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Effectiveness of Digital Contact Tracing Policies in Controlling Infectious Disease Spread

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Abstract: Digital contact tracing applications – a primary extra layer to public health protocols – aim to minimise human interaction in a pandemic by digitally informing users about possible exposure. Evaluation of 290 peer-reviewed studies published in 2020-21 offers early evidence on effectiveness. Transmission reduction derives from the speed and scale with which notified individuals can take preventive action. For now, most estimates suggest moderate population-level impact, reflecting both limited user uptake and modest real-world responsiveness. Geographies with higher adoption rates and greater user engagement see larger effects, notably enhanced case capture and shortened infectious periods. Equity, ethics, and governance considerations are equally important in real-world implementation and future policy recommendations, particularly around device accessibility, data privacy, institutional credibility, and balancing digital tracing with more traditional public health measures. Research in 2021 broadened assessment of existing deployments, shifting from proof of concept to questions of use, uptake, and integration in a wider public health system.

The convergence of a pandemic and technology, notably widespread smartphone uptake and Internet connectivity, has breathed life into the old goal of reducing the spread of infectious disease contagion by shortening the time between potential exposure and notification. Ideas for contact tracing-driven network disruption date back almost 100 years, but new tools offer the chance of multiple layers of risk messaging. Governments have quickly developed innovative apps and massively scaled up systems to make contacting known contacts within hours rather than weeks a reality. Smartphone-enabled digital contact-tracing applications now provide the first extra layer to traditional health department outbreak management systems approved and operating in multiple jurisdictions. Such systems leave little untraced when scale, speed, and granularity are combined with the ability to deliver location alerts without any need for an intermediary.

Keywords: Digital Contact Tracing, Pandemic Response Technologies, Exposure Notification Systems, Smartphone-Based Tracing, Public Health Surveillance, Transmission Reduction, User Adoption Rates, Population-Level Impact, Preventive Action Timing, User Engagement Dynamics, Privacy Preserving Design, Data Governance Frameworks, Ethical Implementation, Equity Considerations, Device Accessibility, Institutional Trust, Public Health Integration, Epidemiological Modeling, Outbreak Management Systems, Health Policy Implications.

I. INTRODUCTION

The COVID-19 pandemic prompted unprecedented public health measures, including alternative methods of disease mitigation, prevention, and control. To augment traditional contact tracing, many countries launched mobile apps that support shortened self-isolation times and inform users of potential virus exposure. These digital contact tracing initiatives combined natural and technological innovations within a key public health process – the notification of infection risk. Effectiveness assessments completed in 2021, notably in Germany and the United States, evaluate whether available evidence supports continued and expanded investment in digital contact tracing.

The theoretical foundations of digital contact tracing rest upon network science and epidemiology; the capacity to shorten periods of contagiousness and risks of secondary transmission, in turn, captures a class of potential outcomes. Digital contact tracing aids in discerning potential virus exposure among app users and can additionally support the case detection and notification process for public health authorities. Data privacy remains a core consideration: the technology supports localised, anonymous, and cryptographic methods across geographies, connecting app users without disclosing personal information.

1.1. Overview of Digital Contact Tracing Initiatives

Counteracting COVID-19 and other potentially pandemic pathogens is essential, and such counteractive processes may benefit from innovative technologies, such as digital contact tracing. Initiatives based on these technologies have been launched by dozens of countries across the world. The effectiveness of many of these systems on reducing the spread of

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the respective infectious diseases has been examined in several evaluative research studies published up until and including August 2021.

Digital technologies have been suggested to mitigate the spread of infectious diseases for many years. During the COVID-19 pandemic, the digital technologies of contact tracing, case notification, and exposure notification have been widely used or explored, partly to counter the inherent limitations of traditional methods. Digital contact tracing uses mobile devices to map proximity between individuals, without requiring that the individuals involved be in a close-verbal or close-visual relationship. Deployment of such a digital contact tracing system across a sufficiently large population may reduce transmission over the entire population by identifying infected individuals before they have been detected through traditional methods. Moreover, exposure notification systems—an accessible term for the case notification process—allow individuals who test positive to notify those with whom they were in close proximity, and to urge them to undergo testing and self-isolation.

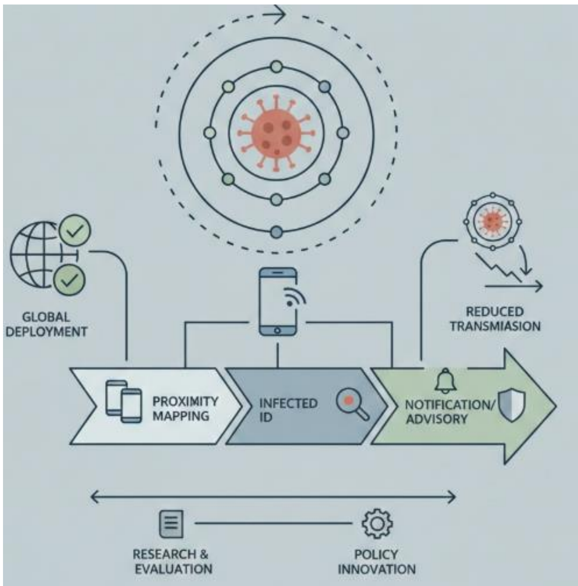

Fig 1: Optimizing Pandemic Mitigation: A Global Evaluation of Digital Contact Tracing and Exposure Notification Systems

