Witness Name:
Christophe Fraser
Statement No.:
M7/Fraser/01
Exhibits:
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UK COVID-19 INQUIRY

WITNESS STATEMENT OF Professor Christophe Fraser

I, Christophe Fraser, will say as follows: -

Present position and career history

1. I am the Moh Family Foundation Professor of Infectious Disease Epidemiology based in the Nuffield Department of Medicine at the University of Oxford. I am part of the senior leadership team of the University's newly founded Pandemic Sciences Institute.

2. Since 1999, I have worked on public health and infectious diseases. My team uses mathematical modelling, pathogen genomics and big data analysis to understand the drivers of infectious disease transmission. We design, support and evaluate public health interventions. My team is particularly focused on areas that benefit from scientific and technological innovation, rather than on the application of tried and tested methods. As part of academic leadership, I have directed a pathogen genomic sequencing laboratory, a mathematical and computational modelling group, and led interdisciplinary international research consortia.

3. **During the COVID-19 pandemic,** I proposed, contributed to the design of, and analysed the UK's digital contact tracing programme, and in particular the NHS

COVID-19 app. My team and I worked as academic consultants for NHSX (a government body tasked with developing best practice for use of data and digital systems in the NHS, which has since merged into NHS England), DHSC, NHS Test and Trace, UKHSA and NHS England, in close collaboration with the wider NHS COVID-19 app team and Go-Science, and with external support from IBM, Google and faculty.ai.

4. In addition to this work, within the national COG-UK (Covid-19 Genomics UK) consortium, we generated a large volume of SARS-CoV-2 genetic sequences. My team also generated and supported an agent-based simulation - called OpenABM-Covid19 - that was used by the NHS England for scenario planning at the NHS Trust level. And finally, we briefly worked with the Rapid Testing Consortium led by Professor Sir John Bell to support the UK's deployment of lateral flow antigen tests.

5. **Career history prior to COVID-19.** I trained as a theoretical physicist, with a first degree (1994), PhD (1997) and postdoctoral fellowship in Physics, before being awarded a Wellcome Trust training and research fellowship aimed at converting to Mathematical Biology (1999-2002). During this conversion fellowship, I trained with Professors Roy Anderson and Neil Ferguson at the University of Oxford and then Imperial College London. From 2004 to 2016, I was at Imperial College London, first as a Lecturer (2004) then Reader (2006) and then Professor (2009) in the Department of Infectious Disease Epidemiology. In 2016, I moved to the University of Oxford, where I was appointed as Professor of Pathogen Dynamics in the Big Data Institute. In 2022, following an endowment from the Moh Family Foundation, I was appointed as the Moh Family Foundation Professor of Infectious Disease Epidemiology in the newly formed Pandemic Sciences Institute.

6. **The Pandemic Sciences Institute,** led by Professor Sir Peter Horby (head of the UK's celebrated RECOVERY trial) and including Professor Dame Sarah Gilbert (inventor of the Oxford-AstraZeneca vaccine), was founded in 2021 with a mission to do research that advances our capacity to respond to new and

emerging pathogens with pandemic potential, and to increase our preparedness to pandemics.

7. **My team's current research** is focused on two new research projects. The first is called The Oxford Martin School for Digital Pandemic Preparedness, that I direct. Oxford Martin School programmes bring together teams within the University of Oxford to focus on interdisciplinary questions of long-term importance. In this case, in addition to ourselves in the Department of Medicine, we include leading professors in Public Health, Statistics, Biology, Economics and Philosophy. We aim to develop a Blueprint for future integrated digital responses to Emerging Pathogens and Pandemics.

8. The second project is called PREparedness using Simulated Trial Optimisation (PRESTO). As part of an international partnership funded by the intergovernmental NGO the Coalition for Epidemic Preparedness Innovation (CEPI), we are using simulations to find out how we can accelerate clinical trials of new vaccines during the earliest phases of epidemics, without sacrificing any of their scientific rigour.

Prior work on analysis of emerging infections, modelling Test Trace Isolate and Quarantine (TTIQ)

9. Between 2003 and 2016, I worked as a Professor in the Medical Research Council Centre for Outbreak Analysis and Modelling at Imperial College London. In that role, I participated in analysis of outbreaks and epidemics. Of relevance, I developed mathematical models of TTIQ that would lay the foundation for our work on the NHS COVID-19 app during COVID-19.

10. Specifically, in 2003-2004 I worked in one of the two teams analysing the SARS-CoV-1 outbreak. That epidemic – involving a pathogen genetically similar to the virus causing COVID-19 – started near Guangdong in China and resulted in cases in 28 countries, with sustained spread in 6 countries. The outbreak caused 8096 recorded cases, of whom 774 died. The outbreak was contained using a policy of TTIQ with few additional measures. I co-led a paper

analysing the outbreak in Hong Kong, highlighting the importance of super-spreading (Exhibit CF/01 [INQ000270158]). I published several follow up papers on modelling TTIQ policies explaining their relative success in containing this virus (Exhibit CF/02 [INQ000574807], Exhibit CF/03 [INQ000574806]). We concluded that the control of SARS-CoV-1 was made a lot easier because most transmissions came from people who were already clearly symptomatic. We developed mathematical models and computer simulations of TTIQ where the proportion of transmissions from people who were symptomatic was a key parameter, and showed that this parameter is as important as the basic reproduction number R_0 in determining the effectiveness of TTIQ in reducing spread. This is important because one of the key ways in which SARS-CoV-2, the virus that causes COVID-19, is different from SARS-CoV-1, is that for COVID-19, only about half of transmissions come from people who are clearly symptomatic.

11. From 2004-2016 I worked on HIV epidemic dynamics and also on antibiotic resistance in bacteria. From 2008-2016, I was the Deputy Director of Imperial College's MRC Centre for Outbreak Analysis and Modelling (the director was Professor Neil Ferguson).

12. In 2007, I published a new method for estimating an epidemic's *R* number, called the renewal equation (Exhibit CF/04 [INQ000574804]). By 2020, statistically robust elaborations of this approach by collaborators and by others were the most widely used method for estimating *R* for COVID-19.

13. In 2009, I co-led the first published analysis of the emerging epidemic of novel swine influenza (H1N1pdm), showing that the spread was already extensive by the time this new virus was discovered, and also showing that the virus was likely relatively mild (Exhibit CF/05 [INQ000574813]). I regularly attended SPI-M to present and discuss these results. During this period I gained some understanding of the nature of scientific advice in the UK government, and in particular of issues surrounding school closures. During the spring of 2009, several policy options including extending school holidays were considered, but there was a clear steer that school closures, even for a week, would cause

harms to children which needed to be considered alongside any benefits of delaying the epidemic waves.

14. In 2015-2016, I worked with the WHO International Ebola Response team, analysing the epidemic devastating West Africa, providing analytical support (remotely, from within Imperial College). This epidemic spread principally in three countries, leading to 28,646 confirmed cases of whom 11,323 died. Many more people are estimated to have died later due to disruption to the healthcare and public health infrastructure. I led analyses quantifying the factors that determine the risk of the virus spreading and quantifying the impact of different non-pharmaceutical interventions in limiting spread (Exhibit CF/06 [INQ000574805]). We submitted regular reports to SAGE (at least once a week). TTIQ was one of the interventions used to help control Ebola. During this work, we also observed that TTIQ is a rich source of data that gives insight into the dynamics of spread, the risk factors for transmission, and the effect of control measures in limiting spread. The two policies that had the greatest impact in controlling the epidemic were likely those of 'safe and dignified funerals' and high levels of compliance with personal protective equipment amongst health care workers within Ebola Treatment Units. The UK was the lead international responder in one of the most affected countries.

15. After moving to Oxford in 2016, I shifted my work to focus on HIV/AIDS, leading an international consortium to apply modern methods in pathogen genomics and mathematical modelling to improve HIV prevention in Southern Africa, in communities where approximately one in four adults are infected with the virus, for which no cure or vaccine exists.

Early analyses of COVID-19: Severity, NHS Capacity, Pre-symptomatic transmission, and Test Trace Isolate and Quarantine

16. Like many other epidemiologists globally, I followed the emergence of COVID-19 in Wuhan very closely. We started tracking the infectiousness and severity of the virus through January 2020, and by the end of January it became clear that with the basic reproduction number (R_0) greater than 2 and the infection

fatality ratio around 1%, this was going to be a severe event. On January 30th, senior staff in Oxford University's Medical Sciences Division met for the first of what became weekly meetings. I reported that both in my opinion, and in the opinion of colleagues I had spoken to in different countries, this was likely to be a pandemic of major international consequence. Sarah Gilbert reported on their vaccine candidate, a repurposed version of their vaccine for MERS-CoV, and presented a timeline of clinical development that seems accurate in hindsight. This ChAdOx vaccine candidate became the Oxford-AstraZeneca vaccine. Peter Horby reported on initial efforts to start clinical trials of therapeutics in China, an effort which led to the foundation of the RECOVERY trial in the UK. The head of department and the head of division were both present, encouraged us to pause all business as usual and to focus on the emerging epidemic; they emphasised that the university would help us deal with the administrative and financial consequences of this pivot. The meeting has been publicly described (Exhibit CF/07 [INQ000574808]).

17. Given the timeline and plausibility of development of therapeutics and vaccination, I felt that the priority that I could help with was supporting public health efforts to hold back the tide of the epidemic until treatments and vaccines became available. I was in touch with several members of SAGE to emphasise the point that there were substantial and realistic efforts to develop these treatments and vaccines, and that policy should be developed accordingly.

18. During February 2020, we collated data from preprints (preliminary academic publications released before peer review) and web reports on the clinical severity of COVID-19 in Mainland China, Taiwan, Hong Kong, and Singapore. These data were consistent with 1% infection fatality rate, but with a larger fraction of individuals being assessed as needing oxygen support in hospital. I became concerned that the fatality rate would be higher if hospital capacity were exceeded, and met with staff at the Oxford John Radcliffe hospital to understand their needs. I developed a simple mathematical model of spread adapted to the level of the Oxfordshire NHS Health Trust, as we had ready access to data on capacity including during winter influenza surges. We rapidly

concluded that an unmitigated epidemic would exceed hospital capacity many times over. Preventing this required reducing the reproduction number *R* close to or below 1. If this is achieved, it is only marginally more demanding to contain spread altogether, and I therefore thought that it would be best to keep spread to low levels until treatments and vaccines were widespread. Several countries pursued this strategy, including Norway, Denmark, New Zealand, Australia, Singapore, Taiwan and South Korea. This was different from what became known as the COVID-zero strategy, since the aim was to keep *R* below 1 for a period of time until better options became available. I also argued that this strategy does not need to be synonymous with a lockdown, since it would be possible to analyse, adapt, and find which measures bring the most benefit for least harm. I offered to present these analyses to SPI-M but this was declined, as their focus was on national models and policy.

19. During February 2020, after discussions with several colleagues, it became clear that it would be useful to model TTIQ in the context of the new virus. I decided to start with the mathematical modelling framework that I had developed in 2003 to model TTIQ for SARS-CoV-1, a virus that is genetically similar to the virus now causing COVID-19, appropriately enough called SARS-CoV-2. A startling difference that became immediately apparent from case reports was that many people appeared to be infected by asymptomatic source cases; over 70% in the case reports from China CDC. I contacted a colleague in Hong Kong to discuss this, and confirm the validity of the results, which he did. We also consulted the dashboard of the Singapore ministry of health. They found that whilst many people seemed to have asymptomatic source cases, these source cases themselves usually became symptomatic after a few days. This proved that transmission was likely happening before people became symptomatic. Our estimates rapidly converged on about 50%, half of all transmissions, coming from cases that were not symptomatic at the time of transmission. Using my framework from 2003, this was precisely the scenario where epidemic control with TTIQ is very challenging, due to the need for extreme speed in reaching contacts. I first presented these results to a medical and a statistical audience, with a rather pessimistic outlook on the potential for TTIQ to make a substantial impact on reducing the spread of COVID-19. My

outlook changed on 3 March when we had the idea that if TTIQ could be digitised with a phone app, then it could be turned from a laborious, slow, human-intensive process to an instant and scalable process.

Contact tracing apps: rapid transition from concept to development

20. **Initial concept.** On 3 March 2020, after reading news articles about the use of smartphone apps for COVID-19 in different countries in Asia, my colleagues and I developed the concept of a smartphone contact tracing app. It seemed intuitively obvious that if an app on each phone recorded a memory of time spent in proximity to other phones using the same app, and then one of the people developed COVID-19, all other users could be notified instantly. We developed a visual representation of this process.

