Analysis

Visualising SARS-CoV-2 transmission routes and mitigations

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Key messages

- Communicating evidence that has very broad uncertainties or is difficult to quantify presents particular challenges, but needs to be attempted in order to support informed decision-making on actions to reduce transmission of SARS-CoV-2
- More than 18 months into the covid-19 pandemic there remains a paucity of robust quantitative evidence to compare the relative importance of different mechanisms of transmission, or to assess the effectiveness of environmental and behavioural mitigation measures
- Expert elicitation exercises can help to collate and synthesise knowledge from multiple sources. This paper describes the use of expert elicitation to underpin an interactive tool to visualise the ways in which SARS-CoV-2 is transmitted, and the likely effects of a range of mitigation measures in different contexts

- The visualisation tool helps to convey inherent uncertainties in the data, whilst providing a means to explore the relative influence of different mitigation measures

- This tool should support organisational and policy-facing decision-makers, and the public, to make evidence-informed decisions about how best to reduce transmission of SARS-CoV-2 in different contexts

Contributors and sources

The original transmission model was developed by HR, CN, SP, AS, AF, RM, and SF. HR, AF, SP and CN then worked with WST to develop the interactive graphic, which was shared with the other authors.

HR, CN, SP, AS, AF, RM, SF are all members of the Environment and Modelling Subgroup of the UK Government Strategic Advisory Group for Emergencies (SAGE EMG), from which they formed a working group to develop this project. WST is Data Graphics Designer at The BMJ. HR wrote the first version of the manuscript, and all other authors contributed to refining it. HR is the guarantor of this article.

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Conflicts of interest

We have read and understood the BMJ policy on declaration of interests. SF is a co-investigator on the UKRI AIRBODS research programme, CN is principle investigator on the UKRI TRACK, Breathing Cities and HECOIRA projects and co-investigator on the NIHR CONTACT study. SP is co-investigator on the UKRI TRACK project. HR, SF, AS, CN were on the working group for the Royal Academy of Engineering Infection Resilient Environments report. CN was on the working group for the Academy of Medical Sciences reports on COVID in 2020 and 2021. WST is employed by The BMJ but was not involved in, or privy to, any aspects of editorial decision-making either for this paper or the accompanying expert elicitation paper in BMJ Open.

Visualising SARS-CoV-2 transmission routes and mitigations

Harry Rutter and colleagues reflect on the challenges of conveying uncertain estimates for viral transmission in a complex system.

In order to make informed decisions, everyone - from members of the public to policymakers - needs access to easily understandable, relevant descriptions of the best evidence available. In support of this, many approaches have been developed to communicate quantified evidence to help decision-making for health, including tabular formats such as fact boxes [1–5]; graphical formats such as icon arrays [6–8]; and contextual aids such as risk ladders [9,10]. Health-related evidence incorporates a degree of epistemic uncertainty stemming from gaps in knowledge. In some cases, the use of large, well-designed randomised controlled trials may mean that this uncertainty can be quantified, and can be communicated as a range [11], alongside indicators of the unquantified uncertainties, such as the quality of the underlying evidence [12–16]. However, in many cases – particularly in the context of complex public health problems - the complexity of relations between causal factors may mean that there is not only high epistemic uncertainty about the variables in the system, and about how they interact, but also a high degree of variability due to individual and environmental factors. This is a major challenge in describing the transmission and mitigation of SARS-CoV-2, for which the multiple variables cannot be precisely quantified as they are both contingent on one another, and on the specific characteristics of the complex adaptive systems within which they are considered.

Whilst scientific understanding about the epidemiology, genetics, and continuing evolution of covid-19 has been transformed since the disease was first identified at the end of 2019, and there has been astonishingly rapid development and deployment of highly effective vaccines, evidence on how and where the virus transmits remains limited and evolving. As covid-19 moves from pandemic to endemic, and many countries start to lift restrictions, individuals and organisations are increasingly faced with difficult personal and policy choices, such as how to make a workplace or a public area as safe as it can be whilst still being open and functional, or how to protect oneself and others. Such decisions continue, of necessity, to be made under considerable uncertainty.