II. THEORETICAL FOUNDATIONS OF DIGITAL CONTACT TRACING

The effectiveness of digital contact tracing policies in controlling infectious disease spread has been evaluated in a growing number of studies across many jurisdictions. Most of these analyses use the original COVID-19 exposure notification applications as the case study. Several characteristics make them especially suitable for assessing their population-level impact: utilization arises from a decision to download and use a specific mobile application; geographic coverage can be closely approximated by the share of adults belonging to the respective application ecosystem; centralized technology enables merging of relevant transmission-related events across users; and ground-truth information on cases is available for an entire population, allowing examination of how the notifications activate and respond.

The theorized mechanisms through which digital contact tracing can reduce disease transmission are examined, followed by a summary of methods and datasets. The evidence is then discussed, categorized along dimensions of population-level effectiveness in decreasing intermediate metrics of transmission, and finally organized according to data collection modalities used in the analyses.

2.1. Mechanisms of transmission reduction

Potential reductions in transmission and spread of infection hinge on the accuracy of exposed individuals being informed of their risk, especially when both the exposure and potential subsequent transmission occurred during the infectious period. When such information is available, the exposed individual must take appropriate action to mitigate risk, either through avoiding contact with high-risk groups or isolating. Digital contract tracing technologies may speed up this information transfer to exposed individuals and may also be applied outside healthcare settings where such data are normally harder to obtain. Faster data transfer should increase the share of exposed individuals who know they are at risk

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and are able to take appropriate action. Moreover, by accelerating risk notification, the potential window for further transmission should be shortened.
Digital contract tracing initiatives that operate primarily through smartphones facilitate a faster communication pathway because people typically carry their smartphones. They store the necessary data automatically and continuously without the need for memory-reliant questionnaires, typically do not require that physically exposed individuals sign up for the service, and have no dependency on whether individuals interact with the healthcare system. Existing studies of COVID-19 trend data from countries and US states with and without such technology from mid-2020 onwards continue to find no evidence for a population-level reduction in COVID-19 transmission. However, this does not preclude the possibility of smaller effects or changes in profile that impact the transmission risk, such as earlier detection and isolation of symptomatic cases or changes in contact behaviour.

Equation 1 — Digital Contact Tracing Adoption Rate

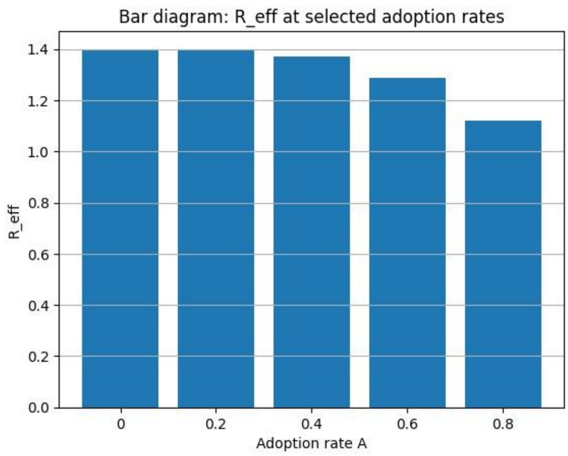
Step-by-step derivation

1. Let:
- N = total population size (or eligible smartphone population)
- N_u = number of active app users
2. Adoption rate is defined as the fraction of the population using the app:

$$A \equiv \frac{N_u}{N}$$

3. Rearrangements commonly used:

$$N_u = A\,N \quad \text{and} \quad A \in [0,1]$$



Adoption_rate_A	P_id (Eq2)	P_compliance (Eq4)	R_eff (Eq3)	False_alert_cost (Eq5, scaled)
0.0	0.0000	0.063	1.400	0.0
0.1	0.0049	0.095	1.399	4.7
0.2	0.0195	0.142	1.397	22.1
0.3	0.0439	0.206	1.389	57.9
0.4	0.0780	0.289	1.372	120.1
0.5	0.1219	0.389	1.340	216.7
0.6	0.1755	0.500	1.289	356.4
0.7	0.2389	0.611	1.216	546.2
0.8	0.3120	0.711	1.121	788.4

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2.2. Technological modalities and data privacy considerations

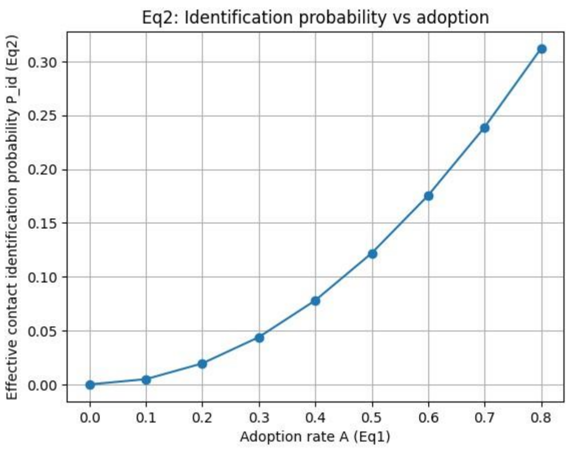
Adoption of digital contact tracing systems varied greatly across jurisdictions. Robust adoption levels are necessary to achieve substantive population-level effects, and diffusion can be limited by demographic patterns in smartphone ownership and utilization. Privacy considerations have emerged as a primary public concern in deploying and scaling digital contact tracing systems. Transparency in the collection and use of personally identifiable information appears critical in making systems acceptable to the public. Technical solutions preserving data privacy, especially through the use of decentralized or anonymized data, have been rapidly developed. A balance among technological design, legal framework, and community trust is likely a prerequisite for robust system functioning.

