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Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in well mixed indoor air

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Abstract

We present a mathematical model and a statistical framework to estimate uncertainty in the number of SARS-CoV-2 genome copies deposited in the respiratory tract of a susceptible person, $\sum n$, over time in a well mixed indoor space.

By relating the predicted median $\sum n$ for a reference scenario to other locations, a Relative Exposure Index (REI) is established that reduces the need to understand the infection dose probability but is nevertheless a function of space volume, viral emission rate, exposure time, occupant respiratory activity, and room ventilation. A 7 hour day in a UK school classroom is used as a reference scenario because its geometry, building services, and occupancy have uniformity and are regulated.

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The REI is used to highlight types of indoor space, respiratory activity, ventilation provision and other factors that increase the likelihood of far field (> 2 m) exposure. The classroom reference scenario and an 8 hour day in a 20 person office both have an $REI \simeq 1$ and so are a suitable for comparison with other scenarios. A poorly ventilated classroom (1.21s^{-1} per person) has $REI > 2$ suggesting that ventilation should be monitored in classrooms to minimise far field aerosol exposure risk. Scenarios involving high aerobic activities or singing have $REI > 1$; a 1 hour gym visit has a median $REI = 1.4$, and the *Skagit Choir* superspreading event has $REI > 12$.

Spaces with occupancy activities and exposure times comparable to those of the reference scenario must preserve the reference scenario volume flow rate as a *minimum* rate to achieve $REI = 1$, irrespective of the number of occupants present.

Keywords: ventilation, airflow, infection, school, classroom

Highlights

- A model to evaluate exposure to SARS-CoV-2 in well-mixed indoor spaces
- A comparison of the relative exposure risk of common indoor scenarios
- Highlights factors that increase exposure
- Identifies the need for a minimum airflow rate

1 **Nomenclature**

2 η_{filt} filter efficiency

3 η_{mask} face covering efficiency

4 γ surface deposition rate (s^{-1})

5 λ biological decay rate (s^{-1})

6 λ_{UV} ultraviolet denaturing rate (s^{-1})

7 ω filtration removal rate (s^{-1})

8 \overline{kq} mean absorption-adjusted breathing rate for all occupants ($m^3 s^{-1}$)

9 ϕ total removal rate (s^{-1})

10 ψ ventilation removal rate (s^{-1})

11 ζ respiratory tract absorption removal rate (s^{-1})

12 A_{floor} floor area (m^2)

13 C_{drop} concentration of droplets in exhaled air (RNA copies m^{-3})

14 C_{RNA} concentration of RNA copies in exhaled droplets (RNA copies m^{-3})

15 G emission rate of RNA copies (RNA copies s^{-1})

16 G_N emission rate of RNA copies per person (RNA copies s^{-1} per person)

17 k fraction of aerosol particles absorbed by respiratory tract

18	k_N	proportion of droplets containing RNA copies absorbed by respiratory
19		tract of a person
20	N	number of people present
21	n	number of RNA copies in well mixed air (RNA copies)
22	$n(0)$	number of RNA copies at start of exposure period
23	N_{inf}	number of infectious people present
24	n_{ss}	steady state number of RNA copies
25	n_{tract}	respiratory tract absorption rate (s^{-1})
26	q_N	respiratory rate of a person ($m^3 s^{-1}$)
27	Q_{filt}	airflow rate through filter ($m^3 s^{-1}$)
28	q_{inf}	infected person respiratory rate ($m^3 s^{-1}$)
29	q_{sus}	susceptible person respiratory rate ($m^3 s^{-1}$)
30	T	exposure period (s)
31	t	time (s)
32	T_D	time interval between the infected person leaving the space and the
33		susceptible person arriving (s)
34	T_I	infected person departure time (s)
35	V	space volume (m^3)

36 V_{drop} volume of single exhaled droplet (m^3)

37 V_{drop}^* ratio of the total volume of expelled droplets to the volume of exhaled
38 air then the total emission rate of RNA copies

39 $\sum n$ number of RNA copies inhaled over exposure period

40 1. Introduction

41 Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) is a
42 novel virus that spread rapidly worldwide leading to the global COVID-19
43 pandemic in 2020. Initially, the primary transmission pathways were thought
44 to be *large* respiratory droplets generated by coughing and sneezing, and
45 contact with infected surfaces via fomites. Later, the Centers for Disease
46 Controls and Prevention [1] suggested that the fomite pathway is less likely.

47 The transmission of some infectious diseases via aerosols is established
48 [2], and evidence for the airborne transmission of SARS-CoV-2 contained in
49 aerosols grew as the pandemic progressed. For example, several case studies
50 reported transmission clusters with high attack rates, so called *superspreader*
51 events, where a single source infects many people in a space. These occurred
52 indoors where aerosol transmission could be an infection pathway [3, 4, 5, 6, 7,
53 8]. Analysis of these events and evidence of the potential for aerosol airborne
54 transmission of SARS-CoV-2 have been presented by [9, 10, 11, 12, 13] and
55 [14].

56 Aerosols originate from different parts of the respiratory tract and form
57 during breathing, talking, shouting, singing, coughing, sneezing or laughing
58 [15, 16]. Droplets range in size from $<1 \mu m$ to $>100 \mu m$, and their size dis-

59 tribution is dependent upon the expiratory activity, but usually follows a
60 log-normal distribution [16, 17, 18, 19]. After their emission, the droplets
61 fall ballistically under gravity in still air. Concurrently, evaporation occurs
62 at a rate dependent upon room temperature and humidity. Evaporation
63 can reduce droplet diameter by 50–80% [20, 21], decreasing their mass and
64 terminal velocity. Aerosols with an evaporated diameter of $<10\ \mu\text{m}$ can re-
65 main airborne for several hours, buoyed and dispersed by local air currents.
66 Ribonucleic acid (RNA) copies of the SARS-CoV-2 genome have been de-
67 tected and calculated at a wide range of concentrations, from 7×10^6 to
68 10^{11} RNA copies per ml, in the sputum of people infected with SARS-CoV-2
69 who may be symptomatic, pre-symptomatic, and asymptomatic [22, 8, 23].
70 Most of the RNA copies are likely to be remnants of the genome or unviable
71 virions, but a proportion will be *virions* that are able to infect an individual
72 who has no immunity to SARS-CoV-2, herein referred to as a *susceptible*
73 person. Laboratory tests demonstrate that SARS-CoV-2 can remain infec-
74 tious in airborne aerosols for up to 16 hours, and have a half-life of over one
75 hour [24, 25]. It is not yet clear what size of respiratory aerosols and droplets
76 carry virus, and how this relates to the viral load in sputum or saliva, how-
77 ever SARS-CoV-2 has been recently sampled from exhaled breath [26] and
78 there is good evidence from exhaled breath studies of influenza and seasonal
79 coronavirus that respiratory viruses are carried in large and small aerosol
80 fractions [27].

81 The identification of the potential for indoor airborne aerosol exposure
82 led international groups responsible for guidance on building services to rec-
83 ommend that buildings should be ventilated with as much outdoor air as

84 reasonably possible to dilute SARS-CoV-2 laden aerosols [28, 29, 30]. In-
85 creasing airflow rates to control diseases is not a new approach. Florence
86 Nightingale’s first canon of nursing was to “keep the air [a person] breathes
87 as pure as the external air, without chilling [them]” [31].

88 It is difficult to determine an acceptable level of exposure to a novel
89 pathogen, such as SARS-CoV-2, because the probability of infection as a
90 function of the number of RNA copies inhaled, defined as a *quantum* [32],
91 is unknown. Therefore, it is also difficult to determine the ventilation rate
92 required to reduce the risk to an acceptable level. Consequently, the current
93 advice is to provide as much outdoor air as reasonably possible [29]. Many
94 buildings are already able to increase airflow rates above the minimum rate
95 required for acceptable indoor air quality because the airflow rates required
96 to control indoor temperatures are typically an order of magnitude higher
97 than those required for contaminant dilution.

98 There are several investigations of the role of aerosol transmission and the
99 efficacy of interventions, such as increased ventilation, face covering use, and
100 activity duration, and tools are publicly available¹. Infection risk is often
101 estimated using the established *Wells-Riley* model that gives the required
102 quanta emission (emission of infective material) from known outbreaks [8],
103 fitting to the reproductive number, R_o [33], or is calculated from first princi-
104 ples [34]. Mass balance models have also been used to investigate transient
105 effects and the role purging room air during breaks [35]. The impact of vary-
106 ing occupancy has also been considered using the re-breathed fraction of air
107 based on respiratory CO₂ generation and removal [36].

¹<https://cires.colorado.edu/news/covid-19-airborne-transmission-tool-available>

108 During a pandemic there are no zero-risk situations, and so the aim of
109 this paper is to propose an analytical model to estimate uncertainty in the
110 relative exposure to RNA copies in the air, of which a proportion are viable
111 SARS-CoV-2 virions, for a range of indoor spaces and ventilation and occu-
112 pancy scenarios. The model considers the probable emission of viable virions
113 by estimating the generation of aerosols, and their subsequent transport and
114 removal via a number of mechanisms, including inhalation. For clarity, the
115 chosen metric is *RNA copies inhaled* because the proportion of viable virions
116 for SARS-CoV-2 is currently unknown [8, 37] and because this fact does not
117 affect the magnitude of relative exposure. Other factors are also unknown,
118 such as the effect of the lung penetration depth on infectiousness, virion
119 characteristics (viability, emasculating droplet size, age, and half-life in air),
120 and the infection probability for an uninfected person as a function of co-
121 morbidities. Therefore, the Wells-Riley method, which requires an estimate
122 the quanta of infection derived from outbreaks (confounded by rare super-
123 spreading events) [32] and a dose-response method are not applied because
124 they cancel when calculating the relative exposure index, which removes an
125 area of significant uncertainty from predictions. However, as information be-
126 comes available, the approach can be amended to determine the exposure of
127 individuals to a specific quantity of virus, using a dose-response approach in
128 risk assessments [38, 39].