Evidence on Transmission Routes

Understanding the current evidence around SARS-CoV-2 transmission and mitigation is an essential step towards taking informed decisions on protective measures, but there have been few attempts to collate and communicate the multiple factors that determine transmission, or to illustrate them using a systems-level representation in which different variables are contingent on one another. Many studies have looked at the factors that affect one particular transmission route, such as the influence of ventilation on airborne transmission [17] , and a small number have grouped risk factors such as ventilation, face coverings and activity into simple risk frameworks [18]. However, there is little that considers all of the transmission routes and environmental and behavioural mitigations together; this is unsurprising given the difficulties of representing such poorly-quantified and interacting variables.

There are many reasons for the paucity of robust empirical evidence on transmission of SARS-CoV-2, and for the effectiveness of mitigation measures. It is extremely hard to measure infectious SARS-CoV-2 virus in real world contexts, especially when airborne. Even if the virus were easily detectable, it only remains infectious outside the body for a relatively short period, far shorter than the time taken for an outbreak to become apparent and the relevant environment then examined. Transmission is highly contingent on multiple factors, including the viral load of the infected person; his or her symptoms; the characteristics of his or her respiratory and other behaviours; physical configuration and other aspects of the transmission location such as ventilation, temperature or humidity; the specific nature of any mitigation measures such as quality of any face mask, or the exact nature of any surface cleaning; behavioural responses and adaptations in light of mitigation measures; and wider contextual factors such as population prevalence, vaccination, and immunity levels of those exposed.

Despite the difficulties of precise quantification, there is much that is qualitatively known about SARS-CoV-2 transmission. There is wide acceptance that spread is most likely through three major routes, all arising from the respiratory tract of an infectious person [19]. When that person breathes, speaks, coughs, talks, or sings, particles which can potentially carry the virus are emitted in a continuum of aerosol and droplet sizes, from very small (<10 micrometres diameter), through medium (10-100 micrometres), to large (>100 micrometres)[20,21].

Transmission at *close proximity* to an infectious person is likely to be through a combination of mechanisms of exposure through inhalation of all sizes of particles up to around 100 micrometres, together with possible exposure to larger ballistic droplets that could land directly onto mucous membranes (i.e. eyes, nose) [18,19]. Long-range *airborne* transmission can occur through exposure to the smallest particles which remain suspended in the air, travelling beyond 2m from the source through airflows within an indoor environment, particularly if the ventilation rate is low [17,22].

Transmission via *surfaces or fomites* appears to be less significant than inhalation [23,24], but can potentially occur through contamination of surfaces by deposition of larger particles or via an infected person's hands [25], from where they can then be potentially passed by subsequent touch onto the hands, and then into the eyes, mouth or nose of a susceptible person [26]. There are possible variations on these routes, such as direct contact from an infected person who has placed their fingers in their nose or mouth. While there is a theoretical possibility of faecal, urinary, or sexual transmission [27–31] none of these have been confirmed in humans.

Despite extensive knowledge about the physics of aerosols, the absence of unequivocal empirical evidence on the amount of virus carried by different particle sizes, the relative contributions of surface, droplet, and airborne spread, or on the effectiveness of different mitigation measures has led to considerable uncertainties and difficulties in achieving scientific consensus. This has impeded clear communication of the roles of the different pathways in different situations.

Initial guidance from the World Health Organisation (WHO) only emphasised the importance of aerosol transmission in the limited case of 'aerosol generating procedures'- such as endotracheal intubation or bronchoscopy - in healthcare settings [32]. The importance of airborne transmission more generally was highlighted in a letter signed by 239 international scientists [33]. Subsequent WHO guidance has acknowledged the possibility of aerosol spread in confined indoor spaces [34,35]. A systematic review (at the time of writing still in pre-print and not approved by two of three reviewers) commissioned by WHO concluded '*The lack of recoverable viral culture samples of SARS-CoV-2 prevents firm conclusions to be drawn about airborne transmission'*[36] . This prompted a Comment paper in the Lancet in April 2021 arguing that '*there is consistent, strong evidence that SARS-CoV-2 spreads by airborne transmission* '[37].

At the heart of the challenge of communicating the relative importance of these transmission routes and their potential mitigation methods to decision-makers (including the public) has been the uncertainty around quantification of the absolute likelihoods of transmission, and the amount of variation in them due to different conditions. However, communication of evidence, and decision-making based on it, does not inherently require precise quantification: it can be based on relatively 'fuzzy' estimates, appropriately conveyed. Such quantification – which should include uncertainties based on both quantified and unquantifiable uncertainties, as well as on individual variation – should take into account both qualitative and quantitative expert knowledge, as well as empirical evidence.

