

Epidemiological Effectiveness of Exposure Notification Applications Implemented During the COVID-19 Pandemic: A Systematic Review

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Abstract

Background

During the COVID-19 pandemic, Public Health Authorities (PHAs) adopted exposure notification (EN) systems—built on an application programming interface created in collaboration with Apple and Google—as a supplementary tool to traditional contact tracing (TCT). These systems informed individuals of a potential exposure to the SARS-CoV-2 virus. Due to limited data collection and the privacy-preserving nature of the system, it is challenging to discern the full epidemiological impact of the EN applications.

Methods

We developed a systematic review protocol informed by the principles of the Cochrane methods, and searched PubMed, Embase, Web of Science, and the ProQuest - PAIS Index to identify studies concerning the global implementation of the GAEN systems. Our search focused on mathematical studies presenting the epidemiological impact of EN systems in relation to the COVID-19 pandemic. Two reviewers applied the eligibility criteria to screen each abstract and full-text article, as well as extracted relevant data and synthesized the evidence base from incorporated studies.

Results

We identified 1552 peer-reviewed studies; of which, we removed 517 duplicates, 700 references during the abstract screening phase, and 327 during full text screenings. This yielded a total of 19 references for extraction. All studies indicated that EN systems can have a positive epidemiological impact on public health communicable disease mitigation strategies; however, the full impact is heavily affected by overall use of the app, and some countries noted that the observed impact during the pandemic was extremely limited due to low app adoption and adherence.

Conclusion

When the GAEN protocol and subsequent EN mobile apps are properly designed and implemented, they provide PHAs with an effective public health disease mitigation tool. However, there were significant barriers that minimized overall adoption of the system, and therefore the systems' overall epidemiological effect. For future EN applications, emphasis should be placed on the importance of public outreach programs in order to increase user adoption and adherence, thereby increasing the overall epidemiological impact of the EN systems.

BACKGROUND

Contact tracing is a mitigation strategy intended to stop the transmission chain of infectious diseases—such as HIV/AIDS and Measles—and it was among the main non-pharmaceutical interventions intended to stop the spread of the SARS-CoV-2 virus during the COVID-19 pandemic.^{1–4} Contact tracing is a process in which individual public health officials reach out to those who tested positive for a disease (an index case) or those who were exposed to a pathogen in order to provide them with public health guidance, such as whether to quarantine or get tested.^{1–4} Traditional contact tracing is very effective if conducted rapidly, as it can reduce the basic reproductive number, R_0 , of the pathogen due to the expeditious identification and testing of those exposed.⁵ However, contact tracing is often labor intensive, costly, and time-consuming.^{3–6}

During the COVID-19 pandemic, Public Health Authorities (PHAs) adopted novel technologies in order to fill the gap in pandemic preparedness initiatives and to reduce transmission of the SARS-CoV-2 virus; this included the deployment of novel digital contact tracing systems to supplement their traditional contact tracing efforts.^{2,7} One such digital system, now commonly referred to as exposure notification (EN) systems, utilized mobile device-based technology to inform individuals of a potential exposure to the SARS-CoV-2 virus.^{1,2,6–8} Several EN protocols were adopted during the pandemic, and systems within different countries and jurisdictions relied on varying proximity sensing technologies (i.e. the technological method of determining an individual's contact with an infected person), application programming interfaces (APIs—a type of software interface with defined functions that enable developers to create a smartphone app), and privacy protection strategies.^{2,4,7}

Google-Apple Exposure Notification System

In April of 2020, Google and Apple launched their joint Google-Apple Exposure Notification (GAEN) system.² Throughout the pandemic, this API would become the most widely implemented EN protocol globally, and was the dominant system used within the United States.^{1,4,7} The system was inherently privacy-preserving, free, and enabled those diagnosed with COVID-19 to anonymously notify anyone they may have exposed via their phone.^{1,2,7,9}

The GAEN system enabled smartphone devices with the activated EN system to interact with each other via low-energy Bluetooth to measure the approximate distance and duration between users.^{1,2,7} If two users were within a specific distance for a specified duration (i.e. within six feet for 15 minutes or more within a 24 hour period), the system would record this as an exposure event.^{1,2,7} These events were recorded via the exchange of anonymous and cryptographically generated random numbers, or keys, that were stored locally via a decentralized protocol and automatically changed every 15 minutes to preserve privacy and anonymity.^{1,2,7} If one of those individuals later tested positive for COVID-19, they would receive a verification code from their PHA.^{1,2,7} Once the verification number was entered into the user's mobile app, their key was uploaded to a key server.^{1,2,7} Every mobile phone with a GAEN system regularly checked this key server, and if a retrieved key matched one exchanged during an exposure event, the exposed user would receive an anonymous digital EN alert.^{1,2,7} This alert included public health information on what to do next, such as whether or not to quarantine and whether to get tested.^{1,2,7} User names, locations and contact information were never stored, and those that received an EN were not provided the name or contact information of the person

that may have exposed them to the SARS-CoV-2 virus.^{1,2,7} Appendix A – GAEN Architecture shows a simplified step-by-step guide of how Canada's national EN app, COVID Alert, functioned.¹⁰