129 The approach is novel because it considers relative risks, transient effects
130 (such as purge ventilation rates and its diminishing returns), and uncertainty
131 in the emission of infectious materials. The model is used to consider the
132 factors that affect the inhalation of RNA copies over a time period in a well

133 mixed space. This also allows the relative benefits of interventions to be
134 considered and, in particular, the identification of upper limits of practical
135 interventions, such as ventilation. This will enable sensible engineering judge-
136 ments to be made about the management and regulation of indoor spaces.

137 The aim is achieved by meeting a series of objectives that are described in
138 each section. Section 2 introduces the model and its inputs. The classroom
139 reference scenario is discussed in Section 3 and other indoor scenarios are
140 explored in Section 4.

141 **2. Modelling approach**

142 An analytical model is developed to predict the number of viral genome
143 copies with the potential to be viable (RNA copies) inhaled over a time pe-
144 riod in an indoor space. The model is implemented to investigate a range
145 of scenarios and spaces using excel spreadsheets and bespoke MATLAB code,
146 contained in a package of Supplementary Materials². A statistical modelling
147 framework, following that of [40, 41, 42], is described in the Supplementary
148 Materials and is used to quantify uncertainty in the relative exposure asso-
149 ciated with a space.

150 *2.1. Mass-balance model*

151 A mass-balance model is used to investigate the number of RNA copies, n
152 (RNA copies), contained in aerosols transported to and from an indoor space.
153 This approach is commonly used to model indoor contaminant concentrations

² The MATLAB code and is available under a creative commons license. All materials may be obtained from DOI: 10.13140/RG.2.2.21307.03361

154 in a well mixed airtight space with volume V (m^3) [43]. Therefore, the model
 155 assumes that RNA copies are generated at single point at a constant rate,
 156 G (RNA copies s^{-1}), and are then mixed rapidly so that the change in the
 157 number of RNA copies in the space, $n(t)$ (RNA copies), with time, t (s), is
 158 approximately the same regardless of the sampling point; see Figure 1. We
 159 assume that no RNA copies are transported into the space from outside or
 160 connected spaces. The number of RNA copies in the space is diluted by a
 161 number of mechanisms that can be normalized by the volume of the space,
 162 V (m^3), and combined into a single removal rate, ϕ (s^{-1}), by addition; see
 163 Section 2.4.1. The rate of change in the number of RNA copies in the space
 164 at time t can then be described by a linear differential equation.

$$\frac{dn}{dt} = G - n(t) \phi \quad (1)$$

165 Integration over a known time period that starts at $t = 0$, gives the
 166 number of RNA copies in the space as a function of time.

$$n(t) = n_{ss} + [n(0) - n_{ss}] e^{-\phi t} \quad (2)$$

167 Here, $n(0)$ is the number of RNA copies at the start of the time period and
 168 n_{ss} is the steady state number of RNA copies in the space where

$$n_{ss} = \frac{G}{\phi} \quad (3)$$

169 The risk of infection can be estimated from the total number of RNA copies
 170 absorbed by the respiratory tract of a susceptible individual, $\sum n$ (RNA
 171 copies inhaled), over an exposure period T (s). It is dependent on the res-

172 piratory rate, q_{sus} ($\text{m}^3 \text{s}^{-1}$), the space volume, and the ratio of the number
 173 of aerosol particles absorbed by the respiratory tract to the total number of
 174 aerosol particles that pass through it, k .

$$\sum n = \frac{k q_{sus}}{V} \int_0^T n(t) dt \quad (4)$$

175 so that

$$\sum n = \frac{k q_{sus}}{\phi V} \{ [n_{ss} (T\phi - 1) + n(0)] + [n_{ss} - n(0)] e^{-\phi T} \} \quad (5)$$

176 These equations can be used to consider unique occupancy periods.

177 2.1.1. Steady state conditions

178 When an infected person is present in the space for a significant period of
 179 time the exponent of Equation 5 becomes relatively small so that $e^{-\phi T} \rightarrow 0$
 180 and the number of RNA copies absorbed by a susceptible person is given by

$$\sum n_{ss} \simeq \frac{k q_{sus} G}{\phi^2 V} \left[(T\phi - 1) + \frac{n(0)}{n_{ss}} \right] \quad (6)$$

181 To model the space where the steady state has been reached when a suscep-
 182 tible person enters, $n(0) = n_{ss}$, Equation 6 reduces further to

$$\sum n_{ss} \simeq \frac{k q_{sus} G T}{\phi V} \quad (7)$$

183 2.1.2. Step response conditions

184 When an infected person enters the space where a susceptible person is
 185 already present when $n(0) = 0$ and $T = 0$, Equation 5 reduces to

$$\sum n = \frac{kq_{sus}G}{\phi^2V} (T\phi + e^{-\phi T} - 1) \quad (8)$$

186 where T (s) is the exposure period.

187 *2.1.3. Step response and decay conditions*

188 When an infected person enters an occupied space when $n(0) = 0$ and
 189 departs at time T_I , a general formula for $\sum n$ is found for those remaining in
 190 the space. Equation 8 describes the occupied period and the decay period is
 191 represented by substituting Equation 2 into Equation 5 and assuming $G = 0$
 192 to give

$$\sum n = \frac{kq_{sus}G}{\phi^2V} [(T_I\phi + e^{-\phi T_I} - 1) + (1 - e^{-\phi T_I}) (1 - e^{-\phi(T-T_I)})] \quad (9)$$

193 where T is the exposure period.

194 *2.1.4. Decay conditions*

195 When a susceptible person enters the space after an infected person has
 196 departed, a general formula for $\sum n$ is found by assuming $G = 0$ during the
 197 decay period and $n(0) = 0$ when the infected person enters the space.

$$\sum n = \frac{kq_{sus}G}{\phi^2V} (1 - e^{-\phi T_I}) (1 - e^{-\phi T}) e^{-\phi T_D} \quad (10)$$

198 Here, T_I is the length of time the infected person spent in the space, T_D
 199 is the time interval between the infected person leaving the space and the
 200 susceptible person arriving, and T is the exposure period. Equation 10 can

201 is simplified by assuming that the infected person is in the space for a long
202 period of time so that $T_I \rightarrow \infty$.

203 *2.2. Mixing volume, V*

204 The volume term in Equation 5 is an important source of bias because the
205 space volume may include people and objects where viral aerosols cannot mix.
206 Then, the mixing volume and the space volume are not equal; see [44]. When
207 their ratio is $\ll 1$, $\sum n$ is under-estimated. This is particularly important in
208 areas of high occupancy density.

209 Space volumes are estimated by their type and are given in Table 1. In
210 this paper we consider situations where space and mixing volumes may be
211 assumed to be identical.

212 *2.3. Virus generation rate, G*

213 G is proportional to the number of people shedding RNA copies in the
214 space, and is also a function of their respiratory rate. This can be given by

$$G = N_{inf} G_N \quad (11)$$

215 where N_{inf} is the number of infectious occupants in the space, and G_N
216 (RNA copies s^{-1} per person) is the emission rate per person. Then, follow-
217 ing Buonanno *et al.* [34], G_N is calculated by

$$G_P = C_{RNA} q_{inf} \sum C_{drop} V_{drop} (1 - \eta_{mask}) \quad (12)$$

218 where C_{RNA} (RNA copies m^{-3}) is the concentration of RNA copies of the
219 SARS-CoV-2 genome in the exhaled droplets, and is assumed to be the same

220 as the concentration in the sputum of the infected individual, q_{inf} is the
 221 breathing rate of the infected individual ($\text{m}^3 \text{s}^{-1}$), C_{drop} is the concentration
 222 of droplets in exhaled air (RNA copies m^{-3}), V_{drop} (m^3) is the volume of
 223 a single droplet (m^3), and η_{mask} is the efficiency of a face covering, herein
 224 assumed to be 0. If V_{drop}^* is the ratio of the total volume of expelled droplets
 225 to the volume of exhaled air then the total emission rate of RNA copies is
 226 given by

$$G = N_{inf} C_{RNA} q_{inf} V_{drop}^* (1 - \eta_{mask}) \quad (13)$$

227 Breathing and respiratory fluid RNA measurements from COVID-19 pa-
 228 tients [22, 26] are used to estimate C_{RNA} . Following Morawska *et al.*, droplet
 229 diameter is assumed to be normally distributed with a mean of 1.84×10^{-6} m
 230 and an arbitrary standard deviation of 10% of the mean. The RNA copies
 231 load of the infected individual is also assumed to be normally distributed
 232 with a mean of 3.75×10^{17} RNA copies per m^3 and a standard deviation of
 233 10% of the mean; see the Supplementary Material for derivations of infector
 234 viral loads per ml of respiratory fluid including variation with vocal activities.

235 Values of q_{inf} and q_{sus} are given by Adams *et al.* [45, 46], and V_{drop}^* is
 236 derived from Morawska *et al.* [18] as a function of C_{drop} and droplet diameter.
 237 The Supplementary Material discusses these parameters in greater detail. We
 238 assume no face coverings are worn in any of the scenarios.

