# Digital pandemic preparedness: key principles and requirements, building on lessons from COVID-19

## White Paper from the Oxford Martin School Programme on Digital Pandemic Preparedness

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# Abstract

The COVID-19 pandemic exposed major gaps in global preparedness. Digital tools supported public health responses but deployments were delayed and impacts limited. We review successes, challenges, and missed opportunities particularly for Bluetooth contact tracing, highlighting research priorities for building on these experiences. Consolidating insights from a multidisciplinary community of experts, we present key requirements for digital public health tools for pandemic preparedness across a range of pathogens and settings.

# Introduction

Most countries entered the COVID-19 pandemic without the ability to interrupt transmission rapidly at population scale[1]. Preparedness had focused more on mitigating pandemic consequences (hospital surge capacity, supply chains, stockpiles, vaccines) than on early epidemic control, particularly in countries with less recent experience of major outbreaks[2]. Digital advances that had transformed large parts of society had typically not been incorporated into public health responses. In early 2020, few countries had the standing capability or institutional responsibility for designing and governing digital public health tools with legitimacy and with public trust[3].

Here we reflect on the Bluetooth contact tracing apps used during the COVID-19 pandemic, recognising their demonstrated potential whilst detailing the key missteps and missed opportunities. We then make practical recommendations encompassing a breadth of possible digital public health tools for future pandemic preparedness and including topics for research, innovation and collaboration spanning public health, technology and academia.

# Reflections from COVID-19

## A brief history of Exposure Notification and contact tracing apps

When SARS-CoV-2 ('COVID-19') began spreading globally in early 2020, traditional contact tracing – which had played a key role in containing and ending the SARS-CoV-1 ('SARS') epidemic[4] – struggled to keep pace. There were two key reasons for this. The first was a property of the virus itself, which, unlike SARS-CoV-1, could be transmitted soon after

getting infected and without symptoms, so infectious individuals could be spreading it unknowingly. For maximum effectiveness, contact tracing for SARS-CoV-2 had to be fast enough to alert people before they were infectious. Secondly, manual approaches, reliant on interviews and recall, did not scale well with the fast spread of COVID-19, particularly in settings characterised by dense social mixing and high mobility[5].

However, widespread smartphone ownership created an opportunity: by keeping a record of low-energy Bluetooth 'pings' between phones, it was possible to automate rapid contact tracing at population scale. The scientific and ethical cases for this approach were circulated in the first week of March 2020[5,6] and workable Bluetooth apps were developed within days[7]. The issues which took longer to solve included governance, population-wide scaling, interoperability, privacy, cybersecurity, calibration, phone interoperability, user interfaces, integration with diagnostic testing, accessibility, marketing and communications.

During March and April 2020, particular concerns about privacy and surveillance were hotly and publicly debated, and tensions emerged in many countries between public health priorities and individual liberties, and between governments and technology platforms[8]. Apps using 'centralised' data collection, relying on storage of potentially sensitive data within government-owned servers, raised fears of function creep and long-term misuse but offered benefits for central evaluation. This approach was pursued by Singapore, France and the first England & Wales app. Decentralised architectures, which emphasised user control by minimising central data collection and focusing more data storage on individual devices, had more support in most countries but posed some challenges for functionality (could an erroneous notification be reversed?) and evaluation[9,10].

In April 2020, Apple and Google announced that they were jointly developing the Google Apple Exposure Notification (GAEN) application programming interface[11], enabling privacy-preserving Bluetooth exposure notification through smartphone operating systems. Its decentralised architecture avoided location tracking, minimised data collection, placed key risk calculations on users' devices, and was customisable to meet the needs of different public health agencies. By embedding these capabilities at the operating-system level, GAEN addressed critical performance, power-management, internationalisation, interoperability, and security challenges that had constrained earlier efforts. GAEN enabled public health authorities to deploy exposure notification without developing the underlying technology themselves. Exposure Notifications Express, released on 1 September 2020, went further by removing the need for a dedicated app.

Digital contact tracing apps were deployed in at least 90 countries[12] (around 75 of which used the GAEN framework[13]) with an estimated 600 million users worldwide. However, there were vast differences in how the apps were received. In some countries there was low

uptake and the apps had no measurable impact on the epidemic. Other countries saw record-breakingly high uptake for a new app[14], strong engagement[15], and correspondingly large epidemiological impacts[16,17].

