Asymptomatic COVID-19 screening tests to facilitate full-time school attendance: model-based analysis of cost and impact

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Abstract

Background: In March 2021, the Biden administration allocated $10 billion for COVID-19 diagnostic and screening tests in schools.

Objective: We address to what extent screening tests reduce the risks of full-time in-person learning and how costs of testing compare to short-term financial costs of reduced in-person educational time, at different levels of community incidence.

Design: We used an agent-based network model to simulate transmission in elementary and middle school communities.

Setting: We parameterized school structure based on a US setting.

Patients (or participants): Students and faculty/staff.

Interventions: We assess the value of asymptomatic screening tests for students and faculty/staff 1-2 times per week. We also consider vaccination of teachers and of middle school students.

Measurements: We project 30-day cumulative incidence of COVID-19, proportion of cases detected, proportion of planned and unplanned days out of school, and cost per COVID-19 case averted in students and staff.

Results: Accounting for programmatic and childcare costs, 5-day school attendance with weekly screening has a lower cost than hybrid models without screening and achieves similarly low rates of transmission. Compared to a 5-day model with no screening, the cost per infection averted with screening drops as community transmission rises. Cost/infection averted is also lower for middle schools than elementary schools, and in settings with less mitigation.

Limitations: We include only screening and childcare costs, and there is uncertainty in transmission parameters.

Conclusions: Schools operating in hybrid models may use screening tests to facilitate 5-day attendance with small transmission risk. In the event of resurgent COVID-19 in the fall due to more transmissible variants or seasonal effects, screening can facilitate safe 5-day in-person education across a wide range of community incidence.

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Introduction

In K-12 education, COVID-19 poses potential risks to student and teacher health, school operations, and local communities. To reduce these risks, many school systems have adopted virtual or hybrid models. As of May 2021, about a third of US students were not offered the option of full-time in-person attendance and, where in-person schooling was offered, a substantial proportion of families had opted for remote learning (1–3). More than a year into the pandemic, there is growing pressure to return students to full-time, in-person schooling. Virtual and hybrid models impose substantial burdens, including educational and mental health risks for students, training and logistical burden for teachers, and productivity or child-care costs for the working parents of younger students (4–10). At the same time, high community incidence in some settings and concern about more transmissible variants necessitate continued attention to the control of school-related transmission (11–15). Districts are currently making plans for the fall, with a priority on safe in-person education even in the event of seasonal increases in transmission or reduced vaccine efficacy against new variants.

One tool to facilitate safer in-person instruction is routine asymptomatic screening. Improvements in SARS-CoV-2 diagnostic technology and infrastructure – such as increased PCR testing capacity, new lateral flow rapid antigen tests, and validations of specimen pooling – make frequent, widespread screening a viable option. When re-opening schools in the spring of 2021 after winter shutdowns, Germany, Austria, and Norway implemented regular COVID-19 screening in schools 1-2 times per week, and some US school systems have adopted a similar approach (16–20). In March, the Biden administration allocated $10 billion for diagnostic and screening tests in schools (21). The Centers for Disease Control and Prevention (CDC) developed guidelines that include asymptomatic screening as an option for districts when community cases exceed 1.4 per 100,000 per day, and pilot programs and modeling analyses predict that frequent screening will reduce in-school transmission (14,22–25).

However, many districts are understandably concerned about the economic and operational burden of asymptomatic screening. As these strategies have lower yield as community incidence falls (22,23), there is a need to understand how the benefits of screening compare to its costs at different levels of community transmission.

In this manuscript, we address several questions regarding the role of asymptomatic screening in educational settings: to what extent screening can support schools' transition from virtual or hybrid to full-time in-person learning; how the disruptions of case detection and quarantine compare to the benefits of reduced transmission; how costs of screening compare to financial costs associated with school closure; and how these benefits may vary depending on local transmission risks and screening implementation. We focus on elementary and middle schools, both because childcare costs are more substantial for these groups and because vaccines are not yet authorized for all students of these ages, although vaccination availability recently expanded to 12-15-year-olds with the Emergency Use Authorization for the Pfizer vaccine (26). We use an agent-based simulation of COVID-19 transmission to compare outcomes associated with school-wide screening strategies and alternatives including hybrid schedules and remote learning, with a particular focus on infections, in-person educational days, and costs.

Methods

We used a previously-described agent-based simulation model to estimate the effects of regular asymptomatic screening in an elementary and a middle school in the US (Figure S1) (24). In brief, the model incorporates interactions between individuals in school, household, and out-of-school childcare settings, as well as infections introduced exogenously through other community interactions.

Model structure

We modeled an elementary (638 students aged ~5-10 and 60 staff) and a middle school (460 students aged ~11-13 and 51 staff) setting. For each, we generated households from synthetic population data (27) and grouped students into fixed classroom cohorts with a primary teacher. The model also included adults outside of a primary classroom to represent other school roles (e.g., administrators, counselors, and teachers of special education and related arts). In schools, individuals had sustained daily contact with their classroom cohort as well as random interactions with members of the school community. We assumed that elementary schoolers are half as susceptible and half as infectious as adults, that moderate levels of mitigation (e.g., masking, ventilation, and distancing) were implemented, and that 90% of teachers and staff were vaccinated. Outside of schools, in addition to an exogenous community infection risk, individuals interacted with household members, and each day that students did not attend school, families mixed with another randomly chosen family from the same school to reflect "learning pods," social interactions, or shared childcare. Further details of model structure and assumptions are described in (24) and the Supplement.

Screening and schedule-based mitigation strategies

Screening strategies were modeled in conjunction with a five-day in-person school attendance schedule. We modeled weekly or twice-weekly screening (Monday ± Thursday) of all students and teachers, and our primary analyses assumed 90% coverage and 90% sensitivity (such that 81% of cases were detected if screening occurred during their period of infectiousness) and a 24-hour test turnaround time. Positive results led to quarantine of the exposed classroom cohort and primary teacher (but not of casual contacts within the school) for 10 days; in a sensitivity analysis, we considered that the screening infrastructure could also be used to test exposed individuals and shorten the duration of classroom quarantine to 7 days (28,29). We compared these screening scenarios to three scenarios without asymptomatic screening: 1) five-day in-person attendance, 2) a hybrid model in which half of students attend class on Monday and Tuesday and the other half on Thursday and Friday, and 3) fully remote learning. In all scenarios, symptom-driven COVID diagnostic testing still occurred outside of the school environment, as described in the Supplement.

