Screening and vaccination against COVID-19 to minimise school closure: a modelling study

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Summary

Background **Schools were closed extensively in 2020–21 to counter SARS-CoV-2 spread, impacting students' education and wellbeing. With highly contagious variants expanding in Europe, safe options to maintain schools open are urgently needed. By estimating school-specific transmissibility, our study evaluates costs and benefits of different protocols for SARS-CoV-2 control at school.**

Methods **We developed an agent-based model of SARS-CoV-2 transmission in schools. We used empirical contact data in a primary and a secondary school and data from pilot screenings in 683 schools during the alpha variant (B.1.1.7) wave in March–June, 2021, in France. We fitted the model to observed school prevalence to estimate the school-specific effective reproductive number for the alpha (R^{alpha}) and delta (B.1.617.2; R^{delta}) variants and performed a cost–benefit analysis examining different intervention protocols.**

Findings **We estimated R^{alpha} to be 1·40 (95% CI 1·35–1·45) in the primary school and 1·46 (1·41–1·51) in the secondary school during the spring wave, higher than the time-varying reproductive number estimated from community surveillance. Considering the delta variant and vaccination coverage in Europe as of mid-September, 2021, we estimated R^{delta} to be 1·66 (1·60–1·71) in primary schools and 1·10 (1·06–1·14) in secondary schools. Under these conditions, weekly testing of 75% of unvaccinated students (PCR tests on saliva samples in primary schools and lateral flow tests in secondary schools), in addition to symptom-based testing, would reduce cases by 34% (95% CI 32–36) in primary schools and 36% (35–39) in secondary schools compared with symptom-based testing alone. Insufficient adherence was recorded in pilot screening (median ≤53%). Regular testing would also reduce student-days lost up to 80% compared with reactive class closures. Moderate vaccination coverage in students would still benefit from regular testing for additional control—ie, weekly testing 75% of unvaccinated students would reduce cases compared with symptom-based testing only, by 23% in primary schools when 50% of children are vaccinated.**

Interpretation **The COVID-19 pandemic will probably continue to pose a risk to the safe and normal functioning of schools. Extending vaccination coverage in students, complemented by regular testing with good adherence, are essential steps to keep schools open when highly transmissible variants are circulating.**

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Introduction

School closure has been extensively used worldwide against the COVID-19 pandemic. The first wave resulted in many countries going into strict lockdowns, closing schools for long periods of time,[1] and their reopening has been continuously challenged by successive waves and the need for physical-distancing restrictions. In Europe, depending on the country, students lost from 10 weeks to almost 50 weeks of school from March, 2020, to October, 2021, due to partial or total school closures (figure 1A). Strategies were affected by the limited understanding of viral circulation in children and their contribution to transmission.[2]

COVID-19 outbreaks in schools are difficult to document, as infections in children are mostly asymptomatic or present mild non-specific symptoms.[3] Despite the lower susceptibility to infections in children than in adults,[4] viral circulation can occur in school settings, especially in secondary schools.[2] Accumulating evidence is consistent with increased transmission in the community if schools are open,[2,5] and model-based findings suggest that school closure might be used as an additional brake against the COVID-19 pandemic if other physical-distancing options are exhausted or undesired.[6,7]

Keeping schools safely open remains a primary objective that goes beyond educational needs, affecting the social and mental development of children,[8] as well as reducing inequality. Several countries implemented safety protocols at schools, including the use of facemasks, hand hygiene, and staggered arrival and breaks. Regular testing[9–12] was introduced in a few countries as an additional control measure. Vaccination was extended to the population aged 5 years and older in Europe, yet it was reported to have

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Research in context

Evidence before this study

We searched PubMed, medRxiv, bioRxiv, and arXiv for articles in English published up to Dec 3, 2021, which had, in the title or abstract, the terms "COVID-19", "testing", and "schools". We found a total of 271 unique articles. 57 works were modelling papers on the spread of COVID-19, and of these 31 (54%) implemented agent-based models. However, very few integrated information from empirical contacts or considered the cost of school closures in terms of school-days lost by students. No study addressed the role of vaccination in children in the school setting or the interplay of adherence to screening with frequency of screening. Modelling studies reached a consensus on the fact that test turnaround time is more important than test sensitivity for efficient testing strategies.

Added value of this study

Governments around the world proposed school closures as a first measure to slow down viral spread; however, the need to safely keep schools open is arguably a primary objective for educational, mental health, and socioeconomic reasons. Using empirical contact data collected in a primary school and a secondary school and data on test results collected in pilot screenings during the 2021 spring wave of the alpha variant in France, we estimated the effective reproductive number specific to each school setting in that period and showed that transmission was higher in schools than in the community. Accounting for the transmission advantage of the delta variant and vaccination coverage in Europe as of mid-September, 2021, we showed the need for regularly testing a partly immunised school population to reduce the number of cases while limiting the number of student-days lost. In particular, we highlighted the importance of adherence to screening, showing that higher screening frequency is needed to compensate for lower adherence. Model estimates indicate that the low levels of adherence recorded in pilot screenings during the third wave would be insufficient to control viral circulation in the school population. Increasing vaccination coverage in teachers did not impact potential outbreaks, mainly due to the large mixing among students. Regular testing would still provide a key benefit in decreasing viral circulation in a moderately vaccinated student population, or under waned protection against infection, and it would be especially important under the high-incidence conditions observed in the omicron wave.

Implications of all the available evidence

By studying different epidemic contexts and vaccination conditions, we provided a range of alternatives to school closure, to be implemented according to the epidemic activity and the reported adherence. These strategies become particularly important as the safety and normal functioning of classrooms are threatened by high community transmission rates. These results can inform national education systems to safely keep schools open while avoiding unnecessary closures.

progressed slowly in the majority of countries as of January, 2022.[13] School protocols were challenged by the rapid surge of cases due to the delta (B.1.617.2) and omicron (B.1.1.529) variants in the 2021–22 winter season in Europe,[14] threatening classroom safety. Assessing vaccination and protocols in schools is therefore key to maintaining schools open in light of a continuously evolving pandemic. Here, through an agent-based transmission model parameterised on empirical contacts at schools and fitted to field screening data in schools, we estimated the school-specific effective reproductive number (R) of SARS-CoV-2. We then evaluated intervention protocols combining school closures and screening, under varying immunity profiles of the school population, and accounting for age-specific differences in susceptibility to infection, contagiousness, contact patterns, and vaccine effectiveness.

See **Online** for appendix

Findings from this work informed the recommendations of the French National Immunisation Technical Advisory Group (Haute Autorité de Santé) on vaccination of children in December, 2021.

Methods

Empirical patterns of contacts

We used empirical data describing time-resolved, face-to-face proximity contacts between individuals in two educational settings, collected in France using wearable radio frequency identification (RFID) sensors before the pandemic. The primary school dataset describes contacts among 232 students (aged 6–11 years) and ten teachers in a primary school in Lyon in October, 2009; the primary school was composed of five grades, each containing two classes.[15] The secondary school dataset describes contacts among 325 students (aged 17–18 years) of nine classes in a secondary school in Marseille in December, 2013.[16] Classes in the secondary school belonged to the second year of classes préparatoires, which is specific to the French schooling system for preparing students for University entry, and were divided into three groups based on the specialisation (mathematics and physics; physics, chemistry, and engineering studies; and biology).