Here we examine the causes of such stark variations in effectiveness. This is important to understand, particularly because the more successful apps played such a powerful role and could easily be optimised further. Singapore's TraceTogether, which used a combination of smartphone app and dedicated physical hardware 'tokens', achieved near-universal population uptake and covered 93.3% of cases during the Delta and Omicron waves, freeing public health officers to focus on high-priority containment clusters[18]. The NHS COVID-19 app for England and Wales reduced the number of cases during the SARS-CoV-2 Alpha variant wave by up to 25%[19], and in its first year averted an estimated 10,000 deaths[15]. In addition to these direct impacts, analysis of its minimal, privacy-preserving data provided unprecedented epidemiological insights[20,21] that could be invaluable for public health intelligence. In December 2022, long after the peak of the emergency, a simple update to the user interface made the NHS COVID-19 app 33% more effective overnight. Together, these observations provide strong motivation for learning lessons from the COVID-19 pandemic and investing in the necessary research and innovation to ensure digital tools are ready to support future pandemic responses.

# Missteps and missed opportunities

## Trust and trustworthiness

Uptake of digital tools and adherence to public-health measures are strongly associated with institutional trust[22–24]. However, trust and trustworthiness are distinct: a trustworthy intervention may fail to secure public confidence, while an untrustworthy intervention may at times be trusted. Preparedness therefore requires *justified trust*, built through ethical design, transparent communication, public engagement and institutional accountability. Levels of public trust depend on a complex set of factors including the extent of pre-pandemic trust in government and health systems, and on perceptions of trustworthiness in the pandemic response (which can vary within-country across institutions[25]).

Early over-promising of digital contact tracing as a 'silver bullet' to end the pandemic anchored public and political expectations to outcomes dependent on many contingent factors beyond the contact tracing tool. When reality proved more complex this eroded public confidence. Public confusion and institutional friction arose in some countries such as Italy, where regional public health agencies launched several surveillance apps before a national GAEN-based app was deployed. Within the EU particularly, digital exposure notification and testing systems became entangled with broader digital certification efforts

later in the epidemic, which drove another wave of app adoption[26] but further complicated governance and blurred public understanding of purpose.

Decisions naturally had to be taken reactively at high speed, but this often left too little time for ethical reflection or public engagement. Whilst there was engagement with ethics expertise within the UK during the pre-GAEN stages of the design process, this was not maintained. Civil society organisations, privacy advocates, and publics were often engaged after key, irreversible choices had already been made. Trust and legitimacy proved fragile and difficult to recover once lost.

## Privacy

Most digital contact tracing systems prioritised privacy in order to be trustworthy and to protect individual liberties, and the GAEN approach adopted by most countries was privacy-preserving by design. This proved both ethically and practically valuable: many centralised (non-privacy-preserving) systems experienced function creep, with data used for purposes other than contact tracing[27], and although initially there were arguments for centralised approaches' value for analysis and evaluation[10,28], in reality the data was often determined to be so sensitive that it was largely inaccessible to public health implementers and researchers during the pandemic, or was even deleted[29].

However, many decentralised systems optimised for privacy in the wider system so extensively that even basic performance monitoring became impossible[28,30,31]. Elsewhere, restrictive agreements severely delayed or completely prevented the publication of analytics, insights and detailed analyses. Paradoxically, a focus on privacy undermined transparency, evaluation and the public feedback needed to sustain trust.

Norms of information disclosure shift during emergencies, necessitating transparent ethical debate and public engagement on appropriate data sharing for the context[32]. Masel et al. argue for framing the debate in terms of 'user autonomy' rather than 'user privacy'[26]. Advance consultation and debate about the precise data fields to collect and their trade-offs for public health versus privacy would have substantially improved the usefulness of app data for public health decision-making, and, via public communication, may have improved uptake. Uptake is a key driver of effectiveness: statistical modelling predicted that there would be a 1-2% reduction in cases for every 1% increase in app uptake[33] and this proved true in practice in England and Wales[19].

## Governance and global co-ordination

As noted in a Council of Europe 2020 review[3], governments and technology companies made rapid design choices early in the pandemic with profound implications for privacy and effectiveness. To our knowledge, this was the first instance of *personal* digital devices, produced by commercial digital platforms, being used for a *public* health response, creating a daunting governance challenge. Decisions had to be made under extreme time pressure. In the absence of decision-making frameworks or systems to co-ordinate responses, mistakes were made in parallel across jurisdictions, while useful advances were not necessarily shared[34]. There was no standing institutional capability to curate lessons, evaluate alternative designs systematically, or to preserve and evolve these capabilities once the acute phase of the pandemic passed.