Cost estimation

We based screening test performance and costs on PCR testing with pooling of specimens to reduce costs. Specifically, we assumed (a) specimens (e.g., anterior nasal swabs) were collected from each student and teacher, and (b) that aliquots from up to eight specimens obtained in a single classroom were combined for pooled PCR testing, with negligible loss of sensitivity to detect active infection (38,39). When a pooled specimen yielded a positive result, all individual specimens that had been included in the pool were immediately tested separately to identify the positive individual(s). Costs of PCR testing were estimated at $100 per assay based on Medicare reimbursement rates, plus an $8 per-specimen cost of labor and supplies for nasal swab collection (Table 1). In a sensitivity analysis, we considered the use of rapid antigen tests ($12 per assay plus the same specimen collection costs as for PCR specimens, 99.5% specificity, and same sensitivity as pooled PCR for infectious individuals) with PCR confirmation of positive results prior to classroom quarantine (1-day turnaround, cost as above) (32,33). Costs for diagnostic testing of symptomatic or exposed students, staff, or household members are excluded, because these are assumed to occur outside of the school setting.

In comparing screening costs to the costs associated with schedule-based risk mitigation, we took a societal perspective but focused on the childcare or parent-productivity costs of remote learning; associated educational and other costs are likely but difficult to estimate. We estimated the cost of a planned day of remote instruction based on the average cost of group childcare (Table 1); estimates are based on the costs of pre-kindergarten in the pre-COVID era (34), which are also similar to summertime childcare costs for school-aged children (35). For unplanned days at home (i.e., while isolated due to COVID-19 diagnosis or symptoms, or quarantine due to COVID-19 exposure), we estimated costs based on the average childcare worker's wages over a 7-hour day (36) to account for the higher costs of last-minute scheduling or inability to use group childcare (Table 1). While parents may choose to supervise remote learning at home, we assume that the average productivity loss of supervising at-home learning is at least equal to childcare costs.

Outcomes

For each scenario, we ran the model 1000 times for 30 days each, and estimated over that one-month period: average cumulative true COVID incidence in staff and students (as a proportion of students and staff infected and as the raw number of infections per school, excluding secondary transmissions to their household members or community contacts), case detection (proportion of all students and staff diagnosed with COVID, and number of cases per school), detection fraction (the ratio between cases detected and true cases), and proportion of weekdays spent at home (for "unplanned" isolation or quarantine reasons, or for "planned" days at home dictated by the virtual/hybrid schedule). Isolation and diagnostic testing for symptoms caused by non-COVID etiologies were not modeled because other respiratory illnesses are expected to occur with similar frequency in all scenarios and also be reduced by masking and distancing (37).

Sensitivity analyses

We performed one-way sensitivity analyses for multiple parameters with regard to two main outcomes: 1) the difference in cumulative COVID incidence in staff and students (number of infections per school per month) between full-time in-person attendance with weekly screening and a hybrid schedule without screening, and 2) the cost of weekly screening (including any incremental childcare costs) per infection averted among students and staff, relative to the same 5-day in-person schedule without screening.

The test parameters considered in these sensitivity analyses included assay sensitivity (reduction from 90% to 70%), turnaround time (increased from 1 to 2 days), testing day (weekly testing days other than Monday), and duration of classroom quarantine (reduced from 10 days to 7 days by leveraging testing infrastructure). Other parameters varied included the average infectivity per case (50% higher or lower than the baseline value, potentially reflecting variation in masking and ventilation or in strain transmissibility), the duration of infectiousness (increased from 5 days to 10, with corresponding 50% reduction in the per-day probability of transmission), the community COVID incidence (varied between 1 and 100 cases per 100,000 population per day, otherwise set to a rate of 10 cases per 100,000 per day for all other sensitivity analyses), cost of child care (±50% change from primary estimate), and the vaccination status of middle schoolers (up to 50% reduction in susceptibility).

The model was implemented in R 4.0.2. Model code is publicly available as an R package at: https://github.com/abilinski/BackToSchool2.

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Results

Incidence

Figure 1 and Table S1 show 30-day incidence, case detection, and school attendance outcomes of different school schedules and asymptomatic screening frequencies. At the elementary school level, in-school transmission is a minor contributor to COVID-19 incidence; compared to fully remote instruction, 5-day in-person attendance with no asymptomatic screening is associated with a 39% increase in COVID incidence among students (2 additional infections per school per month) at a community notification rate of 10/100k/day and a 31% increase (6 additional infections per school per month) at 50 notifications/100k/day (Figure 1A). Among elementary teachers, the increase in incidence attributable to in-person teaching is 26% or 8%, respectively. Middle school attendance has greater potential to increase transmission: for example, at a community notification rate of 25 per 100k per day, attending 5 days in person without screening increases the monthly risk of infection by 160% among middle school students and 17% among their teachers, and results in an average of 13 additional infections per middle school per month (Figure 1E).

Weekly asymptomatic screening at the start of the week, with quarantine at the classroom level once a case is detected, eliminates much of this incremental transmission associated with in-person school attendance. At a community notification rate of 10 per 100k per day, weekly screening averts 47% of the excess incidence relative to remote learning at the elementary level and 67% at the middle school level where school-related outbreaks are more common. If community notifications rise five-fold, this proportion increases to 54% at the elementary level (due to more frequent isolation and quarantine), whereas it declines to 62% at the middle school level (Figure 1 A and E, dotted lines, and Table S1). With a second weekly screening day added later in the week, 60-76% of excess, school-associated transmission is averted at the elementary level and 77-78% at the middle school level, for community notification rates between 10 and 50 per 100k per day. A single weekly screening day is less effective if it occurs late in the week (Figure S10) because much of the averted infectious person-time of the detected cases falls over the weekend.

