Effectiveness of isolation, testing, contact tracing and physical distancing on reducing transmission of SARS-CoV-2 in different settings: a mathematical modelling study

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Abstract

Background: Isolation of symptomatic cases and tracing of contacts has been used as an early COVID-19 containment measure in many countries, with additional physical distancing measures also introduced as outbreaks have grown. To maintain control of infection while also reducing disruption to populations, there is a need to understand what combination of measures – including novel digital tracing approaches and less intensive physical distancing – may be required to reduce transmission.

Methods: Using a model of individual-level transmission stratified by setting (household, work, school, other) based on BBC Pandemic data from 40,162 UK participants, we simulated the impact of a range of different testing, isolation, tracing and physical distancing scenarios. As well as estimating reduction in effective reproduction number, we estimated the number of contacts that would be newly quarantined each day under different strategies.

Results: Under optimistic but plausible assumptions, we estimated that combined isolation and tracing strategies would reduce transmission more than mass testing or self-isolation alone (50–60% compared to 2–30%). If limits are placed on gatherings outside of home/school/work, then manual contact tracing of acquaintances only could have a similar effect on transmission reduction as detailed contact tracing. In a scenario where there were 1,000 new symptomatic cases that met the definition to trigger contact tracing per day, we estimated in most contact tracing strategies, 15,000– 40,000 contacts would be newly quarantined each day.

Conclusions: Consistent with previous modelling studies and country-specific COVID-19 responses to date, our analysis estimates that a high proportion of cases would need to self-isolate and a high proportion of their contacts to be successfully traced to ensure an effective reproduction number that is below one in the absence of other measures. If combined with moderate physical distancing measures, self-isolation and contact tracing would be more likely to achieve control.

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Introduction

The novel SARS-CoV-2 coronavirus spread rapidly across multiple countries in early 2020 (1–3). A staple public health control measure for outbreaks of emerging directly-transmitted infections involves isolation of symptomatic cases as well as tracing, testing and quarantine of their contacts (2). The effectiveness of this measure in containing new outbreaks depends both on the transmission dynamics of the infection and the proportion of transmission that occurs from infections without symptoms (4). There is evidence that SARS-CoV-2 has a reproduction number of around 2–3 in the early stages of an outbreak (1,5) and many infections can occur without symptoms (6), which means isolation of symptomatic cases and contact tracing alone are unlikely to contain an outbreak unless a high proportion of cases are isolated and contacts successfully traced and quarantined (7).

Several countries have used combinations of non-pharmaceutical interventions to reduce SARS-CoV-2 transmission (3,8). As well as isolation of symptomatic individuals and tracing and quarantine of their contacts, measures have included general physical distancing, school closures, remote working, community testing and cancellation of events. It has also been suggested that the effectiveness of contact tracing could be enhanced through app-based digital tracing (9). The effectiveness of contact tracing and the extent of resources required to implement it successfully will depend on the social interactions within a population (10). Targeted interventions such as contact tracing also need to consider individual-level variation in transmission: high variation can lead to superspreading events, which could result in larger numbers of contacts needing to be traced (11). There are several examples of such events occurring for COVID-19, including meals, parties and other social gatherings involving close contacts (12).

We used social contact data from a large-scale UK study of over 40,000 participants (13) to explore a range of different control measures for SARS-CoV-2, including: self-isolation of symptomatic cases; household quarantine; manual tracing of acquaintances (i.e. contacts that have been met before); manual tracing of all contacts; app-based tracing; mass testing regardless of symptoms; a limit on daily contacts made outside home, school and work; and having proportion of the adult population work from home. As well as estimating the reduction in transmission under different scenarios, we estimated how many primary cases and contacts would be quarantined per day in different strategies for a given level of symptomatic case incidence.

Research in context

Evidence before this study

We searched PubMed, BioRxiv, and MedRxiv for articles published in English from inception to Apr 15, 2020, with the keywords "2019-nCoV", "novel coronavirus", "COVID-19", "SARS-CoV-2" AND "contact tracing" AND "model*". Early modelling studies of SARS-CoV-2 suggested that isolation and tracing alone may not be sufficient to control outbreaks, and additional measures may be required; these measures have since been explored in population-level models. However, there has not been an analysis using setting-specific social contact data to quantify the potential impact of combined contact tracing and physical distancing measures on reducing individual-level transmission of SARS-CoV-2.