We built temporal contact networks, composed of nodes representing individuals (classified by class and student or teacher) and links representing empirically measured proximity contacts occurring at a given time (appendix p 14). As each dataset covers only a few days, we developed an approach to temporally extend the datasets by generating synthetic networks of contacts that reproduce the main features observed empirically (class structure, within-class *vs* between-class links, contact duration heterogeneity, and similarity across days; appendix pp 14–18). The secondary school synthetic network was further extended to generate a synthetic first year (to consider the full curriculum of the classes préparatoires), including teachers whose contacts were inferred from an additional dataset for the same school. The resulting network for the secondary school was composed of 650 students and 18 teachers.

Field screening data in schools during the spring, 2021, wave in France

In response to a rising third wave of SARS-CoV-2 in France in March, 2021, due to the alpha variant (B.1.1.7), local authorities in the Auvergne-Rhône-Alpes region proposed pilot screenings at schools on a voluntary basis to detect cases. We used data on adherence to screening and test results collected in 683 schools between March 8 and June 7, 2021 (weeks 10–23), in the Ain, Loire, and Rhône departments of the region (figure 1E). Screening was interrupted in April due to reactive school closure (week 14) and the Easter holidays (weeks 15–16) while the country underwent the third national lockdown; it was resumed in week 17 at school reopening (week 18 for secondary schools; figure 1G). Screenings involved 94 pre-schools (ages 3–5 years), 427 primary schools (ages 6–11 years), 158 middle schools (ages 12–15 years), and four high schools (ages 16–18 years), for a total of 209 564 students and 18 019 staff and teachers tested. PCR tests on saliva samples were proposed in pre-schools and primary schools and anterior nasal lateral flow device (LFD) tests in middle and high schools. More details on the number of participating schools by department and over time, and on the observed adherence to testing, are provided in the appendix (pp 19–22).

Ethics statement

Contact studies were approved by the Commission Nationale de l'Informatique et des Libertés (the French national body responsible for ethics and privacy; 1719527 and 1427054) and school authorities. Informed consent was obtained from participants or their parents if they were minors (age <18 years). No personal information of participants was associated with the RFID identifier. Testing at school was part of surveillance activities approved by school authorities and proposed with parental consent. Screening data were provided in aggregated and anonymised form.

Transmission modelling

We developed a stochastic agent-based model of SARS-CoV-2 transmission on the network of contacts. Infection progression includes prodromic transmission, followed by clinical or subclinical disease stages, informed from empirical distributions. Transmission occurs with a given transmissibility (β) per contact per unit time between an infectious individual and a susceptible one. β was inferred by fitting the model to data from screening results during the 2021 spring wave. Individuals in the asymptomatic compartments were considered less infectious than individuals in the symptomatic compartments and to remain undocumented unless tested;[17] a sensitivity analysis was performed on the value of the reduced transmissibility in the asymptomatic stage.

The model was parameterised with age-specific estimates of susceptibility, transmissibility, probability of developing symptoms, and probability to detect a case based on symptoms (appendix pp 4–6). A systematic review[4] indicated that children (younger than 10–14 years) have lower susceptibility to SARS-CoV-2 than adults, but building evidence suggests that adolescents (older than 10–12 years) might be as susceptible as adults (≥20 years).[4,18] Here, we considered a relative susceptibility of 50% in primary school children and 75% in secondary school adolescents compared with adults for the main analysis and 100% susceptibility in adolescents in a sensitivity analysis. The probability of recognising a suspected SARS-CoV-2 infection from symptoms was set to 30% for children and 50% for adolescents and adults on the basis of studies indicating that about two-thirds of symptomatic children[3] and half of symptomatic adults[19] have unrecognised symptoms before diagnosis. These values were varied in sensitivity analyses (appendix pp 9, 51). We considered a relative transmissibility of 63% in children compared with adults as evidence suggests that transmission in children might be less efficient than in adults,[20] and we tested 80% relative transmissibility in a sensitivity analysis.

The model was further stratified to account for vaccination status and to include vaccine effectiveness against infection, transmission, and clinical symptoms given infection[21] (appendix pp 9–12). Higher and lower values for vaccine effectiveness were tested in sensitivity analyses. Full details on the transmission model are reported in the appendix (pp 4–13).

Closure and screening protocols

Symptom-based testing and case isolation was considered the basic strategy, present in all protocols, and against which interventions were evaluated. Under the basic strategy, confirmed cases isolate for 7 days. In addition to the basic strategy, we considered several intervention protocols. First, we considered a protocol of reactive quarantine of the class, wherein once a case is identified through symptom-based testing their class is closed and put into quarantine for 7 days. If quarantined individuals develop symptoms, they remain in isolation for an additional 7 days before returning to school. This protocol was largely adopted in France before the delta wave in November, 2021. The second protocol was reactive quarantine of the class level or specialisation, which is similar to the reactive quarantine of the class protocol except that quarantine is applied to the classes of the same level (two classes in the primary school) or specialisation (three in the secondary school) of the detected case. This option was considered as empirical data showed a larger mixing between students of the same level or specialisation than between students of different levels or specialisations.[15,16] Third, we considered reactive screening of the entire class on the day after detection of the case by symptom-based testing, followed by a control screening on days 4 or 7 after case identification to detect previously undetected cases. This protocol assumes that 100% of the non-vaccinated school population adheres to screening. This protocol was adopted in France during the delta wave. Fourth, we considered regular testing of the entire school once every 2 weeks or once or twice a week, in addition to symptom-based testing, with adherence among the non-vaccinated informed by field data and further explored in a range between 10% and 100%. Finally, we considered a protocol of regular testing with different levels of adherence among the non-vaccinated and reactive closure of the class triggered at every detected case.

Following protocols adopted in France, we assumed testing consisted of PCR tests on saliva samples for primary schools and anterior nasal LFD tests for secondary schools, with time-varying test sensitivity specific to each test and results available after 24 h for PCR and after 15 min for LFD tests (appendix pp 7–8). Teachers are required to show proof of a negative PCR test when returning to school after infection.

Inference framework

We used data on test results collected in the pilot screenings during the 2021 spring wave in the Ain, Loire, and Rhône departments to estimate the transmissibility per contact per unit time of the alpha variant (β^{alpha}) and the corresponding school-specific R for the alpha variant (R^{alpha}) in that period. The model was fitted to the observed prevalence of cases in students in the tested schools through a maximum likelihood approach. We used data from screenings performed during the rise of the spring wave (March 8 to April 2, 2021) that involved at least five schools and 500 screened students per week per department for each school type (primary or secondary) and with reported adherence to screening of at least 50% (reference inclusion criteria). In sensitivity analyses, we relaxed the constraint on adherence (sensitivity inclusion criteria). Simulations for the fit covered the period from week 8 (starting Feb 22, 2021, at school reopening after winter holidays) to week 13 (ending April 4) before the reactive school closure, and they were initialised with age-specific seroprevalence estimates.[22] Weekly introductions at school were modelled stochastically, inferred from age-specific community surveillance data, and adjusted to account for detection rate and within-school transmission.[23] We computed R in each school as the ratio of the number of individuals infected at the second generation to the number infected at the first generation for each initial seed over 5000 simulated outbreaks. The estimated R refers to the reactive quarantine of the class protocol with a facemask mandate applied in that period. Full details on the procedure are reported in the appendix (pp 23–29).