Case detection and in-person learning days lost

Although asymptomatic screening and the resulting increase in detection fraction reduce transmission, they lead to more students required to isolate and quarantine, disrupting in-person education. At the elementary level, with a community notification rate range of 10 cases per 100k per day, detection fraction increases from 25% with 5-day in-person school and no screening to 67% with weekly screening. Because there are few in-school transmissions for screening to prevent, screening also increases the absolute number of cases detected (Figure 1B) and thus increases the days spent in isolation/quarantine by up to a factor of three; however, the average isolation/quarantine per student per month is limited to <1 day at a community incidence of 10/100k/day and <6 days even at a community notification rate as high as 100 cases/100k/day (Figure 1C). In a middle school, the detection fraction similarly more than doubles from 23% to 60% with weekly screening, but because screening also substantially reduces the total number of infections that occur, it increases time spent in isolation/quarantine by less than a factor of two. If a school's screening infrastructure could also be used for testing to shorten quarantine duration to 7 days (Figure S2), this approach could result in no net increase in quarantine time at the middle school level, compared to the same 5-day schedule without screening.

Scheduling

Compared to weekly or twice-weekly screening (with full-time in-person attendance), hybrid scheduling could reduce COVID-19 incidence (Figure 1 A,E). For example, in a middle school at a community notification rate of 10/100k/day, a hybrid schedule prevents 91% of the excess transmission associated with in-person attendance, compared to 59% and 70% prevented by once and twice weekly screening, respectively (Table S1). The trade-off is a large reduction in in-person school days, from 97% of school days in-person with either testing frequency, to 40% in-person with a hybrid schedule (Figure 1H).

Costs

Screening and childcare costs over the 30-day period were estimated for each school attendance schedule and screening strategy (Figure 2, breakdowns in S3-S6). When no pooled screening tests are positive and all students and staff are in attendance, once-weekly screening requires 465 PCR tests per month in the elementary school (330 tests in the smaller middle school) and costs $117 per student per month; as incidence rises, the costs of individual follow-up testing to deconvolute positive pools are more than offset by the reduction in screening volumes due to quarantine, and the school's screening costs decline (Fig S3-S4). After adding the costs of childcare during isolation and quarantine, the societal costs associated with once-weekly screening in an elementary school range from <$140 per student per month at community notification rates ≤5/100k/day, to $290/student/month at a community notification rate of 50/100k/day, and to $400/student/month at a community notification rate of 100/100k/day (Figure 2, top-right panel). In comparison, the cost of childcare exceeds $400/student/month for a hybrid schedule and exceeds $600/student/month for a fully-remote schedule at all incidence levels. For the costs of weekly screening to exceed the estimated childcare costs of a hybrid schedule at a community notification rate of 10 cases/100k/day, the price of a PCR assay would have to exceed $500, or the cost of specimen collection would have to exceed $60 per person. The estimated costs of a rapid antigen screening strategy were very similar to those of pooled PCR screening (Figure S7).

Figure 3 shows the cost of weekly screening per infection averted among students and teachers/staff, when compared to the same full-time in-person school schedule without asymptomatic screening. Costs include screening and incremental childcare costs. In the elementary school, screening costs per infection averted range from <$40,000 at community notification rates of ≥25 cases/100k/day, to $109,000 per infection averted at 10 cases/100k/day and nearly $1 million per infection averted at 1 case/100k/day. In the middle school, where more in-school transmission occurs, the costs of screening per infection averted are lower than in the elementary school by roughly a factor of five: they range from <$10,000 per infection averted at community notification rates ≥25/100k/day to approximately $200,000 per infection averted at 1 case/100k/day.

Childcare costs induced by 10-day quarantines remain modest at low community incidence but result in a doubling of the total costs per infection averted over screening costs alone at high levels of community incidence. Using testing to reduce quarantine duration to 7 days reduces or eliminates these incremental childcare costs but increases the overall cost per infection averted due to increased testing.

In a scenario analysis, 50% vaccination coverage of middle school students increases the screening cost per infection averted by 3 to 4-fold at most incidence levels, e.g., from $8,000 to $27,000 per infection averted at a community notification rate of 25/100k/day (Figure S9).

Sensitivity analysis

The largest determinants of the absolute incidence difference between a 5-day schedule with screening strategy and a hybrid model without screening were the community notification rate; the timing, sensitivity, and frequency of screening (with Monday being most effective screening day, and a second day of screening reducing the difference between 5-day+screening and hybrid+no screening strategies from 4 infections to 2 infections per school per month in a middle school at a community notification rate of 25/100k/day); and the transmission-mitigating measures in place (with 50% student vaccination similarly reducing the difference between 5-day+screening and hybrid+no screening strategies to <2 infections per middle school per month) (Figure S10 panels A and B). The cost-effectiveness of screening was sensitive to similar variables but was most sensitive to the transmission-mitigating measures in place; at a community notification rate of 25/100k/day, the cost per infection averted ranged from $3,000 with minimal other mitigation to $25,000 with strong mitigation in place in the middle school, and similarly ranged from $26,000 to $150,000 in the elementary school (Figure S10 C and D).

Discussion

Our work highlights that asymptomatic screening tests can support safe school reopening and, for schools that have reopened, can help maintain 5-day in-person education if community incidence rises. With the addition of weekly screening, 5-day in-person school attendance can achieve levels of transmission nearly as low as hybrid or remote models without screening, at a substantially lower net societal cost. For school systems currently favoring hybrid or remote models, our work underscores the importance of considering multiple dimensions of cost in school reopening plans. While incorporation of school-based screening increases school system expenditures and is likely to be feasible only with additional state or federal funding, these costs may be offset societally by reducing the burden of COVID-19-related childcare costs currently borne by parents and caregivers. Similarly, for school systems practicing or considering full-time in-person instruction, our work shows the public health value that screening may offer under different local conditions.

While previous analyses have documented that weekly screening can control transmission, this analysis adds the key finding that 5-day in-person learning with screening is cost-saving from a societal perspective, compared to hybrid or remote models (24,38,39). Cost savings persist across levels of community transmission up to 100 cases per 100,000 per day, even when improved case detection through the screening program increases the time that students spend in quarantine. Therefore, in districts currently operating in hybrid models, it may be possible to use currently-allocated federal funds to add screening and move to a 5-day in-person model without substantially increasing public health risk. The small differences in infection risk between these two models may also be informative for parents deciding about in-person attendance, as opt-out rates remain high, including 65% in New York City public schools and 43% in Boston Public Schools (2,3).