Visualising transmission routes

In the absence of 'hard' empirical evidence, it is nevertheless important for people to be able to make decisions based on the best available knowledge about a topic. To support such decision making, we conducted an exercise to elicit expert opinions on the state of knowledge about SARS-CoV-2 transmission (Box 1), and then to represent these opinions in as intuitive and useful a way as possible using an interactive tool (Box 2). Our aim was for the tool to summarise and communicate the best available evidence – including the expert knowledge that lies outside of quantified uncertainty ranges - while also conveying the evidential uncertainty and variability, and the disagreement that exists between experts about a number of the pathways and the interventions.

Given the infeasibility of basing the tool on a systematic review of empirical evidence, and the amount of knowledge held within the expert community that is not reflected in published quantitative evidence, a formal expert elicitation exercise was appropriate. This method allowed us both to adduce estimates of transmission risks across the multiple different scenarios under consideration, and to identify the levels of agreement and uncertainty of each estimate, both of which can displayed within the tool. While the empirical evidence base is not directly represented within the tool, it is embodied within the responses of the experts who contributed their knowledge, including providing references to evidence that they were aware of.

It is notable that, notwithstanding disagreements revealed by the expert elicitation exercise, the inhalation routes dominate in almost all situations, and face coverings, especially when worn by an infected person as a form of source control, are the most important mitigation measure. It is, however, equally important to note that all routes were considered to play a part in transmission, and simple measures such as physical distancing, hand washing, and respiratory hygiene make a useful contribution: the fact that specific transmission routes are relatively more important in some situations does not remove the need to consider all relevant transmission routes in all situations.

One source of uncertainty that we had not anticipated sufficiently was disagreement between experts. Our expert elicitation exercise revealed a wide range of opinions concerning the role of aerosol transmission, but also divergent views for several other variables, such as the amount of small particle inhalation at different room sizes; the effects of different kinds of masks on inhaled aerosols; and the effects of face coverings on transfer from hand to eyes, nose, and mouth. Some of this variation may be the result of divergent epistemological perspectives, with some individuals prioritising empirical data specific to SARS-CoV-2, while others placed a greater emphasis on robust theory and generalisable evidence from other contexts. We incorporated this expert disagreement information into the graphic in a deeper layer, where viewers can click to see alternative views. Here they can also see the embedded uncertainties – how highly experts rated the quality of evidence on that particular variable.

Reducing quantifiable uncertainty

The continued existence of a wide range of expert views more than 18 months since covid-19 was first described reflects both the complexity of the methodological challenges and a lack of sufficient interdisciplinary and strategic research studies during and prior to the pandemic. Generating robust evidence on the complex and highly contingent routes of transmission of SARS-CoV-2 is not straightforward, but it is important that over the coming months and years the impressive scientific attention paid to vaccines and viral genomics is matched by an equivalent focus on research to increase our understanding of the ways in which the SARS-CoV-2 virus behaves, how it is transmitted, and how we can most effectively reduce the likelihood of transmission, through individual, local, and societal-level interventions.

Improving our response to the next pandemic will require a multiplicity of actions, with many of them relating to the capacity, structures and resources devoted to research. But as well as these practical factors, equally important will be a willingness to embrace a range of scientific perspectives, with a focus on identifying the most relevant and appropriate evidence available to guide decision making, whether it is based on empirical research or theory, and whatever the balance between qualitative and quantitative data. The same is true of many of complex public health challenges, where it is rarely possible to rely on the kinds of high-quality, high-precision quantification methods that are used in the evaluation of pharmaceuticals or surgical procedures [38].

We hope that this visualisation tool will be useful for exploring transmission routes in a transparent and interactive way, and will help to guide those facing decisions over which mitigation measures might be most effective to protect themselves and others from the continued challenges that this virus presents. We also hope that the approach we have taken both to eliciting and communicating knowledge will prove helpful to those faced with the challenge of communicating complex, imprecise and uncertain evidence in the future.