239 2.4. Removal rate, ϕ

240 The number of RNA copies in the air of the space are diluted by a number
 241 of mechanisms, where the total removal rate is given by their sum.

$$\phi = \psi + \gamma + \lambda + \zeta + \omega \tag{14}$$

242 Here, ψ is the removal rate due to ventilation, γ is the removal rate due to
 243 surface deposition, λ is the removal rate due to biological decay, ζ is the
 244 removal rate due to absorption in the respiratory tract, and ω is the removal
 245 rate due to filtration. Re-suspension following surface deposition is not con-
 246 sidered. All terms have units of s^{-1} and are discussed in Sections 2.4.2–2.4.5,
 247 respectively.

248 The system time constant τ (s) is the reciprocal of ϕ , $\tau = \phi^{-1}$. ϕ is a
 249 function of the parameters described in Sections 2.4.1–2.4.5. τ is also known
 250 as the *residence time* since it indicates the time RNA copies remain in the
 251 space after generation and is indicative of the timescale for the system to
 252 reach a new steady state.

253 2.4.1. Air change rate, ψ

254 The air change rate is a function of the ventilation rate and space volume
 255 V . Ventilation rates are normally given by standards and guidelines *per*
 256 *capita* according to the function of the space.

257 2.4.2. Surface deposition rate, γ

258 Surface deposition occurs by two key mechanisms: ballistic deposition,
 259 and momentum-induced deposition. However, empirically derived values of
 260 γ do not differentiate between them and so a single term, γ (s^{-1}), is used.
 261 Thatcher *et al.* [47] give median γ measured in a furnished space as a function
 262 of droplet diameter and u_s with and without mixing fans. Therefore, we
 263 assumed the mixing fans are off where γ is equally probable between values

264 of $1.17 \times 10^{-4} \text{ s}^{-1}$ and $1.69 \times 10^{-4} \text{ s}^{-1}$; see Table 2.

265 2.4.3. Biological decay rate, λ

266 The biological decay rate is a function of the half-life, $t_{1/2}$ (s), and the
267 denaturing rate, λ_{UV} (s^{-1}), where

$$\lambda = \frac{\ln(2)}{t_{1/2}} + \lambda_{UV} \quad (15)$$

268 Van Doremalen *et al.* [25] report that the half-life of SARS-CoV-2 in
269 aerosols has a median of approximately 1.1–1.2 hours and a 95% confidence
270 interval of 0.64 to 2.64 hours. This is approximately represented by a log-
271 normal distribution, which when converted to λ using Equation 15, has a
272 mean of $\mu = 1.75 \times 10^{-4} \text{ s}^{-1}$ and a standard deviation of $\sigma = 0.43 \text{ s}^{-1}$.

273 Inactivation from exposure to ultraviolet light (UV-C) is also a biological
274 process. The denaturing rate at a particular airflow rate should be adjusted
275 when a UV-C device is used. Here, RNA copies are not physically removed
276 from a space, but this model assumes they are because they are no longer
277 harmful.

278 2.4.4. Respiratory tract absorption rate, ζ

279 The respiratory tract absorption rate is assumed to be proportional to
280 q_{sus} (see Section 2.1) and the number of RNA copies in the air, given by

$$n_{tract} = \frac{n(t)}{V} \sum_{i=1}^N k_N q_N \quad (16)$$

281 where k_N is the proportion of droplets containing RNA copies entering the
282 respiratory tract of a person and are absorbed by its surface, assumed to be

283 constant, and q_N ($\text{m}^3 \text{s}^{-1}$) is respiratory rate of a person. Then,

$$n_{tract} = \frac{n(t) N \overline{kq}}{V} \quad (17)$$

284 where N is the total number of occupants within the space, and \overline{kq} ($\text{m}^3 \text{s}^{-1}$)
285 is the mean absorption-adjusted breathing rate for all of the occupants in
286 the space. The respiratory tract absorption is characterised in by a removal
287 rate, ζ (s^{-1}), given by

$$\zeta = \frac{N \overline{kq}}{V} \quad (18)$$

288 This removal rate is a function of occupancy, and occupant metabolic
289 rate. Therefore, it is unique for each space, and not a general constant.

290 Darquenne [48] shows that k is a function of droplet diameter and *tidal*
291 *volume*, the volume of air inhaled per breath. For the droplet diameter given
292 in Table 2, k is 0.43–0.65, depending on the tidal volume. In the absence
293 of knowledge, we assume that all values of k are equally probable between
294 these limits; see Table 2.

295 Respiratory rates are given by Adams [46] for male and female occupants
296 sitting and walking, and generally for children sitting. All values are assumed
297 to be normally distributed and to vary with space use; see Table 3.

298 2.4.5. Filtration Rate, ω

299 Mechanical filters actively remove aerosol-borne viruses from the air either
300 when fitted in a mechanical ventilation system or in a *stand-alone* air purifier.
301 The filtration removal rate is proportional to the volume flow rate of air
302 passing through the filter, Q_{filt} ($\text{m}^3 \text{s}^{-1}$), sometimes known as a *clear air*

303 *delivery rate*, and is given by

$$\omega = \frac{Q_{filt}}{V} \eta_{filt} \quad (19)$$

304 where η_{filt} is the filtration efficiency defined as the ratio of the number of
305 RNA copies removed by the filter to the number of RNA copies in the air
306 that is passed through it, and has a value between 0 and 1.

307 2.5. Indoor spaces

308 A reference scenario is defined that allows uncertainty in the number
309 RNA copies inhaled to be investigated as a function of space volume, emission
310 and exposure times, occupant activity, and room ventilation. These predic-
311 tions can then be compared against those for cases within other non-domestic
312 spaces by developing a *Relative Exposure Index* (REI); see Section 3.2 for its
313 definition. This eliminates the need for an understanding of the dose thresh-
314 old and RNA copies emission rate by an infector, and highlights types of
315 indoor space and activities that lead to the greatest exposure for the same
316 infector; see Section 1. All scenarios assume a single infected person and the
317 *Step response conditions* (Section 2.1.2), unless stated otherwise. All model
318 inputs are given in Tables 1–3.

319 2.5.1. Reference scenario

320 A UK school classroom is used as a reference scenario because its geom-
321 etry and ventilation provision are well described by design guidance docu-
322 ments. Requirements are identified that constitute a *worst case* scenario.
323 Building Bulletin (BB) 103 [49] requires a minimum floor area of $A_{floor} =$

324 55 m^2 for a classroom occupied by 30 students and 2 teachers, giving an oc-
325 cupancy density of 1.7 m^2 per person. A floor to ceiling height of 2.7 m, gives
326 a reference scenario volume of $V = 149 \text{ m}^3$. BB101 [50] specifies maximum
327 carbon dioxide (CO_2) concentrations in learning spaces where natural ventila-
328 tion is used or when hybrid systems are operating in natural mode, requiring
329 a mean concentration of ≤ 1500 ppm averaged over the school day duration,
330 corresponding to an airflow rates of $\geq 5 \text{ l s}^{-1}$ per person, and a maximum con-
331 centration of 2000 ppm for no more than 20 consecutive minutes, correspond-
332 ing to an airflow rate of 3.4 l s^{-1} per person. The mean ventilation rate of
333 5 l s^{-1} per person is used unless otherwise stated. These represent air change
334 rates of 3.9 h^{-1} ($\psi = 1.08 \times 10^{-3} \text{ s}^{-1}$) and 2.7 h^{-1} ($\psi = 7.41 \times 10^{-4} \text{ s}^{-1}$), respec-
335 tively for standard classrooms. Many existing UK schools were built when the
336 maximum CO_2 concentration was 5000 ppm, corresponding to an airflow rate
337 of 1.2 l s^{-1} per person or 0.9 h^{-1} ($\psi = 2.58 \times 10^{-5} \text{ s}^{-1}$) [51]. Post occupancy
338 assessments of UK naturally ventilated classrooms recorded CO_2 concentra-
339 tions of over 5000 ppm when ventilation openings were closed [52, 53]. BB101
340 assumes a school day duration of 7 hours, and so we assume all occupants are
341 present throughout, representing a worst case scenario; for example, pupils
342 remaining indoors to shelter from inclement weather.

343 The ventilation rates given here are generally applicable during the heat-
344 ing season, because higher ventilation rates are required to dissipate heat
345 gains in the summer. They are also less stringent than those required for
346 mechanically ventilated classrooms, where the mean and maximum concen-
347 trations are 1000 ppm ($\psi = 1.72 \times 10^{-3} \text{ s}^{-1}$ or 6.2 h^{-1}) and 1500 ppm, re-
348 spectively [50]. Occupants are assumed to breathe for 75% of the time and

349 talk for 25% of the time. The respiratory activity is used to determine an
350 average number of aerosol droplets and average diameter using data from
351 Morawska *et al.* [18]; see Supplementary Materials. The breathing rate of
352 susceptible and infected occupants (see Sections 2.1 and 2.3) is assumed to
353 be $1.21 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$, following Adams *et al.* [46] for children sitting; see
354 Table 3.

355 2.5.2. Common space scenarios

356 The occupancy density and ventilation provision of many non-domestic
357 spaces is advised by the Chartered Institution of Building Services Engineers
358 (CIBSE) Guide A [54]. This guidance is used to define three typical spaces
359 where a single infected person is present.

360 We consider an office with an occupancy density of 11 m^2 per person, a
361 floor to ceiling height of 2.7 m, and a outdoor airflow rate of 10 l s^{-1} per person
362 ($\psi = 5.05 \times 10^{-4} \text{ s}^{-1}$ or 1.8 h^{-1}). There are 50 occupants who are assumed to
363 be continuously present for 8 hours breathing for 75% and talking for 25%.