A related question is whether school systems that have committed to 5-day in-person education should offer regular COVID-19 screening to students and staff. The value of such screening varies substantially across different levels of community transmission, between elementary and middle schools, and by school attack rate. In turn, school attack rate is influenced by factors including mitigation measures (masking, ventilation, and distancing), vaccination uptake (among staff, parents, and students when available), and the properties of emerging variants of concern. Our results suggest that screening capacity may be useful as an "insurance policy" to maintain in-personal instructional time if cases increase during fall 2021, and would be most efficiently targeted toward older students, groups that are not yet fully vaccinated, settings where adherence to mitigation precautions is low or unknown, and settings in which adults have lower vaccination rates.

In estimating the cost-effectiveness of screening, we did not include the downstream infections averted beyond students and staff. We also excluded many dimensions of cost, including the long-term costs associated with either COVID-19 infection among children and adults or lifetime impact of lost educational time. Our estimates of cost per infection averted are therefore likely to be conservative.

While COVID-19 is generally mild in children, the results presented here nevertheless suggest that screening could be cost-effective in some circumstances, particularly for older students and if the impacts of onward transmission are considered. For example, one report estimated that 1.5 QALYs are gained from averting a case of COVID-19 when considering onward transmission (40); using this value, for a middle school in a community with a COVID-19 notification rate as low as 1 case per 100K per day (where we estimated weekly screening would cost $162,000 per infection averted), screening programs would be cost-effective at a threshold as low as $108,000 per QALY. In practice, the cost per case averted is dependent on local factors, particularly the vaccination rate. As vaccination uptake increases, school-based screening is unlikely to remain cost-effective at low community incidence levels, but an economic case for screening at high community incidence rates is likely to persist through the fall, particularly for US communities (often low-income and minority) where vaccination coverage is lower and in communities (US and international) with more limited vaccine supply.
Last, we provide a number of insights useful for the practical implementation of screening. These include that weekly screening is most beneficial on Mondays and that twice weekly screening, recommended by some guidelines, provides a much smaller incremental benefit than once weekly screening (51). Furthermore, given the costs associated with quarantine days when students are exposed to COVID-19, priority should be given to testing symptomatic and exposed students (including testing in order to shorten quarantines), per CDC guidance, before implementing screening (28). Finally, as the availability of rapid tests expands, individual rapid screening with high-specificity assays (>99.5%) could offer a similar benefit at a comparable cost to a pooled PCR screening strategy, even accounting for PCR confirmation of positive results.

Our model does not address the operational aspects of specimen collection, laboratory transport, and reporting of results, which some schools have navigated successfully but may nevertheless pose barriers to adoption by others. There are a number of additional limitations, including imprecision in attack rates and behavioral mitigation parameters, a focus on households rather than the full community, and limited measures of cost. Nevertheless, this work highlights how asymptomatic screening can help ensure stable 5-day in-person education.

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Table 1: Model parameters

	Estimate	Sources/Notes
Key transmission model parameters (see (24) for full list and sources)		
Duration of infectiousness	Lognormal (5, 2)	
Classroom attack rate	2% (1% or 3% in sensitivity analysis)	Daily transmission rate between two unvaccinated adults during shared full-day contact
Relative attack rate for random school contacts (vs. classroom)	0.13	Based on 45 minutes/day of exposure
Household attack rate	20%	
Probability that disease has clinically recognizable symptoms	20%, children 40%, adults	
Presymptomatic period (days)	Normal (1.2, 0.4)	
School size	Elementary: 638 students, 60 teachers/staff, 30 classes Middle: 460 students, 51 teachers/staff, 21 classes	
Case detection ratio in community	1/3	
Vaccine effectiveness	90%	
Teacher vaccination uptake	90%	(48), assuming full completion of regimens among those who received their first dose and additional 10% uptake
Testing parameters		
Sensitivity of testing during infectious period	0.9	(42–45). Combined with 90% testing coverage, so 81% of infectious students and staff are detected.
Frequency of testing	0, 1x, or 2x per week	Testing is assumed to occur on Monday +- Thursday
Test turnaround time	1 day	
Duration of isolation after COVID-19 diagnosis	10 days	(28)
Duration of quarantine after COVID-19 exposure	7 or 10 days	(28)
Costs		
Cost per PCR run (per 8-sample pool, and per individual in pool for testing after a positive pooled result)	$100	Medicare reimbursement for high-throughput PCR, <2-day turnaround (46)
Added cost per specimen collected	$8	(47)

Cost per planned day at home	$35.50	Based on group childcare costs (34)
Cost per unplanned day at home	$85.90	Based on childcare worker wages (36)

Figure 1: One-month cumulative incidence, case detection, isolation/quarantine, and remote learning days with multiple school schedules and testing frequencies. Results are shown over a range of community COVID-19 notification rates, for an elementary school of 638 students and a middle school of 460 students. Infections (panels A and E) and diagnoses (panels B and F) are shown both as a proportion of all students and staff infected or proportion with detected cases per month (left-hand y axes) and as an expected number of infections/diagnoses among students and staff per school per month (right-hand y axes); these outcomes do not include infections among others in the community that may result from school-associated transmission. Panels C and G show the average proportion of weekdays that students and staff were scheduled to attend school but are in isolation or quarantine due to COVID-19 symptoms, diagnosis, or exposure. Panels D and H show the proportion of weekdays that student and staff attend in person after accounting for the scheduling model and isolation/quarantine. The detection fraction as reported in the text reflects the absolute number of diagnosed cases (B) divided by true cumulative incidence (A).