Analysis of school protocols in a delta winter wave scenario in Europe

To evaluate the efficacy of intervention protocols, we considered a 2021–22 winter scenario due to the delta variant, initialised with 25% natural immunity in the population, 60% of teachers vaccinated, and 40% of adolescents vaccinated, corresponding to the median vaccination coverage registered in countries in Europe by mid-September, 2021 (appendix p 31). The transmissibility per contact per unit time for the delta variant (β^{delta}) was estimated from the maximum likelihood estimate $\beta_{\text{MLE}}=\beta^{\text{alpha}}$, accounting for the transmissibility advantage of the delta variant.[24] The corresponding school-specific R for the delta variant (R^{delta}) was estimated from simulated outbreaks under the above immunity conditions, and considering the reactive quarantine of the class protocol with facemasks mandated. We additionally explored a range of R^{delta} values to account for the uncertainty in the estimate of delta transmissibility,[24] seasonal effects,[25] and variations in β_{MLE} due to the inclusion criteria considered in the inference. We considered low, moderate, sustained, and high weekly introductions modelled stochastically and corresponding to community surveillance incidence in primary school students ranging in time from 25 to more than 600 cases per 100 000 (low introductions), from 50 to 900 cases per 100 000 (moderate), from 100 to 1300 cases per 100 000 (sustained), and from 200 to 1800 cases per 100 000 (high); values for the secondary school are reported in the appendix (p 33).

To assess the efficacy of screening protocols under different immunity conditions, we explored a full range

***Figure 1:* School closure in Europe, empirical contact network features, and field screening data in schools in France**
(A) Number of in-presence weeks lost by students in European countries because of school closures due to the pandemic.[1] (B) Daily mean number of distinct contacts per individual within the class or between classes; horizontal dashed lines represent the mean class size, which was 23·2 students (SD 1·4) in the primary school and 35·8 (4·1) in the secondary school. (C) Daily mean time that an individual spends in interaction with contacts within the class or in other classes. (D) Daily mean time that a teacher or student spends in interaction with contacts. In panels B–D, histogram bars refer to the empirical networks, and points and error bars (with 95% bootstrap CIs) refer to the synthetic networks. In panels B and C, the increase in average number of contacts and duration in the synthetic secondary school networks compared with their empirical counterparts is due to the ad-hoc addition of contacts between school years. In panel D, no empirical data is shown for teachers in secondary schools as they did not participate in the data collection and their contact behaviour was inferred from another dataset (appendix p 15). (E) Number of schools participating in the pilot screenings during the spring 2021 wave in the Ain, Loire, and Rhône departments. (F) Observed adherence to screening; boxplots represent the median (middle line), IQR (box limits), and 2·5th and 97·5th percentiles (whiskers). (G) Number of schools participating in the pilot screenings and weekly incidence (dotted line) over time from community surveillance in the Ain, Loire, and Rhône departments during the 2021 spring wave; the vertical shaded areas indicate the school closures.

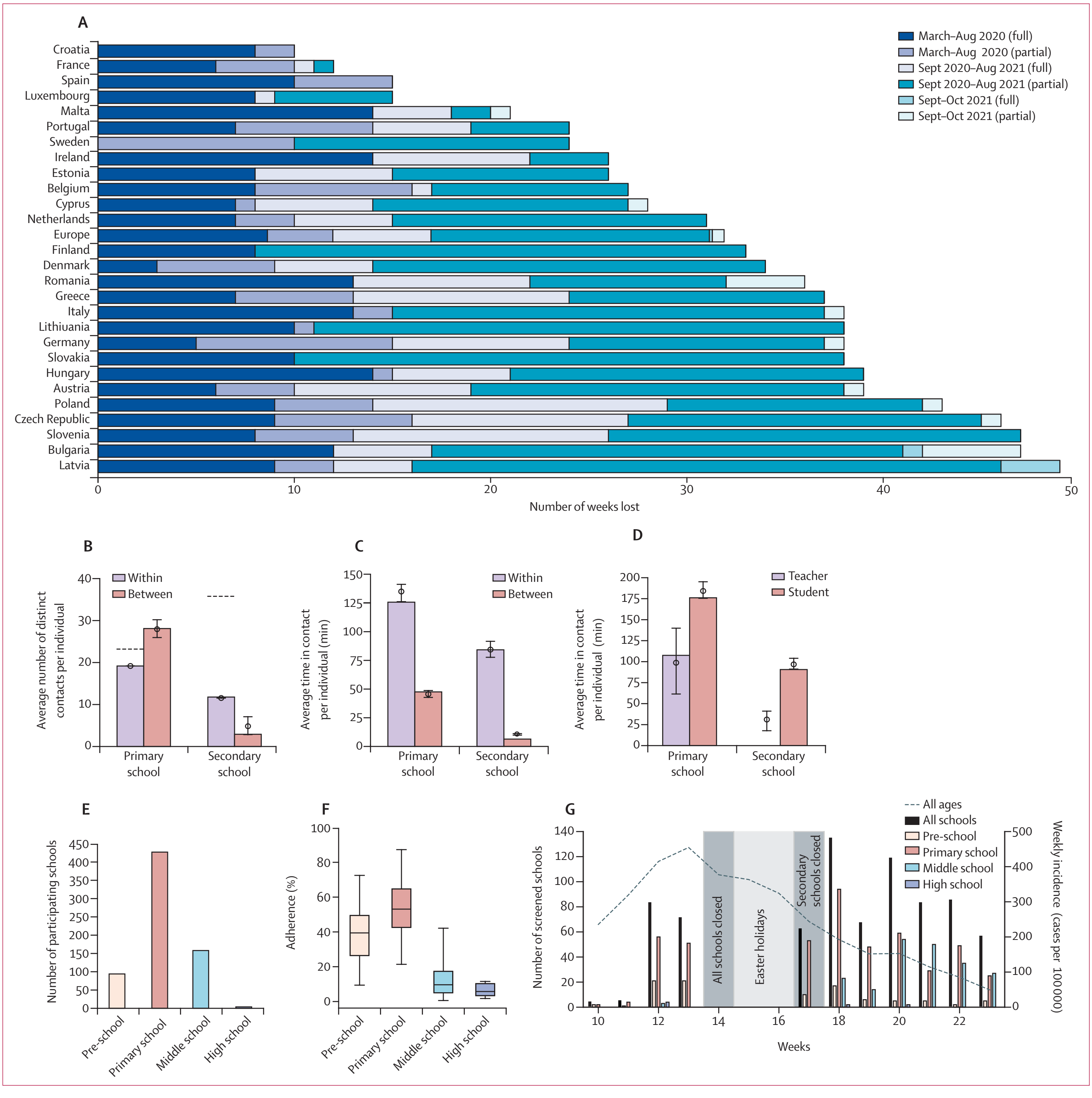
of vaccination coverage in children, adolescents, and teachers.

Analysis of school protocols in an omicron winter wave scenario in Europe

We considered the circulation of the highly transmissible and immune-evasive omicron variant that became dominant in Europe by the start of 2022.[14] We tested the efficacy of school protocols under the high-incidence conditions registered in France by mid-January, 2022 (5500 cases per 100 000 children aged 6–10 years). Details of this analysis are reported in the appendix (p 37).