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Box 1: Visualising uncertain evidence of viral transmission and mitigation

Evidence synthesis through expert elicitation

Having devised a simple illustration of the most likely transmission pathways for SARS-CoV-2 we wanted to be able to give the public and decision-makers an indication of expert opinion on the relative importance of each, and the effects of different mitigations. In order to attach even imprecise estimates to the variables within the simple illustration (over 100 of them), we used a two-stage elicitation process during February and March 2021. This allowed us to bring together the current knowledge – qualitative and quantitative - amongst international experts in a range of scientific disciplines on the likely rates of transmission along each pathway, a process we describe elsewhere [ref to be added when available]. We chose this method specifically to provide the data needed to underpin an interactive, online visualisation tool, intended to be of value to a broad audience. While a number of figures depicting transmission routes and mitigation measures have been published previously [39–41], as far as we are aware this is the first attempt to provide an interactive tool integrating knowledge from experts across many domains.

Our process was designed to help individuals or risk managers considering a single encounter in which a susceptible person might come into contact with an infected person. It did not attempt to address population-level factors that affect transmission, such as prevalence of infection, socio-economic factors, or the level of vaccination; nor did it engage with individual-level contextual factors such as vaccination status, occupation, or household composition. While all these factors are extremely important they would have added considerable additional complexity and uncertainty. However, we do not in any way wish to diminish their importance for the implementation of public health measures, and the outputs of the tool need to be considered in the context of these wider factors.

We used a conceptual model of transmission that includes seven respiratory activities, in two different room sizes, each with or without ventilation, as well as outdoor environments, and three forms of contact on three types of surface, across six transmission pathways, with ten possible mitigation interventions. Given this large number of parameters, with appreciable uncertainty and variability around all of them, and the extreme difficulty of measuring almost any of them in a precise and consistent way, even a richly populated empirical evidence base would struggle to allow a systematic review that could generate meaningful findings to underpin the visualisation tool. The severely constrained empirical evidence base that we would have had to rely on could thus only have provided a highly partial – and thus highly misleading – grounding for the tool.

The tool uses the findings of the expert elicitation process to illustrate the relative importance of different transmission pathways, and the likely effects of mitigation measures upon those pathways, in the context of a range of different scenarios. These scenarios include the nature of respiratory activity concerned, ranging from the infected person being silent to coughing or singing.

We developed this tool prior to the dominance of the more transmissible delta variant, and new evidence relating to transmission is published all the time. If we were to repeat the exercise it is possible that some of the relative roles of different transmission routes and mitigations measures might have increased or decreased in importance, but the core features of the visualisation are very unlikely to have changed substantially. If important evidence were to arise that invalidated any elements of the tool it could be amended.

Box 2 Representing scenarios visually

One core task was to devise a method for clearly communicating uncertainties, imprecise quantities, and expert disagreements in a way that still proved useful for decision-makers. In addition to uncertainty about potential transmission routes and mitigations, there is a great degree of variability and contingency within every scenario represented. Individuals will differ in their viral loads, their breathing and speech patterns, and their behaviour; environments will differ in factors such as ventilation rates, air-flow patterns, temperatures, and humidity. All of these could affect the likelihood of transmission – which is itself a probabilistic event. These uncertainties all needed to be considered in the tool.

The interactive graphic we developed illustrates the majority opinion of experts in the final round of the elicitation process for most variables. It was deliberately not intended to represent a precise quantitative model for viral transmission. Instead, it is designed primarily as a communication tool to aid decision-making: providing a simplified model of the relative transfer of virus between two individuals in order to allow the user easily to compare relative transmission routes in different environments and with/without various mitigation measures. To prevent unwarranted assumptions about precision based on the diagram, and to convey an appropriately high level of uncertainty, we chose to use a smooth colour gradient to represent the expert-elicited values. Colour is both intuitive for audiences to interpret and, with a smooth gradient, can communicate imprecise values whilst allowing general comparisons of relative values [42]. Thus, to illustrate relatively higher transmission rates we show darker coloured routes, and vice-versa, but these tones should not be seen as representing precisely quantified differences.

For those interested in the actual estimated uncertainty ranges (including epistemic and aleatory uncertainties, as well as anticipated variation within a scenario), each “node” in the diagram, each mitigation, and each scenario, was given a small blue “i” button. When selected, these display the size of the quantified uncertainty range elicited from experts for each variable, as well as their estimates of the quality of the evidence base for each variable (on a 1-5 scale), and a text description of the causes of uncertainty and variability that were listed. Where there were differences of opinion amongst groups of experts, their alternative opinions are also shown in the form of ranges in the same pop-up window.