Various studies have proposed policy frameworks sensitive to equity and justice in the development of digital contact tracing applications. Insights from different disciplinary perspectives indicate that policies seeking to address such concerns should prioritize accessibility for underserved populations, integrate technology with traditional public health measures, and foster public trust in the centralization of sensitive health data.

III. METHODOLOGICAL APPROACHES IN 2021 EVALUATIONS

A diverse set of methodological approaches—differences in study design, outcome measure, data source, and analytic strategy—were deployed in 2021 evaluations of digital, evidence-based contact tracing for the COVID-19 pandemic. A majority of studies were quantitative and employed differential or panel designs to identify causal impact. Most analyses investigated countrywide policies, evaluating effects on epidemic transmission rates, case notification counts, or both. Beyond assessing digital applications as standalone interventions, some evaluations divided contacts across digital versus traditional tracing systems; others included proxies for exposure risk implicitly along with tracing component. Empirical sources were varied, most commonly reliant on administrative case counts or contact tracing data.

Transmission-reducing efficacy was examined by extrapolating from user-generated, exposure-notification counts in countries where contact-based and epidemiologic infection data were sufficiently detailed. Supporting analysis drew on infection-model experiments that considered spy-vs.-spai voter behavior, infection testing, properties of agent-based phylogenetic reconstructions, or machine-learning identification of physical proximity in convolutional-stage mobility-trace data. The time from case notification to isolation of detected individuals served as the primary measure of case-detection effectiveness for the analysis group, accounting for testing delays in one setup and controlling for user numbers in another.



Equation 2 — Effective Contact Identification Probability

Step-by-step derivation (mechanism decomposition)

We want the probability that a *random infectious contact* is (i) app-captured and (ii) leads to a notification.

2. **Both-sides adoption (random mixing approximation)**
   If two people meet at random, the probability both use the app is:

$$P(\text{both users}) = A \cdot A = A^2$$

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3. **Technical detection probability**
   Let s = sensitivity (probability the app correctly registers a true risky proximity contact). Then:
   $$P(\text{captured}) = A^2\, s$$
4. **Positive user uploads/shares keys (or equivalent trigger)**
   Let u = probability a positive case triggers notifications (uploads keys / reports through system).
   Then:
   $$P(\text{notified}) = A^2\, s\, u$$

So the effective identification probability is:

$$\boxed{P_{\text{id}} = A^2\, s\, u}$$

3.1. Study designs and outcome measures

The recent assessments of digital contact tracing adopt diverse methodological frameworks. Some evaluate the effect on population-level transmission indicators, including case counts, hospitalizations, and epidemics' growth rates. Such studies encompass multiple jurisdictions and assess policies' effect over time. Different geographic contexts are examined: states in the US, countries (Singapore, South Korea, Israel, and China), and regions in broader areas (Germany, the UK, the EU, the Nordic countries, and Brazil). The temporal focus reflects the period when most jurisdictions launched their digital contact-tracing tools rather than their overall adoption; the App was tested with local incidents before scaling to assist international travel.
Other studies probe the effect of app usage levels on the detection of cases and shortened isolation delays, examining linear and logistic regressions, including fixed effects and instrumental variable designs. All tests find significant impacts—43–53% of the variation in the outcome functions appears explained by app engagement levels, corresponding to a 4.46-fold increase in case detection probability. Despite their distinctive foci, the evaluations indicate that effective digital-contact-tracing strategies are in place.

3.2. Data sources and analytic strategies

Current evaluations of the effects of digital contact tracing on infectious disease control rely largely on two approaches. First, simulation models apply explicitly defined digital tracing parameters in conjunction with other non-pharmaceutical interventions, estimating the expected effect on transmission, confirmed cases, or fatalities over the course of an epidemic. These analyses often draw on user-specified contact networks in conjunction with empirically determined infection transmission probabilities. Second, empirical studies use case registry data to examine whether recent app deployment (or adoption by a certain percentage of the population) is associated with changes in epidemic trajectories. Studies typically focus on COVID-19, but evaluations of post-deployment effects for other diseases also appear. Beyond estimating average effects across studies, a meta-analysis considers both main empirical approaches and examines the contribution of user uptake to observed impact.

