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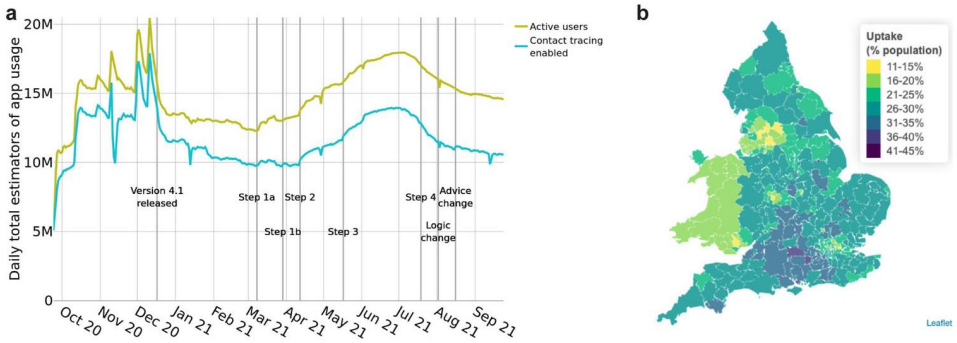

Fig. 1 | App usage. a The number of active app users across England and Wales, and the number of devices with Bluetooth contact tracing enabled. **b** App uptake per LTLA, estimated as the mean number of active users as a proportion of the total population.

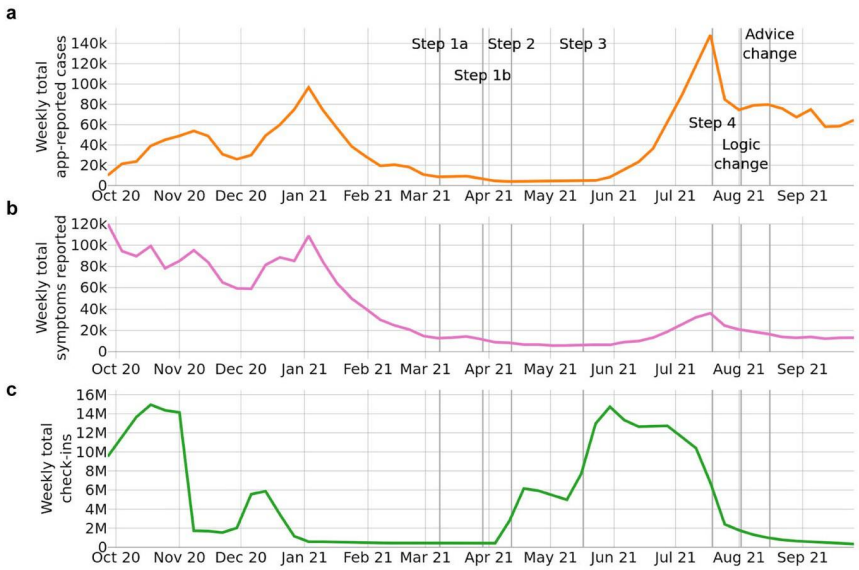

Fig. 2 | App engagement. Weekly numbers of **a** app-reported cases, **b** individuals reporting symptoms through the app, and **c** check-ins via the app's QR code functionality. Annotations refer to: the steps of a 'roadmap out of lockdown'[16]; a change to the contact tracing logic of the app for the contacts of asymptomatic cases, and a policy change where some (mainly vaccinated) users were advised to take a PCR test rather than self-isolate upon notification. These events are described in more detail in a timeline in the Supplementary Materials.

detailed description of how user engagement with the app varied over time, and analysis of the relative increase in the probability of testing positive when recently notified. We adapted the modelling approach of Wymant & Ferretti[10] for estimating cases, hospitalisations and deaths averted, building upon the approach to incorporate the background of changing epidemic dynamics including emerging viral variants, population-level restrictions and vaccination roll-out. Our study adds to the body of evidence which shows that digital contact tracing apps have major potential for reducing transmission of SARS-CoV-2 when combined with strong user engagement[11–14].

Results

App use and engagement

Following the launch of the NHS COVID-19 app on 24 September 2020, the number of active users (devices with the app installed and an internet connection) increased in a matter of days to over 10 million. Before the release of Version 4.1 on 17 December 2020, app usage data suffered from fluctuations caused by missing or duplicated packets, as can be seen from Fig. 1a. Within a few days of the release of Version 4.1 the recorded number of active users stabilised at around 13.5 million, which is 23% of the total population, or 29% of the eligible (over 16) population using ONS population estimates[15]. Of the active users, between 71 and 88% had the Bluetooth contact tracing functionality enabled, with this proportion broadly decreasing over the year (Fig. 1a). There was considerable geographic variation in app uptake as seen in Fig. 1b which shows the number of active users as a proportion of the total population for each Lower Tier Local Authority (LTLA) of England and Wales.