## Public health integration and agility

Where available, vaccines and treatments are the most effective public health measures for sustained disease control. However, they take time and money to develop, manufacture, transport, test, license, distribute and administer. Where digital contact tracing apps were effective, they had a considerable impact on reducing transmissions, hospitalisations and deaths[15,19]. However, many were only deployed after the first epidemic wave, after key therapeutic interventions had been discovered, and shortly before vaccine roll-outs. They were not available when they could have had maximal impact, and many suffered from a loss of momentum after launch. Early urgency and political attention were not matched by sustained investment and communication, and exposure notification systems often lacked clear ownership, leaving them vulnerable to drift, neglect, or quiet decommissioning as priorities shifted. In the future, an integrated public health response would make clear the purpose of testing and tracing to mitigate spread and support epidemiological intelligence from the start of a pandemic through any pre-therapeutic and pre-vaccine era, with transparent communication about epidemic phases and timelines for interventions being phased out when no longer needed.

The effectiveness of exposure notification was closely linked to successes and failures of other aspects of public health systems. Where notifications were closely integrated with self-isolation guidance and support services, individuals were more likely to be able to comply. In settings where exposure notifications could trigger access to restricted diagnostic testing, and where test results linked smoothly back to digital tools, there were clearer incentives to use and trust the technology[35]. Where digital tools reduced friction for other public health interventions, such as QR-code based (rather than paper-based) venue check-ins, this drove app uptake[36]. However, when testing was slow, overwhelmed, or when false negative results were issued[37], problems propagated into the contact tracing system[17].

Over the course of the pandemic, diagnostic testing evolved from scarce, laboratory-based PCR to widespread rapid antigen testing in many countries, enabling individuals to act on risk information within minutes rather than days. The impact on contact tracing was bidirectional: it sped up case identification and therefore gave notified contacts more opportunity to take precautions before becoming infectious, but in settings where free daily testing was routine, there was less need for contact tracing altogether.

Policy rigidity meant that in several contexts, exposure notification continued to trigger quarantine when cheap and rapid testing could have supported test-to-stay or test-to-release approaches, reducing harm while maintaining public health benefit. In the future, integrating app-based findings about 'risky' proximity of contact[20] into policy could lead to less stringent social distancing measures and enable economic activity to resume sooner. Fine-grained app-based behavioural insights could fine-tune policy recommendations by incorporating understanding of the effects of weekdays versus weekends, regional variation, and national events[21].

## Equity

The equity implications of digital contact tracing are complex because benefits extend beyond app users to their contacts and the wider population. By reducing transmission, even unevenly distributed uptake may benefit non-users and reduce reliance on more blanket interventions like lockdowns, which are known to disproportionately affect disadvantaged groups[38,39]. Nevertheless, digital exclusion and unequal capacity to respond to notifications can compound existing inequalities[40,41]. Individuals facing insecure employment, caring responsibilities or overcrowded housing may be unable to isolate even when successfully notified[42]. Incarcerated individuals are an example of a sub-population who were excluded and who presumably received negligible benefit from digital contact tracing's mitigating effects in wider society. Equitable deployment therefore requires more than single-axis fixes: a translated app, a subsidised phone, a hardware device. Identifying which adaptations matter most for a given population, and how the network of interactions between users and non-users affects equity, is itself a substantial research task. However, without it, digital interventions risk reproducing or exacerbating existing health inequalities.

Defaulting to minimal data gathering practices to optimise privacy in app design tended to leave equity impacts insufficiently considered. Where the ages of users and other demographic information were not collected, it was impossible to rigorously analyse reach and equity, or to design evidence-based strategies for improving uptake in under-served populations. In 2021, the European Centre for Disease Prevention and Control and World Health Organisation published an indicator framework which set norms for future digital

proximity tracing solutions, stating that countries should "seek to determine the proportion and characteristics of the app-using population to contextualise the data obtained"[43]. This presents a challenge for privacy-preserving approaches, arguing at least for supporting their deployment with demographic surveys, if not collecting the relevant data directly within-app.