In the early days of the COVID-19 pandemic, PHAs would individually develop and maintain their app using the GAEN API and determine the proximity and duration that was to be considered an exposure.^{2,9} In September 2020, Google and Apple launched the Exposure Notification Express (ENX) system, which simplified the implementation and deployment process for PHAs.² With the ENX API, PHAs could simply provide a configuration file with their defined risk parameters, public health messaging, and branding files in an easy-to-use interface to create a custom EN app.^{2,9} In March of 2023, state applications operating on the GAEN system were turned off in response to the end of the US Federal State of Emergency.¹¹

Effectiveness of GAEN Systems

During the pandemic, these systems have shown to reach potentially exposed individuals faster than those contacted during manual contact tracing efforts, thereby significantly expediting the identification process and informing people to isolate or quarantine earlier.^{1,2,6–8,10–14} However, due to GAEN's limited data collection, it is challenging to discern the full impact of the EN systems. We aimed to consolidate the existing research on the overall impact and effectiveness of the GAEN system and subsequent applications to understand how these systems helped PHAs in their disease mitigation strategies during the COVID-19 pandemic and how they can be leveraged in the future.

METHODS

Study Design and Search Strategy

We developed a systematic review protocol informed by the principles of the Cochrane methods to search, compile, and synthesize the evidence base concerning the global implementation of Bluetooth-based EN systems. This protocol was developed a priori as part of the University of California, San Francisco (UCSF) Institute for Global Health Sciences Master of Science capstone project and was not prospectively registered in PROSPERO. Given the novelty of this technology and scarcity of data about this topic based on our scoping searches, we conducted a broad and inclusive search of the literature to first identify all potentially relevant studies.

Bibliographic databases and Search Terms

For this review, we searched PubMed, Embase, Web of Science, and the ProQuest - PAIS Index for peer-reviewed literature addressing the implementation of GAEN-based applications. A log of each database name, date of search, the strategy used when searching for keywords, and the number of results across each database is identified in Appendix B – Search Strategy and was developed through an iterative process that used appropriate Medical Subject Heading (MeSH) terms and keywords.

Eligibility Criteria

A Population, Intervention, Comparator, Outcomes, and Time-Period (PICO[T]) framework was implemented to define the eligibility criteria for this study.

PICO Eligibility Criteria

Study Types

In order to assess the public health impact of the digital EN systems, we included all types of quantitative studies, including experimental, observational (e.g., cohort, case-control), synthetic cohort, and mathematical modeling studies that evaluated the implementation and effectiveness of Bluetooth-based EN systems. Synthetic cohort studies or mathematical models assessing any non-Bluetooth-based EN systems were excluded. In addition, viewpoints, media articles, and data reported about a public health jurisdiction by a non-affiliated/unofficial source were excluded. Lastly, other systematic reviews were excluded from our criteria, given that all identified systematic reviews reported outcomes that combined data from GAEN and non-GAEN systems. However, references included in related systematic reviews were pulled and assessed individually against our inclusion criteria.

Population

The participants of interest for this review were populations that had access to and utilized an EN mobile app during the COVID-19 pandemic, or simulations of populations using a hypothetical Bluetooth-based system. This included those that used the EN system during the entirety of its deployment, those that elected not to use an EN system, or those that deactivated their mobile app prior to a PHA's discontinuation of the system. EN system effectiveness and impact is proportional to the adoption rates of each system within its jurisdiction; therefore, those that did not use the system were excluded in the evaluation of the performance of the EN technology.¹⁰

Intervention

The intervention of interest included Bluetooth-based EN mobile apps built upon the GAEN system; either through a customized, open-sourced app or one developed through Google and Apple's ENX system. This includes decentralized protocols that utilize a smartphone's Bluetooth technology to determine the distance between two users. Centralized protocols, closed-sourced apps, or those that utilize non-Bluetooth based proximity identifiers—such as GPS—were not included.

Comparator

The comparator was any control/counterfactual condition that allowed us to quantify the effects of Bluetooth-based EN systems on the COVID-19 pandemic within PHAs that deployed such a system (e.g., before-after studies) or the impact of COVID-19 between jurisdictions with and without deployment of EN systems. The PHAs of interest had to report similar rates in the use of pharmaceutical and non-pharmaceutical interventions so as to ensure all variables associated with disease mitigation strategies were consistent across PHAs. This included similarities in mask wearing, vaccination rates, and manual contact tracing efforts. We did not compare the impact of GAEN systems with other digital contact tracing protocols.

Outcomes

The outcome of interest included all metrics that measured COVID-19 related health impacts (e.g. case rates, hospitalizations, and deaths), or changes in respect to COVID-19 transmission among populations who used EN versus those who did not (e.g. changes in the basic reproductive number, R_0). This included studies that aggregated and evaluated the evidence of EN effectiveness by reporting on the estimated cases, hospitalizations, and deaths averted within a public health jurisdiction.

Time-Period

Google and Apple launched their GAEN system in April of 2020; as such, PHAs did not deploy EN systems prior to the COVID-19 pandemic. Therefore, our review included literature published or submitted for review (if deemed necessary) to our bibliographic databases of interest within the time period of April 2020 to May 2024.