364 Small high street shops, such as a coffee shop, generally have an occu-
365 pancy density of 5 m^2 per person and a recommended ventilation rate of
366 10 l s^{-1} per person ($\psi = 1.35 \times 10^{-5} \text{ s}^{-1}$ or 2.7 h^{-1}), representing a *high* ven-
367 tilation scenario. However, there may be circumstances where ventilation is
368 not provided and infiltration is the only source of outdoor air. This represents
369 a *low* ventilation scenario where $\psi = 5.56 \times 10^{-5} \text{ s}^{-1}$ or 0.2 h^{-1} following Bu-
370 nanno *et al.* [34]. Occupancy periods are highly variable, and so we model a
371 30 minute visit to a small coffee shop with breathing for 75% of the time and
372 talking for 25%. Here, a shop worker is assumed to be the infected occupant,
373 representing a steady state scenario; see Section 2.1.1.

374 We model a 1 hour visit to a supermarket with a volume of 27,870 m³ and
375 a ventilation rate of 1.1 h⁻¹ ($\psi = 3.06 \times 10^{-4} \text{ s}^{-1}$) where a store employee is
376 the infected occupant, representing a steady state scenario.

377 The occupants of gyms have an elevated metabolic and respiratory rate;
378 see Section 2.4.4. We model a 1 hour aerobic workout in a small 200 m²
379 600 m³ gym space with a recommended³ maximum occupancy of 20 people
380 and airflow rate of 20 l s⁻¹ per person or 2.4 h⁻¹, where the infected person
381 is an active member of staff, representing a steady state scenario. Deep
382 breathing is likely to generate aerosols with a different number droplets and
383 droplets diameter when compared to breathing at rest and this is reflected
384 by a high respiratory rate; see Supplementary Materials.

385 2.5.3. High transmission scenarios

386 The literature reports incidences of high secondary transmission of SARS-
387 CoV-2 in indoor spaces, and so we consider three of them.

388 A single index case is thought to have transmitted the SARS-CoV-2 virus
389 to nine other patrons of a restaurant in Guangzhou, China, who were sat
390 at adjacent tables; see Li *et al.* [6]. The space volume is 431 m³, but the
391 localisation of the secondary infections and the reported recirculation of air
392 within a zone at the back of the restaurant indicates a mixing volume of
393 127 m³ occupied by 21 people. Li *et al.* report an airflow rate of 0.6 h⁻¹ but
394 the poor mixing suggests that it may be limited to infiltration. Therefore
395 limiting airflow rates of 0.2 h⁻¹ and 0.6 h⁻¹ ($\psi = 1.56 \times 10^{-4} - 2.14 \times 10^{-4} \text{ s}^{-1}$)

³<https://www.gov.uk/guidance/working-safely-during-coronavirus-covid-19/providers-of-grassroots-sport-and-gym-leisure-facilities>

396 are explored with uniform probability. The occupancy time is 1.25 hours and
397 we assume 75% of the time is spent breathing and 25% talking.

398 A single index case is thought to have infected 53 of 61 members of the
399 Skagit Choir over a 2.5 hour period in a rehearsal hall [8]. The space volume
400 is 810 m^3 and the ventilation rate is estimated to be between 0.35 h^{-1} and
401 1.05 h^{-1} ($\psi = 8.33 \times 10^{-5} - 2.77 \times 10^{-4} \text{ s}^{-1}$). The respiratory rate for singing
402 is assumed to be $165 \pm 13\%$ of that at rest, following Bernardi *et al.* [55], in
403 the absence of data on aerosols generated by singing we use the vocalisation
404 data of Morawska *et al.* [18].

405 During a 9.5 hour meeting in a small room in Germany, 11 of 13 partic-
406 ipants were infected by a pre-symptomatic index case; see Hijnen *et al.* [4].
407 The floor area is 70 m^2 but the space height is unknown and so is assumed
408 to be 2.7 m. The ventilation rate is unknown but personal correspondence
409 with Hijnen revealed that the space was naturally ventilated with all windows
410 closed during the meeting due to cold weather. Therefore, we assume outdoor
411 air is solely provided by infiltration at 0.2 h^{-1} ($\psi = 5.56 \times 10^{-5} \text{ s}^{-1}$). The
412 room is assumed to be occupied by all participants throughout the meeting.

413 3. Exposure risk in the reference scenario

414 3.1. Deterministic estimate

415 Figure 2 shows the predicted RNA copies in the volume of the space,
416 $n(t)$, and the number of RNA copies inhaled, $\sum n$, when RNA copies are
417 shed at a concentration of 3×10^9 RNA copies per ml of respiratory fluid
418 in the reference scenario when evaluated deterministically for three scenar-
419 ios; see Sections 2.5.1 and the Supplementary Materials. Line A shows

420 that when the RNA emission is over a 7 hour period, $n(t)$ quickly reaches
 421 a steady state of 16,603 RNA copies causing the total number of RNA copies
 422 inhaled to be approximately linearly related to the exposure period. After
 423 7 hours, an occupant may be expected to inhale 179 RNA copies. The res-
 424 idence time, τ (see Section 2.4), is 12 minutes (723 seconds), and the time
 425 to reach 95% of the steady state concentration, $t_{ss,95}$, is around 35 minutes,
 426 where $t_{ss,95} = -\ln(1 - 0.95) \tau$. The scenario was modelled using Equation 8
 427 for a novel emission source, but is closely approximated by Equation 7 for
 428 steady state occupancy because T is significantly large. Accordingly, Equa-
 429 tion 7 is used to evaluate Figure 2 and to show how $\sum n$ can be minimized
 430 in any space. It shows that there are 6 parameters that affect $\sum n$. Those
 431 located in the numerator are all linearly related, where a percentage change
 432 in their value has a corresponding change in $\sum n$. Not all parameters can
 433 be amended immediately to minimize exposure; for example, the number of
 434 aerosol particles absorbed by the respiratory tract, k (see Section 2.4.4), is a
 435 function of physiology and so changes only occur at a population scale in the
 436 medium to long term. However, the other parameters can all be addressed in
 437 the short term. The respiratory rates of susceptible and infected persons, q_{sus}
 438 and q_{inf} (see Section 2.3), are similarly a function of physiology but are also
 439 affected by occupant activity. Accordingly, the metabolic rate of occupants
 440 should be maintained at as low a rate as possible.

441 Equation 13 shows that the emission rate, G (see Section 2.3), is linearly
 442 related to four parameters, including q_{inf} . We assume a single infected person
 443 is in the space for the entire 7 hours, but adding another doubles both G and
 444 $\sum n$. This highlights the need for public health messages to encourage the

445 reporting and isolation of people with SARS-CoV-2 symptoms. The ratio
446 of the total volume of expelled droplets to the volume of exhaled air, V_{drop}^* ,
447 can be reduced by wearing of face coverings that catch droplets before they
448 are allowed to mix in the indoor air. Therefore, it is logical to recommend
449 that all occupants wear face coverings in indoor spaces at all times when it
450 is feasible to do so.

451 The concentration of RNA copies in exhaled droplets, C_{RNA} , is highly
452 variable and may be substantially increased by a so called *superspreader*, an
453 infected person who transmits the virus to an abnormally large number of
454 other people [56]. Miller *et al.* [8] report that emission rates for superspread-
455 ers are greater than normal infected persons by several orders of magnitude.
456 Then, a corresponding increase in C_{RNA} similarly increases G and $\sum n$. It
457 should be noted that superspreading events are uncommon, however, it has
458 been estimated that around 80% of infections occur from 10% of people and
459 hence there may be a significant proportion of people who may shed a higher
460 amount of virus [57]. It is possible that superspreading occurs when one of
461 these people is in a scenario with a higher REI. The significant uncertainty
462 in C_{RNA} supports the need for a REI because C_{RNA} is not a dose risk and
463 so the value of RNA copies inhaled does not itself indicate the probability of
464 infection, which is currently unknown. Utilising values of inhaled RNA copies
465 should not be used to estimate the risk of harm or the probability of sec-
466 ondary transmission in a space. However, any uncertainty in the values used
467 for the RNA copies per ml of respiratory fluid of an infector cancels in a REI
468 allowing scenarios to be compared; see Section 3.2 and the Supplementary
469 Materials.

470 The final numerator parameter is the exposure time, T . In the context
471 of a school day, this value can be reduced by spending as much time out-
472 side as possible. Exposure is lowest during the period of transition to the
473 steady state concentration and so it is advantageous to limit occupancy to
474 the time where the rate of change of $n(t)$ is greatest. This could be done
475 by allowing frequent outside breaks and purging the indoor air during the
476 changeover. In this example, the value of $t_{ss,95}$ is relatively short, and it
477 would be advantageous to increase it so that it is comparable to a teaching
478 period.

479 Line B of Figure 2 shows the changes to $n(t)$ and $\sum n$ if the infected
480 person leaves the space after 1 hour and all other occupants remain; see
481 Section 2.1.3. Following their departure, $n(t)$ decays quickly towards 0 in
482 around an hour and $\sum n$ plateaus. $\sum n$ is strongly dependent on the length
483 of time the infected person is present in the space with a susceptible person.
484 Line D shows that a susceptible person entering the space as the infected
485 person departs, or afterwards, has a much lower risk; see Section 2.1.4. This
486 is important when the time occupants spend in a space is a variable; for
487 example, there is anecdotal evidence of shop workers who do not wear face
488 coverings even when their customers do. Then, Figure 2 shows that the
489 greatest risk is to a long-term occupant from a fellow long-term occupant.

