Strategies for reducing COVID-19 transmission with social distancing measures

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Summary

Low incidence strategy:

- The social distancing strategies consistent with R_t<1 were S1: schools closed and preventing at least 65% of work and leisure contacts and S2: primary schools open and preventing at least 75% of work and leisure contacts.

High incidence strategy:

- Sequentially releasing social distancing measures could be consistent with keeping the effective reproduction number close to 1.
- Following an easing of restrictions, the new social distancing measures need to be in place for between 3 and 5 months.

Methods

Data description

The Social Contact Survey surveyed 5,388 individuals in the UK in 2010 about their social contacts[1]. Participants were asked about the number of people they met, duration of the contact and the context.

Estimating the Reproduction Number

We use an individual-based approach for to calculate a reproduction number of each of the participants of the Social Contact Survey study[2]. The reproduction number for an individual is given by

$$R_{ind} = \tau \sum_{i=1}^{k} n_i d_i$$

Where k is the number of contact events reported by each participant, n_i is the number individuals in that contact (participants could report groups of similar contacts), d_i is the duration of the contact and τ is the probability of transmission.

The population-wide reproduction number, R_0, is calculated as the age-adjusted mean of the individual reproduction numbers, i.e.

$$R_0 = \frac{\sum_{j=1}^{N} a_j \left(R_{ind}^{j}\right)^2}{\sum_{j=1}^{N} a_j}$$

Where N is the number of participants in the Social Contact Survey and a_j is the age-specific weighting estimated to match the age distribution in the UK population, calculated as the ratio of the proportion of individuals aged a in the UK to the Social Contact Survey sample,

$$a_j = \frac{P_{UK}(a)}{P_{SCS}(a)}$$

We estimated the transmission probability τ by scaling the population-wide R_0 to match the measured reproduction number in the UK pre-control measures of 3.0. We assume that no age groups have pre-existing immunity against COVID-19 and therefore contribute equally to transmission.

The impact of social distancing on the effective reproduction number R_t

We use participant age, contact context and contact duration to simulate the impact of interventions. For each intervention, we sample the contacts to be restricted at random for a given level of adherence, remove those contacts and recalculate the reproduction number.

School closures were modelled by assuming that 95% of school contacts do not occur. We compared each of the following strategies:

Strategy 1: Schools closed, limit work and leisure contacts, elderly shielding
Strategy 2: Primary schools open, limit work and leisure contacts, elderly shielding
Strategy 3: Schools open, limit work and leisure contacts, elderly shielding
Strategy 4: Schools open, work as normal, limit leisure contacts, elderly shielding
Strategy 5: Schools open, work as normal, leisure as normal, elderly shielding

For each strategy, mean and confidence intervals for the reproduction number were calculated by sampling contacts 10 times then bootstrapping the data 1000 times.

Modelling the application of social distancing strategies

To investigate the transmission dynamics associated with the different social distancing strategies, we developed a deterministic, age-structured, compartmental transmission model. The population was divided into 6 age groups. The fraction of people in each age group was determined by the age distribution of England. We assumed that COVID-19 could be captured by seven infection states: susceptible to infection (S), latently infected (E), Asymptomatic and infectious (A), symptomatic and infectious (I), hospitalised (H), critically ill (P) and recovered and immune (R).

$$\frac{dS_i}{dt} = -S_i \sum_{j=1}^{n} \beta_{ij}\,(I_j + \varepsilon A_j)/N_j$$

$$\frac{dE_i}{dt} = +S_i \sum_{j=1}^{n} \beta_{ij}\,(I_j + \varepsilon A_j)/N_j - \sigma_i E_i$$

$$\frac{dA_i}{dt} = f_i \sigma_i E_i - \gamma_a A_i$$

$$\frac{dI_i}{dt} = (1 - f_i)\sigma_i E_i - \gamma I_i$$

$$\frac{dH_i}{dt} = h_i \gamma I_i - \gamma_h H_i$$

$$\frac{dP_i}{dt} = \mu_i \gamma_h H_i - \gamma_p P_i$$

$$\frac{dR_i}{dt} = \gamma_a A_i + (1 - h_i)\gamma I_i + (1 - \mu_i)\gamma_h H_i$$