Study Selection

Selection of Studies

We imported all identified publications into the EndNote citation management software and then uploaded the full list into Covidence, where duplicates were removed. One reviewer screened each title and abstract within the Covidence platform to ensure that included studies met our selection criteria. Once completed, the full text of each identified study was reviewed by two reviewers in order to assess compliance with our selection criteria. Each excluded study and the reason for their exclusion were documented.

Data Extraction

Once the list of all studies meeting the pre-defined inclusion criteria was finalized, one reviewer updated the data extraction template within Covidence to extract data and key components. Data were extracted using a structured data extraction form capturing study characteristics, exposure notification system features, model parameters, and outcomes (Appendix C – Data Extraction Template). Some studies included as part of the review are comprised of multiple evaluations for GAEN and non-GAEN based mobile apps. However, data concerning these non-GAEN systems were not extracted as part of our review, nor did we review data concerning the overall impact of all digital contact tracing systems on the COVID-19 pandemic.

Data Synthesis and Analysis Framework

There was not a sufficient number of studies with homogenous PICO that allowed us to combine data using meta-analysis models. Instead, we used tables to organize and synthesized data to communicate key findings, such as the public health impact of EN systems using risk ratios and 95% confidence intervals where appropriate. We also summarized outputs of included mathematical models—such as cases, hospitalization, and deaths averted—with reported model uncertainties.

Ethical Considerations

Given that we reviewed and analyzed existing public data and information, our study is exempt from review by any human subject or IRB committee. Our research was guided by the main ethical principles as defined by the National Institute of Health.

RESULTS

Search Results

We identified 1,134 references, including 365 duplicates, during our database search. An additional 417 references, including 98 duplicates, were pulled from identified systematic reviews. In total 1,552 references were identified (Figure 1). We screened the abstracts of 1,035 articles, excluding 700 that did not satisfy our PICO(T) requirements, yielding 327 papers that required a full-text eligibility assessment. After excluding 301 articles, we identified 19 studies that met our inclusion criteria (Table 1).

These 19 studies comprised of twelve model-based analyses, five observational studies, one cohort study, and one comparative assessment. In regard to location, 18 studies were conducted in high-income countries, and one study was conducted in a low-income country. With some studies evaluating GAEN applications in multiple jurisdictions, included studies reported data from twelve different countries, with outcomes incorporating data from ten EN applications (remaining studies used hypothetical Bluetooth-based systems). Geographical settings for these studies included the US (6), the UK (2), Germany (2), Switzerland (1), Scotland (1), Spain (1), South Africa (1), the Netherlands (1), Japan (1), Italy (1), Belgium (1), and Canada (1).

Epidemiological Impacts of GAEN Applications

Outcomes related to the full epidemiological impact of the EN applications included the number of reduced SARS-CoV-2 related cases, hospitalizations, and deaths, as well as the overall reduction in the basic reproductive number and the effect on the amount of quarantine events. [citation] Studies were diverse in terms of modeling or data analysis methods and reported outcomes. All 19 studies indicated that EN applications can be a successful disease mitigation tool, although actual impact was limited due to low adoption rates and user adherence. [citation]

Reduced Cases, Hospitalizations, and Deaths

Fifteen studies reported that the use of digital contact tracing applications reduced COVID-19 related cases, hospitalizations, and deaths, therefore lessening the overall disease burden; however, the overall reduction is heavily dependent on adoption and adherence rates.^{13–24} Aronoff-Spencer reported that when 15% of the population ($n = 39.4$ million) adopted California's EN app, CA Notify, over 31,000 cases and over 600 deaths were averted between December 15, 2020, and January 9, 2021.¹⁶ Jeon et al. reported that, with an adoption rate of 3.2% of the COVID Alert PA app in Pennsylvania, EN alerts averted 2–16 additional cases (7–69 cases/1,000 notifications) and <1 hospitalization from November 8, 2020 through January 2, 2021.¹⁴ At 31% adoption, Kendall et al. reported that the UK's NHS Covid app averted one million cases (sensitivity analysis 450,000–1,400,000), 44,000 hospitalizations (SA 20,000–60,000), and 9,600 deaths (SA 4,600–13,000) during the first year of the app's launch.¹³

Abueg et al. used the OpenABM-Covid19 model to determine the case and death reductions in the King, Pierce, and Snohomish counties in Washington, US at various adoption rates during the March 1, 2020, through December 25, 2020, time period.¹⁵ At 15% adoption, cases could be reduced by 0.9–5.8%, 8.1–9.6%, and 6.3–11.8% and deaths could be reduced by 2–6.6%, 11.2–11.3%, and 8.2–15.0% in the King, Pierce, and Snohomish counties, respectively.¹⁵ At 75% adoption, cases could be reduced by 6–73%, 73–79%, and 67–81% and deaths could be reduced by 2–70%, 69–78%, and 63–78% in the King, Pierce, and Snohomish counties, respectively.¹⁵

At 24.9% adoption, Ellmann et al. reported that between its launch on June 16, 2020 through April 1, 2022, the German Corona Warn app reduced cases by a 6.1% (95% CI: 5.8–6.2%), hospitalizations by 4.6% (95% CI: 4.3–4.7%), intensive care treatments by 4.1% (95% CI: 3.8–4.1%), and deaths by 5.6% (95% CI: 5.3–5.7%).¹⁹ Ellmann also reported that this reduction in cases, hospitalizations, intensive care treatments, and deaths subsequently led to reductions in suffering and an increased quality of life in the long term.¹⁹