### Wider research insights

Privacy-preserving contact tracing apps were not designed to collect data for research, and most did not even collect sufficient data for basic performance monitoring. The available data were therefore not optimised for answering important questions for policymakers and researchers. In Germany, the CoronaWarn app enabled voluntary data donation, allowing more detailed research to be conducted albeit on a biased subset of users[44]. Wider consultation on data collection strategies could have concluded that extra data collection was justified in some contexts. For example, if the same app had collected both user vaccination status (as in Germany) and 'testing positive shortly after notification' (as in England & Wales), the data could have underpinned a rapid, efficient and detailed analysis of real-world vaccine effectiveness. Similarly, additional data would have been valuable for behavioural insights: understanding population responses to public health measures and supporting iteratively improving interfaces and usability[17].

# Digital Pandemic Preparedness

We now consider how to build upon the lessons learned from COVID-19 exposure notification systems to build towards more generalised digital pandemic preparedness for the future. First, we clarify the scope of 'digital tools' under consideration, with a range of possible applications including, but not limited to, exposure notifications for contact tracing.

## Scope

There are many digital tools that benefit public health. Here, we focus on the development and deployment of ethical, trustworthy digital public health tools for pandemic preparedness which both:

1. enable direct communication between individuals and public health agencies, and
2. have at least one of the following functions:
    a. users interact directly with a device, either actively (e.g. sending and receiving SMS, reporting symptoms in an app) or passively (e.g. heart rate recorded by a smartwatch)

b. devices interact with each other, such as via Bluetooth.

This scope is illustrated in Figure 1. Examples include devices sending anonymised data to public health agencies for real-time epidemic intelligence, and public health agencies sending general or bespoke information to individuals via their devices, directing them to guidance, diagnostics, therapeutics or vaccines. For clarity, health data repositories and dashboards are out of scope because there are no individual-level devices involved. Personal medical devices such as continuous glucose monitors are out of scope because they do not communicate directly with public health agencies.

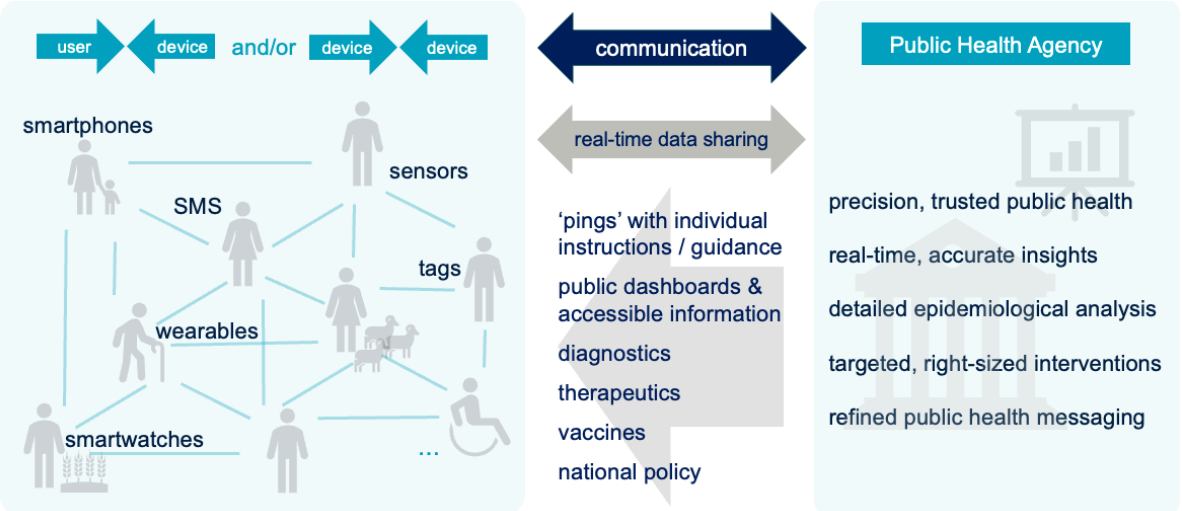



**Figure 1. Diagram to illustrate the scope of digital public health tools we consider: digital tools enabling direct, ethical and trustworthy communication between individuals and public health agencies.**

## 'Peacetime' activities and research priorities

Of course, global epidemic peacetime is rarely - if ever - achieved. Nonetheless, most of the time there are many individual jurisdictions experiencing periods that are not dominated by infectious disease emergencies. Here, we detail priorities for investment at those (loosely defined) times. Although we structure these activities and priorities into broad themes, we emphasise that interdisciplinary, frequent collaboration across the themes will be key to building and deploying robust and effective digital tools.