Simulation details and analysis

Estimates for β and R were obtained from 5000 simulated stochastic outbreaks for each parameter set. Estimates



for R were compared with the age-specific, time-varying reproductive number (R_t), estimated from community surveillance data, with a one-sample t-test. We fitted the predicted offspring distribution to a negative binomial to estimate the overdispersion parameter k.[26] In the analysis of closure and screening protocols, we performed 1000 stochastic runs for the primary school and 2000 for the secondary school for each parameter set, over the course of a trimester (90 days). We computed medians and 95% bootstrap CIs from simulation outputs to compare protocols with a Mood's median test. IQRs were used to describe observed adherence. Network statistics in the primary and secondary schools were compared with a Student's t-test. We used R software version 4.1.1 for the statistical analyses.

Role of the funding source

The funders had no role in study design, data collection, data analysis, data interpretation, writing of the manuscript, or the decision to submit for publication.

Results

Contact networks measured through wearable sensors displayed a strong community structure around the classes, common to both the primary and secondary schools (appendix p 14). The patterns of interaction, however, varied substantially between the two settings. On average, children had a larger number of distinct contacts during a day than adolescents, interacting with almost their entire class (83% *vs* 33% of the class, Student's t-test p<0·0001; figure 1B). Approximately 50% more links occurred between classes than within classes in the primary school (28 *vs* 19 links, p<0·0001), whereas in adolescents, 75% fewer links occurred between than within classes (three *vs* 12 links, p<0·0001). After accounting for duration, students in both settings spent on average more time interacting within the class than outside the class (p<0·0001; figure 1C) and established longer contacts than teachers (64% longer, p=0·009; figure 1D).

Using the empirical contact patterns, we inferred the school-specific transmissibility from screening data in primary schools that satisfied the inclusion criteria: 71 primary schools with 12 146 tested students met the reference inclusion criteria, and 103 primary schools with 15 916 tested students met the sensitivity inclusion criteria. Secondary schools were excluded because of limited participation, but with θ_{MLE} we could estimate the within-school R^{alpha} both in the primary school and in the secondary school. We estimated that R^{alpha} during the 2021 spring wave of the alpha variant in France when reactive class closures and facemask mandates were in place was 1·40 (95% CI 1·35–1·45) in primary schools that met the reference inclusion criteria, 1·44 (1·40–1·48) in primary schools that met the sensitivity inclusion criteria, 1·46 (1·41–1·51) in secondary schools that met the reference inclusion criteria, and 1·50 (1·46–1·54) in secondary schools that met the sensitivity inclusion criteria (figure 2A). Estimates were higher than the R_t obtained from age-specific community surveillance in the same period (one-sample t-test p<0·0001 in the primary and secondary school; figure 2C). We quantified a large individual-level variation in SARS-CoV-2 transmission in both schools, corresponding to an estimated overdispersion parameter k of 0·56 (95% CI 0·49–0·63) in the primary school and 0·52 (0·46–0·58) in the secondary school (figure 2B). Accounting for the transmissibility advantage of the delta variant and vaccination coverage in Europe, we estimated a school-specific R^{delta} of 1·66 (95% CI 1·60–1·71) for primary schools that met the reference inclusion criteria, 1·70 (1·66–1·75) for primary schools that met the sensitivity inclusion criteria, 1·10 (1·06–1·14) for secondary schools that met the reference inclusion criteria, and 1·13 (1·10–1·16) in secondary schools that met the sensitivity inclusion criteria. In the analysis of closure and screening protocols, we used the R^{delta} estimate obtained with the reference inclusion criteria, and explored ranges for R^{delta} of 1·46–2·00 in primary schools and 0·97–1·34 in secondary schools to account for the uncertainty associated with delta transmissibility, seasonal effects, and sensitivity inclusion criteria.

Under the estimated delta transmissibility and with sustained introductions, regular testing constitutes an efficient protocol for preventing infections in a partially immunised school population (figure 3A). If adherence among the non-vaccinated is large enough, regular testing can substantially outperform protocols based on simply identifying cases given recognisable symptoms and additionally closing or screening the class of the detected case (even with a follow-up control screening). However, screenings at schools during the 2021 spring wave in France were met with low or moderate participation rates. Adherence was higher in lower school levels (39% [IQR 26–49] in pre-school and 53% [43–65] in primary school) than in secondary schools (10% [5–17] in middle school and 6% [3–10] in high school; Mood's median test p<0·0001; figure 1F). We found that with 50% adherence among the non-vaccinated—ie, approximately the value recorded in the French primary schools—weekly screening would reduce the number of cases by 21% (95% CI 19–23) in primary schools and 26% (24–28) in secondary schools compared with symptom-based testing alone. Case reduction would rise to 34% (32–36) and 36% (35–39) in primary and secondary schools, respectively, with 75% adherence. Alternatively, similar reductions would be achieved with 50% adherence and twice-weekly testing. These data show how infection prevention improves with both adherence and frequency of tests, and higher frequency is needed to compensate for lower adherence. However, if adherence to regular testing is too low (10%), as recorded in the French secondary schools, weekly testing would have little impact (<10% case reduction, similar to reactive screening and