490 Both the steady state concentration and the time to the steady state are
491 inversely proportional to two parameters, the removal rate, ϕ , and the volume
492 of the space, V , in the denominator of Equation 7. The easiest parameter to
493 amend in any space is the removal rate, ϕ (equation 14), which is dominated
494 by the ventilation rate, ψ (see Section 2.4), which contributes around 80% of

495 the value of ϕ ; see Section 2.4. Ventilation is the standard method of diluting
496 pollutants in buildings and as $\psi \rightarrow \infty$, $\sum n \rightarrow 0$ but with a law of diminishing
497 returns. This is important to note because, in the heating season, there is
498 a near-linear relationship between space heating energy demand and ψ , and
499 care must be taken not to thermally discomfort occupants. Accordingly,
500 there is a trade off between $\sum n$, energy, and thermal comfort that must be
501 considered and will be a function of the dose threshold for infection, which
502 is currently unknown; see Section 1.

503 In the absence of ventilation and infiltration, a removal rate of around
504 1.1 h^{-1} is attributable to other sources. Their importance is shown by line C
505 of Figure 2, which shows that $n(t)$ and $\sum n$ both increase when their contri-
506 bution is ignored and the removal rate is solely attributable to ventilation,
507 where $\phi = \psi$.

508 The surface deposition rate, γ (see Section 2.4.2), is a function of aerosol
509 diameter and room airflow velocity. Thatcher *et al.* [47] suggest that γ can
510 be increased by around 80% by using ceiling or desk fans to increase the
511 room airflow velocity from $<0.02 \text{ m/s}$ to 0.19 m/s . Within the model this
512 increases ϕ to 5.3 h^{-1} ($1.48 \times 10^{-3} \text{ s}^{-1}$) and decreases the residence time by
513 around 45 seconds, although the change in $\sum n$ is negligible. However, in
514 scenarios where ϕ is low, such as during the heating season when occupants
515 may close ventilation openings to preserve thermal comfort, γ becomes an
516 important removal mechanism. Enhancing mixing can increase the number
517 of people exposed to the virus and may increase the overall infection risk
518 [58]. This is particularly relevant in situations where there is very little
519 ventilation, such as in the Guangzo restaurant [6]; see Section 4.2. Care

520 must be taken not to increase the average room velocity beyond 0.21 m s^{-1}
521 in the heating season [59] to maintain thermal comfort and to ensure that
522 lightweight objects do not blow away. It may be possible to site desk fans
523 to generate areas of high velocity away from occupants balancing the need
524 to increase γ and maintain occupant comfort. Surface deposition removes
525 infectious particles from the air but it can create contaminated fomites that
526 may lead to contact spread. Surface deposition rates can then give relative
527 information about the likelihood of fomite risk, and inform dose-response
528 models about contact spread and cleaning regimes. It is important to note
529 that, although deposition of large droplets is greatest close to the infector,
530 the deposition of smaller aerosols is on all surfaces in a room, including those
531 that are out of reach.

532 Finally, the removal rate attributable to mechanical filtration, ω (see
533 Section 2.4.5), can be implemented quickly and easily using a portable air
534 cleaner that contains a high-efficiency particulate air (HEPA) filter. Equa-
535 tion 19 shows that the airflow rate through the filter should be considered
536 in proportion to the space volume; for example, to increase ϕ by 20%, the
537 required clear air delivery rate through a perfect filter is 1 h^{-1} or $0.04 \text{ m}^3 \text{ s}^{-1}$.
538 This method of removal could be useful in the heating season, although con-
539 sideration should be given to noise generated by the system. This model
540 assumes the air in the room is well mixed, and the portable air cleaner will
541 only function as expected if this is the case; stand-alone air cleaners may not
542 be effective at mixing the air throughout a space. Centralised mechanical
543 ventilation systems may also contain HEPA filters, which can be used to fil-
544 ter recirculated air. Here, ω is the room air recirculation rate and ψ is the

545 fresh air supply rate.

546 The second parameter in the denominator, the space volume V , is an
547 important factor in exposure risk. For the same floor area taller spaces
548 theoretically have a lower exposure risk, however this will depend on the
549 mixing within the space. The airflow rate in many buildings, including UK
550 schools, is specified as a volume flux *per capita* and so as V increases there is
551 a corresponding reduction in ψ . Then, increasing V and reducing ψ so that
552 their product is conserved, increases n_{ss} and τ , which increases the time to
553 n_{ss} and decreases $\sum n$. The steady state concentration of RNA copies in the
554 space ($n_{ss}V^{-1}$) changes slightly, and does not change at all when λ and γ
555 are negligible. This would lead to clear changes to the shape of the curves
556 in Figure 2; for example, the gradient of n would decrease and the concavity
557 of the $\sum n$ curve would increase when $0 < T < 1$ hours. Therefore, the risk
558 of exposure is lower in a space with a larger volume where airflow rates are
559 the same.

560 A further analysis of the reference scenario is in the Supplementary Materials².

561 3.2. Probabilistic estimates

562 There is significant uncertainty in the values used in Section 3.1, and the
563 corresponding uncertainty in predictions of $\sum n$ is assessed using the sta-
564 tistical framework described in the Supplementary Materials and the inputs
565 given in Tables 1–3.

566 Figure 3 quantifies uncertainty in $\sum n$ using a histogram and cumulative
567 distribution function (CDF), with $77 \leq \sum n \leq 352$ RNA copies inhaled, with
568 95% confidence. The distribution of $\sum n$ is not normal and so P_{50} is a more
569 appropriate descriptive statistic for RNA copies inhaled than μ . The P_{50}

570 value is approximately equal to that calculated by the deterministic approach
571 (see Section 3.1), and so it can be used for a quick estimate of $\sum n$, although
572 the stochastic approach is required to quantify uncertainty in $\sum n$, to perform
573 a global sensitivity analysis, and to determine effect sizes² (the magnitude of
574 the differences between the distribution of $\sum n$ for the reference space and
575 other spaces) between the reference and other spaces.

576 The utility of the P_{50} makes it a suitable choice for a REI where all
577 predicted centiles are given relative to P_{50} for the reference scenario. Figure 3
578 shows the REI on the top x-axis for the reference scenario. The 95% REI
579 confidence interval is $0.45 \leq \sum n \leq 2.05$ RNA copies inhaled. This REI is
580 now used in Section 4 to compare exposure risk in other spaces relative to the
581 reference scenario. Clearly, the value of the P_{50} calculated here is a function
582 of the inputs used, which are uncertain and may change as more evidence
583 becomes available or if the scenario changes; for example, to mitigate against
584 more than one infected person or a reduction in the number of classroom
585 occupants. However, the reference P_{50} is easily revised using the model.

586 Any space that wishes to have a REI of unity or less, must at least balance
587 the parameters in Equation 7. If k , q_{sus} , G , and T are identical to those
588 of the reference scenario, then a ventilation rate of $\psi V = 0.16 \text{ m}^3 \text{ s}^{-1}$ per
589 infected person (determined by population prevalence) must be preserved
590 as a minimum rate to ensure the REI does not exceed 1, irrespective of
591 the number of occupants present. The total removal rate must be at least
592 $\phi V = 0.21 \text{ m}^3 \text{ s}^{-1}$ per infected person. It is also important to note that
593 providing a fixed air change rate will lead to $\text{REI} > 1$ when the volume of
594 the space is smaller than that of the reference classroom. Conversely, the

595 REI will increase for a smaller volume. This reinforces the importance of
596 providing a minimum airflow rate with units of $\text{m}^3 \text{s}^{-1}$ or an equivalent. *Per*
597 *capita* and air change rates should only be used with the minimum airflow
598 rate.

599 The model predictions are dependent on the assumptions made in Sec-
600 tion 2.1. Therefore, the sensitivity analysis described in the Supplementary
601 Materials is used to determine the relative importance of stochastic paramete-
602 rs in Equation 7 (k , q_{sus} , G , and ϕ) on predicted values of $\sum n$. Parameters
603 V and T are not tested because they are held constant. All tests indicate
604 that the most sensitive parameters, in order of sensitivity, are: G , k , q_{sus} , and
605 ϕ . All parameters are statistically significant and so their values are impor-
606 tant. The test statistics and their p -values are given in the Supplementary
607 Materials². There is limited evidence for many of the input distributions
608 applied here and so these should be updated in the future as information
609 becomes available.

610 4. Exposure risk in other indoor spaces

611 Input parameters for all scenarios are given in Table 1–3. Uncertainty in
612 the REI for the common and high transmission spaces (see Section 2.5) is
613 shown in Figure 4. REIs and effect sizes are given in Table 4.

614 4.1. Common spaces

615 Four additional classroom scenarios are explored by varying the *per capita*
616 ventilation rate between 1.2, 3.4, 9.2, and 15.7 l s^{-1} per person to achieve
617 maximum mean CO_2 concentrations of 5000, 2000, 1000, and 750 ppm, re-
618 spectively, as described in Section 2.5.2. Hereon P_{50} REI values are used for

619 comparison, but confidence intervals are given in Table 4. The poorest venti-
620 lated classroom has a REI of 2.33 and a *very large* effect size (the magnitude
621 of the difference between its distributions and the reference scenario's), and
622 so adequate ventilation is necessary and important. Increasing ψ has clear
623 advantages, reducing the REI to 0.38 when increased 3-fold. The REI de-
624 creases as the ventilation airflow rate in the space increases. The potential
625 benefits of increasing the ventilation rate in a poorly ventilated space are
626 greater than increasing a well ventilated space by the same amount.

