/2020/jun/18/contact-tracers-in-england-get-no-data-from-26-of-people-with-coronavirus> (assessed 20 May 2020)
16. 90% of contacts of people tested positive are traced in the UK [https://www.bbc.co.uk/news/health-53009775?intlink\\_from\\_url=https://www.bbc.co.uk/news/topics/ck219qxx17nt/coronavirus-testing&link\\_location=live-reporting-story](https://www.bbc.co.uk/news/health-53009775?intlink_from_url=https://www.bbc.co.uk/news/topics/ck219qxx17nt/coronavirus-testing&link_location=live-reporting-story) (assessed 20 May 2020)



17. Davies NG, Klepac P, Liu Y, Prem K, Jit M, CMMID COVID-19 working group, Eggo R. Age-dependent effects in the transmission and control of COVID-19 epidemics. assessed 27/05/2020. <https://www.medrxiv.org/content/10.1101/2020.03.24.20043018v1.full.pdf>
18. Prem K, Cook AR, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Comput Biol* 2017; **13**(9): e1005697.
19. World Health Organisation. Coronavirus disease 2019 (COVID-19) Situation Report – 46, 2020.
20. Qiu H, Wu J, Hong L, Luo Y, Song Q, Chen D. Clinical and epidemiological features of 36 children with coronavirus disease 2019 (COVID-19) in Zhejiang, China: an observational cohort study. *Lancet Infect Dis* 2020.
21. Mizumoto K, Kagaya K, Zarebski A, Chowell G. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan, 2020. *Euro Surveill* 2020; **25**(10).
22. Nishiura H, Kobayashi T, Miyama T, et al. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). *Int J Infect Dis* 2020; **94**: 154-5.
23. Shim E, Tariq A, Choi W, Lee Y, Chowell G. Transmission potential and severity of COVID-19 in South Korea. *Int J Infect Dis* 2020; **93**: 339-44.
24. Cohen J, Kupferschmidt. Countries test tactics in 'war' against COVID-19. *Science* 2020; 367(6484):1287-1288.
25. Gao Z, Xu Y, Sun C, Wang X, Guo Y, Qiu S, Ma K. A systematics review of asymptomatic infections with COVID-19. *J Microbiol Immunol Infect* 2020. doi: 10.1016/j.jmii.2020.05.001 (Epub ahead of print)