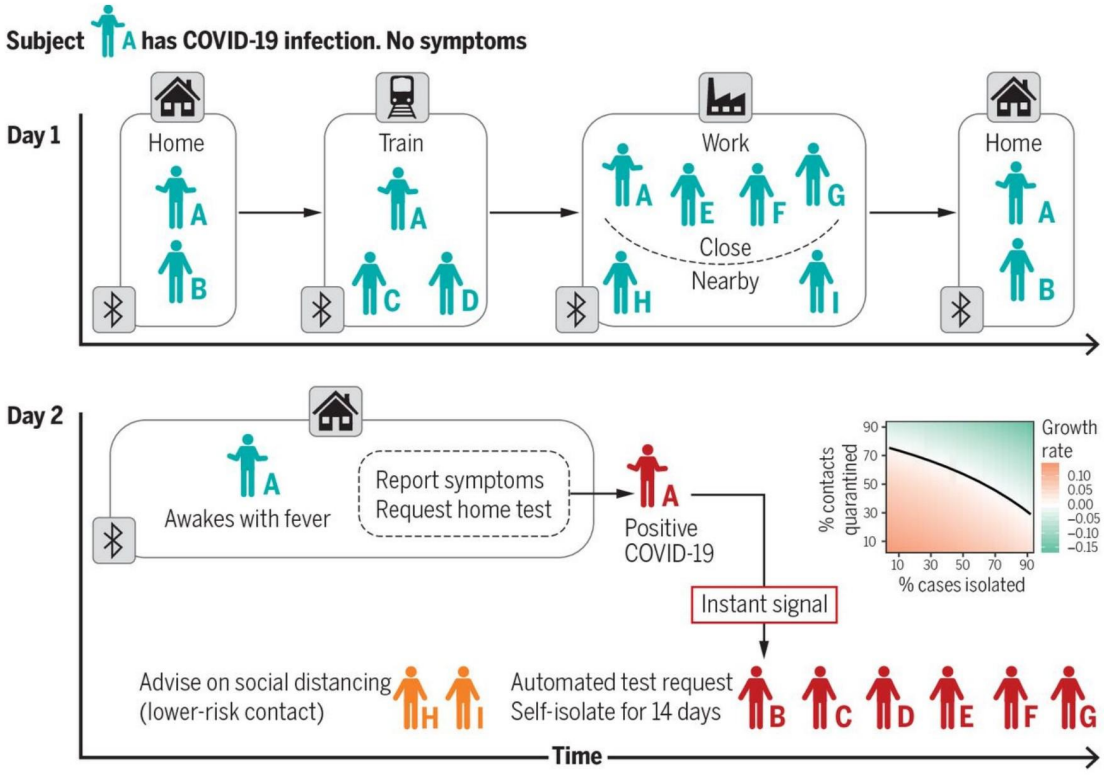


Figure legend: The figure shows a group of individuals, each using a Bluetooth contact tracing app that records physical proximity and duration of contact between them on day 1. On day 2, person A is sick and tests positive for COVID-19. The other people are

instantly notified and depending on how close and long their physical interaction was on day 1, they are either advised to be cautious (amber warning) or asked to self-isolate in line with national guidelines (14 days at the time this paper was written). The inset shows the output of the mathematical model that predicted the impact of this system on the epidemic growth rate dependent on the uptake of testing, tracing and self-isolation. From reference (Exhibit CF/10 [INQ000574799]). (In the end, the UK NHS COVID-19 app did not issue amber warnings, though for example the German CoronaWarn app that used the same Google Apple system did.)

21. In fact, this idea was not original: a group in Cambridge had developed the 'flu-phone' a decade earlier, and the UK's BBC had used a Bluetooth proximity app for a Pandemic simulation in 2018. In early 2020, several groups proposed digital contact tracing apps contemporaneous with UK efforts, notably in the Fraunhofer institute in Germany, and in the government digital transformation team in Singapore. Several groups also got involved early in the USA, with MIT and Microsoft providing some degree of coordination.

22. Our work in Oxford nonetheless garnered a substantial amount of attention. I can only speculate as to why, but relevant factors might include:

- that we were epidemiologists not technologists;

- by quantifying the transmission drivers of COVID-19, we found that 50% of transmission was from people who were pre-symptomatic, pauci-symptomatic or asymptomatic. We therefore found that a contact tracing app addressed a real present issue;

- that we could leverage the modelling work that I had led in 2003 on the problem of modelling the effect of TTIQ on coronavirus outbreaks;

- that the population adoption and sophistication of smartphones made the widespread use of digital contact tracing technically feasible and at least plausible in a way that it had not even a decade earlier.

23. My team and I developed the model of how a contact tracing app would impact the spread of COVID-19. We realised that there were a range of scenarios with very high population adoption, where instantaneous TTIQ could contribute substantially to preventing epidemic spread altogether, and that with lower population adoption, spread could be slowed especially in the context of a combination of other non-pharmaceutical interventions such as social distancing.

24. We decided to follow best practice in assuring the robustness and utility of our models. First, we double coded the model, to ensure that the findings were replicable and to increase the likelihood that they were technically correct. Second, following guidance from an article by Chris Whitty called "What makes an academic paper useful for health policy" (Exhibit CF/08 [INQ000574817]), we developed a version of the model where readers could explore a range of assumptions on uptake of primary testing or secondary quarantine, with outputs showing the full range of assumptions from 0% to 100% and also vary other assumptions of the model. Third, as we realised that there were substantial ethical considerations, including privacy, we reached out to my colleague Michael Parker, Professor of Bioethics, and director of the Ethox centre, to discuss the proposal with him. Fourth, we committed to transparency: we posted our findings online on March 8th (Exhibit CF/09 [INQ000574811]) – our site is here https://github.com/BDI-pathogens/covid-19_instant_tracing – and shared the preprints with selected colleagues proactively asking for critique, with our contacts including the Technology Innovation Team at the Bill and Melinda Gates Foundation, and the Office of the Chief Scientist in the UK. Fifth, we committed to scrutiny and peer review, and so submitted our preprints on March 6th for consideration in the journal Science who have a track record of garnering rapid yet rigorous peer review and rapid publication of papers that pass editorial and peer review.

25. Our work led to many meetings, calls and emails. My bookkeeping for this period is not good.

26. Two meetings stand out as being particularly significant. On 5th March, we had a meeting with Dan Wattendorf and his team at the Gates Foundation. He indicated that Bill Gates had read our note with interest, and that his team had reviewed it and found the concept sound. In the coming days he mentioned that Bill Gates had spoken to leaders of the tech industry and they had declined to take the concept forwards to development. He asked Microsoft to coordinate independent efforts within the USA, which they did. They also asked a not-for-profit, Audere, to develop a proof of concept for the app, but to my knowledge nothing came of these discussions and efforts.

27. After a call with Patrick Vallance, David Bonsall, Michael Parker and I were invited to a meeting with the leadership of NHSX that took place on March 7th in London. The meeting, chaired by Matthew Gould, lasted approximately two hours. Within the discussion, I presented the concept and model outputs for digital contact tracing for SARS-CoV-2. Approximately a dozen people were present. Geraint Thomas represented Public Health England. Anthony Finkelstein, then Chief Scientific Advisor for National Security, represented Go-Science. The meeting was fast paced, and at the end of the meeting Matthew Gould informed us that NHSX would seek approval to develop a digital contact tracing app at speed, which they did.

28. We were quickly appointed as academic advisors to NHSX. From this point on, many communications used NHSX's servers, which I no longer have access to.

29. NHSX took on the development of the contact tracing app. The implementing partner was a company called Pivotal. Our role from this point was to advise on the epidemiology, impact on hospitals, and ethics. As our first model was rather simple, we started building a detailed agent-based simulation that could encode important information, of which age effects were the most important. Contact rates vary by age; smartphone usage varies by age; susceptibility to serious disease, hospitalisation and death varies by age.

30. The development of the first app was remarkably fast, with test versions available within two weeks – as I recall, this was before even the first UK lockdown started. My group's focus within the team was epidemiological considerations in risk scoring for the app, and understanding the likely public health impact of the app under different assumptions about population uptake and adherence to advice.

31. The app used 'Bluetooth low energy' whereby phones in proximity to each other could exchange anonymous identifiers that could later be used to pass the message (via a central server) that one of the owners of one of the phones had tested positive for COVID-19. This is the same technology that allows a phone to connect to nearby Bluetooth devices, such as headphones. The strength of the radio signal is used as a proxy for the physical distance, which itself is a measure of the risk of transmitting the virus from one person to another.

32. For delivering COVID-19 insights, we quickly reorganised my research team in Oxford which had been hitherto focussed on HIV epidemiology. I worked with David Bonsall, a senior research fellow in my team (who is now an independent researcher) and my team's scientific manager Lucie Abeler-Dorner coordinated to steer our efforts at speed. David, Lucie and I became advisors to NHSX, as well as Mike Parker leading on ethics. Mike Parker was shortly appointed to SAGE as an advisor on ethics. Luca Ferretti, Chris Wymant and Michelle Kendall worked on the modelling for the app, and the four of us later become the core epidemiological team in the reconfigured NHS COVID-19 app from September 2020. Andrea Stewart was a communications officer for my team with prior experience of the UK Press - her job was to help us communicate findings on HIV/AIDS research, but she repurposed to helping us field the numerous enquiries for information on the NHS COVID-19 app. Robert Hinch, Will Probert, Matthew Hall and Anel Nurtay developed our agent based simulation OpenABM-COVID19 that was used to explore realistic scenarios for the app.

33. Finally, the rest of my team operated independently, and focussed on generating and analysing SARS-CoV-2 viral genomes, contributing numerous data and analyses to the national COG-UK consortium, the Office for National Statistics (ONS) Community Surveillance Studies, and specific studies supporting Oxford's vaccine trials. I will not describe this work in detail here, as though it led to impactful findings, it is well documented elsewhere and seems mostly out of scope to the COVID Inquiry's Module 7.

34. Whilst the digital contact tracing app commissioned by NHSX was developed quickly, there were many areas needing investigation before it could be made available to the public. NHSX assembled a team with wide ranges of expertise to advise on different aspects of the project. Professor Mark Briers was seconded from the Turing Institute as Chief Scientist. He and his team developed the algorithms for meaningfully interpreting Bluetooth signals in terms of physical distance, and developed the data architecture for the app. I would recommend the Inquiry speak to Mark Briers, with whom I worked very closely, as he was also involved in many communications with the app's management team, and would therefore be able to shed more light into how decisions were made about data systems, risk scoring, the switch from the first to the second NHS app, and other aspects of implementation. Dr Ian Levy from the National Cyber Security Centre attended meetings to assure the safety of the app. Professor Anthony Finkelstein provided a link to Go-Science, and worked on the engineering perspective. Geraint Thomas provided a link with Public Health England. My team and I advised on epidemiological design and effectiveness.

35. After editorial screening and peer review, Science published our article on 31 March 2020 (Exhibit CF/10 [INQ000574799]).

Development during lockdown: how to measure the riskiness of physical contacts, predicting the possible impact of digital contact tracing, and formulating consensus recommendations from epidemiologists.

36. From 23 March 2020 the UK was in national lockdown. Version 1 of the NHSX contact tracing app was launched on 5 May as a pilot of an integrated NHS Test and Trace package on the Isle of Wight.

37. A basic timeline of this period is found in Figure 1 of our published analysis of the Isle of Wight pilot (Exhibit CF/11 [INQ000574810]).

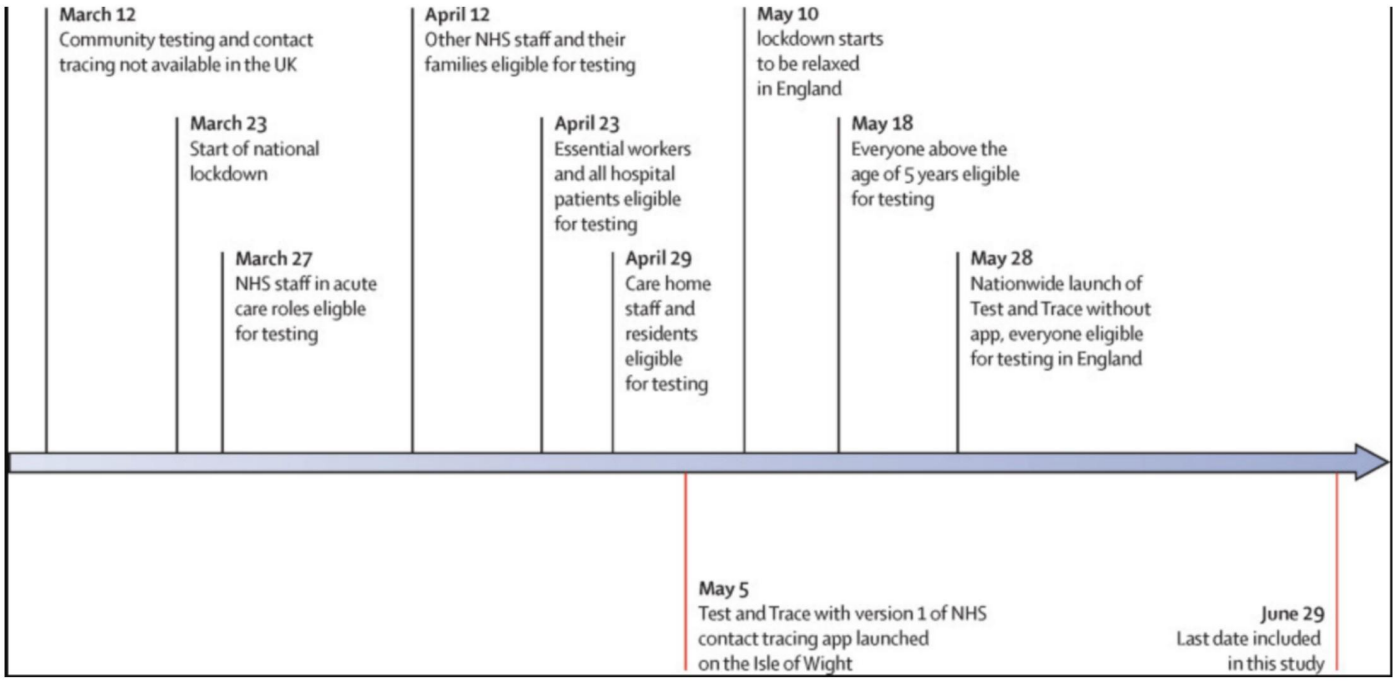


Figure legend: timeline of the pilot of NHS Test and Trace and the NHS Contact tracing app on the Isle of Wight, from Exhibit CF/11 [INQ000574810].