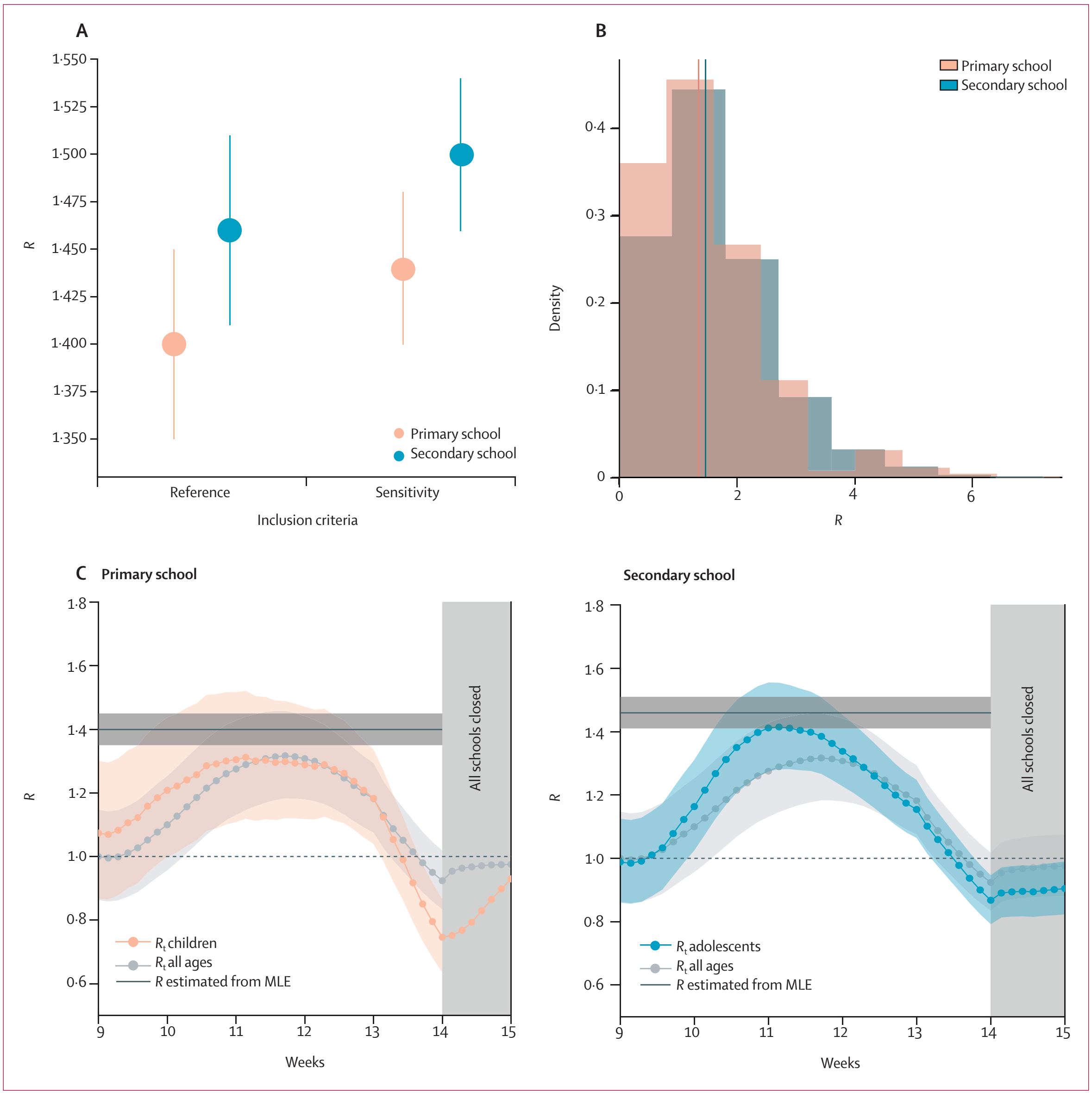


Figure 2: **Estimates of *R* in the school setting during the 2021 spring wave in France due to the alpha variant**
(A) Estimates of *R* in primary and secondary schools obtained with the reference and the sensitivity inclusion criteria by fitting the model to pilot screening data; estimates refer to the alpha variant during the 2021 spring wave in France, when reactive closure of classes and facemask mandates were in place, and error bars indicate 95% CIs. (B) Predicted offspring distribution in primary and secondary schools; bold vertical lines indicate *R* (ie, the average of the distribution) obtained with the reference inclusion criteria. (C) Comparison between the estimate of *R* for the alpha variant (bold horizontal line; the shaded area corresponds to its 95% CI) and R_t estimated from community surveillance in the Ain, Loire, and Rhône departments during the rise of the 2021 spring wave for primary schools and secondary schools. MLE=maximum likelihood estimate. *R*=effective reproductive number. R_t=time-varying reproductive number.

lower than reactive closure). Although trends are similar across settings, partial vaccination coverage in adolescents leads to smaller epidemic sizes in the secondary school than in the primary school (relative to the school size; figure 3B; appendix p 41).

As well as reducing the number of infections, regular testing is predicted to strongly limit the number of days of absence of students. Quarantine of the class leads to 17·7 (95% CI 17·4–17·9) and 32·6 (31·9–33·5) times more student-days lost in primary and secondary schools, respectively, than when symptom-based testing is used alone (figure 4A). Days lost inevitably increase when reactive closure is extended to classes of the same level or specialisation. Not being sufficiently targeted, reactive closure quarantines individuals while their risk of infection might be low, and the virus might have spread to other classes (figure 3C). Reducing mixing across classes through cohorting improves control (appendix p 44). Despite detecting more cases, regular testing leads to a small increase in student-days lost, less than 6·6 (6·4–6·8)