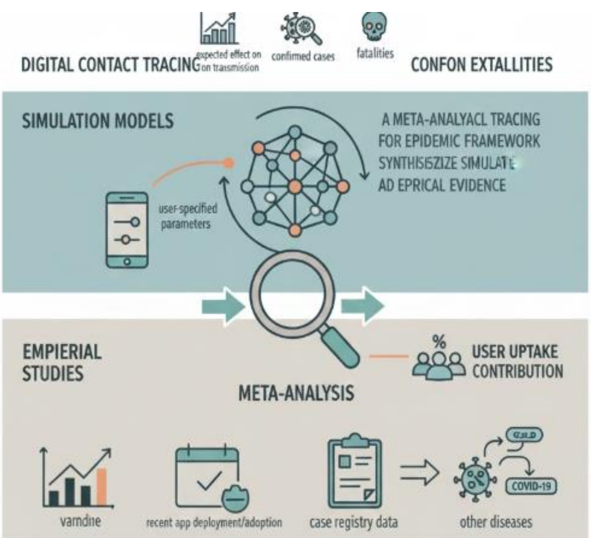

Fig 2: Evaluating Digital Disease Control: A Meta-Analysis of Simulation Modeling and Empirical Evidence in Contact Tracing

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IV. EVIDENCE ON EFFECTIVENESS ACROSS SETTINGS

Different studies and methods yield interesting considerations and suggestions for policymakers planning to deploy digital contact tracing. Recent evidence shows that these initiatives can reduce COVID-19 transmission. In particular, the results are consistent with a greater impact as user adoption rates increase and correspond to a higher level of engagement and adherence.

Digital contact tracing can reduce transmission and assist in the rapid detection of positive cases and isolation of infected individuals. The effect size appears to be larger when the enabling technology easily captures and shares exposures. Reliable and thorough assessments of real-world data are currently limited for many implementations, particularly in low- and middle-income countries. The evident potential should motivate implementation under conditions of use and support that facilitate equity in access and promote broad uptake. Digital contact tracing is unlikely to substantially reduce transmission by itself but can complement and enhance traditional public health measures, depending on local context.

4.1. Population-level impact on transmission metrics

Estimates of population-level impact on disease transmission metrics remain scarce. Where available, evidence suggests an association between the density of COVID-19 case notifications and the use of digital contact tracing applications. In a longitudinal analysis, Case et al. found that both the incidence of confirmed cases and the reproduction number of COVID-19 were significantly lower in areas with higher usage of Britain's NHS Test and Trace app. Differences in the strength of temporal association for summer and winter points to a potential weakening of effect during periods of high contact volumes. Similarly, in the Dutch context, application engagement correlated with an increased share of downward trends in notifications. Costs involved in application development and maintenance, however, exerted downward pressure on effect size. Reductions in incidence were also reported for Ireland and Israel, although confidence intervals were calculated to include the null. Dolgov et al. went further, estimating local-level correlations between COVID-19 notifications and directional indicators of transport density; countries with drop-in tracing applications exhibited a significant association in the pattern of offsets, while no such relationship emerged for others.

Indirect effects operating through adoption of alternative measures are nevertheless plausible. In an assessment conditional on supplementary health measures in Scotland and the wider United Kingdom, Case et al. denied an association between app usage and case notifications yet maintained that collective action inspired by the application likely attenuated disease transmission. Tests of this latter hypothesis generated suggestive yet inconclusive evidence. Expanding on previous Dickey–Fuller regression methods with a Bayesian detective analogy, Newberry eventually uncovered a conceivable propagation path. Analyzed jointly with the density of symptomatic COVID-19 case notifications, the volume of digital alerts correlated positively with shift points in case notification dynamics—an observation consistent with the notion of online warnings reinforcing the implementation of self-isolation behavior.

Month	Adoption_A(t)	Trust_proxy	P_id(t)	P_comp(t)	Effectiveness_E(t) (Eq6)
1	0.150	-0.050	0.0110	0.277	0.000
2	0.203	0.017	0.0200	0.293	0.004
3	0.250	0.044	0.0305	0.300	0.009
4	0.289	0.051	0.0407	0.302	0.014
5	0.318	0.065	0.0493	0.305	0.019
6	0.339	0.114	0.0561	0.317	0.025
7	0.361	0.218	0.0634	0.343	0.030
8	0.389	0.376	0.0736	0.383	0.038
9	0.425	0.560	0.0880	0.428	0.048
10	0.468	0.721	0.1068	0.466	0.063
11	0.515	0.820	0.1293	0.488	0.083
12	0.550	0.750	0.1475	0.472	0.109

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Equation 3 — Reduction in Effective Reproduction Number

Step-by-step derivation

3. Baseline:

$$R_0 = \text{expected secondary infections per case without digital tracing}$$

4. Digital tracing reduces transmission only when:

- a risky contact is identified (P_{id})
- the notified person complies (P_{comp})
- and that compliance actually prevents onward transmission (capture this as effectiveness factor $k \in [0,1]$)

5. The fraction of transmissions prevented is:

$$\Delta = k\, P_{\text{id}}\, P_{\text{comp}}$$

4. Therefore:

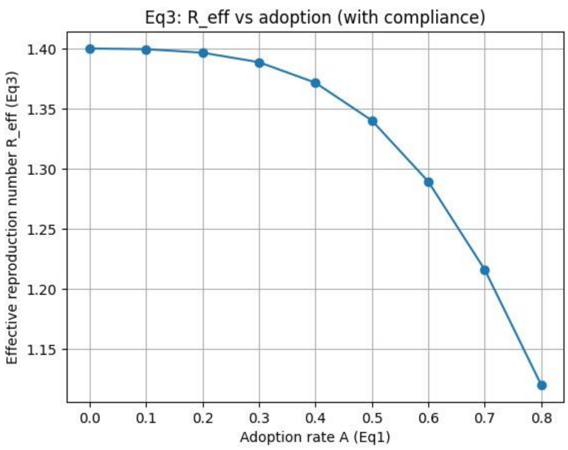
$$R_{\text{eff}} = R_0(1 - \Delta)$$

So:

$$\boxed{R_{\text{eff}} = R_0\left(1 - k\, P_{\text{id}}\, P_{\text{comp}}\right)}$$