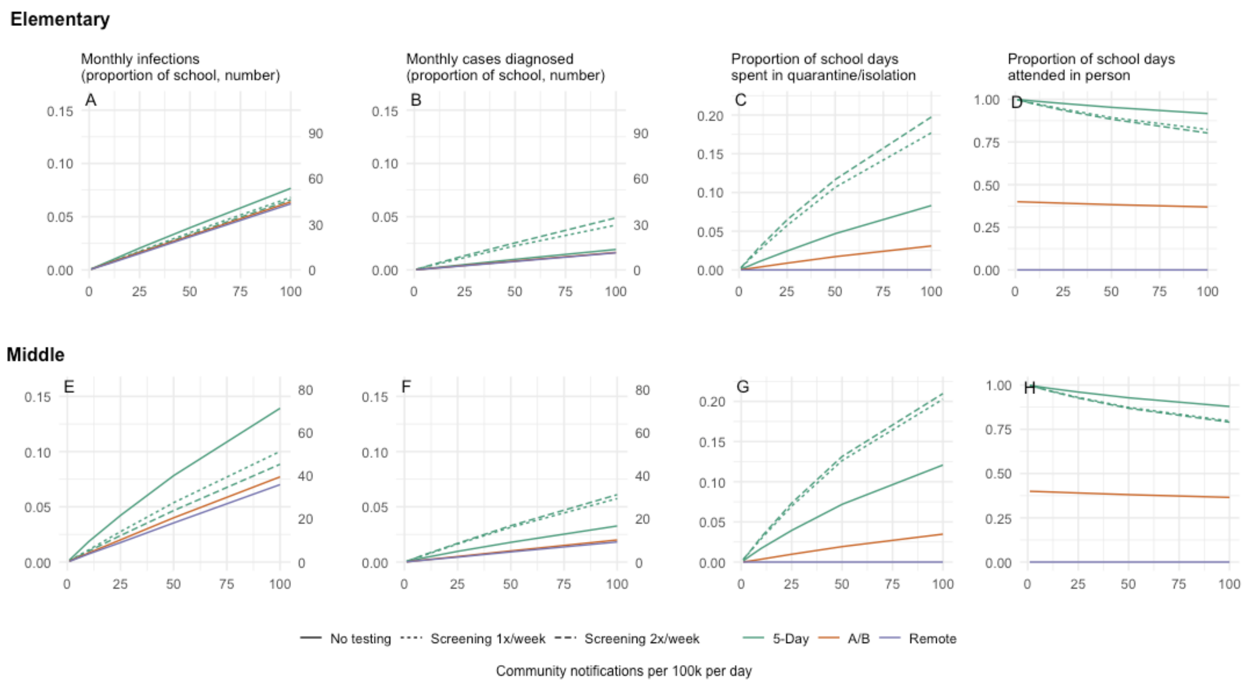


Figure 2: Costs associated with in-school COVID-19 testing and/or out-of-school childcare for different risk-reduction strategies, at varying community notification rates.

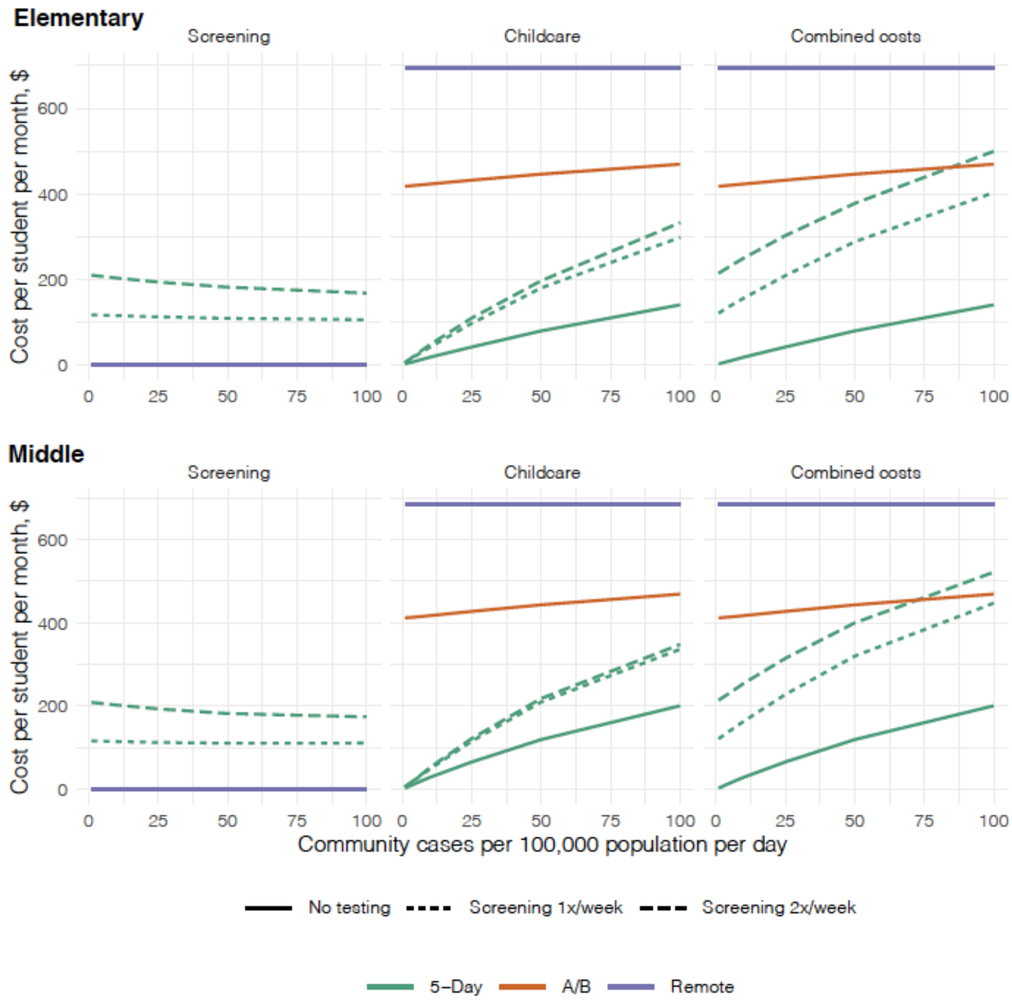
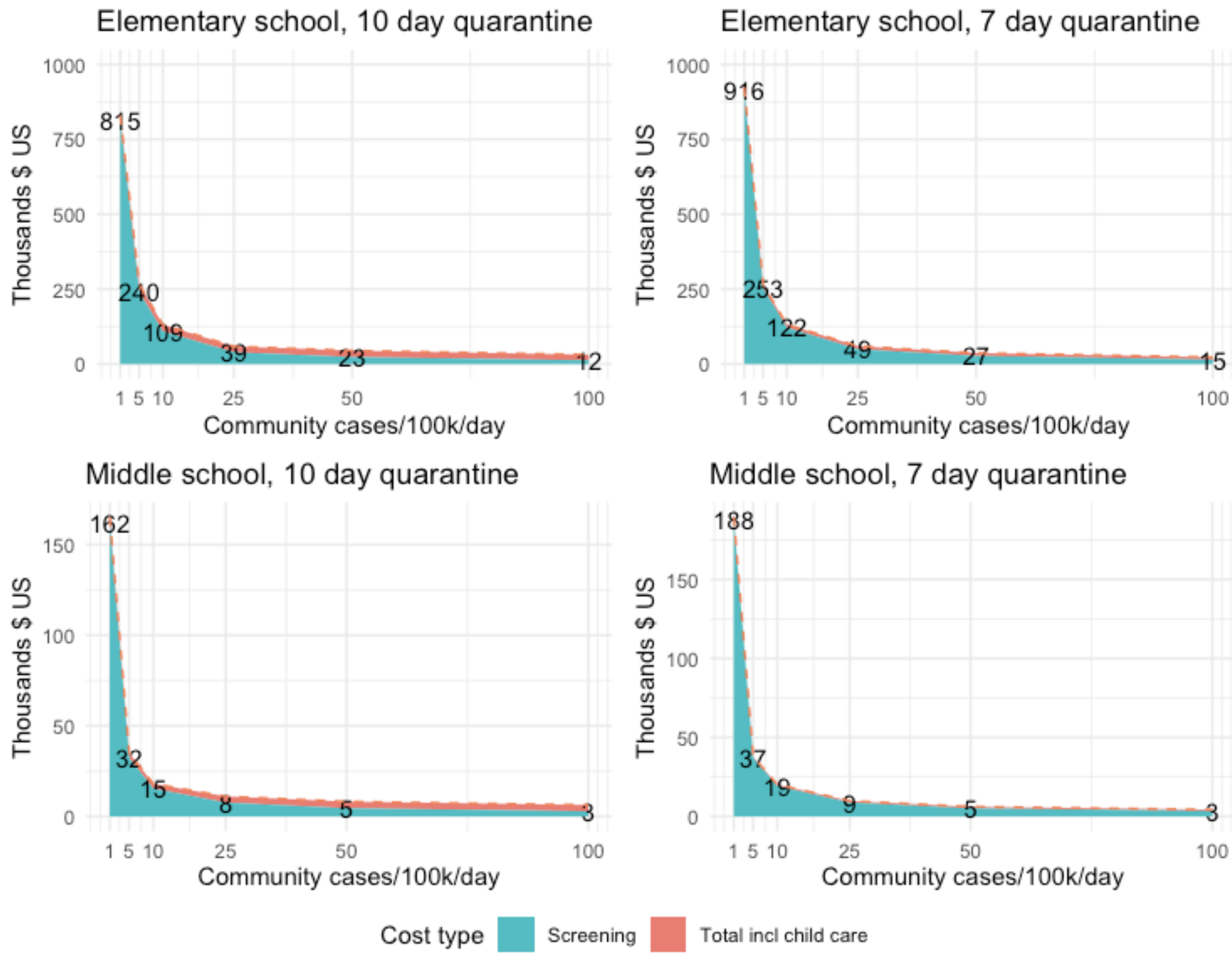