38. There was a lot of press interest in our work, both in the UK and internationally. Committed to transparency, my team and I responded to as many press enquiries as we could whilst still prioritising our work as epidemiological advisors to NHSX. We also met regularly with colleagues in the Pan-European

Privacy Proximity Tracing collaboration who were developing similar apps for the EU and other European nations.

39. One of the tasks we advised on was the development of a risk score that could be used to define whether a contact measured by the app was risky or not, that is whether it should lead to the notification of the user that they have had a risky contact with a case. We worked together with Anthony Finkelstein from Go-Science and together we produced three versions of a document, the third version was made publicly available on 4 June 2020. The document is called "Defining an epidemiologically meaningful contact from phone proximity events: uses for digital contact tracing (version 3)" (Exhibit CF/12 [INQ000574803]). The document was written in pseudo-code for ease of use by app developers.

40. Our initial proposal incorporated three key considerations: using a model of the physics of spread by droplets and aerosols, taking into account the likely infectiousness of the case as determined by their time before or after symptoms at the time of contact, and the ability to add scores from multiple contact events. We proposed that scores should be adjusted if the contact took place indoors or outdoors, and if the contact person shared a household, was a workplace contact or was neither, reflecting the different types of settings. Since there was considerable uncertainty in the nature of contacts, we proposed that the system be adaptive, and quickly be improved to 'learn' the true risk score based on the first few weeks of functioning. The system could be made 'safe' by making sure that the average number of notifications sent per case were epidemiologically consistent with the epidemic dynamic. During the summer of 2020, Mark Briers and team showed that it was technically feasible to detect whether a contact occurred indoors or outdoors.

41. However, my understanding is that after a number of consultations with Public Health England amongst others, it was decided that the app should be calibrated to match manual contact tracing and the social distancing heuristic in place at the time, namely that a risky contact be defined as a contact within 2 meters that lasts at least 15 minutes. In my view, an opportunity to test the "2

metre 15 minute" heuristic – and then generate evidence to update it – was missed, with consequences leading to substantial added health impacts and economic cost.

42. Furthermore, privacy considerations ruled out the measuring of indoor or outdoor context, and ruled out the passing of most contextual information between app users – the exception being an indicator of likely infectiousness of the case on a scale of 0, 1 or 2.

43. Another strand of work was developing a detailed computer simulation of how COVID-19 spread and how TTIQ could contribute to control of spread. The model that we published in early March 2020 was a simple mathematical model that captured high-level system dynamics. There was a need for something more realistic, and so we developed a detailed simulation that we called OpenABM-COVID19. Initially, the two main ingredients that we included were:

- A more realistic model of social networks, with mixing in households, in schools/workplaces/social spaces, and via random ephemeral contacts;

- A more realistic model of how people mix by age, of infection dynamics by age, of disease severity, hospitalisation and death by age, and of mobile phone usage by age.

44. We had input and assistance from faculty.ai, IBM-UK, DHSC, DCMS, Anthony Finkelstein, and colleagues at the Crick institute with developing this code, making sure it was robust ('unit testing'), and making it easy to use. The model was parameterised with data on realistic household and age composition provided by the ONS, and with smartphone usage provided to DCMS by OFCOM.

45. The output of this model, calibrated to model the second wave of the epidemic in the UK following the exit from lockdown, was presented in a public report called "Effective Configurations of a Digital Contact Tracing App: A report to

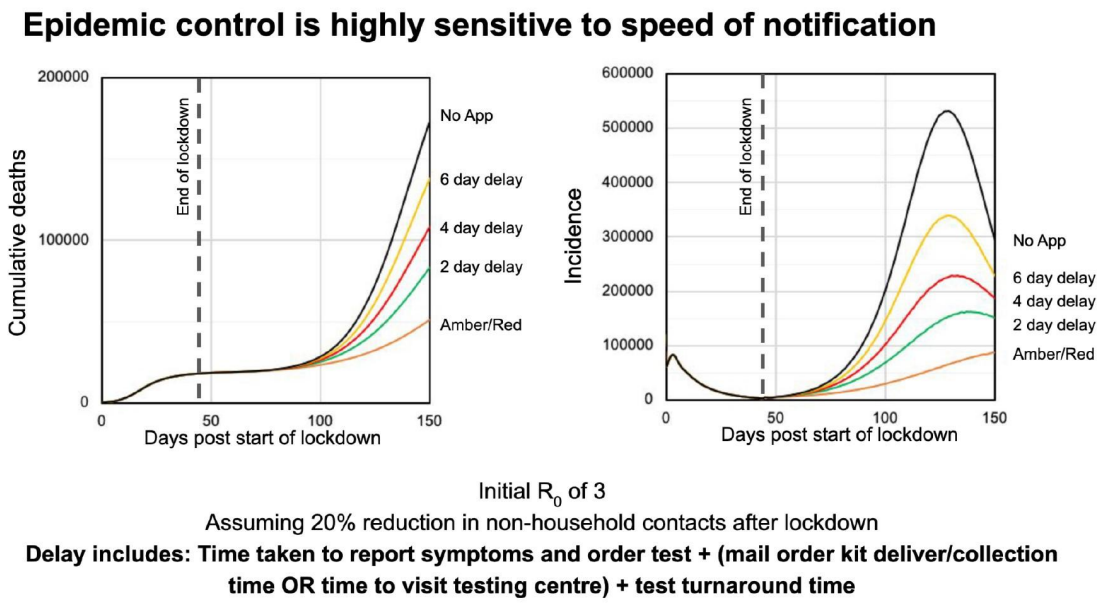
NHSX" published on 16 April 2020 and updated 10 August 2020 (Exhibit CF/13 [INQ000574815]). The paper primarily covered three areas:

- TTIQ wouldn't contain the epidemic without additional measures to protect the elderly;

- proposing policies that could be sparing of tests, such as for example testing one person in a household, and assuming that the other symptomatic individuals also were infected with COVID if the first person tested positive;

- the effect of digital contact tracing for a wide range of assumptions about population uptake of the app. This was illustrated for example in Figure 6 from this report that showed for several scenarios the total number of deaths expected in the first 40 days of the second wave epidemic for a range of app uptakes. Scenario 2 is closest to the implementation that was later chosen for the UK.

46. We updated our model in the brief summary report entitled "Digital contact tracing: advice and simulations from the Oxford Pathogen Dynamics Group" published on 25 May 2020 (Exhibit CF/14 [INQ000574814]). In this report, we showed the importance of the speed of testing, and the potential impact of using a form of contact tracing that differentiated between contacts of probable COVID-19 cases (amber warning) and confirmed COVID-19 cases (red warning).



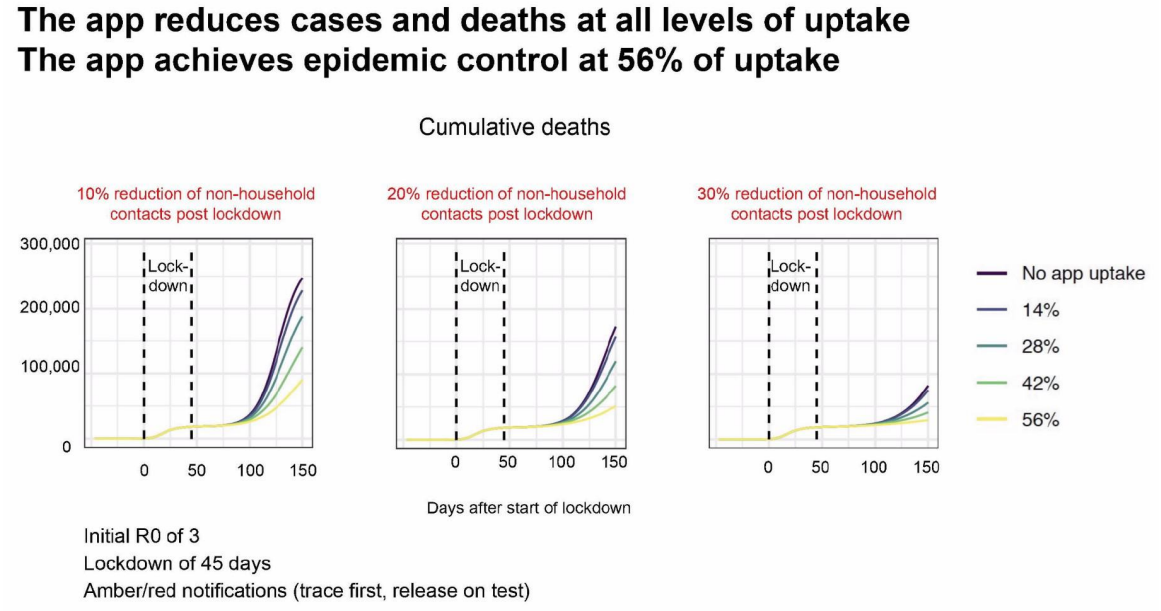


Figure legend: results from simulations of epidemic dynamics for a second wave in the UK following the end of the first lockdown. The initial transmissibility is calibrated so that R_0 is 3 at the start of the epidemic. We assume that after the lockdown is ended, that mixing rates outside the household are reduced by 20%. In the top figure, we explore a range of delays in completing the testing and tracing process (including time to report symptoms and order test, time to receive the test kit or visit the test centre, and time from testing to the result being returned and the contact tracing process being

completed), with an app uptake of 56%. This uptake of the app is varied in the next figure, see paragraph 47 below. The model with an Amber alert was based on a hypothetical development the app used on the Isle of Wight, where an initial notification could be sent to contact of someone displaying symptoms, informing them that they were exposed to a 'probable case'. The notification would be followed by a green or red update dependent on whether the index case tested negative or positive for COVID-19. Figure from Exhibit CF/14 [INQ000574814].

47. We also showed that the app has benefits in terms of reduced epidemic size for all assumptions about the uptake of the app, and can achieve substantial reductions in mortality when combined with moderate levels of social distancing.

The app reduces cases and deaths at all levels of uptake
The app achieves epidemic control at 56% of uptake

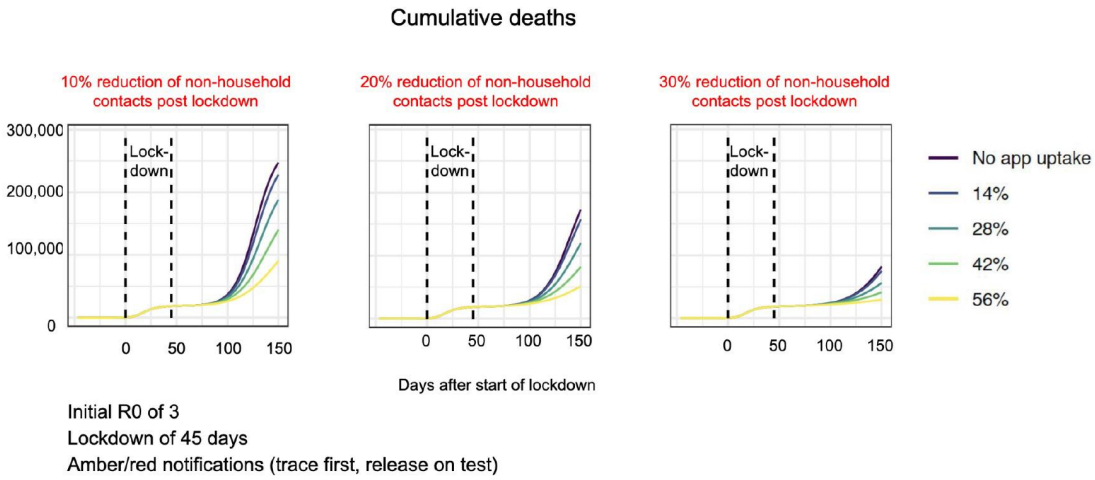


Figure legend: The model is as described in Paragraph 46 above, but in this version the uptake of the app is varied taking values from 14% to 56%, and the degree of social distancing outside the household is varied from 10% to 30%. Figure from Exhibit CF/14 [INQ000574814].