Substituting Eq2 into Eq3:

$$R_{\text{eff}} = R_0\left(1 - k\,(A^2 su)\, P_{\text{comp}}\right)$$



4.2. Effects on case detection and timely isolation

Evidence from multiple countries supports the idea that digital contact tracing accelerates the identification of newly infected individuals, which allows for their timely isolation and contributes to a reduction in transmission. Comparison of the data generated by the Austrian app enables the early detection of cases and pre-emptive public health measures. Whereas the accumulation of evidence remains limited, results from the United States suggest that exposure notifications may influence behavioral change.

In Germany, the risk of not entering a self-isolation after a positive test result is significantly reduced among users of the COVID-19 Warning App. Evidence from several regions in France demonstrates that contact-tracing delays are shorter for positive cases who received a notification from the French app and that tests are taken sooner after the exposure notification. In the Netherlands, results indicate that an app implementation could also shorten the delay and speed up the subsequent self-isolation while reducing interpersonal contact.

4.3. Variability by adoption rates and user engagement

A growing body of evidence confirms that the effectiveness of digital contact tracing depends on the proportion of the population that uses the application and how frequently individuals engage in proximity with others on the app. Early evaluations of the COVID-19 contact-tracing apps in Germany and Switzerland showed a high estimated ratio of secondary infections among notified contacts. However, these evaluations—using a top-down SIR modeling approach—

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found that the reduction in transmission remained limited, with the uncertain user base and low levels of adoption and engagement driving the relative impact of the apps.

For direct effects on case notification, the power of digital contact tracing is controlled not only by an app's size but also by the quantity and speed of notifications. When considering the duration of infectiousness, these factors converge to demonstrate unimodal relationships. An optimal set of parameters—a large population, elevated frequency of proximity per user, and limited duration of infectiousness—triggers an effect size that approaches saturation. While this effect size predicts a relatively high loss in R0 for an app with low levels of engagement, both short-skirt and long-tail settings can be countered only by drastic market support of app users, diminishing the potential gain of these applications.

A modeled evaluation for New Zealand suggests that the apps can contribute beneficially when combined with low-area R0 estimates driven down by other NPIs and a proportion of likely infected and near contacts that is much greater than that among the general population. These components permit the country's app to approach the predictive strengths of conventional contact-tracing efforts, but rapidly shrinking user bases yield only limited direct value, even in extraordinarily well-governed regions. In contrast, assessment of the Singapore–Malaysia experience suggests that detecting a monoclonal signal and rapid isolation of a handful of cases with a non-standard notification relationship remain the essential functions for digital contact-tracing applications—thus far, the only function that these apps are therefore capable of executing well at any scale.

Equation 4 — Quarantine Compliance Probability

Step-by-step derivation

4. Start with a linear "compliance propensity" score:

$$z = \alpha + \beta_T T - \beta_B B$$

Where:

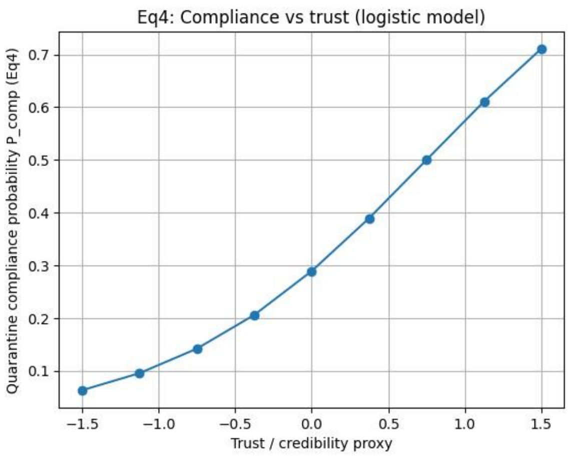
- T = trust/credibility proxy (privacy confidence, institutional credibility)
- B = burden/cost proxy (income loss, inconvenience, stigma, etc.)
- α, β_T, β_B are parameters

5. Convert the score to a probability using the logistic function:

$$P_{\text{comp}} = \sigma(z) = \frac{1}{1+e^{-z}}$$

So:

$$\boxed{P_{\text{comp}} = \frac{1}{1+\exp[-(\alpha+\beta_T T-\beta_B B)]}}$$



V. EQUITY, ETHICS, AND GOVERNANCE IN DIGITAL TRACING

Concerns about access disparities and other dimensions of equity may limit the range and effectiveness of digital contact tracing. As with previous technologies, people who are younger, lower-income, or older tend to have lower uptake of apps. A large share of the global population, particularly in lower-income countries, may lack access to a smartphone. Digital divides may also intersect in troubling ways across regions, with lower or no protection in areas with the highest

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prevalence of COVID-19. To counter inequitable access, some groups have proposed supplementing app-based systems with low-tech solutions such as providing users with Bluetooth-based beacons that support traditional contact-tracing efforts.