### Platform approaches

'Platform' approaches establish a core architecture which can be rapidly adapted to new situations. As evidenced by vaccine platforms and CEPI's 100 Days Mission[45], advance investment in research, protocols, infrastructure and regulatory processes can substantially accelerate emergency responses. Digital pandemic preparedness could take

an analogous approach. Technical platforms, frameworks for ethics and governance, response playbooks, standards, and stakeholder relationships (including but not limited to operating system manufacturers, cloud providers, public health agencies, hardware manufacturers, researchers) can all to differing degrees be developed during epidemic peacetime in pathogen-agnostic ways, with minimal editing needed to tailor them to a particular pathogen and setting.

Pre-established frameworks can quickly articulate trade-offs both within and across values and decisions as they relate to contact tracing design and deployment. Methods for substantively engaging public values such as citizens juries, assemblies, and deliberative polling are valuable for exploring design trade-offs and for building justified trust. Peacetime engagement should extend beyond consultation to meaningful co-production with communities likely to be disproportionately affected by both infectious disease emergencies and the measures introduced in response. Statutory advisory bodies are needed, where members have pre-established working relationships and are well-practiced in considering competing priorities and making rapid decisions.

## Data and analysis

Following the platform approach, much of the data and analysis architecture could - and ideally would - be prepared in advance. This includes Data Protection Impact Assessments (as required by information commissioning authorities), servers and data storage, data access agreements, data safeguarding through penetration testing, pipelines, analytics platforms, and even some analysis and output templates (basic reports, dashboards). To do so requires pre-agreement on core data fields and availability, with standardised formats, and careful governance regarding the potential use of 'commercial' data from privately-owned platforms for public health[34].

Ideally there would also be pre-agreement, or at least some pre-articulated trade-offs, on the types of data collected, possible data to consider for donation, and permissible data linkage, for the benefits of public health and research. Even with voluntary data donation, the collection of demographic information involves important ethical trade-offs, particularly where data relate to characteristics associated with discrimination or heightened vulnerability. Decisions about whether, how and by whom such information is collected should be informed by engagement with affected communities, with clear justification of its intended use, appropriate safeguards against identification or misuse, and consideration of less intrusive alternatives. The objective should be to generate sufficient evidence to inform equitable public health responses without creating additional risks for any populations.

The Intelligence for Value (IFV) framework[46], developed for health systems in NHS Wales, treats the capability to turn existing data into decisions, and to evaluate their effect, as the joint product of eight interrelated domains: leadership, workforce and collaboration (people); governance, data strategy and outcome translation (process); and digital integration and analytics (technology). Because overall readiness is set by the weakest of these groups rather than their average, such a framework offers a structured way to identify gaps, which are often procedural rather than technical.

## Artificial Intelligence

There is significant potential for Artificial Intelligence (AI) to improve both digital tools themselves and their indirect benefits. Federated learning approaches (where individual-level data from a digital public health tool remain local but are analysed centrally in a privacy-preserving way) have already demonstrated potential for improving risk estimates from exposure notification data[47,48]. Areas that are ripe for innovation include Large Language Model-based chatbots for personalised communication between public health and individuals, federated learning applications including AI-enhanced symptom tracking with multimodal integration (e.g. combining free text, medical records, voice/cough detection and automated interpretation of rapid antigen test readings), and population-level applications such as identifying emerging signals and rapidly synthesising evidence to support research and public health decision-making[49].

It is also likely that AI will present new challenges. During the COVID-19 pandemic there was strong opposition to using machine learning to help determine Public Health interventions, and sensitivities are likely to remain for the foreseeable future, particularly related to data privacy and re-identification, biases and unequal requirements across population groups, and issues of accountability and regulation[50,51]. A critical issue will be the regulation of public health communication tools to ensure they supply correct, consistent and appropriate advice[52]. The speed of change in this field underlines the need for close collaboration between AI specialists and experts across the public health space, who together can help digital tools use the latest advances while navigating the governance issues raised by using private companies' AI tools for public health applications.