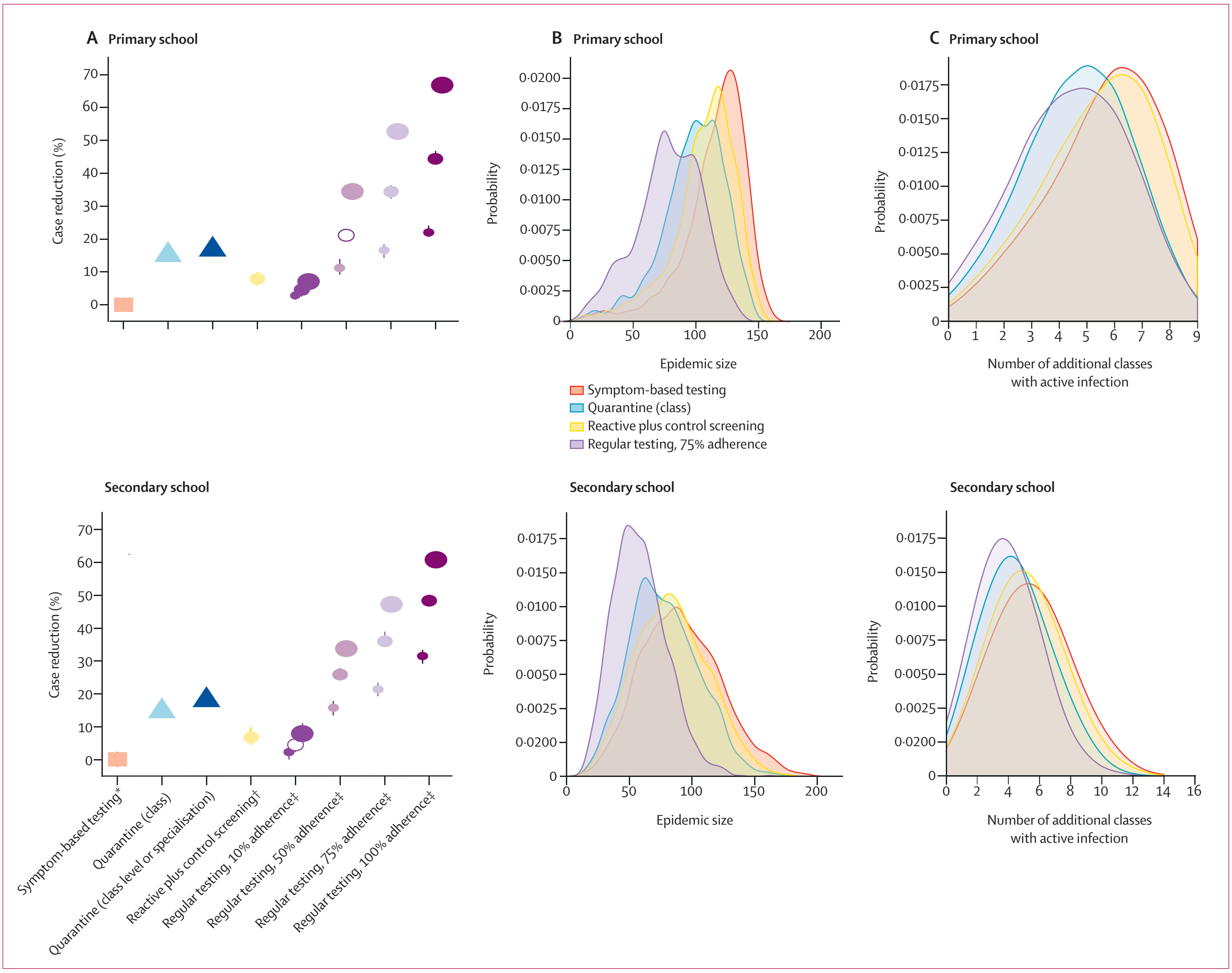


Figure 3: **Efficiency of regular testing in educational environments**

(A) Predicted case reduction relative to symptom-based testing alone in primary schools and secondary schools; the reduction is computed on the final epidemic size over 90 days. Error bars correspond to 95% bootstrap CIs (in some cases smaller than the symbol size). The empty marker corresponds to the adherence estimated from empirical data. (B) Probability distribution of the simulated epidemic size over 90 days in the primary school and secondary school for selected protocols (regular testing is performed weekly). C) Probability distribution of the additional number of classes in the primary school and secondary school with at least one active infection when a case is confirmed, for selected protocols (regular testing is performed weekly). In all panels, simulations are parameterised with sustained introductions and the estimated effective reproductive number for the delta variant when reactive class closures and facemask mandates are in place, and accounting for differences in vaccination coverage. *All protocols involve symptom-based testing. †Reactive screening of the class is done on the day after detection of the case, followed by a control screening on day 4 after case identification, with 100% adherence among the non-vaccinated. ‡Regular testing is performed with one test every 1 week (medium-sized circle) or 2 weeks (smallest circle) or two tests per week (largest circle).

times the number of days lost with the basic strategy and about 63–80% less than reactive class closure as isolation is applied only to detected cases. The cost–benefit analysis shows that for all regular testing strategies, the cost expressed as student-days lost remains low, even when the benefit becomes high, for a range of different epidemic conditions (figure 4B). Strategies based on class closures do not reach substantial benefit, even at large costs. Reactive screening limits days lost but with a negligible impact on viral circulation. Closing the class at each case detected by regular testing improves case reduction but at the cost of increased absence from school (appendix p 43). Findings were robust to changes in detection rates and test sensitivity (appendix pp 51–52).

Higher incidence in the community (increasing the expected introductions at school) and larger values for *R* (increasing within-school transmission) reduce the benefit of weekly testing in primary schools, thus requiring increased adherence or frequency (figure 4C,D). The impact of introductions is milder in the secondary

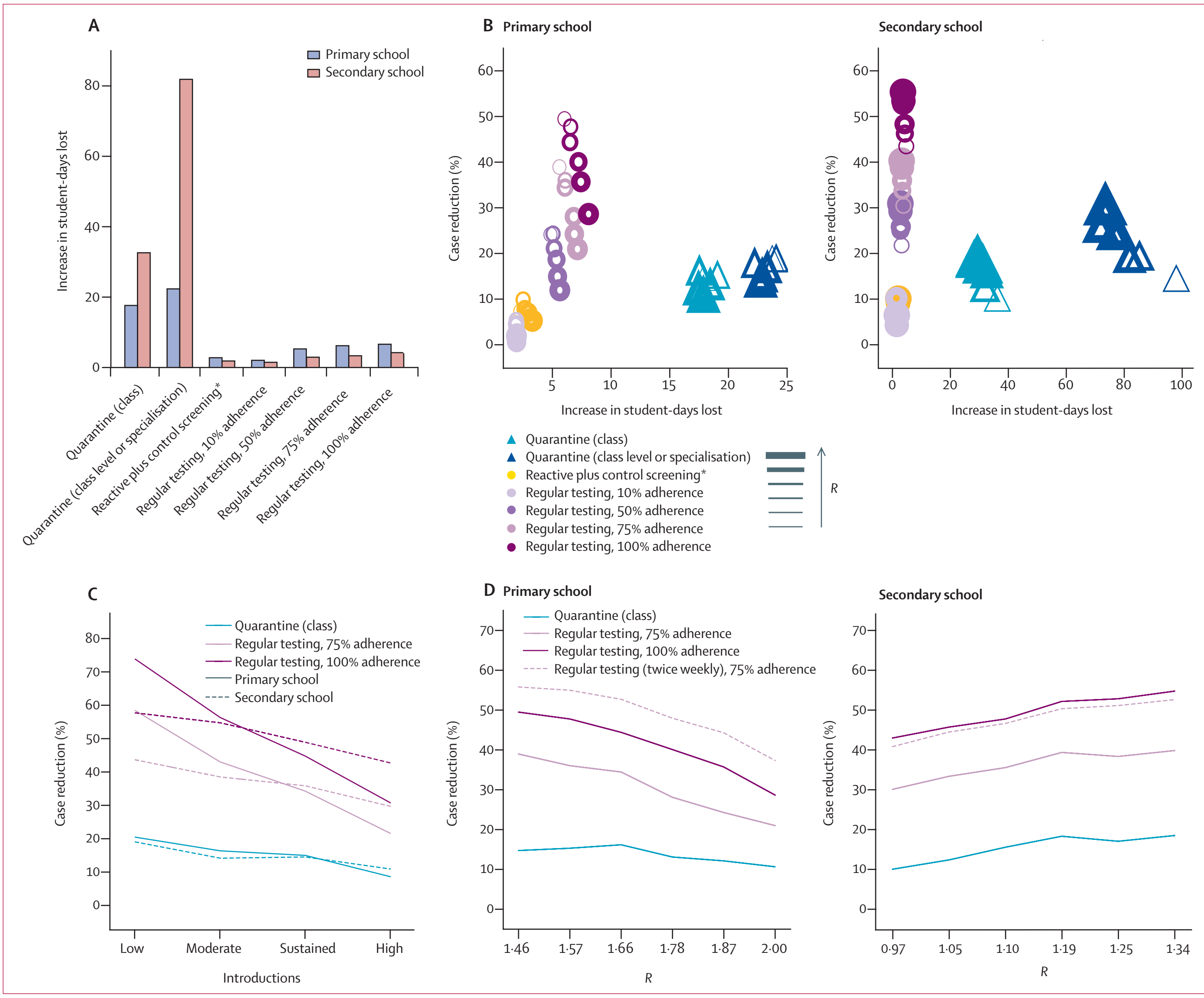


Figure 4: **Cost–benefit analysis of regular testing in educational environments and the impact of introductions and *R***

(A) Predicted increase in student-days lost relative to symptom-based testing alone. Regular testing is performed weekly. Simulations are parameterised with sustained introductions and the estimated R^{delta} when reactive class closures and facemask mandates are in place, accounting for differences in vaccination coverage. (B) Predicted case reduction versus predicted increase in student-days lost in the primary school (*R* 1·46–2·00) and secondary school (*R* 0·97–1·34) for each protocol relative to symptom-based testing only. Regular testing is performed weekly. Simulations are parameterised with sustained introductions. (C) Predicted case reduction relative to symptom-based testing only for selected protocols (regular testing is performed weekly) as a function of the level of introductions; simulations are parameterised with the estimated R^{delta}. (D) Predicted case reduction relative to symptom-based testing alone for selected protocols in the primary school and secondary school as a function of *R*. Regular testing involves weekly screening unless otherwise indicated. Simulations are parameterised with sustained introductions. All protocols involve symptom-based testing. *R*=effective reproductive number. R^{delta}=effective reproductive number for the delta variant. *Reactive screening of the class is done on the day after detection of the case, followed by a control screening on day 4 after case identification, with 100% adherence among the non-vaccinated.