Model parameters

Parameter	Meaning	Value
β_{ij}	Transmission rate from group j to group i	Age-specific mixing matrix scaled to achieve desired R_t
ε	Relative infectiousness of asymptomatic cases	0.6
$1/\sigma_i$	Incubation period	5.2 days
f_i	Age-specific fraction of cases that are asymptomatic	{0.6,0.6,0.5,0.4,0.4,0.3}

$1/\gamma_a$	Length of time asymptomatically infected	2 times the infectious period
$1/\gamma$	Infectious period	1.2 days
h_i	Age-specific fraction of cases that are hospitalised	{0.001, 0.0013, 0.0075, 0.0268, 0.1, 0.18}
$1/\gamma_h$	Time in hospital if cured	4 days
$1/\gamma_p$	Additional time in hospital if case dies	8 days
μ_i	Age-specific mortality rate	{0.04, 0.04, 0.04, 0.05, 0.18, 0.44}

The model was initialised with a single infectious case and run with a baseline reproduction number of $R_0 = 3.0$. When the number of deaths reached 200 deaths (equivalent to the number of deaths recorded on 30 March 2020 in England), Strategy 1 with 80% adherence ("lockdown") was simulated by decreasing the reproduction number to $R_t = 0.8$ by scaling the transmission matrix by R_t/R_0.

In order to maintain an effective reproduction number around or slightly greater than 1, we simulated a gradual lifting of restrictions by increasing the reproduction number to values consistent with the analysis of the Social Contact Survey.

We took the following approach: once the number of deaths has decreased to 200 per day, we implement Strategy S2 in which primary schools are open, but work and leisure contacts remain reduced by 80%. Once the number of deaths has decreased to 200 per day, we implement Strategy 3 in which schools are open, but work remain reduced by 80%. Finally, once the number of deaths has returned to 200 per day, we lift all restrictions and $R_0 = 3.0$.

Results

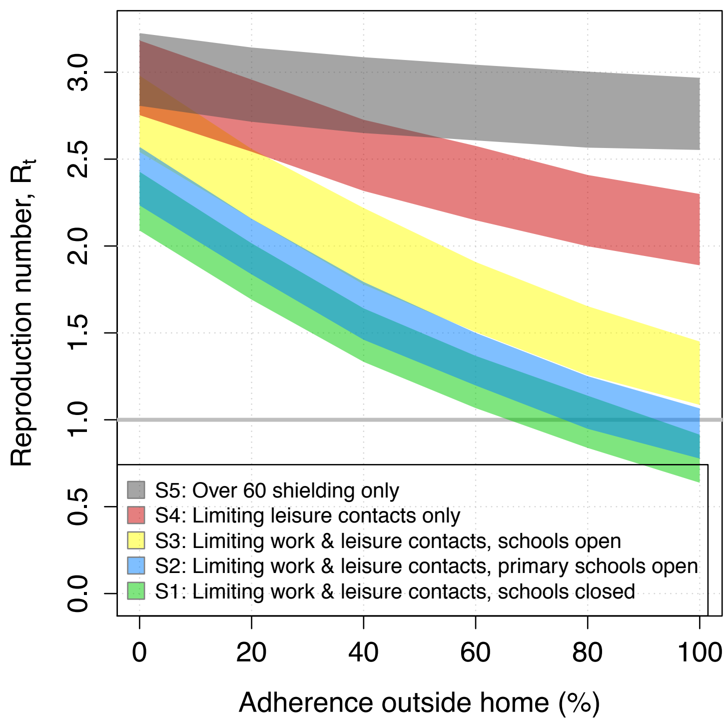

Figure 1: The estimated effective reproduction number R_t as a function of adherence for various social distancing strategies. For this figure, the baseline R_0 was set to 3.0.