627 The REI of the office is 0.98 and the effect size *negligible* and so could also
628 be used as a reference scenario. The ventilation rate is greater than that of
629 the reference scenario, but respiratory rates are slightly bigger to reflect adult
630 occupants. In offices with different respiratory activity, such as a call centre
631 where talking predominates breathing, the model should be recalculated with
632 appropriate changes to the volume of respiratory fluid released as aerosols as
633 a function of droplet diameter and volume, V_{drop}^* . Reducing the airflow rate
634 by 80% to 2 l s^{-1} per person increases the REI to 1.63.

635 The REI of the high street coffee shop are 0.04 and 0.06 for the standard
636 and *low* airflow scenarios, respectively. The effect size for both scenarios is
637 *very large*. The low values of REI are attributable to the shorter exposure
638 period and highlights the value of avoiding prolonged contact with an infected
639 person. Increasing the exposure time to 8 hours results in an REI of 1.07 and
640 3.37 for the *high* and *low* airflow scenarios, respectively, showing that the
641 airflow rate becomes more important for reducing transmission risk as the
642 exposure time increases. This scenario highlights the importance of purpose-
643 provided ventilation provision and the danger of relying on infiltration for

644 virus removal.

645 The supermarket has the lowest REI of 10^{-3} and a *very large* effect size
646 because the airflow rate of $8,528 \text{ m}^3 \text{ s}^{-1}$ is over 50 times that of the reference
647 scenario and the exposure period is 7 times less. Here, the risk of exposure
648 is likely to be dominated by close range transmission rather than aerosols,
649 whereas both pose a risk in the classroom and office.

650 A 1 hour aerobic workout in a gym poses the greatest risk a REIs of 1.42,
651 representing a *large* effect size. The airflow rate is 2.5 times that of the
652 reference scenario but the magnitude of the REI is highly dependent on the
653 emission rate, which is a function of volume of respiratory fluid released as
654 aerosols during. Further work is required to understand this.

655 4.2. High transmission spaces

656 The Skagit Choir and German Meeting superspreader scenarios have REIs
657 of 12 and 7 and *very large* effect sizes, respectively. These scenarios do not
658 amend C_{RNA} suggesting that the increased REI occurs here regardless of the
659 viral load of the infectious case. The choir scenario has a 35-fold increase
660 in the P_{50} emission rate attributable to an increase in the weighted average
661 droplet size and respiratory rate, which increases the volume of respiratory
662 fluid released as aerosols. The German Meeting has a modest 1.3-fold increase
663 in the P_{50} emission rate due to speaking, but the exposure period is the
664 longest of any scenario. This indicates that it is possible to generate a *very*
665 *large* increase in REI by increasing the exposure period and by increasing
666 the volume of respiratory fluid released as aerosols.

667 A REI of 0.68 is predicted for the Guangzhou restaurant corresponding
668 to a *large* effect size. Although the ventilation rate for this space is very low,

669 it is mitigated by the relatively short duration of exposure compared to some
670 of the other scenarios. However, the number of infections that occurred in
671 the space suggest that it is not a safe space and so a REI $\gg 1$ would be
672 expected. It could be that we have underestimated q_{inf} and the respiratory
673 activity. More vocalisation increases the geometric mean aerosol droplet vol-
674 ume [18] and, if the volume of conversations was high, it might also increase
675 aerosol generation [60]. Furthermore, air movement generated by a split air
676 conditioning system may have helped to spread the exhaled puff further; see
677 Bourouiba *et al.* [61].

678 It is also possible that the infector's viral load, C_{RNA} , is significantly
679 greater than that considered here; see the Supplementary Materials. This
680 suggests that even in a scenario with a low REI, there may be circumstances
681 where the risk may be substantially higher due to the characteristics of the
682 infector.

683 4.3. Other considerations

684 The results presented in the scenarios above illustrate how the relation-
685 ships between the physical environment, activity and time determined the
686 exposure to viral aerosols. However, it is important to acknowledge that this
687 model makes a number of assumptions which need to be considered when
688 applying the model in reality.

689 The model only considers aerosol transmission in a well mixed scenario.
690 In reality there are important variations in mixing which will change the
691 risk. The most significant is proximity to the infected person. Bourouiba *et*
692 *al.* [61] discuss turbulent gas clouds showing greater RNA concentrations
693 closer to source of infection. Then, close contact to exhaled *puffs* of breath

694 will substantially increase risk because the RNA concentration and therefore
695 virion is higher. This may result in enhanced aerosol exposure, as well as
696 direct exposure to large droplets that can land on the mucous membrane.
697 Several studies have explored this using idealised models, suggesting that
698 the concentration of aerosols at 1.5–2 m from an infectious source is deter-
699 mined by the room ventilation. At a distance of < 1 m the concentration is
700 determined by the exhaled plume and may be much higher [61, 62]. This risk
701 should particularly be considered in spaces with a high occupancy density
702 where it is difficult to maintain distance, or where the nature of the activity
703 means that it is essential to have closer contact. Similarly, the model pre-
704 sented here assumes a well-mixed space, which may not be the case in reality
705 [58]. In some circumstances this may be important and this, and the risks of
706 close proximity, should be considered and, if appropriate, investigated with
707 more detailed models, such as computational fluid dynamics, to be able to
708 quantify the transport of RNA copies around the space.

709 We have not considered any behavioural interventions in the model. Al-
710 though actions such as hand hygiene will not affect the outcome of this model,
711 the use of face coverings would have an important effect in reducing both
712 the source emission rate and the exposure; see Equation 13. These were de-
713 liberately excluded as the purpose of the model was to assess the physical
714 environment, but it is important to acknowledge that in some of the cases
715 presented here (the supermarket and coffee shop), face coverings are required,
716 which would reduce the REI further.

717 The scenarios presented here assume that only one infector is present in
718 the space. This is likely to be a valid assumption where prevalence of the

719 virus is low or the number of people sharing the space is small. However as
720 prevalence or occupancy increases, the probability of more than one infec-
721 tious source also increases. For large spaces this should be factored into the
722 analysis of the REI using Equation 13. Similarly the number of occupants,
723 and hence potential number of new cases of infection, is also not explicitly
724 included. The REI essentially gives an individual exposure risk, however this
725 may not give an accurate reflection of risks where there are a higher num-
726 ber of people; a high REI in a space with a very small number of occupants
727 could result in less secondary cases than a space with a lower REI but much a
728 higher occupancy. When considering the influence of a space on community
729 transmission risk, this is an important parameter.

730 The model only considers exposure and does not estimate the probability
731 of infection. The dose-response for SARS-CoV-2 is not yet known, however
732 information on dose-response behaviour for SARS and coronavirus 229E have
733 been used to estimate transmission by both air and surface contact routes
734 [39]. It is likely that the dose-response for SARS-CoV-2 is similar, following
735 an exponential or beta-poisson relationship with the exposure. This means
736 that there may be upper or lower thresholds for REI where transmission is
737 more or less likely to occur than that suggested by exposure alone.

738 Finally, it should be noted that although the probability of secondary
739 transmissions are likely to decrease with a corresponding reduction in the
740 REI, a low REI does not necessarily mean that infections will not occur. A
741 superspreader is likely to be uncommon, but will increase the RNA copy con-
742 centration in the air and hence the number inhaled by susceptible occupants.
743 High transmission events are likely to be a combination of high emissions, a

744 long exposure time, and poor ventilation in a confined space. All these are
745 important factors and the REI can assess how different indoor activities can
746 be related to the reference scenario by indicating if mitigation measures are
747 required.

748 5. Conclusions

749 A mass-balance model is developed for the number of RNA copies inhaled
750 over a period of time, $\sum n$, by the occupants of a well mixed indoor space
751 comprising six factors that can be moderated to reduce exposure risk. The
752 model is applied to a reference scenario, a standard school classroom with a
753 ventilation rate of $0.16 \text{ m}^3 \text{ s}^{-1}$ (51 l s^{-1} per person) and a total removal rate of
754 $0.21 \text{ m}^3 \text{ s}^{-1}$ (4.98 h^{-1}), and 32 occupants of which one is infected with SARS-
755 CoV-2, over a 7 hour school day. A Monte Carlo approach is used to quan-
756 tify uncertainty in predictions. It shows that $77 \leq \sum n \leq 352$ RNA copies
757 inhaled, with 95% confidence. The distribution of data is not normally dis-
758 tributed and so the median (P_{50}) is the most appropriate descriptive statistic,
759 and here $P_{50} = 172$ RNA copies inhaled.

760 The P_{50} for the reference scenario is used as a relative exposure index
761 (REI) by comparing it to predictions for other spaces. This is a measure of
762 the risk of a space relative to the geometry, occupant activities, and exposure
763 times of the reference scenario and so it is not a measure of the probability
764 of infection. It can be used to assess existing and new spaces and to assess
765 the efficacy of mitigation measures. The P_{50} can be modified in the future
766 as more evidence becomes available or to meet new demands, such as a need
767 to mitigate against more than one infected person.

768 The $\sum n$ is particularly affected by the respiratory rate of a susceptible
769 person, the emission rate of RNA copies, the exposure time, the space volume,
770 and the removal rate. A sensitivity analysis shows that predictions of $\sum n$ in
771 the reference scenario are most sensitive to the emission rate of RNA copies.
772 $\sum n$ is linearly related to the emission rate and so public health messages
773 to encourage self isolation when exhibiting symptoms of COVID-19 and the
774 wearing of face coverings are important.