48. In addition to generating recommendations based on our own modelling work, we convened an international group of epidemiologists to agree on guidelines for digital contact tracing. As the first version of the report was based on informal conversations, we penned it as an Oxford report, entitled "Epidemiological requirements for app-based contact tracing of COVID-19" that we released on 7 May 2020 (Exhibit CF/15 [INQ000574802]). It was substantially updated with the international collaboration of epidemiologists and published as a public preprint on 31 January 2021 (Exhibit CF/16 [INQ000574798]), and subsequently published in abridged form in an academic journal (Exhibit CF/17 [INQ000574821]). Our five recommendations were titled

- Integration with local health policy
- Prioritise choices that lead to high user uptake and adherence
- Quarantine infectious people as accurately as possible
- Rapid notification
- Ability to evaluate effectiveness transparently

49. Another area we revisited from our first paper in March 2020 was around the timing of transmissions relative to the onset of symptoms in the index case. A central point in our first research paper was that about ~50% of transmissions originate from index cases who are not yet symptomatic (and may in some cases remain asymptomatic). A large number of datasets and studies were produced during early 2020 on this point, and we revisited the question in an academic preprint titled "The timing of COVID-19 transmission" (Exhibit CF/18 [INQ000574796]) that was made public on 16 September. We re-analysed the data in a way that was more useful for risk scoring in contact tracing. We found that for transmissions from symptomatic individuals, 41% (95% confidence interval 31%-50%) of transmissions came from strictly pre-symptomatic individuals.

50. The analyses described above were all circulated within the team at NHSX, to our international partners, to Anthony Finkelstein as representative of Go-Science, and were made open as public documents. Some of these reports generated press interest and we fielded questions and interviews.

51. I interacted regularly with the app team, attended NHSX meetings and occasionally presented. Some of our reports were discussed within SAGE and NERVTAG. I attended NERVTAG once as an observer during this period, in a meeting where the app was discussed.

52. During 2020, I was invited to and served as a witness to the UK House of Commons Health Select Committee, the Commons Science Select Committee, and the UK House of Lords Science Select Committee.

53. During this time, the first NHS COVID-19 app was developed. It was launched as part of a pilot for integrated NHS Test and Trace on the Isle of Wight.

A pilot for Test and Trace on the Isle of Wight

54. During May 2020 the National NHS Test and Trace service was being rolled out, and as part of this roll out, the first NHS digital contact tracing app was piloted on the Isle of Wight.

55. To quote our article: "*The Isle of Wight Test and Trace programme was launched on May 5, 2020. The app was available for download by the general public from May 7, and was downloaded by more than 54 000 (38%) people on the island during the trial period. On May 18, community testing was introduced nationwide, initially for all people over the age of 5 years, and for everyone on May 28, when the national contact tracing service reintroduced traditional contact tracing. There was no nationwide contact tracing app during the period of study.*

Between May 6, and May 28, 2020, 160 COVID-19 cases on the Isle of Wight were reported to traditional contact tracing, resulting in 163 individuals receiving

a notification and request to self-isolate. During the same period, 1524 people reported symptoms to the app, resulting in 1188 people receiving an exposure notification. [...] We analysed the epidemic trajectory on the Isle of Wight before and after the Test and Trace programme launch and compared this with the epidemic trajectory in other areas of England. We focused on estimated per-capita incidence and the reproduction number (R)."

56. To cut a long-story short, we found that just before the introduction of the app, the Isle of Wight had one of the fastest growing COVID epidemics in the country (compared to all other Upper Tier Local Areas), and immediately after the introduction of the app, the island had one of the lowest *R* numbers in the country, corresponding to a rapid contraction of the epidemic. It's difficult to prove the public health impact of an intervention applied once in one modest sized locality, but the data are certainly consistent with a large public health impact.

57. The app that was piloted relied on people's self-report of symptoms, so that the app could work at speed and without stretching the newly formed testing service.

58. Press reports indicated that the people of the island (and their MP) were happy with the pilot. Nonetheless, a learning from this experience was that a national contact tracing app should be integrated with the new PCR testing service for COVID, and not trace people based on self-reported symptoms of the index case.

59. One oddity of the pilot was that no member of the app team, to my knowledge, had access to the data generated by the app. Our analysis relied on NHS Test and Trace data and COVID dashboard data to infer the possible effect of the app, not on data from the app itself.

60. Our findings from the pilot were peer reviewed and published in the Lancet Digital Health in an article titled "Epidemiological changes on the Isle of Wight

after the launch of the NHS Test and Trace programme: a preliminary analysis" (Exhibit CF/11 [INQ000574810]).

Privacy, Google and Apple's Exposure Notification, and System Evaluation

61. The data architecture for the first NHS contact tracing app was 'centralised', meaning the contact network of COVID-19 cases and their immediate contacts is stored on a central server. This contrasts with the decentralised architecture used by the second app developed using Google and Apple's Exposure Notification system, whereby no network information is stored on central servers.

62. Privacy campaigners and scholars are particularly concerned about storage of network information on the history of contacts between people in the population, which is regarded as more sensitive than information that individuals volunteer about themselves. During the development of the first NHSX app, there was a vigorous public debate about privacy, including media coverage and petitions. Most public voices expressed concern about privacy infringements, with a few prominent experts in computer science supporting the app. Several reports also commented on cybersecurity considerations, which are substantive. The UK's National Cyber Security Centre advised on the NHSX app.

63. My team and I had no role (or expertise) in the development of data architectures. We were asked by NHSX to comment on what could be done epidemiologically using contact network information generated by the centralised app design, and commented so in a public document titled "Digital contact tracing: comparing the capabilities of centralised and decentralised data architectures to effectively suppress the COVID-19 epidemic whilst maximising freedom of movement and maintaining privacy." (Exhibit CF/19 [INQ000574801]). Our conclusion was that there was potential additional public health utility in using contact network information, such as being able to understand and respond to superspreading, but that the most important aspect to consider overall was public trust and uptake of the app. As I have no

expertise in data architecture, technical privacy, or cybersecurity, I would refer the Inquiry to Mark Briers or Anthony Finkelstein for comment.

64. Some ethical issues around digital contact tracing, including privacy, were discussed in an article that I co-authored titled "Ethics of instantaneous contact tracing using mobile phone apps in the control of the COVID-19 pandemic" (Exhibit CF/20 [INQ000574812]).

65. The development of the first NHSX app was homegrown, though it was highly collaborative with other apps in development at the same time, in particular those used for TraceTogether in Singapore, and proposed apps in Germany, France and Italy. Quickly, a European consortium called PEPP-PT was formed, and source code was shared. In addition, experimental data were shared between countries on the performance of apps in experiments, such as with volunteers being asked to use their phones in different settings to replicate social environments.

66. The Swiss team within PEPP-PT quickly found that they dissented from the consensus within that new organisation, and founded a separate organisation and protocol called Decentralized Privacy-Preserving Proximity Tracing ('DP-3T'), released on 4 April 2020.

67. On March 30th, we had a meeting with Google engineers who informed us that they were interested in our work, and on April 4th they confirmed that they had their own programme. On April 10th Google and Apple announced their joint programme, called Exposure Notification (GAEN), closely related to DP-3T. The Application Programming Interface (API) was released through May, and in June, NHS Test and Trace announced a change of strategy from the first NHSX app to a new app that used the Google Apple Exposure Notification system (GAEN). The commercial developer was Zuhlke engineering. The app's ownership would change from NHSX to NHS Test and Trace.

68. The changeover from the first to the second app, with an overlap of efforts, was a difficult time within the app team, with conflicting accounts. I was not

involved in decision making around that change. My understanding is that there were at least five considerations. First, privacy, since the GAEN system was decentralised and therefore did not expose users' contact network information to a central server. Second, the technical and reputational benefit of being supported by Google and Apple. Third, issues in accurately measuring distance between phones. Fourth, specific issues hindering the consistent functioning of the app on Apple iPhones. Fifth, the apps had different commercial suppliers, namely Pivotal and Zuhlke, and therefore it is possible that there was preference for one supplier over the other. My team's only involvement in the decision was that I was asked to model a scenario where communication between Apple iOS devices was ineffective. These devices make up about half the smartphones in use in the UK. I quickly emailed the leadership team of NHSX to indicate that if this was the problem with the first NHS app, then my recommendation was to switch to the GAEN system.

69. A new app team was quickly assembled. Baroness Dido Harding was appointed as CEO of NHS Test and Trace. A new CEO of the app team was appointed. Mark Briers remained as chief scientist, and my team in Oxford was incorporated into his team via a subcontract from the Turing Institute to Oxford University. These changes clarified our management structure, and defined clear roles and objectives for my team as the new NHS COVID-19 app was to be released.

70. The NHS COVID-19 app was the national GAEN for England and Wales. Separate apps were released for Scotland and Northern Ireland. I did not have many opportunities to interact with colleagues from the team(s) behind those apps.

71. My understanding is that, since Zuhlke was appointed to start development as soon as Google and Apple released the GAEN protocols, the NHS COVID-19 app was developed as fast as could be done given the reliance on this external system. Little time was lost due to the initial development of the previous discontinued app; the public perception is likely very different. I would suggest referring to the witness statement of Wolfgang Emmerich for more information.

72. During 2020, digital contact tracing was rolled out in many countries, either with the Google Apple Exposure Notification (GAEN) system as in the UK, or with other systems. Privacy was often the top design consideration. A side effect of this is that most systems were not evaluated, or were evaluated with so little detail that one could not reasonably assess whether the intervention was useful or not. A Council of Europe Resolution was passed in 2022 to 'ensure that recourse to digital public health technologies is part of a comprehensive national epidemiological strategy, articulated in different tools, balancing all interests at stake and based on an appropriate evaluation of its real impact and effectiveness' (Exhibit CF/21 [INQ000574800]).

73. My view is that the NHS COVID-19 app was one of the very few apps to meet this standard. Our task was to articulate epidemiological expectations from the outset, and then to consider in detail how to evaluate ongoing effectiveness. This involved collecting enough anonymous data within the privacy-by-design approach of GAEN, achieving a reasonable balance. Achieving these evaluations was our priority from September 2020 onwards. For this, Mark Briers and team led the data architecture, with input, guidance and review from the app's internal teams, the Information Commissioner's office, and an independent Ethics Review Group.

Launch of NHS Test and Trace, and of the NHS COVID-19 app

74. The app was launched on 24 September 2020, with a national advertising campaign. Over 10 million people downloaded the app in the first week. Figure 1 in our paper "Epidemiological impacts of the NHS COVID-19 app in England and Wales throughout its first year" (Exhibit CF/22 [INQ000574818]) shows the changing number of unique users, and those with the contact tracing functionality turned on.

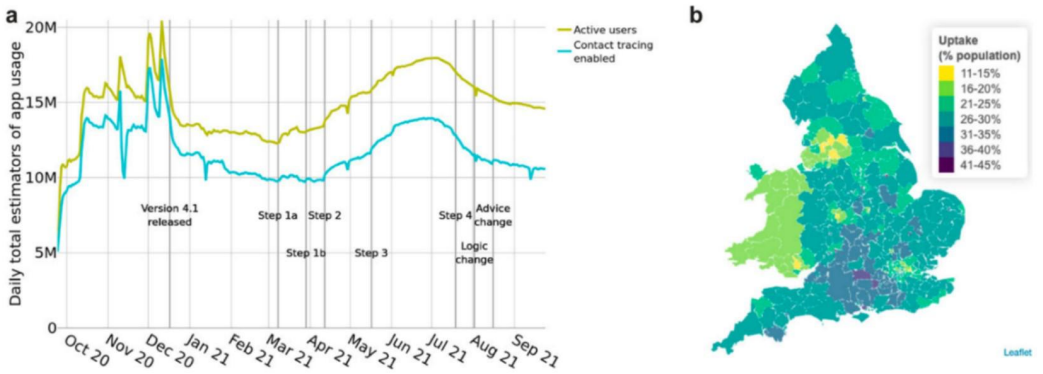


Fig. 1 | App usage. a The number of active app users across England and Wales, and the number of devices with Bluetooth contact tracing enabled. **b** App uptake per LTLA, estimated as the mean number of active users as a proportion of the total population.