## Deployment in bounded settings

Digital public health tools need to be in active use to keep pace with - and make full use of - the latest developments in wearable technologies, software releases and updates, to monitor and assess public acceptability, and for security research to uncover their vulnerabilities. Although digital tools should be available to as wide a population as possible in the event of an emergency, peacetime applications can achieve many of the benefits of

active deployment within much smaller, bounded settings. We emphasise that, even for small or perceived low-threat outbreaks, experimental technologies in testing phases should never be deployed in place of, but always in conjunction with, other interventions that are known to be effective.

Surveillance and research studies can be conducted via time-limited deployments (e.g. apps for seasonal influenza), spatially-limited settings (e.g. wearables for tracing hospital-acquired infections[53]), or both (e.g. virus transmission in schools[54] and universities[55]). These could be expanded to incorporate pilot deployments of the wider public health toolkit and can include traditional non-digital methods in parallel for testing, calibration and richer behavioural insights.

Epigames[56] and citizen science experiments[57] provide rich opportunities for learning in controlled settings where there is no actual public health risk. There is therefore more freedom for researchers to experiment with design choices and data collection, and to enhance the understanding of epidemics and behavioural responses to policies and incentives[58,59]. Such experiments can help establish principles for evaluation and expected measures for a correctly-functioning technology.

Digital tools may be integrated into other public health research and development to maximise the effectiveness of the combined toolkit. For example, digital data can provide valuable insights into population movements, social interactions, behavioural responses, and potential transmission dynamics, which are often complex, context-dependent, and subject to change over time. However, such insights require independent peacetime validation against empirical observations and epidemiological outcomes, with particular attention to population heterogeneity, representativeness, and potential biases. Another example is wearable sensors that monitor exposure via low power radio or Ultra Wide Band. These can be combined into Phase III vaccine efficacy trials to both (a) help to evaluate vaccine efficacy by controlling for disease exposure - a known confounder in these studies[60], and (b) maintain and test the wearable sensor technology.

## Testing, accreditation, evaluation and updates

Digital public-health tools require pre-established accreditation, calibration and continuous evaluation systems, with capability to apply iterative improvements via rapid updates. For example, if the sensitivity and specificity of a digital measurement of risk are found to be suboptimal - notifying individuals that they are ‘high risk’ when they are not, or vice versa - the algorithm should be corrected and refined as soon as possible. Notice that this needs to be flexible to adapt to evolving epidemic dynamics: a new variant of the pathogen, a new diagnostic test, an effective vaccine roll-out, or widespread use of a therapeutic would likely alter case ascertainment and transmission risks across the

population, with possible impacts for the sensitivity and specificity thresholds of the notification algorithm.

This flexibility and fine-tuning would ideally extend to updating fundamental aspects of the design. For example, if it is found that risks vary substantially between contacts made indoors versus outdoors, there should be a well-established mechanism, prepared in peacetime, for considering and approving updates to the data captured and its role in the risk calculation. Digital tool design should expect policy changes and be able to adapt to them. For example, it is likely that at the start of an outbreak widespread diagnostic testing would not be available, and contact tracing may have to be triggered by symptom-reporting alone. Over time, limited testing capacity may become available and digital tools could play a key role in the booking process, as well as in identifying the key symptoms which are likely to be associated with an infection. Further along, there may be widespread availability of cheap rapid testing, which would affect many aspects of policy including the role of contact tracing itself. There should be a pre-established path for making such updates and acquiring the necessary approvals rapidly.

It is crucial that a malfunctioning digital tool can be rapidly identified. Systems must have predefined criteria for correction, suspension or withdrawal when performance falls below acceptable thresholds, which may be context and disease-specific. Indeed, in Resolution 2478 (2023), the Council of Europe's Parliamentary Assembly stated that such evaluation and monitoring are essential "to ensure compliance with the right to respect for private life and with the data protection standards laid down by Convention 108 and its updated version, Convention 108+."[61]

## Behavioural science and public trust

Complex, inaccessible or non-intuitive user interfaces can lead users of a technologically sound product to abandon their user journeys before completion, drastically reducing effectiveness. Psychological and behavioural science should be embedded in tool design and evaluation from the outset, drawing on established frameworks such as the COM-B model, the Health Belief Model, and Protection Motivation Theory[62]. Such frameworks explain health behaviour as a function of perceived capability, opportunity, and motivation. Post-hoc analyses of COVID-19 apps in Ireland, Switzerland, Germany and India identified the strongest predictors of uptake to be perceived benefit, self-protection, and trust in the deploying institution[22–24,63]. Better understanding of the factors which affect public behaviour, particularly regarding the framing of public messaging, will help maximise uptake and engagement with digital tools.