Restrictions were gradually eased through the spring and summer of 2021 according to steps of a 'roadmap out of lockdown'[16]. At Step 1b it became mandatory to provide details to NHS Test and Trace when entering some public venues, with QR code check-ins via the NHS COVID-19 app a convenient way to do this; this step was followed by a rapid increase in app check-ins (Fig. 2). This change appeared to drive uptake of the app, with the number of active users reaching 18 million in early July 2021 (38% of the eligible population), while the number of devices with contact tracing enabled peaked at 13.9 million in late June 2021 (29% of the eligible population). There was a consistent decrease in these measures from that point, possibly as a result of the large number of notifications in June–July 2021 which attracted negative media attention and the coining of the term 'pingdemic'. At the end of the period of study on 24 September 2021 the number of active users was 14.6 million (31% of the eligible population) and the number with contact tracing enabled was 10.6 million (22% of the eligible

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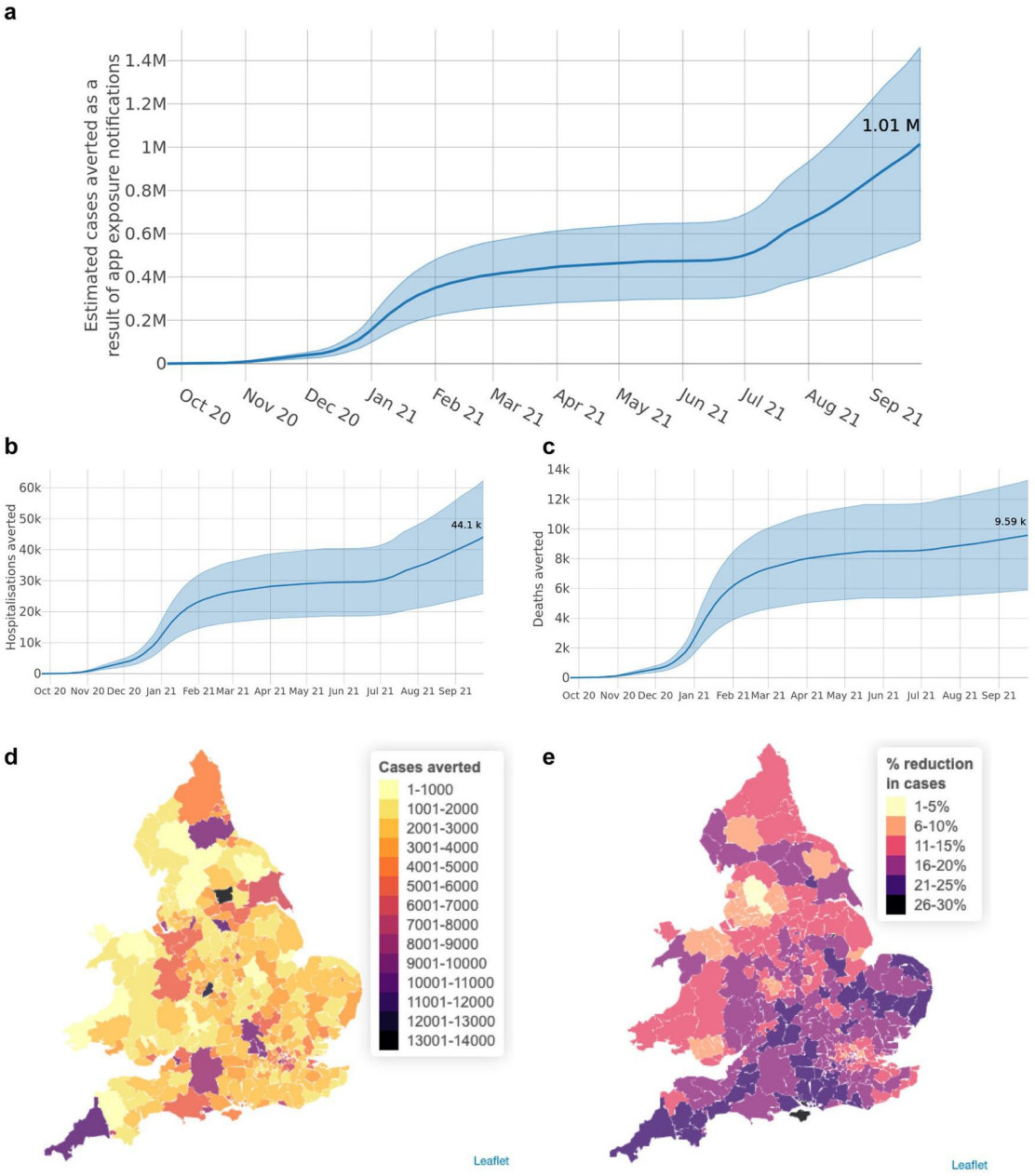

Fig. 6 | Epidemiological impacts. Cumulative estimated numbers of **a** cases, **b** hospitalisations and **c** deaths averted by app exposure notifications between 24 September 2020 and 24 September 2021. Shading in panels **a**–**c** indicates the range of outcomes between upper and lower plausible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

infection via another means are poorly informed by data, as are our estimates of adherence levels to app notifications, and so we considered a wide range of plausible values for these parameters. We include a sensitivity analysis in the Supplementary Materials. In our analysis of hospitalisations and deaths averted we assume that app users together with their onward chain of contacts are representative of the population of England. This assumption is unlikely to be true for short transmission chains, for which individual characteristics are expected to be close to those of the app-using population rather than the general population. It becomes better justified when the initial case directly averted by the app occurs nearer the start of a wave—allowing for more population mixing as the counterfactual transmission chain proceeds through more generations—and these larger chains contribute more to the total result. We implicitly assume that the entire onward transmission chain remains in the same LTLA as the notified app user. This is unlikely to be true in general and is a limitation of our approach. However, we note that this assumption is better justified during the "Tiered" social restrictions of Autumn–Winter 2020, when there was more heterogeneity between case numbers across LTLAs, whereas later in the period of study when there was more freedom of movement there was also more homogeneity of case numbers across LTLAs. Finally, we also assume that the individual risk of getting infected during each wave was small, neglecting risk saturation for repeatedly exposed individuals.

When we calculate the numbers of cases, hospitalisations and deaths averted we are implicitly comparing to a counterfactual scenario where the app is not present but all other interventions and behaviours remain unchanged. The *potential* impact of the app is