Figure 3: Cost per infection directly prevented among students/staff, compared to a 5-day in-person schedule with no in-school testing. Plots show the incremental cost of testing (blue, and numerical labels) or testing plus childcare (orange), per infection directly averted.



SUPPLEMENT: Asymptomatic SARS-CoV-2 screening tests to facilitate full-time school attendance: model-based analysis of cost and impact

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Model Details

We assumed an SEIR model of COVID-18 transmission (1). Briefly, when individuals interacted with an agent (i.e. person) infected with SARS-CoV-2, transmission risk was proportional to duration and intensity of exposure. The model drew stochastic outcomes assuming an average incubation period of three days prior to the onset of infectiousness, two days of pre-symptomatic transmission if symptoms develop (2,3), total infectious time of five days (4–7), and overdispersion of infectivity in adolescents and adults (4,8) (Table 1). We assumed that adults with fully asymptomatic disease transmit COVID-19 at half the rate of those with any symptoms (9). We assumed vaccine coverage among teachers sufficient to reduce susceptibility to infection by 80%, with approximately 90% coverage and 90% reduction in infection risk among vaccinated individuals. Students were not vaccinated in the primary model, but 50% reduction in the susceptibility of middle school students is included as a sensitivity analysis. Based on data from household contact tracing studies, we further specified that, in absence of vaccination, children under 10 are half as susceptible and half as infectious as symptomatic adolescents and adults (10–14). Beyond interactions with infectious agents within the simulation, students, staff, and their families had a probability of becoming infected through other community interactions equivalent to an age-adjusted community per capita daily incidence, with children and adolescents having half the incidence of unvaccinated adults.

In all scenarios, symptom-driven COVID diagnostic testing still occurred outside of the school environment: individuals with COVID-19 who developed clinically-recognizable symptoms were assumed to self-isolate from out-of-household contacts (including staying home from school) and to obtain testing in the community. Results became available 24 hours after the first appearance of symptoms, at which point classrooms were notified and quarantined for 10 days. Symptom-driven community-based testing, and self-isolation of symptomatic individuals who had not been tested since symptom onset, were assumed to occur with the same probabilities regardless of in-school screening practices.

Fig S1 Model diagram

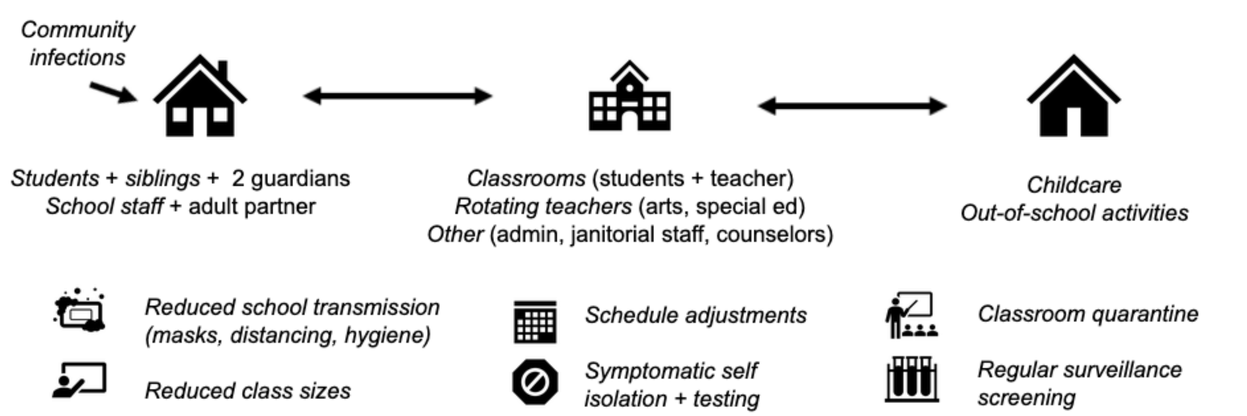


Fig S2. Incidence, case detection, and school attendance outcomes if screening strategies are accompanied by a reduction of the classroom quarantine duration to 7 days.