R_t Estimates

The effective reproduction number R_t depends critically on the baseline estimate of R_0 in the population and levels of adherence to social distancing measures (Figure 1).

For a baseline estimate of R_0=3 and low levels of adherence, R_t was greater than 1 for all the strategies we investigated.

The only strategies that were consistent with R_t less than 1 were S1: limiting work and leisure contacts with at least ~65% adherence, schools closed and elderly shielding and S2: limiting work and leisure contacts with at least ~75% adherence, primary schools open and elderly shielding.

Achieving $R_t \approx 1.5$ was consistent with strategies S1: schools closed and ~30% of work and leisure contacts prevented, S2: primary schools open and ~40% of work and leisure contacts prevented, and S3: schools open and ~60% of work and leisure contacts prevented.

Achieving $R_t \approx 2$ was consistent with strategies S1: schools closed and ~5% of work and leisure contacts prevented, S2: primary schools open and ~10% of work and leisure contacts prevented, S3: schools open and ~30% of work and leisure contacts prevented and S4: schools open, work contacts as normal and ~80% of leisure contacts prevented.

Shielding of individuals over 60 years old in isolation had a minimal impact on overall transmission.

Taking a higher baseline R_0 increases R_t estimates for all of the strategies making it harder to achieve R_t less than 1. For example, for R_0=3.5, strategy S1 required 80%+ adherence to social distancing measures and strategy S2 required 90%+ adherence for $R_t < 1$.

Epidemic trajectories for gradual lifting of restrictions

Gradually lifting restrictions from a full lockdown to opening primary schools to allowing limited work and social contacts to no restrictions is able to theoretically reduce the overall number of deaths and prevent breaching hospital capacity (Figure 3).

Such a strategy results in multiple epidemic waves corresponding to each change in the reproduction number, with the effective reproduction number close to 1. Using a minimum threshold criterion to move to the next stage results in each strategy being implemented for between 3 and 5 months. Under such a strategy, approximately 20% to 25% of people are immune by September 2020.

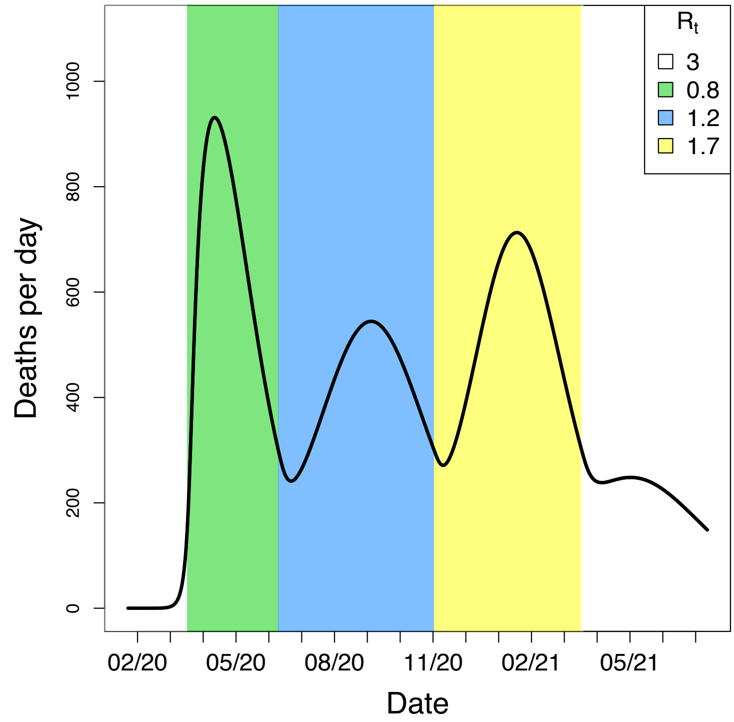

Figure 3: An example COVID-19 epidemic trajectory for England when social distancing restrictions are gradually lifted over time. The epidemic trajectory is shown in black.

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