Added value of this study

We use data from over 40,000 individuals to assess contact patterns and SARS-CoV-2 transmission in different settings, and compare how combinations of self-isolation, contact tracing and physical distancing could reduce secondary cases. We assessed a range of combined physical distancing and testing/tracing measures, including app-based tracing, remote working, limits on different sized gatherings, and mass population-based testing. We also estimated the number of contacts that would be quarantined under different strategies.

Implications of all the available evidence

Several characteristics of SARS-CoV-2 make effective isolation and contact tracing challenging, including high transmissibility, a relatively short serial interval, and transmission that can occur without symptoms. Combining isolation and contact tracing with physical distancing measures – particularly measures that reduce contacts in settings that would otherwise be difficult to trace – could therefore increase the likelihood of achieving sustained control.

Methods

Secondary attack rate data sources

To estimate the risk of transmission per contact in different community settings, we collated contact tracing studies for COVID-19 from multiple settings that stratified contacts within and outside households (Table 1). Across studies, the estimated secondary attack rate (SAR) within households was 10–20%, with a much smaller SAR among close contacts made outside households, with estimates for the SAR among these contacts ranging from 0% to 5% across studies. However, all these studies were conducted in an 'under control' scenario (i.e. effective reproduction number R<1) and some reported relatively few contacts, which may omit superspreading events, and isolation outside of household. This suggests that SARS-CoV-2 may be driven by community transmission events as well as household contacts. In our main analysis, we assumed 30% HH SAR and 6% among all contacts, which led to an overall reproduction number of 2.6 in our model (described in next section) when no control measures were in place, consistent with estimated values of the reproduction number in the early stages of the epidemic (1,5).

Transmission model

Our analysis is based on data on 40,162 UK participants with recorded social contacts in the BBC Pandemic dataset (13). A contact was defined as an interaction that either involved a face-to-face conversation or physical contact, which broadly reflect the types of close contacts that have been linked to SARS-CoV-2 transmission clusters to date (12). Using these data, we simulated a large number of individual-level transmission events by repeatedly generating contact distributions for a primary case and randomly generating infections among these contacts. In each simulation, we randomly specify a primary case as either under 18 or 18 and over, based on UK demography, in which 21% of the population are under 18 (14). We then generate contacts by randomly sampling values from the marginal distributions of daily contacts made in three different settings for their age group (i.e. under 18 or adults): in household (defined as household size minus one); at work & school; and in 'other' settings (Figure 1A–B). We used the marginal distributions rather than raw participant data to ensure non-identifiability and reproducibility in our model code.

In the model, we assumed infected individuals had a certain probability of being symptomatic and of being tested if symptomatic, as well as an infectious period that depended on when/if they self-isolated following onset of symptoms (details and justification for model parameters provided in Table 2). We assumed a mean delay of 2.6 days from onset-to-isolation in our baseline scenario (Appendix, page 2). We assumed individuals became infectious one day before onset of symptoms. During each day of the effective infectious period, individuals made a given number of contacts equal to their simulated daily contacts. To avoid double-counting household members, household contacts were not tallied over the entire infectious period, but instead were fixed. Once individual-level contacts had been defined, we generated secondary infections at random based on assumed secondary attack rates among contacts made in different settings, and estimated how many contacts would be successfully traced in each of these settings under different scenarios (full description in Appendix, page 1). First, we generated the number of secondary cases without any control measures in place. Second, we randomly sampled the proportion of these secondary cases that were either successfully traced and quarantined, and hence removed from the potentially infectious pool, or averted through isolation of the primary case. The difference between these two values gave the overall number of secondary cases that would contribute to further transmission, i.e. the effective reproduction number R_{eff} (Figure 1C–D).