Our modeling studies also demonstrated that an increase in app usage correlates with a lowered diseases burden. Wymant et al. modeled that, with a 30% app adoption rate, approximately one infection could be averted for every four infections during a 4.5-month period.²⁴ Their modeling and statistical analyses also showed that, for every percentage point increase in the adoption rate of the app, the number of cases could be reduced by 0.8% (using modelling) or 2.3% (using statistical analysis).²⁴ Almagor et al. also noted that an increase in app use correlated with an overall decrease in the infection rate, especially in relation to the testing strategy deployed in the population (cite). They note that even in scenarios without testing strategies, there showed to be a reduction in the number of infections as adoption rates increase. In their model, an infection reduction of 40% was seen with an 80% adoption rate, and the peak of the epidemic at this adoption rate showed an 89% reduction in infections. However, they note that the use of an EN app needs to be accompanied by an adequate testing strategy, due to the fact that an increase in the amount of ENs received by users results in an increasing in testing rates. For testing capacities between 0 and 6%, an increase of app users does not tend to lead to a decrease in the overall infection rate. If there is an inadequate supply of tests, the app becomes counterproductive and leads to a depletion of tests.

Burdinski et al. noted that app usage can help to slow the spread of the disease and potentially reduce the mortality rate due to the potential for those that receive an alert to seek medical treatment earlier. However, they note that overall effectiveness is dependent on adoption and adherence, and the apps can only support manual contact tracing efforts rather than substantially reduce infections rates when used in isolation.

Esposito et al. noted that within 100 days of app implementation and 87% adoption and adherence, the number of deaths was reduced from approximately 2,000 to 500. A decrease in the number of hospitalizations was also observed, with hospitalizations reduced from 10,000 to 2,500 at day 20. Hernández-Orallo et al. showed that at adoption rates of 28%, approximately 590,000 infections and 5,900 deaths were averted. However, they noted that this is not sufficient to actually control the pandemic, which would require an adoption level of 80%.

Reduced Reproductive Number of SARS-CoV-2

Six studies indicated that the use of a digital contact tracing app reduced the overall reproductive number, R , of the SARS-CoV-2 virus. [citation] According to Ellmann et al., an adoption rate of 24.9% of the Germany Corona Warn App led to an R -value reduction of up to 5.4% (95% CI: 5.3–5.6%).¹⁹ Leung et al. also reported reductions in the reproductive number, observing a reduction of 0.3% when 16% of the population adopted the Netherlands CoronaMelder app.²¹ When a self-reporting feature was later added, enabling users to upload codes from a positive at-home test, the reduction in the R -value increased to 0.5%.²¹ They, therefore, concluded that the app did not contribute much to transmission control measures in the Netherlands; however, they reported that with an 80% adoption rate, the R -value could be reduced by 14.1%.²¹ Similarly, Kinyili et al. reported that a 30% adoption rate of the COVID Alert SA app in South Africa, in addition to testing, would “greatly diminish the basic reproduction number.”²⁰

In our modeling studies, Hernández-Orallo et al. also noted that the effective reproduction number could be reduced but would require adoption levels of at least 65%. Even at this rate, however, the reproductive number would not be reduced to below one. Nakamoto et al. also noted that the effective reproductive

number decreases slowly when adoption is increased, but an adoption and adherence of 90% would be required to reduce the effective reproductive number to less than one.

Increased Quarantine Events & Contacts Notification

Three studies indicated a positive effect on the overall quarantine levels of EN users.^{15,18} Abueg et al. used the OpenABM-Covid19 model to determine the percentage increase in quarantine events within the King, Pierce, and Snohomish counties in Washington, US, using an adoption level of 15%.¹⁵ Between March 1 and Dec 25, 2020, there was a 4.6–6.4% increase in quarantine events in King county, a 6.6–6.8% increase in Pierce county, and a 5.8–10.2% increase in Snohomish county.¹⁵ The study reported that quarantine events plateau or start to decrease at higher levels of adoption (60% to 70%).¹⁵ Esposito et al. also noted that app use is associated with an increase in the number of quarantined individuals.

Using data from a cohort study in Switzerland, Ballouz et al. reported that between August 7 and September 30, 2020, those that received an EN alert from the SwissCovid app entered into quarantine one-day earlier, on average, than those that were only notified of a potential exposure by a manual contact tracer.¹⁸ This was due to the expeditious identification and notification by the EN system, in that it reached users one-day earlier than manual contact tracers.¹⁸

Additionally, two studies noted how apps identified additional cases when used in conjunction with manual contact tracing efforts. Wymant et al. reported that between February 25 and July 27, 2021, UK's NHS Covid app traced 4.2 contacts per consenting index case in comparison to the 1.8 contacts traced through manual tracing.²⁴ A large fraction of these additional contacts traced through the app were expected to be outside the household of the index case.²⁴ Geenen et al. also noted that while manual contact tracing detected over ten times the number of infected contacts than those found through the use of an EN app alone, the app found an addition 5.2% of cases than through manual contact tracing when the strategies were used together.