75. Sudden spikes in the data reflect temporary issues in the app's backend data system involving duplicate counts. This phenomenon illustrates a broader phenomenon, which is that the data systems for analysis of app data were being built over time – to borrow the metaphor 'the plane was being built as it was flying'. It is a remarkable testament to the work of the app team, and the degree of coordination between national app teams and the separate engineering teams at Google and at Apple, who were all coordinating sequential updates to their phone operating systems and to the app, that this system mostly held together. The Zuhlke CEO Wolfgang Emmerich has in multiple presentations detailed the developments and changes that were incorporated in the app. I would refer to the witness statement by Wolfgang Emmerich for further details.

76. Ideally, national testing and tracing would have been scaled up at a period of low COVID transmission during the summer of 2020 rather than launching in the autumn. My understanding is that this was not possible due to the time needed to develop the systems. On the one hand, there would have been substantial public health benefit in launching earlier, even if by a few weeks, due to the low rate of infection during the summer. On the other hand, it was

important that the app be launched only after it was technically ready, since first impressions were likely to shape longer-term users' impression.

How many cases and lives did the NHS COVID-19 app save?

77. The app was a novel intervention and no real-world data existed a priori on its effectiveness. We worked with the app team, the Department of Health, and the office of the Information Commissioner, and with Professor Mark Briers to design an analytical process to evaluate the app in real-time, and to provide insights into the epidemic based on this tool that was being used by over 10 million people over the first year of the pandemic.

78. At the same time, the requirement for the app was to be privacy-preserving by design, and so the design of the back end data systems and analyses was a highly complex process.

79. We initially focussed on estimating the public health impact of the app, that is cases prevented and lives saved. We published interim findings after 3 months, and again after one year.

80. Estimating the impact of the app was, in my opinion, only possible to do rigorously for a team working closely with the evolving data system being built by Mark Brier's team. To provide independent scrutiny on our estimates, we therefore focused on statistical robustness and peer review in the leading academic journals (Exhibit CF/22 [INQ000574818], Exhibit CF/23 [INQ000574819).

81. A fundamental issue when assessing public health interventions is that of correlation between adoption of different measures, e.g. adherence to social distancing, masks, vaccination and of course uptake of the app. It is therefore difficult to disentangle the effect of one single aspect of the intervention, a problem called confounding. There is a very strong association between the proportion of people using the app in a given geographic area and the amount of COVID cases and deaths there.

82. Our statistical method for removing the effect of confounding, called an emulated target trial, focused on identifying geographic neighbouring areas that were matched in the number of COVID cases before the app was introduced, and looking at whether the difference in app usage correlated with the difference in case counts. We cross referenced this method with a modelling method that took into account things such as the number of app reported cases and how many contacts were notified. These methods broadly agreed on the number of deaths averted in England and Wales during the first three months, placing the central estimate between 4,200 and 8,700. We disseminated these findings in a paper rapidly accepted for publication in Nature, titled "The epidemiological impact of the NHS COVID-19 app" (Exhibit CF/23 [INQ000574819]), and associated press release.

83. Notably, as additional proof of causality, we found that the effect of the app was much smaller for the first month (phase 1 of our analysis) during which the app threshold for notifying contacts was set very high, as a safety measure to reflect that this was a new intervention.

84. An additional key result from this work was that each additional percentage of the population that used the app would reduce the number of cases (and deaths) by 0.79% to 2.26%. The mechanism for these reductions was to reduce transmission a little but consistently over time, therefore delaying the epidemic curves so that people had a chance to get vaccinated before they were infected.

Table 1 | The estimated effect of the NHS COVID-19 app

SAR among individuals notified by the app			**6%**
Cases and deaths averted in phases 1 and 2:		**Cases**	**Deaths**
From modelling of digital tracing		284,000 (108,000–450,000)	4,200 (1,600–6,600)
From matched-neighbours regression		594,000 (317,000–914,000)	8,700 (4,700–13,500)
	Per cent reduction in cases for every percentage point increase in app use		
Main analysis	**Phase 1**	**Phase 2**	**Overall**
Modelling	0.33 (0.13–0.49)	0.93 (0.46–1.24)	0.79 (0.37–1.10)
Matched-neighbours regression	1.09 (0.04–2.14) (bootstrap: 0.15–2.16)	2.66 (1.75–3.56) (bootstrap: 0.80–4.71)	2.26 (1.50–3.00) (bootstrap: 1.60–3.19)

85. We updated our analysis in a follow up paper published in Nature Communications titled "Epidemiological impacts of the NHS COVID-19 app in England and Wales throughout its first year", that showed that with conservative estimates, up to September 2021 about 1 million cases and over 9000 deaths had been prevented by the app (Exhibit CF/22 [INQ000574818]).

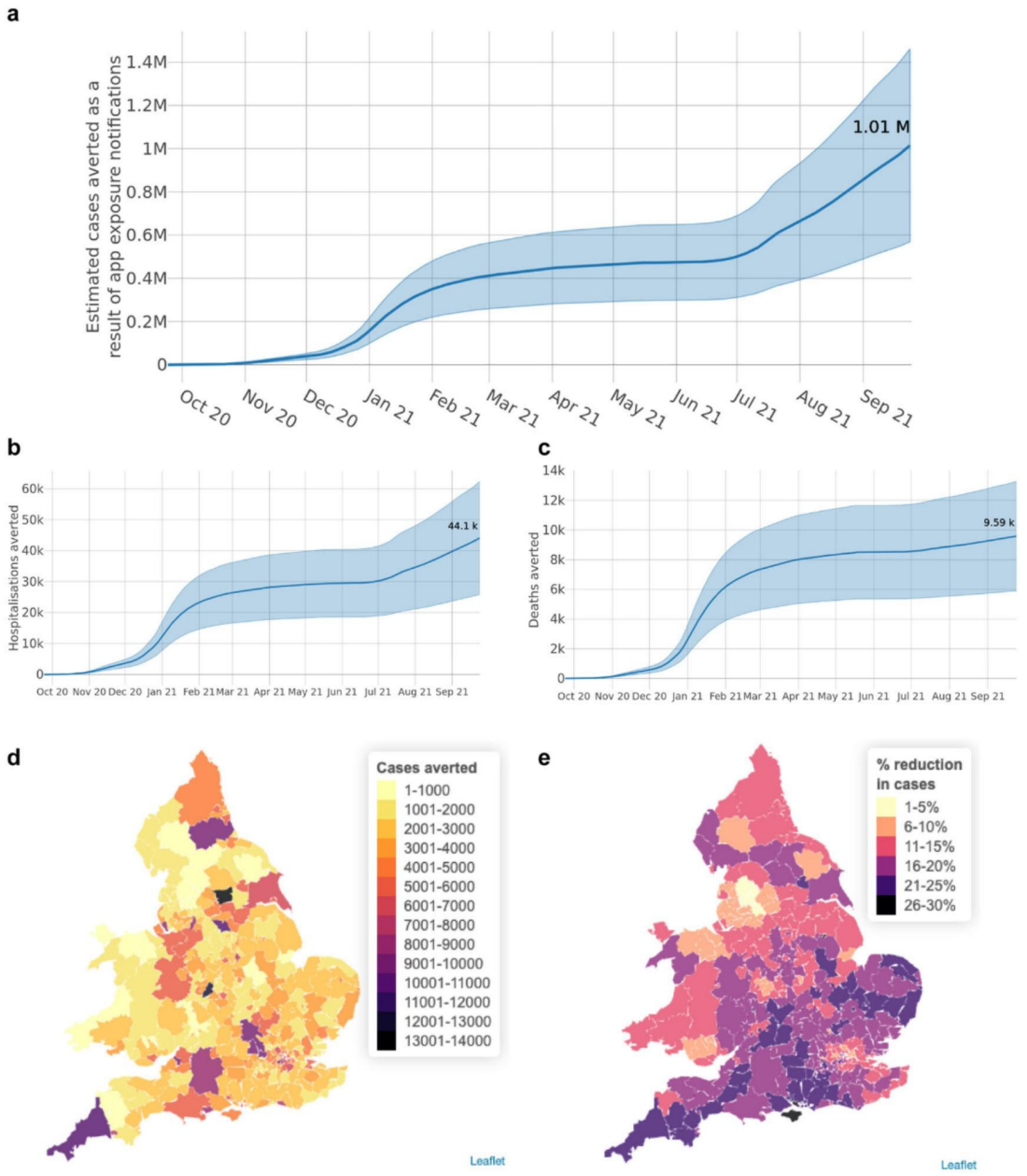


Fig. 6 | Epidemiological impacts. Cumulative estimated numbers of **a** cases, **b** hospitalisations and **c** deaths averted by app exposure notifications between 24 September 2020 and 24 September 2021. Shading in panels **a**–**c** indicates the range of outcomes between upper and lower plausible estimates of an individual's reduction in risky contacts as a result of receiving an app notification, while the central estimates correspond to moderate reductions in risky contacts. **d** Estimated cases averted in each LTLA. **e** Estimated percent reduction in cases in each LTLA.

86. As for every other public health intervention in the UK, the adoption in the country was quite unequal. Over the first year, the mean adoption of the app was 25.3%, with mean adoption of 15.8% in the lower tier local areas (LTLAs) in the bottom decile of uptake and 35.3% in the LTLAs with highest decile of

uptake. For comparison, by 21 Sept 2021, the uptake of the two first doses of vaccination was 67.7% overall, with mean 75.4% in the LTLAs in the highest decile of vaccine uptake and 56% for the LTLAs in the lowest decile. In summary, efforts to make the NHS COVID-19 used across socioeconomic groups and geographic locations, including multi-language support, links to personal support payments, and targeted adverts, were not as successful as corresponding efforts with vaccination.

87. A notable feature of the app's use during the first year was the high level of engagement amongst its users. Usually above a third, and for a long period over half of all positive test results nationally were entered into the app by users (Exhibit CF/22 [INQ000574818]).

88. Another notable feature of the app's functionality was that it scaled with the changing size of the epidemic and the number of exposure notifications reflected the changing contact rates of the population. In contrast, the manual contact tracing process functioned more effectively when case numbers were low, particularly for example during the early phase of the emergence of the severe Delta variant in May 2021 (Exhibit CF/22 [INQ000574818]).

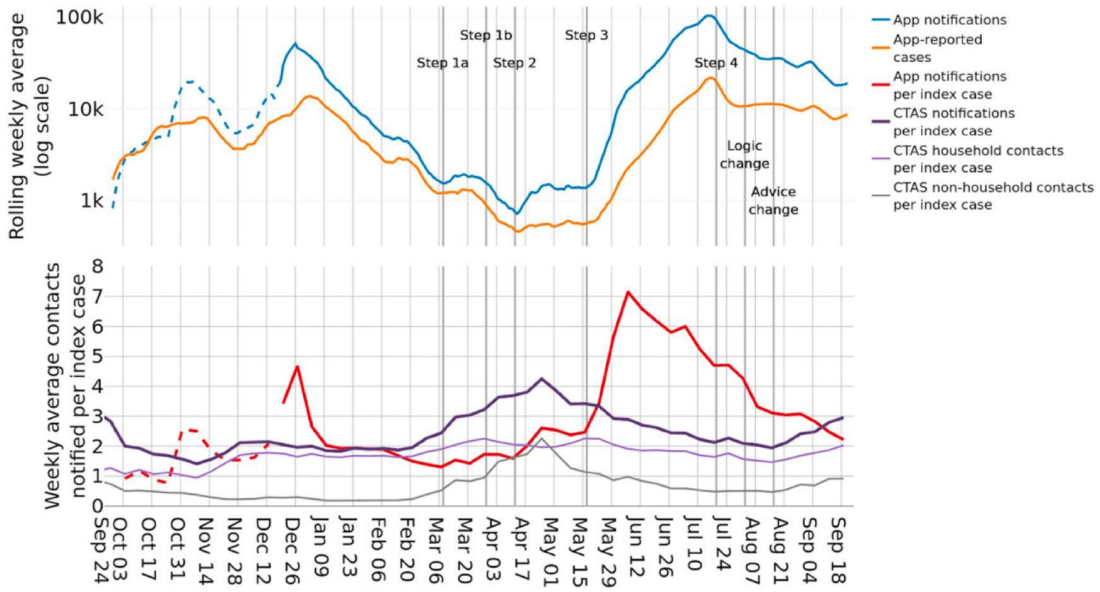


Figure legend: Top panel shows the number of test-positive cases reported into the app, and the number of exposure notifications reported by the app during its first year of operation covering Sep 24 2020 to Sep 23 2021. Overlaid are the steps in the government's roadmap for re-opening following lockdown. The bottom panel shows the number of exposure notifications per case issued by the app, and by the conventional ('manual') Contact Tracing and Advisory Service (CTAS). The app can be seen to scale with the contracting and growing epidemic, whereas the CTAS service functioned most effectively during May 2021 when case numbers were low and the Delta variant was emerging.