775 If all occupants in a space are undertaking the same activity, the respira-
776 tory rate and the emission rate are related. Activities such as exercise and
777 singing increase the REI of a space because the volume of respiratory fluid
778 released as aerosols also increases. This is highlighted by a 1 hour workout in
779 a gym where the P_{50} REI is 1.42 when standard breathing is assumed. This
780 indicates that strenuous activity or singing indoors should be avoided. The
781 REI confidence intervals for an office, a high street coffee shop, and a su-
782 permarket are estimated to be < 1 , although varying the scenarios for these
783 spaces could lead to different estimations of the REI and will be the subject
784 of further work.

785 To achieve a REI of unity, and ideally less, a space must at least balance
786 the six parameters that affect $\sum n$. If the occupancy activities and exposure
787 time are identical to those of the reference scenario, then a removal rate of
788 of at least $0.21 \text{ m}^3 \text{ s}^{-1}$ per infected occupant must be achieved as a *minimum*
789 rate (of which ventilation is likely to be a primary component), irrespective
790 of the number of occupants present. Using a fixed air change rate will lead
791 to $\text{REI} > 1$ when its volume is less than that of the reference classroom. *Per*
792 *capita* airflow rates will cause the space to exceed unity when there are fewer

793 than 32 occupants present. Therefore, *per capita* and air change rates should
794 only be used with the minimum airflow rate. Here, using CO₂ sensors that
795 relate pre-determined concentrations to *per capita* ventilation rates could be
796 problematic if a space is under-occupied.

797 Ventilation strategies should decrease the residence time, which governs
798 the time taken to reach a steady state number of RNA copies in a space. This
799 can be achieved by increasing the airflow rate and by filtration and denaturing
800 in secondary air systems. The steady state number of RNA copies in a space
801 and $\sum n$ are also reduced by increasing the airflow rate, but there is a law of
802 diminishing returns. Maintaining adequate ventilation in the heating season
803 is particularly important because ventilation rates are often lower at this
804 time but risks must be balanced against the thermal comfort of occupants
805 and heating energy demand.

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Table 1: Scenario deterministic inputs

	Floor area	Room volume,	Occupants	Exposure	Infected occupancy	Conditions
	A_{floor}	V	N	time, T	time, T_I	
	(m ²)	(m ³)		(s)	(s)	
reference scenario	55	148.5	32	25200	25200	Step response
Class 750	55	148.5	32	25200	25200	Step response
Class 1000	55	148.5	32	25200	25200	Step response
Class 2000	55	148.5	32	25200	25200	Step response
Class 5000	55	148.5	32	25200	25200	Step response
Office	220	594	20	28800	28800	Step response
Office Low	220	594	20	28800	28800	Step response
Coffee	110	297	2	1800	1800	Steady state
Coffee Low	110	297	2	1800	1800	Steady state
Supermarket	4645	27870	160	3600	3600	Steady state
Gym	200	600	20	3600	3600	Steady state
Guangzhou	40.5	127	21	4500	4500	Step response
Skagit Choir	180	810	61	9000	9000	Step response
German Meeting	70	189	13	34200	34200	Step response

39

Table 2: General inputs

Input variable	Assumed PDF	Source
Biological decay, λ (s^{-1})	LN($1.75 \times 10^{-4}, 0.43$)	[25]
Inhaled deposition fraction, k	U(0.43, 0.65)	[48]
RNA concentration in exhaled droplets, C_{RNA} (RNA copies m^{-3})	N($3.75 \times 10^{17}, 3.75 \times 10^{18}$)	[8, 21, 22, 26, 63]
Surface deposition rate, γ (s^{-1})	U($1.17 \times 10^{-4}, 1.69 \times 10^{-4}$)	[47]
Concentration of aerosols in exhaled air, C_{drop} (m^{-3})	9.8×10^4	[18]

N, normal; LN, log-normal; U, uniform.

Table 3: Scenario probabilistic inputs

Input variable	Droplet diameter (μm)	Respiratory rates, $q_{sus}, q_{inf}, \bar{q}$ ($\text{m}^3 \text{h}^{-1}$)	Air change rate, ψ (h^{-1})	Airflow rate (l s^{-1})	Respiratory activity <i>breathing: talking: vocalisation</i> (%)
reference scenario	N(1.840,0.184)	N(0.440,0.044)	3.9	160	75:25:0
Class 750	N(1.840,0.184)	N(0.440,0.044)	12.2	505	75:25:0
Class 1000	N(1.840,0.184)	N(0.440,0.044)	7.1	296	75:25:0
Class 2000	N(1.840,0.184)	N(0.440,0.044)	2.7	110	75:25:0
Class 5000	N(1.840,0.184)	N(0.440,0.044)	0.9	38	75:25:0
Office	N(1.840,0.184)	N(0.560,0.056)	1.2	200	75:25:0
Office Low	N(1.840,0.184)	N(0.560,0.056)	0.2	40	75:25:0
Coffee	N(1.840,0.184)	N(0.560,0.056)	3.3	270	75:25:0
Coffee Low	N(1.840,0.184)	N(0.560,0.056)	0.2	16	75:25:0
Supermarket	N(1.780,0.178)	N(0.560,0.056)	1.1	8528	100:0:0
Gym	N(1.780,0.178)	N(3.510,0.351)	2.4	400	100:0:0
Guangzhou	N(1.840,0.184)	N(0.560,0.056)	U(0.2,0.4)	U(7,14)	75:25:0
Skagit Choir	N(2.50,0.25)	N(0.910,0.091)	U(0.3,0.7)	U(68,158)	0:0:100
German Meeting	N(1.840,0.184)	N(0.560,0.056)	0.2	105	75:25:0

N, normal; U, uniform.

Values are converted into SI units before they are applied to the model; see Section 2.1.

Table 4: Relative Exposure Index for common spaces and high emission scenarios

	$P_{2.5}$	P_{25}	P_{50}	P_{75}	$P_{97.5}$	μ	σ	C_v (%)	Cohen's d	Effect size
reference scenario	0.45	0.77	1.00	1.30	2.05	1.06	0.41	39		
Class 750	0.17	0.29	0.38	0.50	0.78	0.41	0.16	39	2.09	very large
Class 1000	0.28	0.47	0.62	0.80	1.25	0.66	0.25	39	1.19	large
Class 2000	0.59	1.00	1.31	1.68	2.71	1.39	0.55	39	-0.68	medium
Class 5000	1.02	1.77	2.33	3.02	4.84	2.49	1.00	40	-1.86	very large
Office	0.43	0.75	0.98	1.28	2.07	1.05	0.43	41	0.03	negligible
Office Low	0.67	1.22	1.63	2.16	3.55	1.76	0.75	43	-1.14	large
Coffee	0.02	0.03	0.04	0.05	0.08	0.04	0.02	38	3.48	very large
Coffee Low	0.03	0.05	0.06	0.08	0.12	0.07	0.03	39	3.40	very large
Supermarket ($\times 10^{-3}$)	0.45	0.77	1.01	1.30	2.05	1.07	0.41	39	3.63	very large
Gym	0.64	1.09	1.42	1.84	2.94	1.52	0.59	39	-0.88	large
Guangzhou	0.30	0.52	0.68	0.88	1.44	0.73	0.29	40	0.95	large
Skagit Choir	5.26	9.42	12.56	16.50	26.63	13.45	5.53	41	-3.16	very large
German Meeting	2.75	5.14	7.00	9.37	16.12	7.62	3.47	46	-2.65	very large

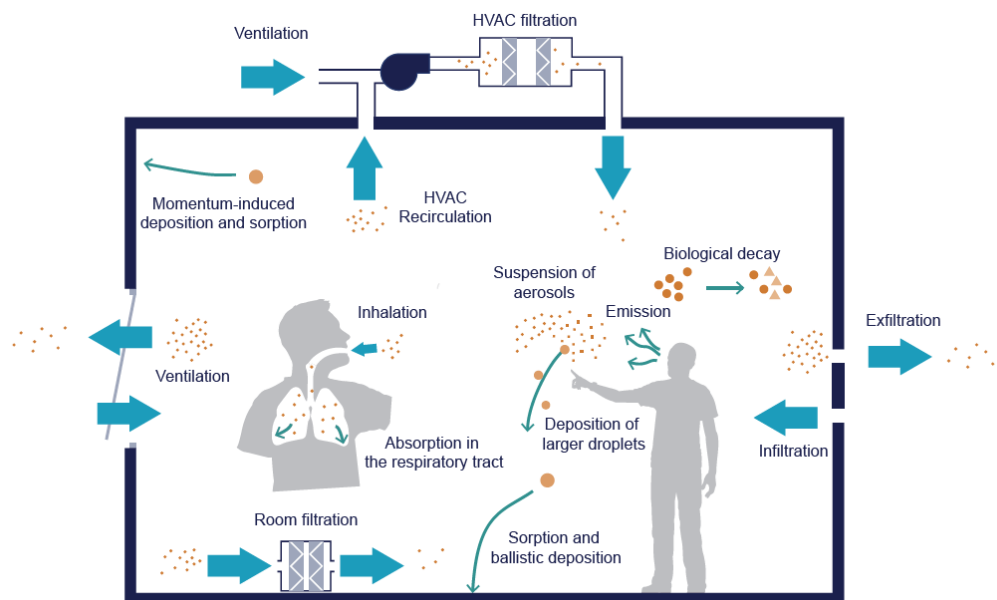


Figure 1: Single-zone mass-balance model of virus transport via exhaled aerosols.
Image used under a creative commons license¹.