Privacy risks were not only a concern among users but were also amplified by the incorporation of sensitive information on public health, location, and potentially socio-demographic variables into centralized data warehouses. Concerns of this kind raise specific issues about the governance of contact-tracing systems. The ethics of DCT data collection, management, and access have become an area of intense scrutiny. Legal frameworks governing data privacy can facilitate governance and prevent appropriation of data for unintended uses, easing public concerns and bolstering trust in digital initiatives.

5.1. Access disparities and digital divides

An unbalanced distribution of digital technology is likely to hinder the efficacy of contact-tracing apps, especially if they depend on a large share of the population using them. Two dimensions of access have received particular attention: the availability of devices and the ability to use them. The devices require a compatible operating system, for example, Apple's iOS 13.5 and Google's Android 6.0; these conditions mean that owners of older smartphones are unable to participate. Moreover, the supply of devices has fallen sharply among poorer populations during the pandemic, increasing the risk of accentuated inequalities. Sufficient financial resources to purchase a smartphone may also not suffice without the ability to read and properly use the app. Digital smartphones and the use of portable devices may therefore increase inequalities in populations. The more unequal a society is, the more difficult it becomes for a country to implement an efficient digital public health measure.

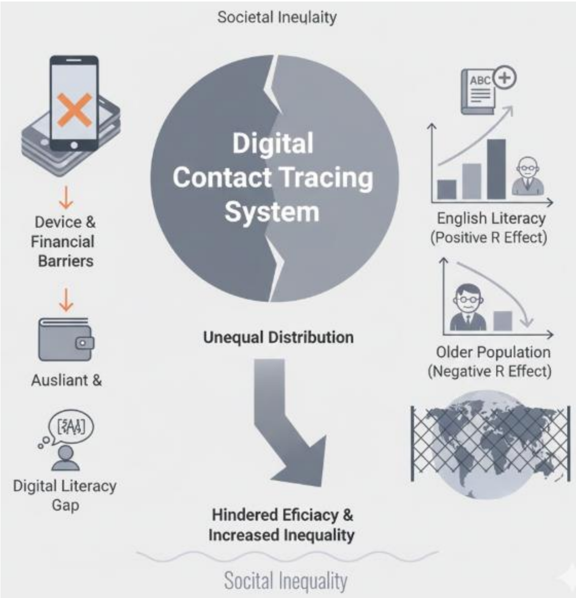

Fig 3: The Digital Divide in Public Health: Socio-Technical Barriers to Contact-Tracing Efficacy and Epidemiological Equity

The increase in the share of the population that speak and read English also has a positive effect on reducing the R2 associated with the effective reproduction number of COVID-19 just as the increase in the share of people older than 70 years has a negative effect. This is not surprising in light of the lowering literacy rates and the decreasing percentage of the adult population in English-speaking countries.

5.2. Privacy-preserving design and public trust

Effective contact tracing relies on achieving high levels of user compliance. For apps to be widely adopted, privacy concerns must be minimized, as demonstrated by previous research on prescription databases and social media platforms. Instances of data misuse and inadequate data protection measures significantly reduce trust. Confidence that user data will remain private is therefore paramount for effective public health initiatives. Peer-to-peer systems that protect the privacy of users' locations and identities may help prevent the exploitation of such data by third parties. Similarly, information campaigns providing context for data collection would promote user engagement.

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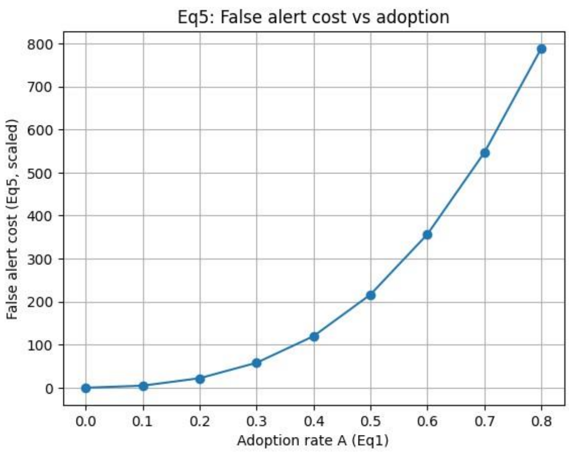
End-to-end encrypted data and simple, intuitive app designs are instrumental to building confidence. The crypto-covid app, developed for a regional pilot study in France, is an example of an initiative that allays privacy concerns. Location data are stored locally on users' phones and only processed if a user becomes COVID-positive. A negative test result resets the app, deleting all data. Stressing the temporary nature of data storage may improve participation. Clear messaging may also ensure that trusted institutions manage solutions. Confidence that any data collected will also be destroyed at the end of the pandemic will mitigate privacy concerns.