Scenarios

We considered several scenarios, both individually and in combination (Appendix, page 2). These included: no control; self-isolation of symptomatic cases within and away from household; household quarantine; quarantine of work/school contacts; manual tracing of acquaintances (i.e. contacts that have been met before); manual tracing of all contacts; app-based tracing; mass testing of cases regardless of symptoms; a limit on daily contacts made in 'other' settings (with the baseline limit being 4 contacts, equal to the mean number reported by adults in the BBC data); and a proportion of the population with no school/work contacts. In the self-isolation only scenario, we assumed individuals who were successfully isolated either had no risk of onward transmission (even to household members), or they had no risk to contacts outside the household, but household members could still be infected. Otherwise we assumed household quarantine was in place alongside other measures. For app-based tracing to be successfully implemented in a given simulation, both the infectious individual and their contacts needed to have and use the app. We assumed individuals under age 10 or over 80 would not use a smartphone app (Table 2). In the scenario with mass testing of cases regardless of symptoms, we assumed infected individuals would be identified and immediately self-isolate at a random point during or after their 5 day infectious period. We assumed that infected individuals would not test positive if tested during the latent period. No other measures (e.g. self-isolation when symptomatic) were in place for this scenario. In the baseline scenario for reduced work contacts, we assumed 50% of the population had no work contacts, as 54% of respondents in a UK social contact survey reported not visiting work in the days after lockdown was introduced in March 2020 (15). For each intervention scenario, we simulated 20,000 primary cases, generating individual-level contact distributions and secondary cases with and without the control measure in place, as described in the previous section. Model code is available from: https://github.com/adamkucharski/2020-cov-tracing

Ethical considerations
Information was provided and consent obtained from all participants in the study before the app recorded any data. The study was approved by London School of Hygiene & Tropical Medicine Observational Research Ethics Committee (ref 14400).

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

Results

Under the control measures considered, we found that combined testing and tracing strategies reduced the effective reproduction number more than mass testing or self-isolation alone (Table 3). If only self-isolation of symptomatic cases was included, our optimistic scenario resulted in a mean transmission reduction of 29% if self-isolation was within household and 35% if self-isolation was outside household. The addition of household quarantine resulted in an overall mean reduction of 37%. In simulations, self-isolation combined with manual contact tracing of all contacts reduced transmission by 64%; manual tracing of acquaintances only (i.e. contacts that had been met before) led to a 57% reduction in transmission. We estimated that self-isolation combined with app-based tracing with our baseline assumption of 53% coverage reduced transmission by around 47%. Contact tracing measures also substantially reduced the probability that a primary symptomatic case would generate more than one secondary case (Table 3).

We estimated that if some level of physical distancing were maintained, it could supplement reductions in transmission from contact tracing. For example, if daily contacts in 'other' settings (i.e. outside the home, work and school) were limited to four people (the mean number in our dataset), manual tracing of acquaintances only led to a 64% reduction in transmission, and the addition of app-based tracing alongside this gave a 66% reduction overall. We estimated that mass random testing of 5% of the population each week would reduce transmission by only 2%, because relatively few infections would be detected and many of those that were would have already transmitted infection.

We also considered the number of contacts that would be traced under different strategies. In a scenario where there were 20,000 new symptomatic cases per day, most contact tracing strategies would require over 500,000 contacts to be newly quarantined each day on average (Table 4). Note that if contact tracing is triggered based on suspected COVID-19-like symptoms, rather than confirmation of COVID-19, the number of symptomatic cases in these scenarios would reflect total incidence of illness, not just of confirmed COVID-19 cases. Although there was a similar reduction in transmission from manual tracing of all contacts and manual tracing of only acquaintances with a limit to four daily contacts in other settings (Table 3), the latter combination required fewer people to be quarantined each day (Table 4). We obtained similar results for the relative reductions in transmission and number of contacts traced when we assumed a higher secondary attack rate within-household or among other contacts, which corresponded to baseline reproduction numbers of 2.6–2.9 (Appendix, page 4).