school than in the primary school due to vaccination of adolescents (figure 4D). Moreover, increasing *R* in this setting would increase the benefit of regular testing, contrary to the primary school case. This is due to a bell-shaped dependence of the infection prevention capacity of regular testing versus *R* (appendix p 46): in low-transmission conditions, only a few cases are present even under the scenario of symptom-based testing and case isolation, so that additional protocols yield marginal benefit; as transmission increases from small values (the secondary school case, where *R* is small thanks to vaccination), efficiency increases. In high-transmission conditions, case prevention is hindered by too many infections generated between successive screenings, and efficiency decreases as transmission increases (the primary school case, with high *R* because of unvaccinated children). Changes in epidemiological parameters (transmissibility and susceptibility) yield changes in *R*

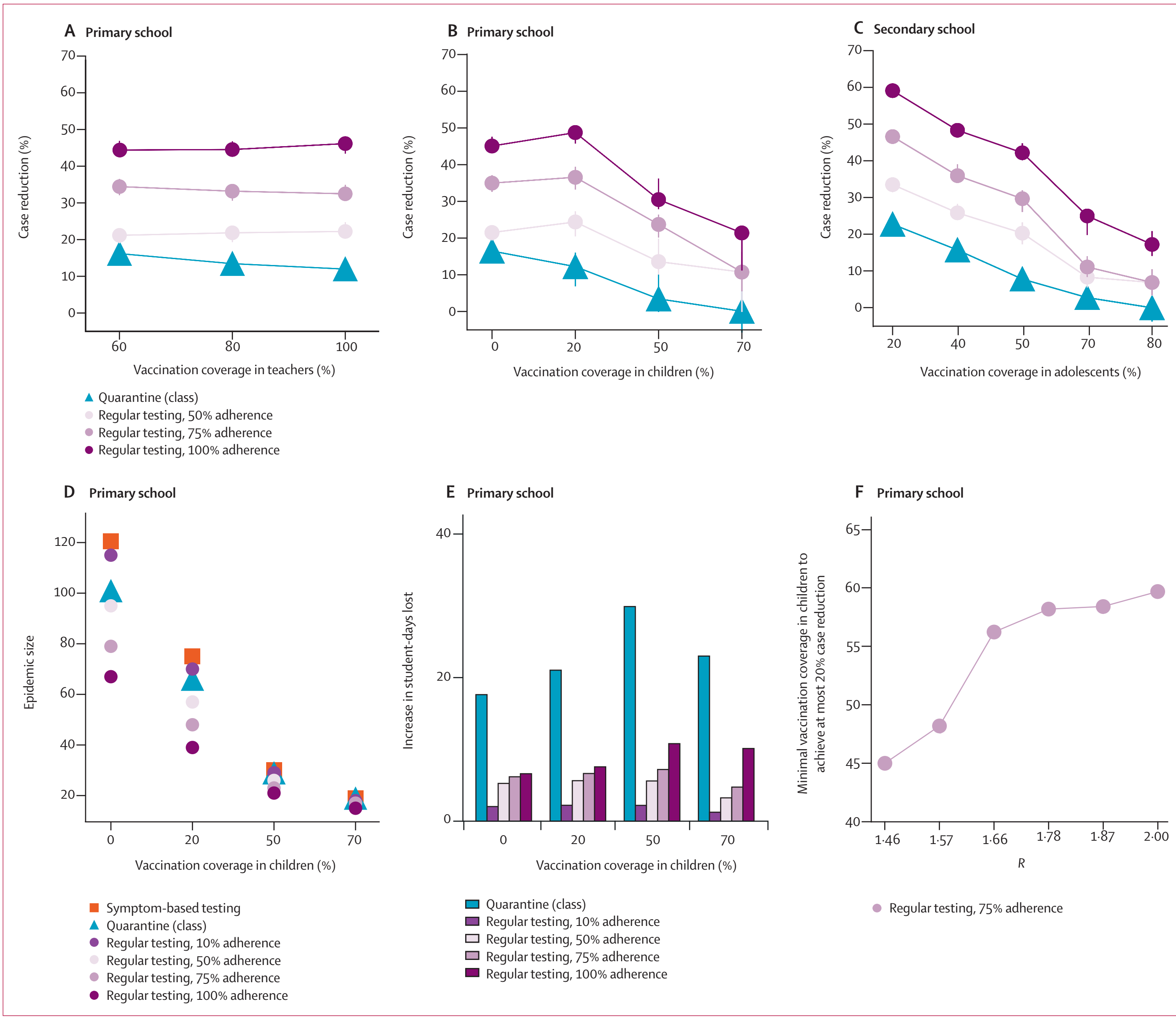


Figure 5: **Impact of vaccination coverage on case reduction, epidemic size, and student-days lost**

(A) Predicted case reduction relative to symptom-based testing alone for selected protocols as a function of the vaccination coverage in teachers in the primary school. (B) Predicted case reduction relative to symptom-based testing alone for selected protocols as a function of vaccination coverage in children in the primary school. (C) Predicted case reduction relative to symptom-based testing alone for selected protocols as a function of vaccination coverage inç adolescents in the secondary school. (D) Predicted final epidemic size over 90 days versus vaccination coverage in children in the primary school for selected protocols. (E) Predicted increase in student-days lost relative to symptom-based testing alone for selected protocols as a function of the vaccination coverage in children in the primary school. (F) Minimal vaccination coverage in children above which regular testing with 75% adherence among the non-vaccinated in the primary school has at most a benefit of 20% case reduction, as a function of *R*. In all panels, simulations are parameterised with sustained introductions, all protocols include symptom-based testing, and regular testing is performed weekly. *R*=effective reproductive number.

and consequently in protocols' efficiencies, but protocols' ranking according to their benefit remains robust (appendix pp 48–50). High-incidence conditions due to immune evasion and higher transmissibility, compatible with an omicron scenario, confirm the value of screening with high frequency (appendix p 37).

Benefits and costs of regular testing remain stable when vaccination coverage of teachers increases from 60% to 100% (figure 5A; appendix pp 41). Increasing vaccination coverage in students, both in primary and secondary schools, is a strong protective factor against school outbreaks (figure 5B–D), and compared with no vaccination, is expected to reduce the epidemic size by 38% (95% CI 36–40) with 20% coverage and by 75% (74–76) with 50% coverage in children under the basic protocol, considering vaccine effectiveness before waning occurs with time (figure 5D, appendix p 40). Regular testing would provide an important supplementary control, especially while rolling out vaccination campaigns in primary schools: weekly screening 75% of non-vaccinated students would additionally reduce cases compared with the basic protocol by 36% (95% CI 32–39) with 20% vaccination coverage in children, and by 23% (20–26) with 50% coverage, without impacting student-days lost (figure 5E). Similar results are obtained with lower vaccine effectiveness (appendix p 54). The minimum vaccination coverage to reduce the benefit of regular testing to 20% case reduction or below increases with *R*; for *R* between 1·6 and 2·0, the required coverage stabilises at around 55–60% (figure 5F).