5.3. Institutional and legal frameworks

Successful deployment and sustained public use of DCT systems require supportive institutional and legal frameworks. While SARS-CoV-2 has prompted the rapid development of DCT technologies, past episodes of infectious disease spread have rekindled interest in digital proximity tracing. Equitable and adequate access to digital devices and infrastructure is, therefore, important. In particular, the public health measures must not further exacerbate existing socio-economic inequalities that thwart full-access, full-function use. Privacy-preserving design is paramount: people are unlikely to trust their data to systems that do not ensure that sensitive personal information is not stored centrally. Apart from the fear of being tracked and traced, individuals may also fear the stigma associated with being infected with SARS-CoV-2 or COVID-19. As such, the fear of surveillance, disclosure, and the stigma of being infected can diminish a system's value and viability.

Non-adoption or under-utilization of the technology results from a lack of understanding or belief that a DCT system protects others in the community. Strides in computational modeling that integrate attitudes toward the disease and related to risk and contagion into human mobility and contact patterns suggest that effective and influential communication campaigns may facilitate public engagement with DCT. Extensive public information campaigns are also necessary to persuade individuals to download, install, and use the app. DCT does not relieve the need for contact-tracing expertise and manual work; its heightened and novel functionality can complement and augment human dedication, skill-acquirement, and capability. The offer of associated incentives or rewards could also encourage continued use of DCT.



Equation 5 — False Alert Cost Function
Step-by-step derivation

5. Let:

- FP = expected number of false alerts (false positives)
- c_n = cost per notification (support, hotline, admin burden)
- c_q = cost per unnecessary quarantine (lost work, disruption), weighted by compliance
- c_t = trust/credibility penalty cost per false alert (reduces future adoption/compliance)

6. Expected total cost:

$$C_{\text{FA}} = c_n\,\text{FP} + c_q\left(\text{FP} \cdot P_{\text{comp}}\right) + c_t\,\text{FP}$$

6. Combine terms:

$$\boxed{C_{\text{FA}} = \text{FP}\left(c_n + c_q P_{\text{comp}} + c_t\right)}$$

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5. How FP scales (one reasonable approximation):

   If specificity is spec, false alert probability is $(1 - \text{spec})$. With both-sides adoption A^2 and average contact volume m:

$$\text{FP} \propto (1 - \text{spec})\, A^2\, m$$

VI. POLICY IMPLICATIONS AND IMPLEMENTATION CHALLENGES IN 2021

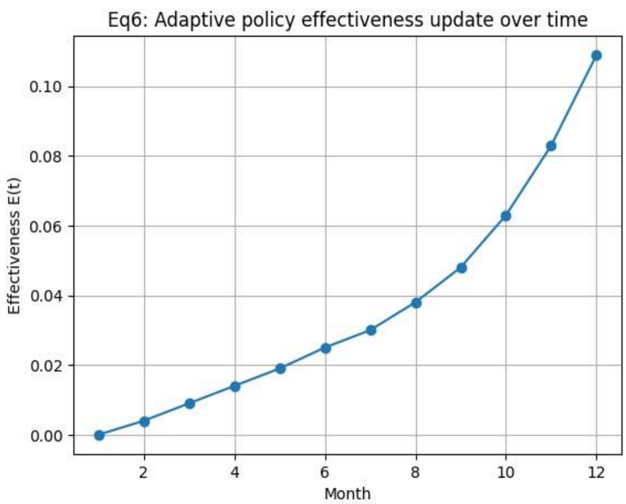
In addition to the research evidence now available, two key considerations shape how digital contact tracing may still be used in the COVID-19 response. The first concerns the adoption and engagement of the population that has access to the technology. Empirical assessment of deployment in clinical and commonly cited simulated studies indicates that transmission reduction is sensitive to how widely the technology is taken up and to how carefully users manage their exposure notifications. Countries that are operating their own systems are advised to pay close attention to these factors and adapt strategies accordingly, up to and including the degree of governmental coercion — but also societal consent — that governments choose to invoke. The second consideration relates to a country's broader digital architecture and the extent to which all relevant datasets are connected. For instance, simple models of within-country transmission across regions with different contact-tracing intervention intensities suggest additional case and hospitalizations reductions emerge only if the digital-tracing activity is Not limited to detection but also systematically supports the isolation and mitigation of cases and contacts.

Conjunctive use with non-digital intervention measures remains an essential benefit of digital contact tracing, as it is for most complementary health interventions. The evidence points toward greatest utility if the degree of digital contact tracing is pitched high before unavoidably intense non-digital damage-limiting measures — such as broad-based closures or lockdowns — are incurred. Use of the technology to guide the timing and intensity of such indirect damage-limiting measures is also a valuable contribution where it can be developed and applied with validation.

6.1. Recommendations for deployment and scaling

For real-time transmission mitigation, digital contact tracing solutions should not be viewed as replacements for traditional containment strategies but should complement and enhance the existing public health response. DSCT setups should be rapidly deployed in active transmission clusters, even if in low-prevalence mountain regions, because local transmission dynamics can change quickly. In addition, system promotion and roll-out require higher user engagement beyond initial adoption, ensuring that sufficient populations are in active use so that more alerts can escalate the effects. When regional clusters show exponential growth, DSCT systems should be rapidly scaled up for the target group and the ability of nearby noncontributing groups to supply alerts on their past locations.