We found that effectiveness of manual contact tracing strategies were highly dependent on how many contacts were successfully traced, with a high level of tracing required to ensure R_{eff}<1 in our baseline scenario (Figure 2A). If contact tracing was combined with a maximum limit to daily contacts made in other settings (e.g. by restricting gatherings), we found that this limit would have to be relatively small (i.e. fewer than 10–20 contacts) before a discernible effect could be seen on R_{eff}. The limit would have to be small (i.e. fewer than around 10 contacts) to ensure R_{eff}<1 for app-based tracing, even if half of adults also had no work contacts (Figure 2B). When app-based tracing was in place, we estimated that if only work contacts are restricted, a substantial proportion of the adult population would need to have zero work contacts to ensure R_{eff}<1 (Figure 2C). Under our baseline assumptions, we estimated that app-based tracing would require a high level of coverage to ensure R_{eff}<1 (Figure 2D), because both primary case and contacts would need the app.

We also considered the impact of the proportion of infections assumed to be symptomatic and the relative contribution of asymptomatic individuals to transmission. We estimated that if a high proportion of cases were symptomatic, self-isolation and contact tracing measures would lead to a greater relative reduction in transmission (Appendix, page 3); this is mostly because more primary cases would be detected. Control measures were slightly less effective if the relative transmissibility of asymptomatic infections was higher (Appendix, page 3), because it would mean more undetectable transmission. However, because our baseline scenario assumed 70% of adults were symptomatic, the overall effect was less than it would be if the majority of cases were asymptomatic. We estimated that if individuals self-isolated rapidly (i.e. with 1.2 days on average rather than 2.6 days), self-isolation and household quarantine would lead to a larger reduction in transmission (Appendix, page 5); correspondingly, if we assumed cases took longer to self-isolate after becoming symptomatic (i.e. 3.6 days on average), these measures were less effective. However, the estimated overall reduction from self-isolation and manual contact tracing was similar across the three scenarios, because although more secondary infections occurred before isolation, a large proportion of them would be traced under our baseline model assumptions.

Discussion

Using a model of setting-specific interactions, we estimated that strategies that combined isolation of symptomatic cases, as well as tracing and quarantine of their contacts, reduced the effective reproduction number more than mass testing or self-isolation alone. The effectiveness of these isolation and tracing strategies was further enhanced when combined with physical distancing measures, such as a reduction in work contacts, or a limit to the number of contacts made outside of home, school or work settings. Not only does physical distancing reduce transmission, it is likely to reduce the number of unknown contacts that can be harder to trace. Several countries have achieved a prolonged suppression of SARS-CoV-2 transmission using a combination of case isolation, contact tracing and physical distancing. In Hong Kong, isolation of cases and tracing of contacts was combined with other physical distancing measures, which resulted in an estimated effective reproduction number near 1 throughout February and March 2020 (16). In South Korea, testing and tracing has been combined with school closures and remote working (17).

In our analysis, we estimated that a large number of contacts would need to be traced and tested if incidence of symptomatic cases was high. This logistical constraint may influence how and when it is possible to transition from ensuring R_{eff}<1 through extensive physical distancing measures to reducing transmission predominantly through targeted isolation and tracing-based measures. Our estimate of a large number of contacts potentially being traced per case in the manual tracing strategies we considered (Table 4) suggests any planning for ongoing control based on isolation and tracing should account for the likely need to conduct at least 30–50 additional tests for each symptomatic case reported. If contact tracing is initiated based on suspected rather than confirmed SARS-CoV-2 infections, then the number of symptomatic cases that require follow-up tracing and testing may be considerably higher than the level of confirmed COVID-19 incidence. Given the role of pre-symptomatic transmission for SARS-CoV-2, quarantine of these contacts rather than symptom monitoring alone is likely to more effective at reducing onward transmission (18).