89. In addition to Exposure Notification, the NHS COVID-19 app had a number of additional features: local area warnings (based on analyses by the Joint Biosecurity Centre), venue check-ins, a symptom checker, the capacity to directly order a test via a portal in the app, a self-isolation countdown timer, and the capacity to pause the EN feature. It was available in a number of languages, and the language was extensively tested for comprehension. Of these features, the capacity to order a test was seldom used by users. The symptom checker was somewhat limited due to the limited number of official symptoms of COVID. The venue check-in feature was linked to posters placed in venues displaying a QR code, which would lead to a warning to users if a confirmed case had checked in to the same venue on the same day. Users were not asked to self-isolate based on a check-in, only warned of potential risk or recommended to take a test. The check-in feature likely drove adoption due to the convenience of the method for checking in – it was easier than signing into a book leaving contact details – but the feature was under-used for public health, due to a manual step requiring a follow-up interview with a manual contact tracer.

Lateral flow tests, the Alpha variant, and school closures

90. During December 2020, we contributed to the application to the UK's Medicine and Health Regulatory Agency in December 2020, modelling the use of lateral flow rapid tests for COVID. The application was coordinated by the Oxford Rapid Test Consortium, led by Sir John Bell at the University of Oxford.

91. The consortium had generated data that showed that rapid antigen tests were very sensitive at detecting who was infectious, rather than PCR tests that were sensitive at detecting who was infected. During the course of infection, this distinction is important, as people shed virus for many days which can be detected by PCR, but which is not sufficient to infect someone else.

92. We produced a rapid modelling analysis that we later published as a preprint titled "Modelling the effectiveness and social costs of daily lateral flow antigen tests versus quarantine in preventing onward transmission of COVID-19 from traced contacts" (Exhibit CF/24 [INQ000574797]). This was considered alongside a report led by Billy Quilty at the London School of Hygiene and Tropical Medicine which came to very similar conclusions.

93. Quarantine was the most harmful aspect of NHS Test and Trace. There was evidence that it could be replaced by daily testing with lateral flow tests, or at least offered as an alternative.

94. In my opinion quarantine stopped being proportionate at some point during the spring of 2021, as the government pursued the roadmap to re-opening and vaccinations were rolled out. In particular during the 'pingdemic' of June 2021, contact tracing would have been perceived as less problematic, had quarantine been replaced with regular testing. Unfortunately, the policy of quarantine was maintained until 18 August 2021, generating substantial negative opinion. In July 2021, with support of the Science Media Centre, I wrote an op-ed criticising the Government's policy on quarantine in the Daily Mirror (Exhibit CF/24a [INQ000475151]).

95. We also met with a team from the Department for Education, who planned to re-open schools in January 2021 after the Christmas break by making tests available for daily testing with lateral flow tests. Unfortunately, due to logistical issues, and the characterisation of the new Alpha (Kent) variant of the virus that was more virulent, schools were closed in January 2021, which was also the month of the whole pandemic with the highest mortality.

The OpenABM COVID-19 model

96. From May 2020, our agent-based simulation framework for modelling the spread of SARS-CoV-2, called OpenABM-COVID19, was made open source and was used by several groups in the UK and internationally. Agent-based simulations are models of detailed interactions, where each person interacts with others in a contact network, status is stored in memory, and updated every day. This can be essential for example for modelling the impact of contact tracing policies on different contact networks, as might occur in and out of lockdowns. These models are an alternative to the compartmental models such as the SIR model.

97. Our model's code was improved with contributions from three companies: faculty.ai, IBM, and Google. faculty.ai were contracted by NHS-X to support the development of the contact tracing app, and later contracted by NHS England to use the OpenABM model to support decision making in the NHS. From late 2020, after the completion of the contract with faculty.ai, we assisted NHS England directly with the use of this model, in a collaboration which still continues.

98. The OpenABM model was also used by the UK Health Security Agency as one of the two agent-based simulations for situational awareness in the UK. This happened alongside the use of compartmental models, many of which developed by members of SPI-M-O.

99. We produced four peer review publications with collaborators describing this work and our findings

    a. "OpenABM-Covid19-An agent-based model for non-pharmaceutical interventions against COVID-19 including contact tracing" (Exhibit CF/25 [INQ000574809])

b. "Modeling the effect of exposure notification and non-pharmaceutical interventions on COVID-19 transmission in Washington state" (Exhibit CF/26 [INQ000574825])

c. "Estimating SARS-CoV-2 variant fitness and the impact of Interventions in England using statistical and geo-spatial agent-based models" (Exhibit CF/27 [INQ000574816])

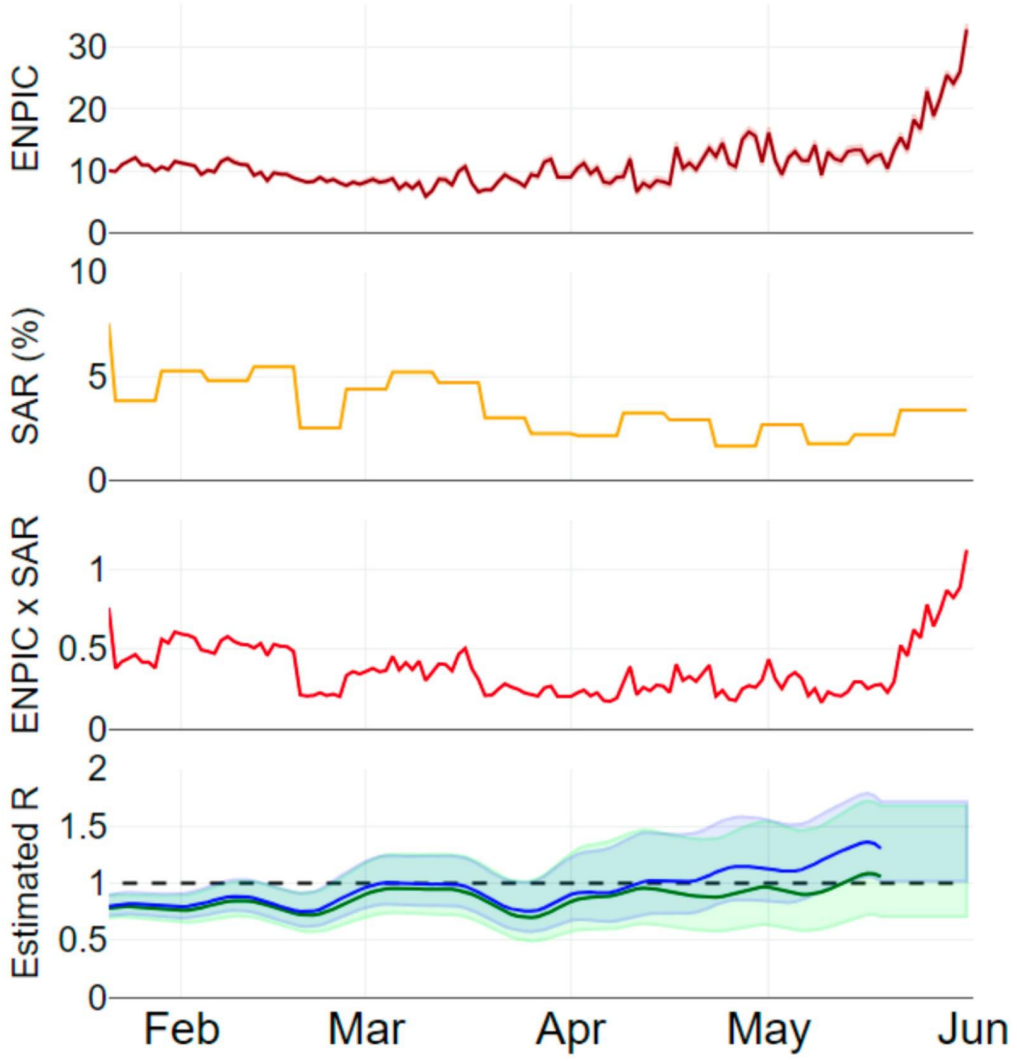
d. "Large-scale calibration and simulation of COVID-19 epidemiologic scenarios to support healthcare planning" (Exhibit CF/28 [INQ000574795])

The roadmap to re-opening, the delayed Euro football tournament, the Delta variant, and the so-called "pingdemic"

100. After the lockdown in January 2021 and the national roll out of vaccination, the government announced a staged roadmap to re-opening, with criteria for progressing through stages each with fewer restrictions, with Stage 4 being the return of normalcy.

101. During this period in 2021, we began to analyse the data from the app to produce insights into the changing drivers of the epidemic, namely 1) increasing immunity 2) changing risk behaviour and 3) a rapidly evolving virus. Though the app user base was not intended as a representative sample, it was used by a large fraction of the UK population.

102. These analyses evolved into a report, which we first distributed to colleagues in SPI-M-O and to the Joint Biosecurity Centre (JBC). It took some time to establish that the time trends we were observing were robust, to check the data back end system, and to take on board feedback from the stakeholders. We released a first of what became a weekly situation report on 1 June 2021 (Exhibit CF/29 [INQ000474934]). The first of these reports focused on an increase in the epidemic *R* that was entirely driven by a three-fold increase in contact rates of infected individuals.



The figure shows

- the ENPIC estimate since 21 Jan up till 31 May 2021. Increases during the last week are very apparent - an increase of more than a factor 2.
- SAR. We interpret the downwards trend in SAR during 2021 as being driven primarily by vaccination. The baseline is similar to the value of 6% reported in Wymant & Ferretti et al, similar also to the value for non-household close contacts reported by PHE. The downward trend appears to slow down or reverse in the past week. These increases are consistent with those reported in the SAR from manual contact tracing

103. "ENPIC" labels the number of exposure notifications per infected case, extrapolated to the hypothetical situation where everyone used the app. An estimate of 30 was roughly in line with expectations for normal life without restrictions, based on surveys conducted before the pandemic. Our analysis showed an increase in ENPIC from about 10 during lockdown to 30 by 1 June.

104. SAR labels the secondary attack rate, that is the proportion of users who received a notification, then tested positive, and then entered their test results back into their app.

105. We updated this analysis weekly. A version of this analysis was mounted on the government Gold/Silver dashboard (or so I understand, I never saw this dashboard), was sent to SPI-M weekly, and was distributed widely in JBC, and UKHSA as it came to be known after the merger between JBC and PHE.

106. Two pictures became clear as the situation evolved. The first was that the population had spontaneously ended restrictions after Stage 3 of the roadmap, and we later saw that Stage 4 had no discernible effect on contact rates. The second was that the combination of population increases in contact rates, and the postponed Euro football tournament, led to sharp peaks in contact rates. We presume these are due to people meeting in homes and pubs, and we saw for example different peaks in England and Wales depending on which of the national teams was playing. These spikes in contact rates were the highest of any period where the app was operational.

107. Because the contact rates increased initially during a period of low transmission, the app provided an early warning that a change had occurred. Once levels of infection had increased, then the combination of the app and manual contact tracing resulted in a very large number of people being notified of contact. The press became aware of this and termed the phenomenon a 'pingdemic'. The app performed as designed: the large number of notifications was the outcome of high contact rates combined with a high number of

infected people. The negative effects of the situation would have been mitigated had the recommendation been to test rather than to quarantine, which would also have been more proportionate. Nonetheless, infection rates quickly subsided, in part because of large numbers of people having been asked to quarantine. It is noteworthy that this period coincided with the appearance and spread of the Delta variant of the virus, which was the most lethal of the variants experienced to date.

108. From this period onwards until the eventual decommissioning of the app, we continued producing weekly reports. As an example of the utility of the reports, the app was the earliest indicator to detect the effect of the new highly infectious Omicron variant emerging in the autumn of 2021. The indicators were also useful in early 2022, when it appeared that the UK population spontaneously adopted contact rates more typical of lockdown periods. Our final report to DHSC and SAGE, report 94 (Exhibit CF/30 [INQ000474935]), was published on 28 March 2023.

How the NHS COVID-19 app was used to gain real-time insights into the effect of policies, behaviour, vaccines, and immunity.

109. The app was decommissioned on 27 April 2023. The app team was disbanded, and our contract as advisors to DHSC came to an end. Google and Apple decommissioned Exposure Notification on September 28th 2023; they had committed from the outset that this software was a functionality developed specifically for COVID-19 and would not become a permanent feature of their operating systems.

110. During 2023, I mostly focused on academic activities unrelated to the app, and in particular financially stabilising my team by seeking new research funding. We also worked on retrospective analyses of the UK app, in collaboration with the Data Analytics and Epidemiology division of UKHSA. We returned to the concept that I had put forward in our original conception in 2020 (Exhibit CF/12 [INQ000574803]), that the app's risk scoring could be used to provide

quantitative insights into the biological risks and sociological drivers of transmission. We divided this work into two levels.