DISCUSSION

Our systematic review aimed to assess the epidemiological impact of Bluetooth-based EN applications deployed during the COVID-19 pandemic. This review contributes to the growing body of evidence exemplifying how EN applications, particularly those created with the GAEN API, successfully supplemented manual contact tracing efforts and helped to ease the global burden of disease.^{1,2,6–8,10–14} In conjunction with manual contact tracing, these systems reduced COVID-19 cases, hospitalizations, deaths, while increasing the quarantine events for those that were exposed, even with adoption rates as low as 15%.^{12–15,20,21,23,24} These systems also have the potential to lower the effective reproductive rate of an infectious disease if used in conjunction with additional non-pharmaceutical interventions.^{19–21} However, even though these systems are effective, the overall impact these systems had on disease mitigation strategies were heavily influenced by both the adoption of and adherence to the system.^{25–32} Additional research is required in order to assess the barriers and facilitators for user adoption and adherence from the perspective of the end-user in order to assess how app usage could be increased in future iterations of the EN apps. Mitigating these barriers and increasing overall adoption would have yielded higher reductions in the overall COVID-19 disease burden.

Even with minimal data collection due to the privacy-preserving nature of the systems, multiple models have been developed to quantify the epidemiological effects these systems had within their respective jurisdictions, showing that this system is a low cost, user-friendly, scalable, and privacy preserving intervention that has the potential to supplement manual contact tracing for any infectious disease with similar transmission pathways to the SARS-CoV-2 virus.^{13–34}

The studies included in our systematic review exhibit considerable diversity and heterogeneity in terms of their settings and methodologies, given that the research spans multiple continents, reflecting a wide range of cultural, economic, and healthcare contexts. This global representation ensures that our findings are applicable to a broad audience and enhances the generalizability of the results, while demonstrating how EN applications within different global contexts contributed to disease mitigation strategies.

Our study has several limitations. First, we were unable to systematically assess the methodological rigor and underlying assumptions of the included modeling studies. As a result, we could not formally evaluate the validity or robustness of the predicted epidemiological impacts of exposure notification (EN) interventions. Second, the literature search was conducted in May of 2023 and was not updated prior to publication. While this may limit the inclusion of more recent studies, the use of all GAEN applications ended in 2023 due to the discontinuation of the system by Google and Apple, and we are not aware of a significant body of newer modeling studies published since that time.²

CONCLUSION

EN applications deployed during the COVID-19 pandemic reduced SARS-CoV-2 cases, hospitalizations, and deaths, reducing the overall reproductive number of the pathogen and easing the disease burden across the globe.^{13–34} Although there were significant barriers in the deployment and adoption of these applications, further development of the infrastructure surrounding the implementation of such applications and a dedicated focus on strategies aimed at increasing adoption would yield an environment in which GAEN-based applications could successfully supplement manual contact tracing for infectious diseases with similar transmission pathways to the SARS-CoV-2 virus.^{13–34}

Declarations

Competing interests

All authors declare no financial or non-financial competing interests.

Author Contribution

NS conceptualized and designed the study, conducted the literature search, performed screening and data extraction, synthesized the findings, and drafted the manuscript. CL contributed to study screening and data extraction. MM provided overall supervision and guidance for the project.

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Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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Tables

Table 1: Summary of included studies and reported epidemiological outcomes

Author/Year	Date of study	Type of Study	Data Source	Outcome	Comparator	Model Used	Full epidemi impact
Abueg 2021	March 1, 2020, through Dec 25, 2020, plus the additional calibrated seeding period before March 1	Mathematical Modeling	County level data; epidemiological data from Washington state and Google's Community Mobility Reports for a time-varying infection rate	% reduction in infections and deaths per, and % increase in quarantine events by adoption level	Self-isolation due to symptoms only	OpenABM-Covid19 by Hinch et al	Case rec at 75%: 6 (K), 73–7 and 67–7 at 15%: 6 5.8%, 8.1 and 6.3– Death reduction 75%: 2–69–78%, 63–78%, 15%: 2–11.2–11 8.2–15.0 Quarant events: a 4.6–6.4% 6.8%, an 10.2%; e plateaus decrease high leve adoptior to 70%)
Almagor 2020	2020	Mathematical Modeling	2011 UK census	%infections; quarantine events/testing	no app use; 0, 0.5, 1, 1.5, 3, 6, unlimited testing capacity; low app compliance of 0.5, high compliance of 0.9	agent based model	“When symptom agents a prioritise testing, a proportion CTA use increase overall infection through epidemic decrease so do inf at the pe the epid irrespec testing c some re in overall infection observed CTA ado rates inc even in t scenario testing. decrease most sul when tes not limit Moreove intermec levels of adoptior 60%) and capacity 3%), ove infection decrease 27% of tl populati cases at peak red 70–85%, dependi the scen When th testing c is restric symptom agents a prioritise testing, a increase proportion CTA use