Our analysis has several limitations. We focused on individual-level transmission between a primary case and their contacts, rather than considering higher degree network effects. Our results therefore focus on possible reductions in transmission, rather than temporal ranges of outbreak size or dynamics. Network structure may also influence specific interventions. If contacts were clustered (i.e. know each other), it could reduce the number of contacts that need to be traced over multiple generations of transmission. Additionally, if there is an inverse relationship between probability of detectable symptoms and app coverage, as may be the case for young children, it could reduce the effectiveness of symptom-based tracing for such index cases. We also assumed that contacts made within the home are the same people daily, but contacts outside home are made independently each day. Repeated contacts would also reduce the number that need to be traced. However, our estimates are consistent with the upper bound of numbers traced in empirical studies (Table 1), as well as analysis of UK social interactions that accounts for higher degree contacts (10). Because our data was not stratified beyond the four contact settings we considered (home, work, school, other), we could not consider further specific settings, e.g. mass gatherings. However, our finding that gatherings in other settings needed to be restricted to relatively small sizes before there was a noticeable impact on transmission is consistent with findings that groups between 10–50 people have a larger impact on SARS-CoV-2 dynamics than groups of more than 50 (19). In our main analysis we use a limit of four daily contacts as an illustrative example. In reality, any control strategies would also need to consider the likely behaviour of a population in complying with social restrictions.

Our baseline assumptions were plausible but optimistic. In particular, we assume a delay of symptom onset to isolation of 2.6 days in the baseline scenario, and quarantine within two days for successfully manually traced contacts and immediately for app-based tracing, with 90% assumed to adhere to quarantine. For context, based on viral shedding dynamics, onset of infectiousness typically occurs 2–3 days after exposure (6). In our model, we considered self-isolation both within and outside household, finding that isolation outside household led to slightly higher reduction in onward transmission; the reduction was not larger because some pre-symptomatic transmission had often already occurred. However, our conclusions about onwards transmission in the different control tracing scenarios were not dependent on assumptions about household transmission, because in these scenarios we assumed that household quarantine would be in place too. We also simulated contact patterns at random for each individual in our population, whereas in an outbreak, there is likely to be a correlation between degree and infection risk; individuals with multiple contacts may be more likely to acquire infection as well as transmit to others. If this were the case, and we assume the same secondary attack rates, the overall reduction may be lower than we have estimated; however, to keep the baseline reproduction number consistent, this correlation would have to be offset by a lower SAR among contacts. We also do not include the potential for imported infections; when local infection prevalence is low, additional screening or restrictions may need to be considered to reduce the risk of new importations.

Our results highlight the challenges involved in controlling SARS-CoV-2. Consistent with previous modelling studies (7,10) and observed early global outbreak dynamics, our analysis suggests that, depending on the overall effectiveness of testing, tracing, isolation and quarantine, a combination of self-isolation, contact tracing and physical distancing may be required to maintain $R_{eff}<1$. Further, in a scenario where incidence is high, a considerable number of individuals may need to be quarantined to achieve control using strategies that involve contact tracing.

Contributors

AJK, PK, and WJE designed analysis. AJK developed the model. AJK, PK, AJKC, SMK, MT, HF, and JRG contributed to collection, processing and interpretation of the original BBC dataset, as well as interpretation of the study findings. The CMMID COVID-19 working group members contributed to interpretation of the study results. All authors contributed to writing the manuscript and approved the final version.

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Conflicts of interest
We declare that we have no conflicts of interest.

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Figure 1: Model of social interactions and SARS-CoV-2 transmission and control. *A) Distribution of daily contacts made at home, work/school and other settings in the BBC Pandemic dataset. B) Examples of daily social contact patterns for four randomly selected individuals in the model. Black point shows the individual reporting contacts, with social contacts coloured as in A. C) Factors that influence whether an individual is isolated and whether contacts are successfully traced in the model (parameters in Table 2). D) Implementation of contact tracing in the model. Timeline shows a primary case with four daily contacts self-isolating either 1 or 3 days after onset of symptoms. We assume the household contact is the same person throughout, whereas other contacts are made independently. Had the primary case not been isolated, there would have been 7 secondary cases in this illustration (shown with circulations). For isolation 1 day after onset, 4 secondary infections are prevented immediately. Then 7 contacts are potentially traceable, 3 of whom are infected. In this example, two infected contacts pre-isolation are successfully traced and quarantined (i.e. one is missed), so overall the isolation-and-tracing control measure results in a 4+2 = 6 reduction in effective reproduction number. A similar illustration is shown for isolation 3 days after onset.*