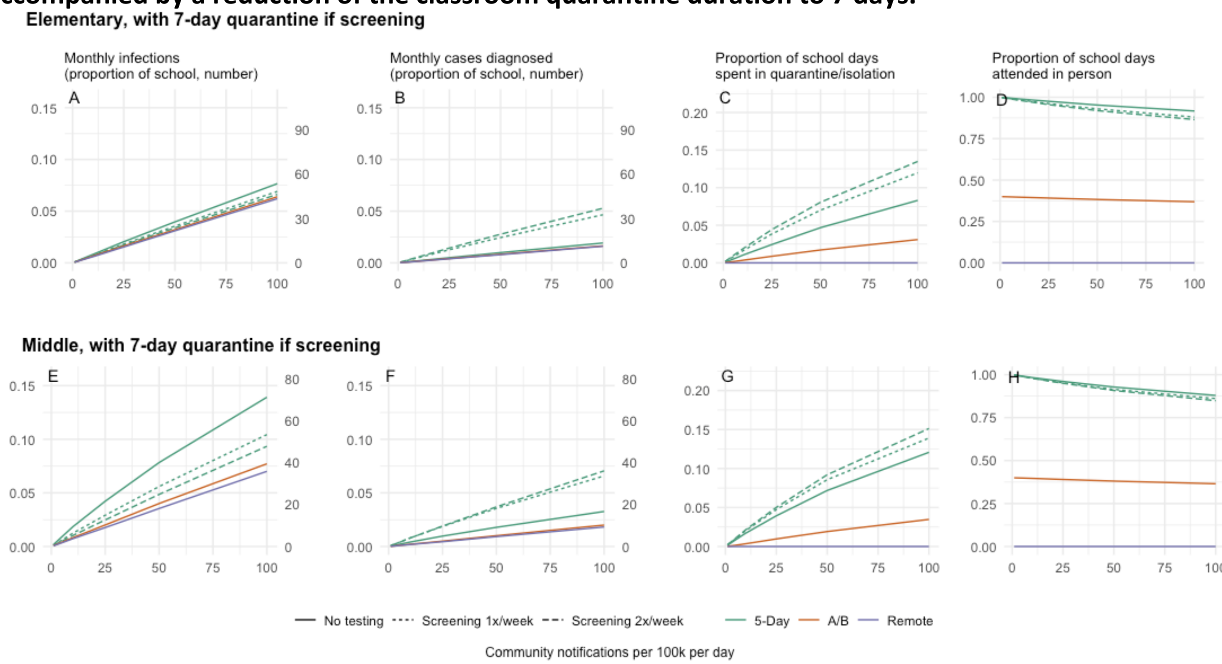


Fig S3. Screening costs, as dollars per student per month in an elementary school. Costs decline at higher levels of incidence because increases in classroom quarantine cause screening days to be missed; potential costs of community-based testing by exposed students or their contacts are not modeled.

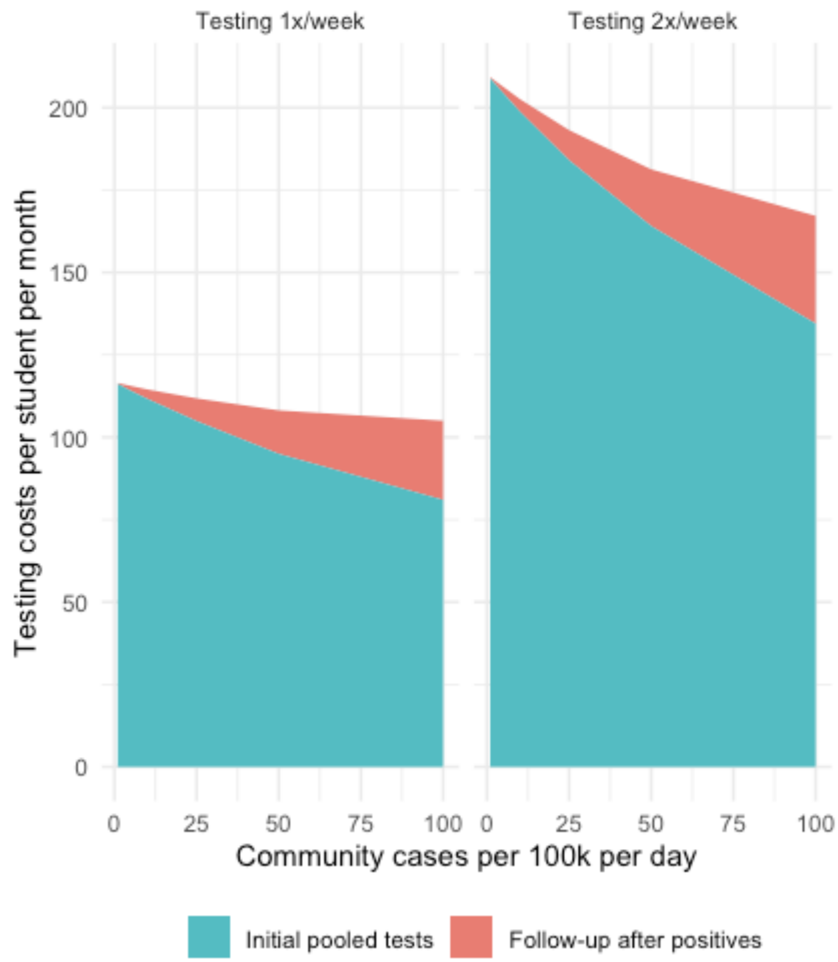


Fig S4. Screening costs, as dollars per student per month in a middle school. As incidence rises, the spending on initial tests declines because increases in classroom quarantine cause screening days to be missed, but the higher proportion of pooled results that are positive and require individual follow-up testing results in little change in overall cost per student.