Discussion

Strategies to safely keep schools open during the COVID-19 pandemic are a matter of controversial debate, and knowledge from the field is scarce. Using screening data from schools during the 2021 spring wave in France and empirical contact data, our study provides the first estimate of SARS-CoV-2 transmissibility in different school settings, suggesting that contacts at school increase SARS-CoV-2 transmission potential compared with transmission in the community. With countries in Europe experiencing record-high cases due to the omicron variant,[14] protocols at school remain a central issue as high community transmission leaves schools vulnerable and vaccination of children progresses slowly in most countries.[13] Our analysis indicates that regularly screening the school population is efficient in preventing infections while reducing absence from school, especially in settings where the school population is not yet vaccinated, coverage is low to moderate, or vaccine protection has largely waned.

We estimated a higher transmissibility in the school than in the community during the 2021 spring wave of the alpha variant in France. This finding suggests that repeated contacts in dense classrooms, even with facemask mandates in place, except for during sport and at lunch, favour transmission in the absence of screening protocols, with potentially high overdispersion.[26,27] These findings align with available evidence of increased transmission in the population if schools are open.[2,5] In the absence of vaccination, secondary school students are predicted to infect on average a larger number of individuals than primary school students, consistent with previous observations,[2] due to age-specific epidemiological properties and contact patterns. However, more contagious variants and limited vaccination coverage in children currently put them at higher risk compared with the rest of the population, which is partially protected by vaccination. A disproportionately higher omicron circulation has been observed in children than in the general population (5500 cases per 100 000 children aged 6–10 years *vs* 3000 per 100 000 population in all age classes in France by mid-January, 2022) that is further sustained by transmission at school, resulting in large school disruption,[28,29] a higher risk of infection for students' household members,[30] and rapid transmission in the community.[31] Even when conditions due to the circulating variant and vaccination coverage bring the school-specific *R* to below 1 (eg, as estimated under a delta wave in secondary schools in France with 77% vaccinated adolescents and high vaccine effectiveness; appendix pp 35–36), the predicted highly overdispersed offspring distribution suggests that, together with highly likely extinctions, chains of transmissions in schools are relatively rare but possible.

Using the estimated school-specific transmission rate for delta and a range of realistic epidemic conditions (with regard to introductions, seasonality, and vaccination coverage), we found that regular testing with large enough adherence provides an optimal balance in controlling school outbreaks while maintaining schools open. This finding is consistent with results showing that twice-weekly testing in England helped to control within-school transmission in secondary schools.[12] Adherence is, however, critical, suggesting that at least three-quarters of non-vaccinated individuals should participate in weekly testing to achieve a considerable case reduction. This level of adherence was not achieved in the pilot screenings in early 2021 in France. Implementing regular testing should consider improving strategies for the communication and engagement of the school community to considerably boost participation and maintain it over time.

Our findings corroborate previous numerical evidence on the value of regular testing in preventing infections.[9–11] Our study adds to previous work by estimating the school-specific *R* in primary and secondary schools and integrating empirical face-to-face proximity data, allowing us to quantify individual-level variation in SARS-CoV-2 transmission. It also provides a cost–benefit analysis considering successive variants, comparing multiple protocols, and evaluating the key role of adherence in the context of partly vaccinated school populations.

Reactive class closure is highly costly in terms of student-days lost, even though detecting a case is rarer in children than in adults. Countries adopting this strategy during the omicron wave registered record-high absenteeism from school (20% of students were in remote learning in Italy in January, 2022[28]). It also has a limited value in epidemic control, as other classes might be already affected due to unobserved introductions from the community or silent spreading within the school. The effect of silent spreading becomes particularly important when between-classes mixing is higher, as observed in the primary school. Cohorting that reduces contacts between classes is therefore an important component of school protocols, in support to screening. While regular testing detects more cases than symptom-based detection, it keeps days lost low for two main reasons. First, isolation is only applied to cases during their infectious period, being therefore more targeted than class quarantine. Second, detecting cases that otherwise go unnoticed helps control the epidemic, breaking the chains of transmission and preventing further diffusion. As a consequence, the overall time spent in isolation is also reduced. Reactive screening, instead, would leave many cases undetected even when retesting a few days after. The iterative nature of regular testing is key to ensure control over time.

Our analysis on the omicron wave (appendix p 37) confirms the large benefit of regularly screening students compared with reactive strategies, even when these strategies are strengthened, for example, by increasing the number of reactive screenings following the index case. The reinforced reactive protocol adopted in France at the reopening of schools in January, 2022, required three screenings to be performed at days 0, 2, and 4 from detection. But under the high omicron incidence experienced at the start of 2022, this protocol led to an unprecedented demand in tests, impacting logistics, available resources, and surveillance capacity.[29] Our findings support instead strengthening regular screening by increasing adherence and adjusting frequency to local incidence and policy expectations, next to cohorting, facemask use, and ventilation.

Increasing vaccination in teachers protects them from infection and symptomatic disease[21] but yields limited protection for the school population, even under full coverage. This results from the small number of teachers and the observed lower rate of interaction they have with students, and it is confirmed even when community incidence in adults is much higher than in the student-age classes. Extending vaccination to students is needed to achieve a collective benefit, reducing the likelihood and size of school outbreaks with active vaccination protection. In these conditions, regular testing would bring a supplementary control whose application should be evaluated in light of resources, logistics, adherence, epidemic conditions, and waning of vaccine effectiveness. Regular testing remains, however, critical in moderate (or lower) coverage situations, or when protection against infection has waned, as it would prevent a substantial proportion of undetected infections, having a direct impact on the school environment, reducing the number of infections and long-COVID in children,[32] and an indirect impact on the community, protecting students' contacts.[30]

This study has limitations. First, it focuses on two school settings for which empirical contact data were available, but contacts in other schools might be different, depending on the structure of curricula and the organisation of activities. Findings on the efficiency of regular testing and vaccination are, however, robust across a range of epidemic conditions and synthetic contact patterns and can thus inform on the choice of strategies to safely keep schools open. Second, data availability for the inference was limited by the pilot screening. Further work could also focus on the downward phase of the alpha wave. Third, the study focuses on school outbreaks and it does not assess the impact that these strategies will have on the viral circulation in the community. Fourth, we did not model waning of vaccine effectiveness throughout the epidemic wave but tested lower effectiveness values that confirmed the efficiency of regular testing.

The COVID-19 pandemic will probably continue to pose a risk to the safe and normal functioning of schools. Regular testing remains a key strategy to epidemic control in school settings with moderate vaccination coverage or following waned vaccine protection, all the while minimising days lost.

Contributors

VC and AB conceived and designed the study. EC, GB, and VC accessed and verified all the data and were responsible for the decision to submit for publication. EC, GB, DAC, and CP analysed the data. EC, GB, P-YB, and VC developed the inference framework. EC and DAC developed the code. EC and GB performed the numerical simulations and analysed the results. All authors interpreted the results. VC wrote the Article. All authors contributed to and approved the final version of the Article.

Declaration of interests

We declare no competing interests.

Data sharing

De-identified individual data on contacts of the two schools under study are publicly available at the SocioPatterns project website (http://www.sociopatterns.org/datasets/). De-identified aggregated COVID-19 community surveillance data by age class are publicly available at Santé publique France data observatory platform (https://geodes.santepubliquefrance.fr/). De-identified aggregated COVID-19 prevalence data from pilot screenings during the alpha wave used in this study are available in the tables reported in the appendix (pp 24–25).

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