							not alwa to a deci infection is obser all testin capacitie between 6%. In th of a 3% t capacity adoptio of 40–80 result in substani more inf than the scenario CTA use for high compliai the CTA because inefficien testing p In a sce with 1% and 80% users, ov infection 23% whe compliai high and when compliai low. the the epid compare baseline scenario reduced 80% whe compliai high and 74% whe complia low"
Aronoff- Spencer 2023	Dec 15, 2020 to Jan 9, 202	Mathematical Modeling	Anonymous aggregate state level code usage data (described below), and state and county level exposure notification web traffic statistics from CDPH	EN-based prediction model to short term forecast COVID-19 reported cases in California	omnibus measures of the performance of a model including EN data to a case-only mode;	Bayesian predictive model	Near pas related t future ca counts a its inclus improve forecast accuracy case col 6 or mor into the t
Aronoff- Spencer 2022	December 10, 2020, to July 1, 2021	Mathematical Modeling	activity data generated by CA Notify; aggregated data and reported as KPI	KPIs	Assumed that the secondary attack rate, level of quarantine adherence, and transmission dynamics, as well as other background interventions, policies, and protective behaviors, in California are similar to those in the UK	Wymant et al	cases av >31 000 Deaths : > 600 de
Ballouz 2021	August 07, 2020 and September 30, 2020	Other: Cohort study	REDCap of cases and close contacts ≥18 years old, residing in the Canton of Zurich, and had sufficient knowledge of the German language	"primary outcomes included the frequency of cases who received and uploaded the CovidCode, frequency of close contacts who received a SwissCovid app	individuals notified only by manual contact tracing (MCT)	N/A	app-noti contacts entering quaranti average earlier th those nc notified l app "Fer al. demonst a modeli

				notification and among those, and the frequency of close contacts who received the notification before being contacted by MCT. Regarding effectiveness, primary outcome was the time interval (in days) between exposure date and the beginning of quarantine among close contacts, comparing those notified by the app to those not notified by the app"			study that reducing time to quarantine 3 to 2 days a substantial impact on reducing spread of CoV-2, and that a large fraction of the population using the
Burdinski 2022	2022	Mathematical Modeling				stochastic epidemic network model that combines the mechanistic aspects of DCT with the disease-dynamical components	"DCT indeed prevents even if the number of single-day percentages DCT can benefit compared to slow down the of the disease potential reducing harm of mortality earlier in treatment infected. Also, our analysis suggests efficacy enhance increasing participation rates, closure of app use, random symptom testing, the proportion of test results uploaded to the app, the proportion of contacts people trigger notification, generative tracing, and as the introduction of strict NPIs strongly suppresses after an outbreak emerge."
Ellmann 2022	1 April 2022	Mathematical Modeling	The cumulative download numbers of the CWA are published as a time series by the German Robert Koch Institut (RKI)	reduction in R, cases, hospitalizations, and deaths	None use of CWA	Mathematical and statistical modeling	"R-value reduction 5.4% (95% CI: 5.3-5.6%) minimum reduction 2020 at 1 95% CI: 0.0056; 1 second half 2021, increase in absolute

reduction
value was
followed
maximum
0.058 (95%
0.057–0.059)
early March
2022

By 1 April, the CWA prevented 1.48 million cases (95% CI: 1.48 million–1.48 million). It is noticeable that the cumulative reduction number stagnated below 20 cases over a long period of time, and an example year after release of the CWA there were 101,000 (95% CI: 93,000–109,000) as of 1 July 2021). A massive increase began in winter of 2021, coinciding with the dynamic delta/omicron waves already in adoption to that point.

The reduction in infectious cases due to the CWA we reflected reduction in hospital intensive treatment deaths. In April 2022, the CWA had avoided hospitalization (95% CI: 16,600–17,400) deaths (95% CI: 7,400–8,200), and intensive treatment (95% CI: 4,400–4,800). By this time, the CWA had reduced infection by 6.1% (95% CI: 5.8–6.2%), hospitalization by 4.6% (95% CI: 4.3–4.7%), intensive treatment by 4.1% (95% CI: 3.8–4.1%), and deaths by 5.7% (95% CI: 5.4–6.0%)."

Esposito 2021	First 100 days of pandemic	Mathematical Modeling	# of death and hospitalization reduction;	No DDEIS use	a deterministic compartment model based	"a remarkable reduction in exposed
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				increase in quarantined people		on the well- known SEIR (Susceptible– Exposed– Infectious– Recovered) model; a novel set of dynamic equations were elaborated to mimic the flux of people among a set of compartments that represents the variety of scenarios according to the DDEIS proposed	individuals the incre quaranti people d the impleme of the E Detectio strategy; fraction decease people v respect 1 total nur individu 0.5% (co to 2.1% \n DDEIS sce within 10 # of dec goes fro approx 2 DDEIS) t approx 5 reductio hospitali (at day 2 DDEIS is 10k com to appro
Geenen 2023	18 October 2021 - 9 January 2022	Observational					“MCT de over 10 1 the num infected contacts through alone, al in a com strategy, could ide 5.2% of addition; not foun through
Hernández- Orallo 2022	simulation between Sept and Dec 2020	Mathematical Modeling		effectiveness of digital contact tracing	non-use of app	based on the basic SIR model, also considering quarantine, isolation measures, and incubation periods	“approx. million ir cases ar deaths v averted; from cor the epide Satisfyin conditio require a adoptio greater t with a tri positive 0.8, clea unrealist Consider applicati mild me that cou reduce tl of Re to around 1 utilisatio required have bee which is value determin the first
Jeon 2023	November 8, 2020– January 2, 2021	Observational	Pennsylvania Department of Health; daily number of COVID- 19 cases pulled CDC COVID Data Tracker	cases and hospitalizations averted over an 8-week period	non-use of DCT; MCT only	CDC's COVIDTracer modeling tool	“estimat digital notificat averted ; addition; (7–69 cases/1, notificat and <1 hospitali In comp; we estim standarc