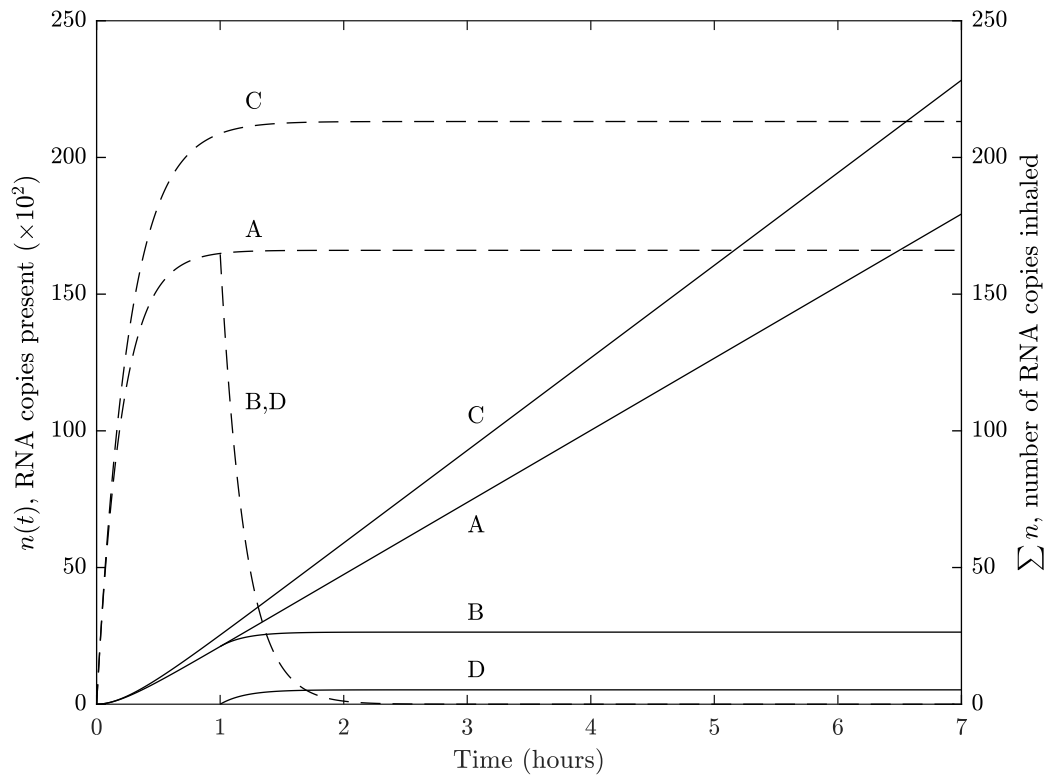


Figure 2: reference scenario: a single infector shedding RNA copies at a concentration of 3×10^9 RNA copies per ml of respiratory fluid in a standard school classroom with a volume of 148.5 m^3 .

—, number of RNA copies inhaled; - - -, RNA copies present.

A, constant emission over a 7 hour period; **B**, infected person leaves space after 1 hour and susceptible occupants remain; **C**, constant emission with removal solely via ventilation where $\phi = \psi$; **D**, at hour 1 the infected person leaves the space and is replaced by a susceptible person.

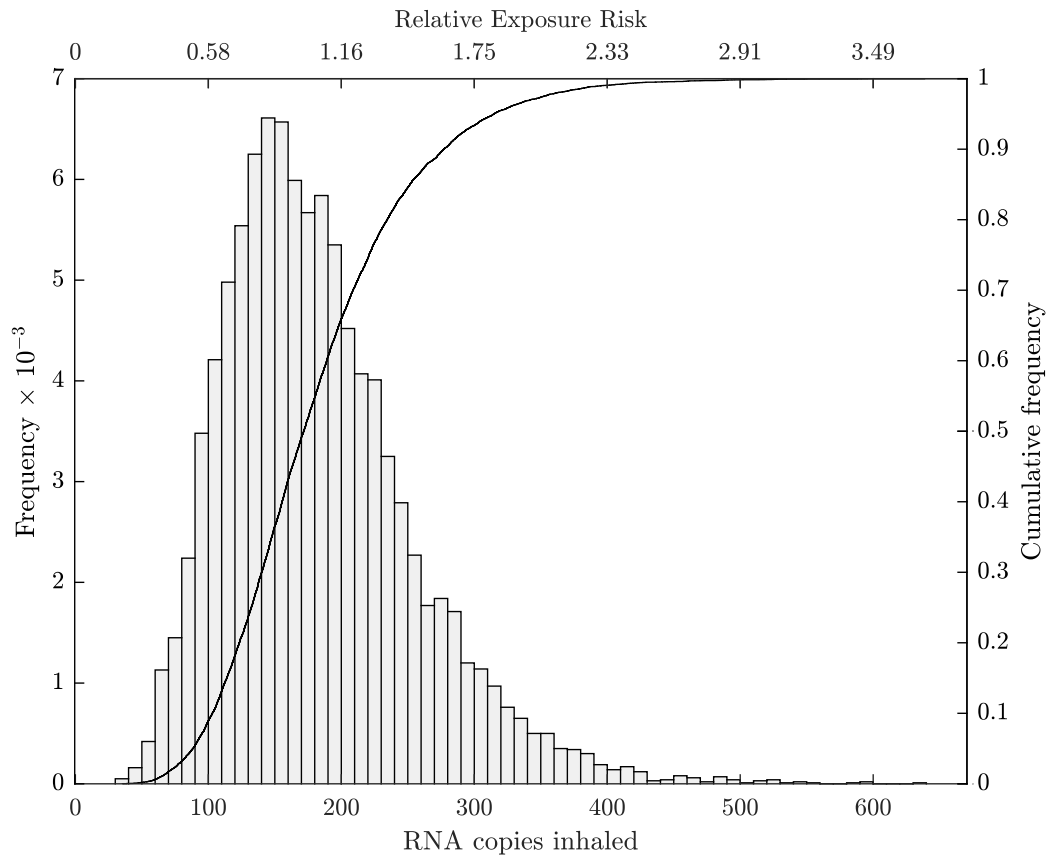


Figure 3: Reference scenario: uncertainty in RNA copies inhaled when a single infector is shedding RNA copies over a 7 hour period in a standard junior school classroom.

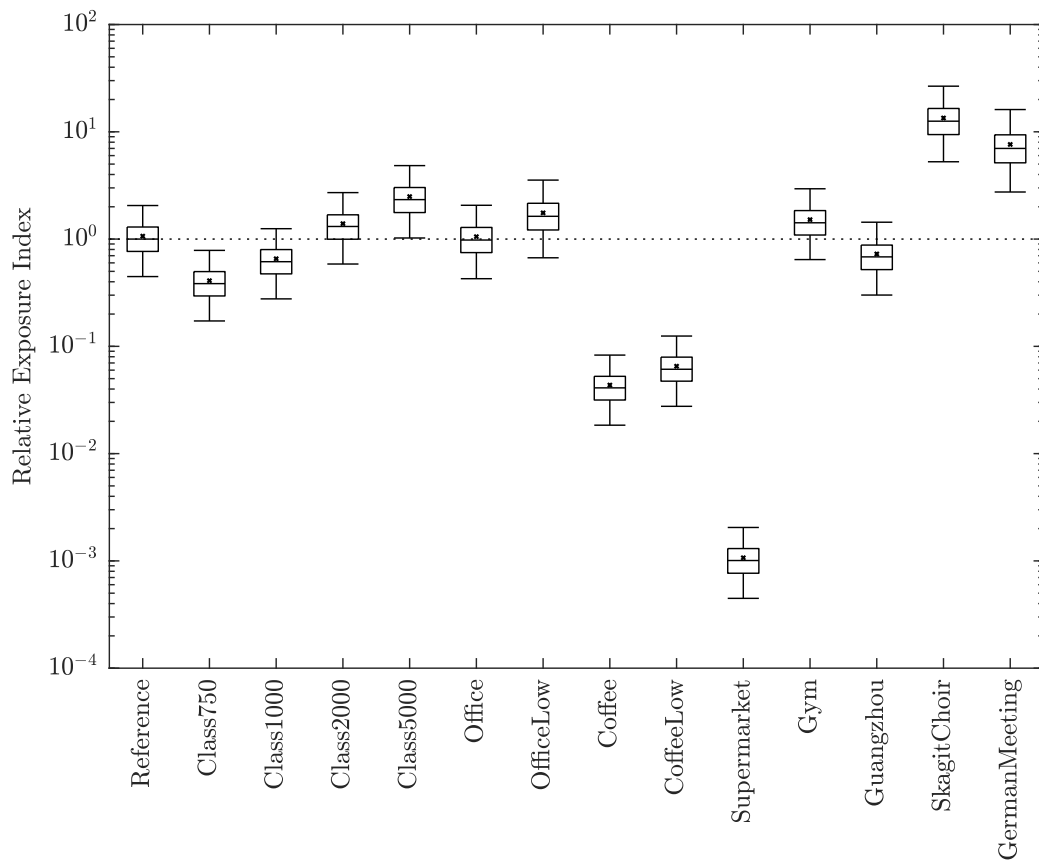


Figure 4: Relative Exposure Index. A comparison of RNA copies inhaled in common and high emitting spaces relative to the Reference Classroom geometry, and its occupants' activities and exposure time. The lower and upper bars are the 2.5th and 97.5th centiles, the central box bounds the inter-quartile range, the central bar is the median (P_{50}), and the cross is the sample mean. The reference scenario is the first entry with its P_{50} used as the REI, indicated by the horizontal dotted line.

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