- At a per contact level, what is the actual risk of the virus being transmitted?

- At the population level, how much risk is there on any given day, and how much of the variability in risk is due to the virus changing and due to the behaviour changing?

111. From the beginning of the app deployment, the app was endowed with capabilities for anonymous data collection across multiple data streams. As mentioned above, this data collection was motivated by the requirement to evaluate the correct functioning and the effectiveness of the app. Given the complexity of the backend and the analytics process, its design started before the initial release of the app but was not completed before April 2021. (One of the analytics data streams contained anonymous data packets concerning the operation of the app, sent daily by each app to the backend in order to assess the correct behaviour of the app. This stream was used to assess the epidemiological effectiveness of the app. A separate data stream collected anonymous information about all exposures to confirmed COVID-19 cases who reported their test positivity through the app. Packets containing information about exposure events were sent by the app to the backend during the exposure notification process and collected in order to assess if the app was correctly assessing the risk of infection during exposures. This data stream was fully operational from April 2021.) This data collection activity happened under the supervision of the ICO, following principles of data minimisation and anonymity while collecting a significant part of the information needed to assess that the app behaved as intended and evaluate its effectiveness.

112. A statistical analysis of the exposure events dataset confirmed that the risk scoring of the app provided a very good estimate of the relative probability of transmission to contacts, as shown in the figure below from (Exhibit CF/31 [INQ000574820]), therefore directly validating the technical work done by the app team. This result also provided direct and strong evidence that the

fundamental assumption behind digital contact tracing – i.e. that it is possible to estimate transmission risk through Bluetooth proximity measurements – is epidemiologically sound.

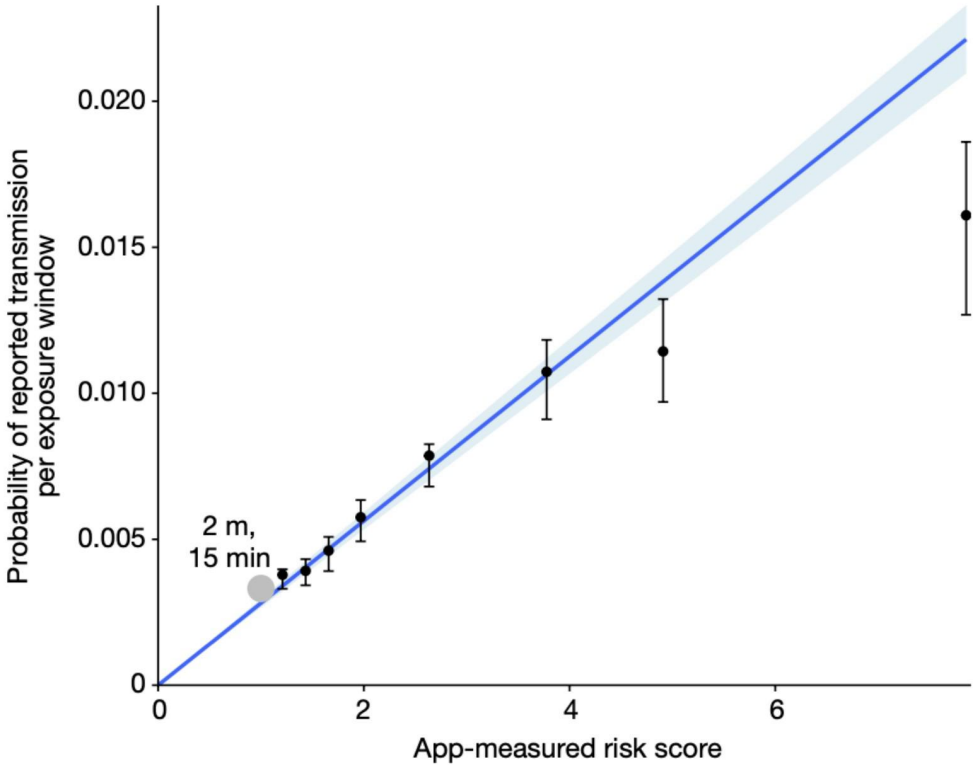
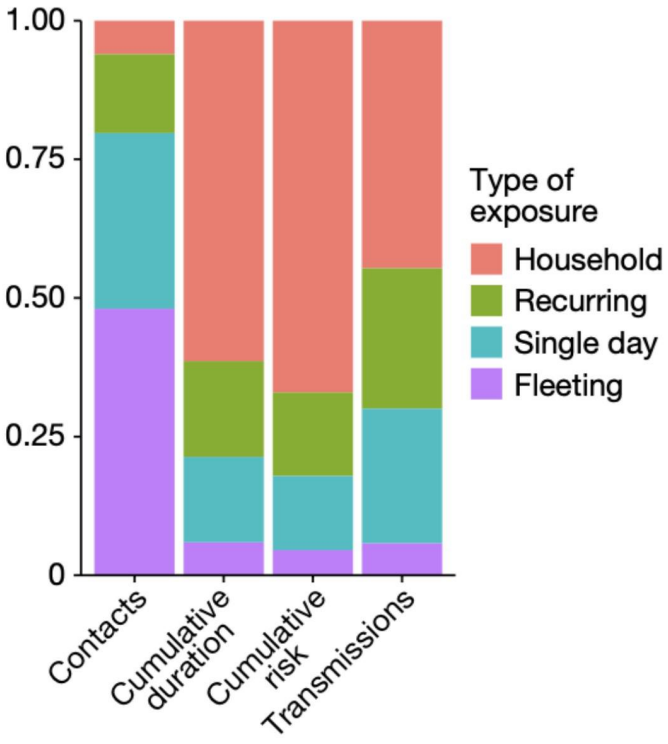


Figure legend: Transmission probability per exposure window increasing almost linearly with risk score. The probability of reported transmission per exposure window – that is, the estimated probability of a transmission in an individual 30-minute window followed by reporting of a positive test — as a function of the app-measured risk score for that window. Points show the best estimate and error bars indicate the 95% uncertainty individuals. The grey point denotes our estimate for the probability of reported transmission after 15 minutes at 2 meters distance from an individual with standard infectiousness.

113. These results also confirmed that the app could be used as a tool for precise epidemiological measurements, therefore enabling two main retrospective analyses that leveraged the data collected by the app analytics back-end.

114. The first retrospective analysis on "Digital measurement of SARS-CoV-2 transmission risk from 7 million contacts" was published in Nature (Exhibit CF/31 [INQ000574820]). In this work, we were able to assess how proximity and duration of exposure contribute to the risk of transmitting COVID-19 to contacts. A major finding was that duration of exposure plays a more important role than proximity in determining the risk of transmission. In particular, the risk of transmission is small for brief exposures (about 1-2% per hour of exposure in 2021/22), while it is very high for exposures lasting several days, as typical for household contacts. Long exposures have therefore a disproportionate role in COVID-19 transmission: household contacts and contacts recurring over multiple days (such as workplace contacts) represent less than a quarter of all recorded contacts, but account for about two thirds of all detected transmission events, as can be seen in the Figure below from (Exhibit CF/31 [INQ000574820]).



115. Quantitative information of this kind would have been extremely helpful in designing better policies if it would have been available early in the pandemic. Duration of exposure was not emphasised as a risk factor in public health advice, despite being the main factor in our analysis. A risk assessment more focused on duration of exposure would have been possible both for manual and app-based contact tracing, and it would have provided improved impact on the epidemic while reducing the number of individuals in self-isolation and therefore the socio-economic costs. Designing an optimised protocol for this scenario could have increased the effectiveness or reduced the number of days in quarantine by about 40% (Exhibit CF/31 [INQ000574820]).

116. If the infrastructure would have been ready and tested beforehand, these analyses could have been performed almost in real time during the pandemic, with results available in a matter of weeks, or even days during a period of high viral prevalence.

117. The second retrospective analysis is an evolution of the weekly reports produced during the pandemic. It was focused on "Drivers of epidemic dynamics in real time from daily digital COVID-19 measurements" and was published in Science (Exhibit CF/32 [INQ000574826]).

118. In this work, we have shown how it would have been possible to build an almost real-time, high-resolution picture of contacts and transmissions from the app's exposure events analytics. For the first time, we quantified patterns of exposure to confirmed cases and transmission to contacts with a daily resolution. The figure below shows clear daily peaks in contacts and/or transmissions in association with major events such as the weekends of the Christmas period and the Euro football matches in 2021. The day of the final of the Euro tournament between England and Italy is the day with the highest number of transmissions ever observed in our data.

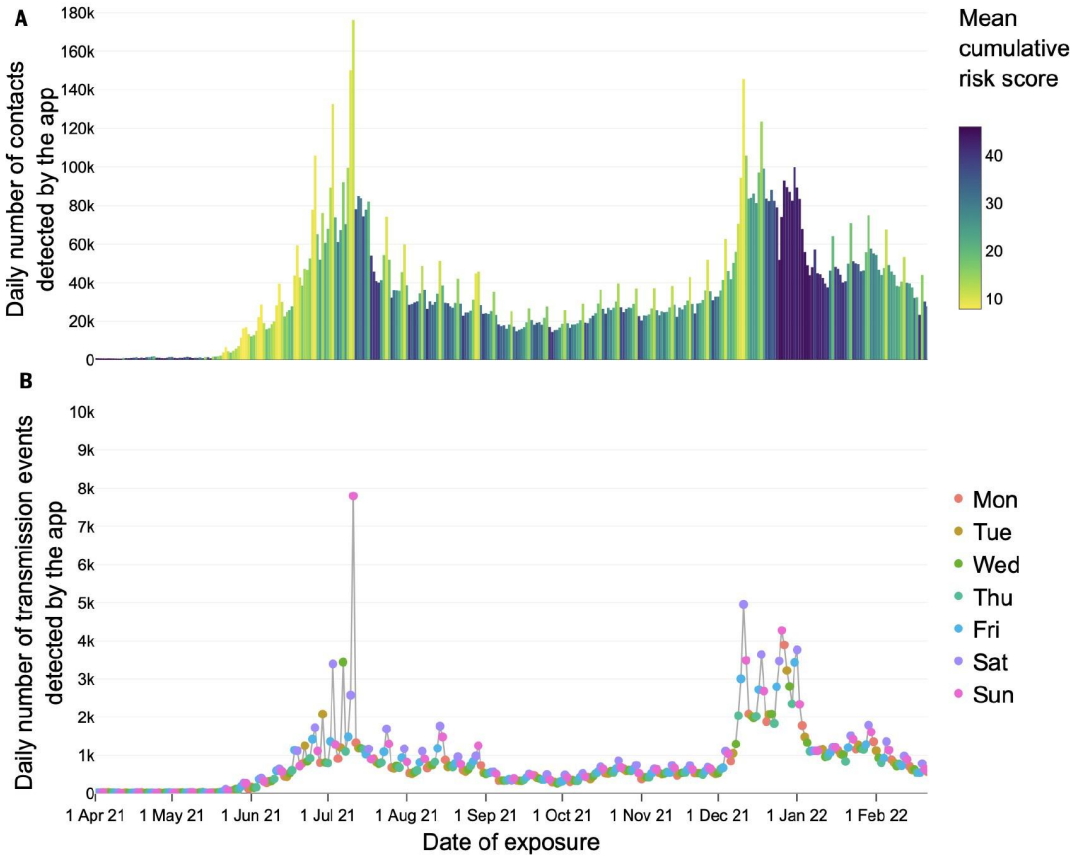


Fig. 4. Daily numbers of contacts (risky exposures) and estimated transmission events detected by the app, indexed by their date of exposure.
(**A**) Contacts, colored by the mean of their cumulative risk scores. (**B**) Transmission events, colored by day of the week. Infection events are shown in fig. S11.

119. Most importantly, we showed how it was possible to use the information collected by the app to build early indicators of the epidemic dynamics that would inform policymakers about the cause of changes in epidemic trends. These indicators could show if the changes were due to change in contact rates in the population, or to changes in the transmission risk of individual interactions. It is also possible to assess if changes in transmission risk could either be due to changes in the type, duration or proximity of interactions, or biological changes such as viral transmissibility or population immunity.

120. As an example, we observed a large increase in the reproduction number R_t in Spring 2021, more than doubling after Stage 3 of the roadmap. The majority of this increase was due to a dramatic change in population contact patterns, together with a small contribution from an increase in riskiness of contacts.

121. During the period analysed, the app-based indicator for the reproduction number R_t was able to detect changes in transmission patterns several days ahead of other indicators based on reported numbers of cases. Contact-tracing apps and similar tools can provide valuable information to policymakers.