The combination of digital and traditional contact tracing, as advised by Robert Koch Institute in Germany, is likely to be the optimal approach to shrinking transmission potential. A virtual word-of-mouth effect exists between DSCT alerts and traditional contact tracing. When many nonrequired users receive alerts, this amplifies the effects on target users, including faster case detection and smaller isolation delays. More generally, links between DSCT alerts and traditional contact tracing results should be promoted to maximize their public health effects.



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Equation 6 — Adaptive Policy Effectiveness Update

Step-by-step derivation

6. Let $E_t \in [0,1]$ be a policy effectiveness index at time t (e.g., monthly).
7. Let the "instantaneous effectiveness signal" be:

$$S_t = f\left(P_{\mathrm{id},t} P_{\mathrm{comp},t}\right)$$

where $f(\cdot)$ is a saturating function such as $\tanh(\cdot)$ to keep values bounded.

7. Exponential smoothing update:

$$E_t = \gamma E_{t-1} + (1-\gamma)S_t, \quad \gamma \in [0,1]$$

So:

$$\boxed{E_t = \gamma E_{t-1} + (1-\gamma)\tanh\left(\eta\, P_{\mathrm{id},t}\, P_{\mathrm{comp},t}\right)}$$

6.2. Integration with traditional public health measures

The results of the analyses highlight the need for support and investment to make DT a core component of national responses for COVID-19 and future pandemics. Such measures include securing the resources for building and maintaining systems before the next emergency; devising communication campaigns that clearly inform the public of the risks of DT; monitoring the appropriate balance between TST, TB, and DT; and implementing protocols to downscale DT towards the end of an epidemic or waning pandemic and turn it into an emergency public health tool for future outbreaks. These recommendations are crucial if DT is to deliver on its promise.

Enhanced contact tracing via digital technology provides the potential to raise the speed of case isolation and reduce the risk of being infected. Thus, the outcome of analyses examining the speed of case isolation and test before the next infection may provide insight on whether the reduction in TST observed during the initial phase of the pandemic in many countries could be compensated for—or even surpassed—by the availability of DT. Ideally, at any given moment in the pandemic evolution, TST, TB, and DT should be orchestrated to achieve the best possible combination of case isolation and infection detection. Nevertheless, DT cannot be viewed in isolation. Any increases in detection speed and efficiency achieved by DT deployment or user engagement can only affect the transmission dynamics as long as TST and TB are able to keep pace.

VII. CONCLUSION

Evidence amassed across diverse environments has ruled out population-wide effectiveness of digital contact tracing—even when adoption rates are high—but suggests that timely responses from localised, non-public health actors, particularly when favourably combined with reduced sensitivity of case definitions, may help reduce the spread of the disease. Digital contact-tracing applications can indeed make it faster and easier to identify contacts and support their effective isolation, and this type of device-based support can be especially effective when case numbers have been very large locally. The localised nature of the evidence, however, highlights the importance of appropriately framing the conditions under which these applications are tested, and therefore deployed.

But the combination of environmental circumstances and available evidence indicates that full population-wide deployment is not currently warranted, and that scaling strategies should therefore focus on ensuring that devices can be made available, and attractively designed for use, where they may be needed most: directly relevant to the current epidemiological conditions. The evidence also points to a direct trade-off effect: the extent to which the device-based processes are engaged with matters for their effectiveness, relative to simply following existing recognised exposure connections. Scaling up the sensitivity of case definitions may be particularly favourable, given the potential for naturally shorter transmission chains at that stage; at high overall case numbers, the rate of recognised connections may be less of a limit; and at the very end of an epidemic wave, focusing as far as possible on the last few remaining connections may be a fruitful strategy.

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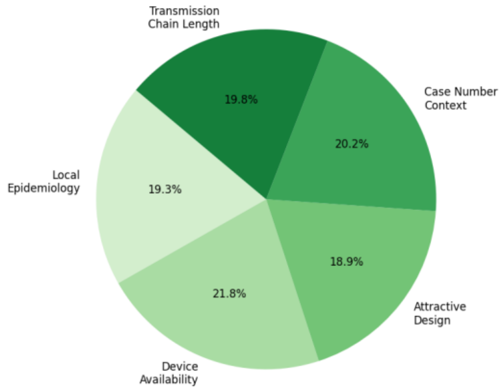

Fig 4: Optimal Deployment Conditions

7.1. Key Takeaways and Future Directions

Continued assessment of implementation and performance across settings is necessary to refine guidance.
Evaluations undertaken during 2021 confirmed that, under certain conditions, adoption of digital contact tracing systems may help to reduce transmission of SARS-CoV-2, support broader pandemic control efforts, and be implemented, governed, and used in ways that address equity and ethical concerns. Conclusively, collective experience gathered to date provides a foundation for future deployment in the event of similar outbreaks. Digital contact tracing is most likely to contribute meaningfully to controlling outbreaks or endemic transmission when combined with robust investment in traditional public health measures such as extensive, rapid, population-wide case identification and isolation, and when evidence of effectiveness is communicated clearly.

"Evidence of Effectiveness of Digital Contact Tracing in Controlling the Spread of COVID-19 – Systematic Review and Meta-Analysis: Imminent N-of-1 Experiment of Multi-Country Systematic Review and Meta-Analysis: Imminent N-of-1 Experiments of Multi-Country Consolidated Evaluation and Cost-Effectiveness Analysis: Imminent N-of-1 Experiment".

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