							averted 17,151 cases and 250 hospitalizations during the period."
Kendall 2023	24 September 2020 - 24 September 2021	Observational	The UK Health Security Agency (UKHSA), publicly available data	estimated cases, hospitalisations and deaths averted	counterfactual scenario where the app is not present but all other interventions and behaviours remain unchanged	modelling approach of Wymant & Ferretti	app's contribution to averted cases (sensitivity analysis 450,000-1,400,000 corresponds to 44,000 hospitalizations (SA 20,060,000); 9600 deaths; 4,600-1 over the of its first
Kinyili 2022	1st of May 2020 and 21st of June 2020	Mathematical Modeling	the government of the Republic of South Africa	the impact(s) of the use of the COVID Alert SA app	testing exposed individuals not using the app (assumed perfect testing)	modified SEIR deterministic model	"The implementation of the use of the COVID Alert SA app by the general population, in the presence of testing, would greatly decrease the basic reproduction number, thus the free equilibrium would hence eradicate the epidemic relatively quickly." If the use of the COVID Alert SA app by the general population would increase, the implementation of the app would coincide with the test of the COVID-19 then this would remarkably diminish the basic reproduction number. The DFE would become stable and consequently the COVID-19 pandemic would be relatively quickly stabilized." implementation of at least 30% of the app simultaneously alongside gradually increasing measures for individuals not using the app would sufficiently stabilize the system." As the number of the use of the app increases, the extreme

							the plate number cumulative infection declines more people that use the lower number infection wider the distribution of infection
Leung 2024	December 2020 - 31 March 2021	Mathematical Modeling	Epidemiological data from three surveillance systems were used: -Osiris: the national case notification registry containing all confirmed COVID-19 cases (Ward et al., 2005) - CoronIT: tests carried out by the Municipal Health Services, from all public testing facilities - HPZone: all contact tracing data Behavioural data from three large studies were used: - CGU: questionnaires about beliefs and adherence to measures, ran by the Corona Behavioural Unit of the RIVM (RIVM, 2021) - LISS: questionnaires about the tracing app, beliefs and adherence to measures, with an existing longitudinal Social Sciences cohort panel (Van der Laan, 2021) -PanelClix: questionnaire about the tracing app and how it is used, with an existing internet panel (	reduction in the reproduction number, R	with contact tracing compared to the reference reproduction number without testing and tracing	a simulation model for SARS-CoV-2 transmission and contact tracing	The base parameter resulted total reduction of the reproduction number only 0.3 contact tracing apps The contribution of app-based tracing is limited in sensitivity analyses 0.5 % reduction in R In the absence of the population would use contact tracing app, the reduction could be 14.1 %
Nakamoto 2020	August 2020	Mathematical Modeling	National Institute of Infectious Diseases in Japan	adoption rate to reduce $R < 1$	the model evaluates scenarios in which the epidemic is established and countermeasures such as contact tracing are employed to control the spread of COVID-19; it can be observed how the trend of the effective reproduction number (R_t) and thus of the outbreak would dynamically change.	Kurita et al. simulation model	“that when participation rate increases starting from zero, the effective reproduction number decreases gradually, value >1 however meaning containment spread of COVID-19 ($R_t < 1$), approximately 90% participation the population would be required”
Segal 2022	November 30, 2020–March 31, 2021	Observational	iOS EN Setting and Activations and Android Downloads; APHL EN Verification Server; EN Private Analytics; WA State DOH; User survey	cases averted	non-use	Wymant et al	5500 infections prevented the first 6 months; of SARS-CoV-2 cases averted modeling include 13.7% during the first months of Notify
Streilein 2022	NA	Mathematical Modeling	we calibrated the default probability values for interaction based on documented EN experiences from the United Kingdom and	R reduction	0% adoption with manual contact tracing in place	Simulated Automated Exposure Notification (SimAEN)	“(scenario identifier of the total number

Switzerland and from consultations with subject matter experts; derived the initial active case count from COVID-19 US surveillance in early 2021

infected persons; identified an additional 2.1% infected through and wide respectively scenario identified of the total number infected persons; identified an additional 1.9% infected through and wide respectively regardless decrease specificity wide net effective reproduction number, minimally affected decrease when change from narrow wide set

(different adoption The total number decrease higher EN adoption which results in a lower and in the overall rate of cases identified and traditional contact tracing. adoption had a moderate effect or reducing counts (in scenario 1.46, 1.41, 1.24)(R scenario 1.01; 0.9 In scenario EN adoption increase 75%, the trended downward RE reach 0.90;