A trustworthy and trusted response requires ethical concerns to be addressed in app design and deployment decisions, with public engagement and co-production wherever

possible. Interpersonal and institutional trust must therefore be measured, monitored, and, where found to be low, strategically addressed before and throughout any deployment[64,65]. Trust can serve as a preparedness indicator in its own right, measured between emergencies[24] and actively maintained throughout deployment. Low levels of trust may reflect legitimate concerns or previous experiences of discrimination, exclusion, surveillance or institutional failure, rather than deficits in public understanding[66].

### Public health integration

The barriers to developing digital tools are relatively low, and it might be tempting to see this as an opportunity to launch ad hoc solutions. However, public health oversight is a prerequisite for ethical and trustworthy interventions. Ideally, digital public health tools should be an integral part of the pandemic response playbook and included in national pandemic exercises[67]. (They were not included in the 2025 UK Department of Health and Social Care National Pandemic exercise 'Pegasus'[68] which tested many areas of the public health response to a fictional outbreak.) Full integration does not simply mean adding digital tools to a list of proposed interventions. Instead it could include (a) adaptable use of the tools to support relevant epidemic phases, (b) insights feeding back into wider public health measures, for example whether to open or close public venues, (c) insights feeding into real-time epidemic intelligence, for example sharing a real-time estimate of the effective reproduction number (R) and rapidly disseminating information about the detection of a new variant or a geographic hotspot, (d) linkage to other aspects of the public health system including diagnostics, referrals and treatments, as an efficient way of distributing stockpiles and also driving uptake via more direct and easier-to understand personal incentives.

## Key requirements

In summary, we have identified the following set of requirements for digital tools to be prepared for pandemic response:

1. **Day 1 readiness**. The majority of the design should be developed, governed and tested proactively, not reactively, with expert input from **behavioural science**, **ethics, technology, public health** and **epidemiology**, and engagement with relevant **publics**, particularly communities at risk of exclusion or disproportionate harm. This can be achieved via:
    a. Platform solutions with rehearsed playbooks for quickly tailoring to the pathogen and setting, to enable clear identification of gaps and how to fill them.

    b. Peacetime use cases, which can have direct public health benefits, help with testing and calibration, and ensuring that systems do not atrophy due to hardware-compatibility drift. These should be ready to scale up in an emergency, ideally from an established core user base where trust and trustworthiness have been built robustly over time.
2. **Public health integration**. Digital tools must be integrated into the wider toolkit of outbreak response, with easy-to-navigate links to - where available - support services, diagnostic testing, therapeutics and vaccines. They must be adaptable and regularly updated according to changing epidemic dynamics, and incorporating the latest understanding of symptoms and risk factors, which may even be informed by analysis of data from the digital tools themselves.
3. **Autonomy-preserving data and analytics.** There should be pre-agreement of (or at least a rapid decision-making tool for selecting) a collection of sufficient, relevant, and publicly acceptable data fields, guided by the principle of user autonomy. Storage and access agreements should be ready for sharing relevant data with stakeholders, researchers and the general public. Analysis pipelines should be ready to analyse data as soon as it starts flowing in, for:
    a. evaluation of effectiveness;
    b. iterative improvements to the digital tools;
    c. iterative improvements to the wider public health response;
    d. real-time epidemic intelligence;
    e. internal and public dashboards.

We conclude that, as comparatively low-cost and high-benefit interventions, digital public health tools warrant significant peacetime investment. At the time of writing, there are significant gaps in awareness, governance, and technology, which would prevent their timely deployment in a crisis. Closing these gaps and attaining the ‘key requirements’ detailed here is achievable and would significantly mitigate health risks and socio-economic harms in the event of an infectious disease emergency.

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# Author contributions

MK, LAD, JW, TR, YK, LF, İK, JA, PH, MK, MM, MP, CD and CF contributed to the conceptualisation, investigation, writing and reviewing of the manuscript. JB, CC, WE, NK, MS and JW contributed to the writing and reviewing of the manuscript.

# Competing interests

There are no competing interests to declare

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