Figure 2: Impact of contact tracing effectiveness and physical distancing on reduction in reproduction number (baseline R=2.6). *A) Reduction in R under different strategies for different proportions of work/school/other contacts that are successfully traced. B) Effect of the maximum limit on the number of daily contacts in other settings and control tracing strategies on R, either when adults are working as normal, or when 50% have no work contacts. C) Effect of proportion of population with no work contacts. D) Effect of app-based tracing under different assumptions about app coverage. In all panels, other parameters are as in Table 2.*

Location	**SAR among HH contacts**	**SAR among close contacts outside HH**	**Contacts traced per case**	**Observed reproduction number**	**Source**
Shenzhen	12.9%	0.9%	3.0	0.4	(20)
USA	10.5%	0.0%	44.5	0.20	(21)
Guangzhou	10.1%	0.5%	14.3	0.34	(22)
Taiwan	6.6%	0.4%	27.6	0.21	(23)
Ningbo	13.3%	5.1%	11.2	0.69	(24)
Guangzhou	19.3%	5.3%	9.8	0.62	(25)

Table 1: Secondary attack rates estimated from COVID-19 contact tracing studies. Note the table includes two separate analyses of contact tracing data from Guangzhou and differing estimates are likely to be influenced by control measures in place at the time.

Parameter	**Assumed value**	**Details & references**
Individual-level dynamics		
Reproduction number in absence of control measures	2.6	Secondary attack rates were chosen to be consistent with empirical estimates (Table 1) and produce a reproduction number consistent with a meta-analysis of early studies (26). Sensitivity analysis shown in Appendix, page 4.
Duration of infectiousness	5 days (for cases that will become symptomatic, 1st day is pre-symptomatic)	Given incubation period around 5 days, this assumption implies serial interval of around 6.5 days (27). Sensitivity analysis shown in Appendix, page 35.
Relative infectiousness of asymptomatic cases	50%	Point estimate was 65% in (24), but secondary cases from asymptomatics were more likely to in turn be asymptomatic, suggesting lower contribution to transmission. Sensitivity analysis shown in Appendix, page 3.
Proportion of cases that are eventually symptomatic	30% of children 70% of adults	Based on evidence synthesis of age-stratified COVID-19 data (28). Sensitivity analysis in Appendix, page 3.
Probability symptomatic individual will eventually self-isolate and be tested	90%	We assume virus is only detectable by PCR during the infectious period. 90% UK survey respondents said would likely comply with app request to self-isolate if rapid test available (29).
Effective duration of infectiousness if self-isolate when symptomatic	Mean delay from onset to isolation of 2.6 days. Distribution shown in Appendix, page 2.	Assume most likely to self-isolate 0–4 days after onset (i.e. 1–5 days after becoming infectious). For 269 cases with known date of onset and confirmation in Singapore, of those who were confirmed within 5 days, 2% were confirmed on date of onset, 26% on second day, 27% on 3rd day, 14% on 4th day and 31% on 5th day (30). We assume isolation could occur 1 day before confirmation.
Secondary attack rate among contacts in home	20%	See 'secondary attack rate' section of methods.
Secondary attack rate among other contacts	6%	See 'secondary attack rate' section of methods.
Contact tracing		
Proportion of contacts that are acquaintances (i.e. have been met before)	100% in household 90% at school 79% at work 52% in other settings	Data from BBC Pandemic dataset (13); for each contact reported, participants were asked 'have you met this person before?'
Proportion of potentially traceable household contacts that are successfully traced	100%	Assumed
Proportion of potentially traceable workplace, school or	95%	Assumed, with sensitivity analysis shown in Figure 2.