SimAEN modeling confirmed EN effect depends on several factors including detector settings degree of adoption more sensitive (wider) to detector the more were identified via EN; hence the number of persons

							unneces instructe quaranti increase
Sun 2022	February 25, 2021 to July 27, 2021	Other: comparative assessment	Canadian Digital Service	number of cases averted	non-use of app	Wymant et al	Cases A At 45% quaranti effective 5% SAR 6% SAR: At 65% quaranti effective 5% SAR 6% SAR: Deaths , At 45% quaranti effective 5% SAR SAR: 69 At 65% quaranti effective 5% SAR SAR: 10 03/03/2 15/07/2 Cases a 382,215 ratio of averted 1 cases: 0 -0.029 ratio of averted 1 deaths: 0 0.029 (Lower I 5% SAR quaranti effective Upper bc SAR and quarant effective Canada estimat cases av (% of tot cases): 6 -10, 894 0.81%) estimat deaths a (% of tot cases): 6 (0.004 - 1 the prop of app u: positivel associat the ratio cases averted cases, w supporte positive intervent effects c Alert on reducing burden c disease "Nation: COVID A had limit impact. I the app widely a in some more po province overall ir

							was quit limited, preventing 1.6-2.9% cases and deaths during the study period"
Wymant 2021	24 September 2020 to the end of December 2020	Observational	The COVID-19 case numbers per day we used here are those reported at https://coronavirus.data.gov.uk/ ,	number of cases averted	non-use of the app	two approaches: mechanistically modelling the app's function, and a statistical approach	the fraction of cases averted (among cases that would have occurred or averted) increase 0.8% for increase uptake Cases averted: 1,000 (Cases: 108,000-450,000), modelling digital tracing: 594,000 (317,000-914,000), matched neighbor regression: Deaths: (1,600-6,000) (from model of digital tracing); (4,700-14,000) (From model neighbor regression) For comparison, the total number of cases and deaths that actually occurred in the period was 1,892,000 and 32,500, respectively "30% app uptake would avert approximately every 4 infections that would have arisen during the study period" estimate for every percentage increase in uptake, the number of cases that could be averted (using model) is 2.3% (using statistical analysis)

Figures

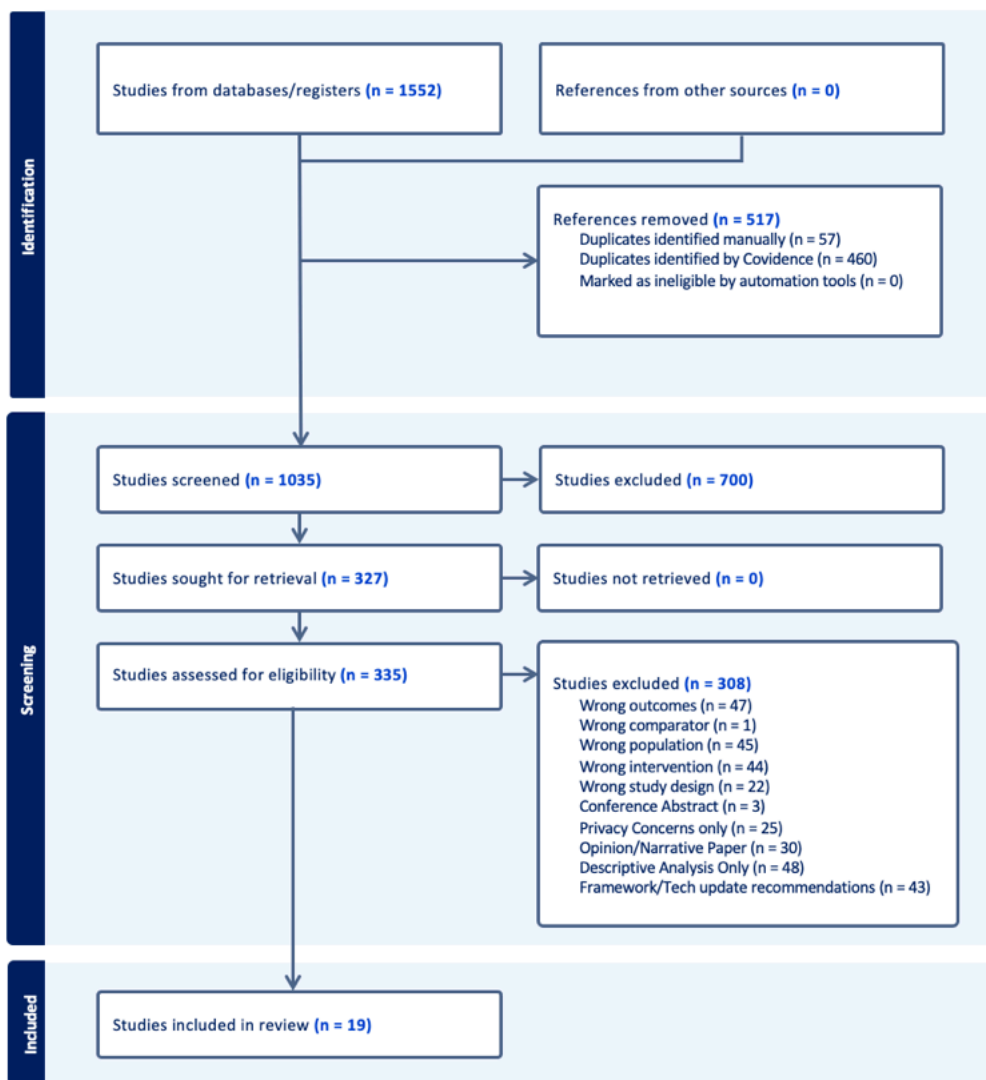


Figure 1

PRISMA flowchart

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