Some international comparisons

122. Internationally, several countries were able to successfully suppress COVID-19, and quickly re-opened after vaccination became widespread. Singapore is one of the best examples with a centralised response, a policy of suppressing viral transmission, an effective TTIQ system based on rapid testing with results available in a few hours, and a combination of manual and digital contact tracing. Several other countries in Northern Europe, East Asia and Oceania followed similar strategies. Singapore was the first country to develop a contact-tracing app, following an approach resembling the first app designed by NHSX for England. The app was complemented by wearables with the same function, i.e. a physical dongle with Bluetooth functionality interoperable with the app on phones. The resulting system, known as TraceTogether and OpenSafely, was used by over 90% of the population.

123. More than 80 countries in the world developed contact tracing apps, but with variable outcomes. Of these, 41 countries and 21 US States used the Google Apple Exposure Notification approach, the system used by the UK NHS COVID-19 app, and the apps of Scotland and Northern Ireland. Several countries in Europe deployed exposure notification apps with uptake comparable to the NHS COVID-19 app. An example is Germany: despite being a federal state with each Lander responsible for their own public health policies, the federal government ensured a coordinated response, based on reasonably effective testing and contact tracing programmes. Contact tracing was both manual and app-based, and with venue-based tracing. The effectiveness of the German exposure notification Corona-Warn-app was probably comparable to the NHS COVID-19 app, but the Corona-Warn app included a more fine-grained risk assessment for contacts. Despite these efforts, Germany was only partially successful, mitigating rather than

suppressing the epidemic. Several problems may have hampered efforts in Germany, such as high levels of heterogeneity between different areas, and a relatively slow start to the response. As in the UK, the public health system was overwhelmed for all of the first epidemic wave.

124. Other European countries were less effective in controlling the epidemic, either because of a regionally fragmented response (Spain) or long turnaround times for testing and ineffective manual and digital contact tracing, as well as poor integration between the app and the testing system (Italy).

Relevant work since COVID-19

125. Since 2022 I have been a member of two of the UK Department of Health and Social Care's (DHSC) standing committees, the SPI-M committee and the NERVTAG committee. SPI-M, the Scientific Pandemic Infections Modelling group, is a committee of mathematical modellers that advises DHSC on pandemic planning and emerging threats. NERVTAG, the New and Emerging Respiratory Virus Threats Advisory Group, is a multi-disciplinary group that provides a wealth of perspectives and guidance based on current and emerging situations.

126. I am also a member of the UKHSA Expert Technical Working Group on mpox, standing since 2022, providing multidisciplinary academic advice to UKHSA on this new emerging virus.

127. Since 2022, I have been a faculty member in Oxford University's newly formed Pandemic Sciences Institute. I lead on Data Analytics and Epidemiology, and collaborate closely with colleagues in themes on Vaccines, Treatments, Ethics and Social Sciences.

128. I have continued some of my pre-COVID academic projects, and also obtained external funding for two new projects. The first of these projects is called PREparedness using Simulated Trial Optimisation (PRESTO). The project is funded by an intergovernmental organisation called the Coalition for Epidemic

Preparedness Innovation (CEPI). The aim of the project is to accelerate trials of new vaccines during emerging epidemics by using modelling to decide what kind of trial is most efficient dependent on the setting and the new pathogen. We are working closely within a new ecosystem of clinical trial sites, sponsors and vaccine developers focused on the so-called '100 days mission', to have a vaccine ready within 100 days of an epidemic starting.

129. The second new project is called the Oxford Martin School for Digital Pandemic Preparedness, of which I am Director. The School will run in Oxford for 3 years bringing together thought leaders in Medicine, Public Health, Philosophy, Economics and Statistics to develop a blueprint for an integrated digital system that could strengthen and transform future public health responses to pandemics.

Recommendations for improving UK capacity to respond to future novel and emerging virus threats

130. The first line of defence to any novel pathogen involves test, trace, isolate and quarantine (TTIQ) as a key intervention. TTIQ can play an especially important role in both slowing epidemic spread and finding out the risks of transmission and the health impacts of the new disease. **Recommendation: The UK should develop standing capacity to test many people for novel viruses, to perform manual contact tracing with accuracy and speed, and to roll out digital contact tracing within weeks of the start of a public health emergency.** The UK currently has none of these, despite a present threat from multiple variants of highly pathogenic avian influenza, multiple new variants of the mpox virus, and incursions of Ebola and Marburg virus in countries from which we draw a substantial fraction of our NHS workforce. A reasonable question is about the relative benefits of a) a substantial standing capacity or b) a plan for scaling up with sleeping contracts. I think there are two reasons to favour standing capacity. First, the start of a pandemic is an international crisis, during which there will be acute competition for resources and disruptions to supplies. During the start of 2020, there was an acute shortage of consumables for PCR testing. Second, if a response is started early and keeps

the number of cases low, then in fact the response may remain more focused and ultimately require fewer staff and resources than if the situation grows exponentially out of control. During COVID-19, there was a lot of focus on the problem of overwhelming NHS health capacity. In my view, more consideration should be given to the problem of overwhelming public health capacity. During COVID-19, this happened so quickly and for so long, that an alternative situation where public health capacity would have been sufficient and scaled up in time was never considered feasible. It should be a priority to make this feasible for future responses.

131. Exposure Notification (EN) – the name given to the privacy-preserving form of Digital Contact Tracing (DCT) co-developed with Google and Apple and used in the NHS COVID-19 app – proved to be a valuable addition to the TTIQ toolkit in the UK. The cost of the app was very low relative to other interventions. (I would be happy to follow up on this point with the Inquiry team if needed.) There is substantial scope for improvement with several issues that were left unresolved following its deployment during the pandemic. There is currently no standing capacity to deploy EN or any other form of digital contact tracing DCT, and UKHSA estimates that it would take about three months to develop and deploy a new version of the technology. Interventions that are started early in an epidemic, and maintained until vaccines and treatments are widespread, make a disproportionate impact in reducing total mortality. **Recommendation: The UK should prepare in advance the technological infrastructure for EN, or another suitable form of digital contact tracing, such that it is ready to be deployed within three to four weeks of a new outbreak starting.** The trigger for could be early evidence of international transmission clusters and evidence of a new pathogen or significantly new variant, as reviewed for example by NERVTAG and/or SAGE. In 2020, this would have been the first or second week of January 2020. EN deployed in the UK before the end of January 2020 would have delayed the epidemic, given a large volume of high-quality intelligence on the risks of transmission, and given the UK many more policy options by March 2020. It is plausible that it would have been possible to avert the lockdown as implemented, both

because of slower spread and because of much better information on which contacts were most risk for transmission.

132. **Recommendation: the successors to the NHS COVID-19 app, including EN or other forms of digital contact tracing, should be developed as a collaboration between stakeholders. Development should be a partnership between the public health sector, epidemiologists, and the companies that control the phone operating systems. It should be agreed in advance whether there is one app for the UK, interoperable apps for the devolved nations, or a plurality of apps with a common core specification. The UK should engage with, or convene, international working groups to develop standards.**

    a. The public health sector can best advise on the integration of EN to be synergistic with testing, outbreak response, manual contact tracing, and public information.

    b. Epidemiologists can best advise on the underlying epidemiological design of apps in order to achieve their primary aim of reducing transmission. They can also advise on how EN apps can generate valuable epidemic intelligence, and can develop the monitoring and evaluation framework used during deployment.

    c. Over 99% of smartphones used in the UK have operating systems developed by Google or Apple, and therefore those two companies need to be proactively engaged in at the very least approving the next generation of EN apps. The EN system relied on Google and Apple in two respects: first was that the core technology recording contacts between phones was run within the operating system, not in the app; second, the companies reviewed and decided what was acceptable or not in the exposure notification apps. The first step was optional but helpful for maintaining reliability, the second step was non-negotiable. During COVID-19, no better governance system was available; better governance could be envisaged for future pandemics.

d. Decisions on having one or more apps for the UK should be based on having systems that are functional and appeal to a wide range of the population.

e. International interoperability would reduce the need for travel restrictions during outbreaks, and therefore international cooperation is mutually beneficial for responding to future outbreaks.

133. So-called 'rules' about which contacts are risky and which are not, such as the notorious 'two-meter-fifteen-minute' rule, are no more than initial heuristics. Data from TTIQ can be used to rapidly generate quantitative data on the risk of transmission for different types of events. During COVID-19, such analyses could have rapidly shown, for example, that outdoor contacts were much safer than indoors, and that the transmission risk was concentrated in contact events that lasted several hours, such as sharing a meal, working or living together, and was very low for short contacts. Knowing this quickly would have had substantial economic benefit, and would have allowed self-isolation and quarantine advice to be focussed on the most high risk contact events rather than many contacts that were extremely low risk. **Recommendation: the public should be informed that initial heuristics of risk are likely to be updated as we find out more about a new virus, to help prevent media coverage of policy "U-turns" from undermining trust. Digital approaches such as the NHS COVID-19 app should be prioritised for learning about transmission risk as they are suitable for generating such data within weeks of an outbreak starting.** This requires standing capacity that the UK does not currently have.

134. Policy making during emergencies can be greatly improved by the availability of real-time information on how the emergency is affecting people and how people are responding to the emergency. **Recommendation: The UK should develop in advance an integrated data system to measure current infections, population mobility, and population response to public health measures. Next-generation technologies such as wastewater sampling, digital symptom tracking and digital contact tracing should be integrated**

with community and hospital testing. The UK should build on the legacy of the NHS COVID-19 app that provided unique daily information on the contact rates of the infected population, on the changing infectiousness of the virus, and the changing immunity of the population; this information was typically available about a week ahead of other indicators, providing a valuable source of data for policy makers. Rapid evaluation of the effectiveness of interventions should be transparent and publicly available, for example via a dashboard, to inform the public that their efforts are working, and to thereby drive uptake and adherence to the measures.

135. **Recommendation: The UK should change doctrine in preparing for novel viruses to reflect that most epidemics are controllable. The central question should be to ask whether the efforts needed to control the epidemic might cause more harm than the epidemic itself. The task of public health is to develop control measures that reduce harms and maximise effectiveness. When a new epidemic begins spreading, initial efforts should focus on containing or suppressing spread and collecting necessary data for decision making.** In particular, we need better systems for rapidly quantifying the effectiveness and harms associated with different intervention measures. A number of countries (including Norway, Denmark, Taiwan, South Korea, Singapore, New Zealand, Australia) controlled infection during 2020, holding back the epidemic until vaccines were rolled out in 2021. These countries did not experience excess mortality from the pandemic, nor did they suffer worse economically, nor were they all undemocratic. There was no single playbook for achieving this level of outcome, but TTIQ of some form during 2020 was a key element in each case.

136. **Recommendation: The UK should develop new computer simulations to explore, and new pandemic playbooks to advise on, the variety of ways in which TTIQ can be implemented, including forwards and backwards tracing, and investigation of individual outbreaks.** Policies centred on TTIQ should be a first line of defence, because in many situations they have a favourable ratio of benefits in reducing infections relative to the social and economic harms that they cause, and because they can also be a rich source

of data for understanding transmission and quantifying the harms caused by the new disease. This work requires a collaboration between UKHSA, academic epidemiologists and modellers, and groups with expertise in economic costs, both macroeconomic costs and costs to individuals.

137. Within TTIQ, most of the harms to individuals come from 'Q', namely the quarantining of individuals who are not infected but rather have come into contact with someone who may be infectious. The policy of quarantine is confusing and unpopular. **Recommendation: the UK should plan a system of financial and social support for quarantine, and plan to replace it if possible by a policy of regular testing.** As a pandemic is a whole-of-government crisis, this requires planned clear lines of communication between the Department of Health and Social Security and the Treasury.

138. School closures should not be a first line of defence for new viruses, but rather a measure of last resort. TTIQ is very challenging in schools due to the way in which children mix. The most effective ways of controlling infections in schools that minimise disruption to education are cohorting, air-cleaning for respiratory infections, outdoor learning and regular, possibly daily testing. **Recommendation: closing schools should be a measure of last resort, and NPIs other than TTIQ such as regular asymptomatic testing are needed to balance controlling infections with keeping schools open.**

139. **Recommendation: The UK should address the substantial social, ethnic and geographic disparities in health, and in uptake of public health interventions. The UK should learn from countries where inequalities were not so stark, as well as from its own vaccine roll out during COVID-19 that suffered from fewer problems of inequality.** Despite substantial efforts the population uptake of the NHS COVID-19 app was less than a third as high in the UK's most deprived lower tier local authorities than in the more affluent ones. This affects populations in these areas adversely, as well as the national capacity to respond to new outbreaks. This requires formative research including trials, with work needed from both UKHSA and perhaps funded to universities through the funding agencies such as UKRI and NIHR.

Selected publications, public reports and repositories

Timeline
https://www.digitalhealth.net/2020/04/timeline-what-happened-with-the-nhs-covid-19-app/

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Statement of Truth

I believe that the facts stated in this witness statement are true. I understand that proceedings may be brought against anyone who makes, or causes to be made, a false statement in a document verified by a statement of truth without an honest belief of its truth.

Signed: _____ Personal Data _____

Dated: _____19 March 2025 _____