'other' contacts that are successfully traced		
Probability traced contacts adhere to quarantine	90%	Proportion of traced contacts that are successfully removed from the potentially infectious group. Same justification as 'Probability symptomatic individual will eventually self-isolate and be tested' parameter above. We assumed contacts traced by app would be quarantined immediately, and manually traced contacts would take two days to quarantine after isolation of the index case (9,20).
App-based tracing		
Proportion of population that would have app	53% (= 71% x 75%)	85% of age 16+ in UK are smartphone users (Ofcom, 2019). 16% of UK are under 10 or over 80 (14), so we assume 71% of population use smartphones. 75% of UK survey respondents said would probably or definitely download app (29).
Mass testing		
Proportion of population that are tested per week	5% (i.e. 460,000 tests per day for UK)	0.7% of population tested per day, i.e. equal to the highest number of daily per capita tests performed anywhere in world as of mid-April 2020 (Iceland, 7 per 1000).

Table 2: Parameter definitions and assumptions for the baseline model.

Scenario	**Self-Isolation (SI)**	**Contact tracing**	**% non-HH contacts that are potentially traceable**	**% cases that have R>1**	**R_{eff}**	**Mean reduction in R_{eff}**
No control	No	No	–	50%	2.6	0%
Self-isolation within home (SI)	Yes	No	–	40%	1.8	29%
Self-isolation outside home				37%	1.7	35%
SI & HH quarantine (HHQ)	Yes	HH	–	35%	1.6	37%
SI + HHQ + work/school contact tracing (CT)	Yes	HH & work/ school	100%	27%	1.2	53%
SI + HHQ + manual CT of acquaintances	Yes	All	90% school, 79% work, 52% other	26%	1.1	57%
SI + HHQ + manual contact tracing of all contacts	Yes	All	100%	21%	0.94	64%
SI + HHQ + app-based tracing	Yes	All	53%	30%	1.4	47%
SI + HHQ + manual CT of acquaintances + app-based tracing			Manual: 90% school, 79% work, 52% other.	23%	1	61%

			App: 53%			
SI + HHQ + manual CT of acquaintances + limit to 4 daily ‘other’ contacts	Yes	All	90% school, 79% work, 52% other	21%	0.93	64%
SI + HHQ + manual CT of acquaintances + app-based tracing + limit to 4 daily ‘other’ contacts	Yes	All	Manual: 90% school, 79% work, 52% other. App: 53%	20%	0.87	66%
Mass testing of 5% of population per week	No	–	–	49%	2.5	2%

Table 3: Mean reduction in effective reproduction number under different control measures (i.e. the relative reduction from quarantining infectious individuals that would have gone undetected with no intervention). Results from 20,000 simulated setting-specific secondary transmission, assuming secondary attack rate of 20% among household contacts and 6% among other contacts. Results under the assumption of some workplace restrictions remaining in place are shown in Table 4. Estimates are shown to two significant figures. HH = household.

Scenario	**Number of people quarantined per detected case (median, 90% PI)**	**Mean newly quarantined per day assuming 20,000 new symptomatic cases per day.**	**Mean newly quarantined per day assuming 5000 new symptomatic cases per day.**	**Mean newly quarantined per day assuming 1000 new symptomatic cases per day.**
SI & HH quarantine (HHQ)	2 (0-4)	38000	9400	1900
SI + HHQ + work/school contact tracing (CT)	13 (1-110)	540000	140000	27000
SI + HHQ + manual CT of acquaintances	22 (1-120)	650000	160000	32000
SI + HHQ + manual contact tracing of all contacts	29 (1-140)	830000	210000	41000
SI + HHQ + app-based tracing	4 (1-69)	310000	76000	15000
SI + HHQ + manual CT of acquaintances + app-based tracing	25 (1-130)	740000	180000	37000
SI + HHQ + manual CT of acquaintances + limit to 4 daily ‘other’ contacts	17 (1-110)	560000	140000	28000
SI + HHQ + manual CT of acquaintances	21 (1-110)	630000	160000	32000

+ app-based tracing + limit to 4 daily 'other' contacts				

Table 4: Numbers of additional people quarantined per symptomatic case under different scenarios for the absolute number of new symptomatic cases per day. We assume quarantined contacts are independent. Estimates shown to two significant figures, with median and 90% prediction interval given for additional contacts quarantined per detected symptomatic case. If contact tracing is initiated based on suspected rather than confirmed COVID-19 cases, the symptomatic case numbers here would reflect total incidence of COVID-19-like illness, which may be considerably higher than the number of confirmed cases.