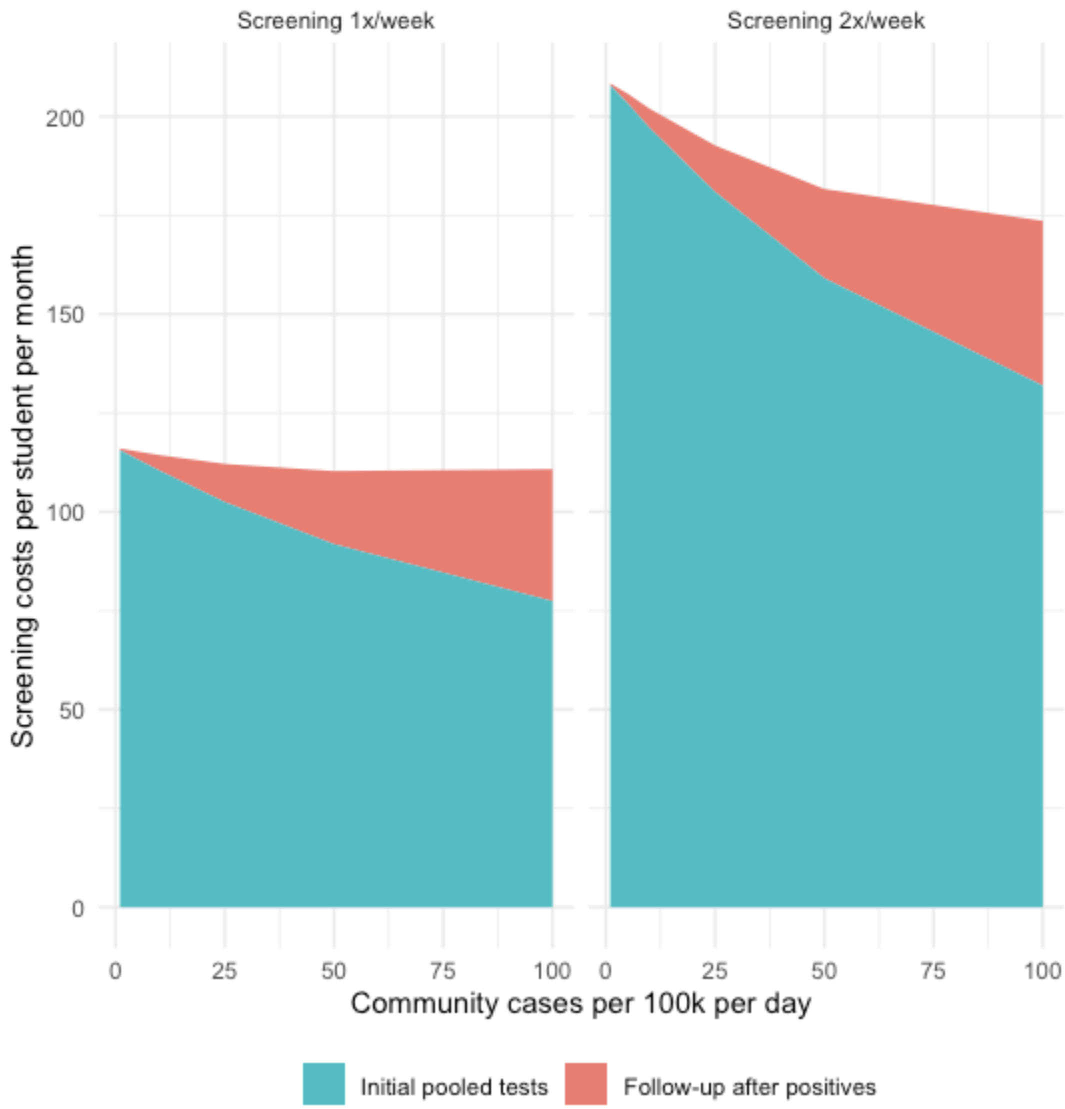


Fig S5. Childcare costs (elementary school)

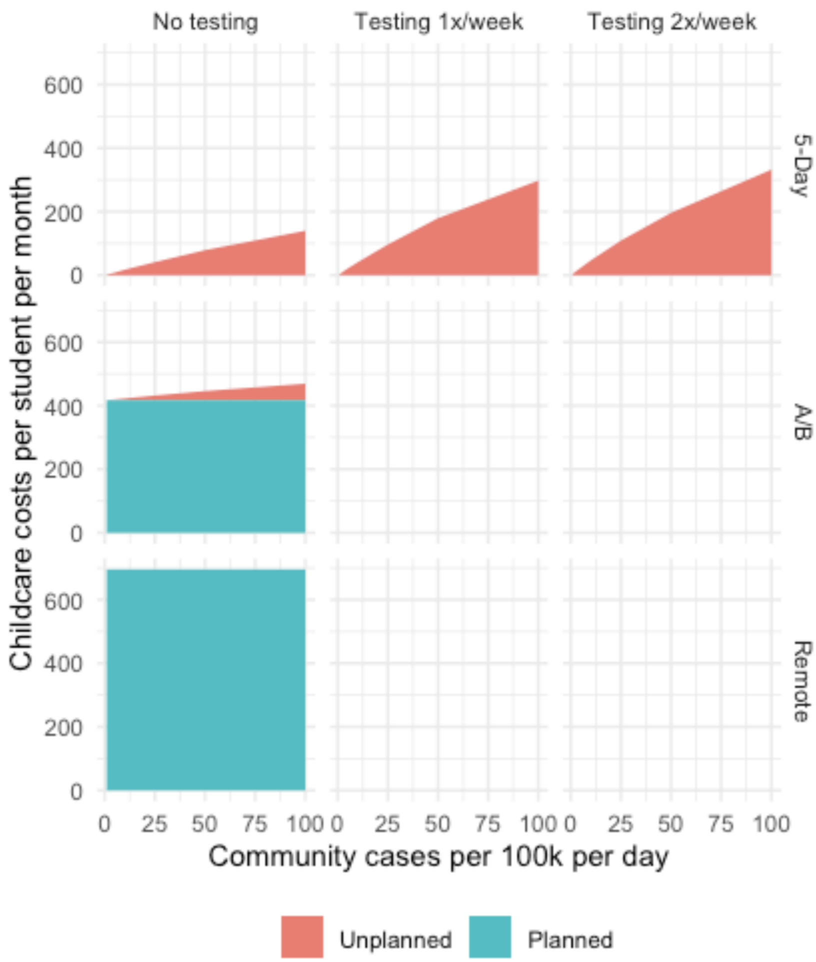


Fig S6. Childcare costs (middle school)

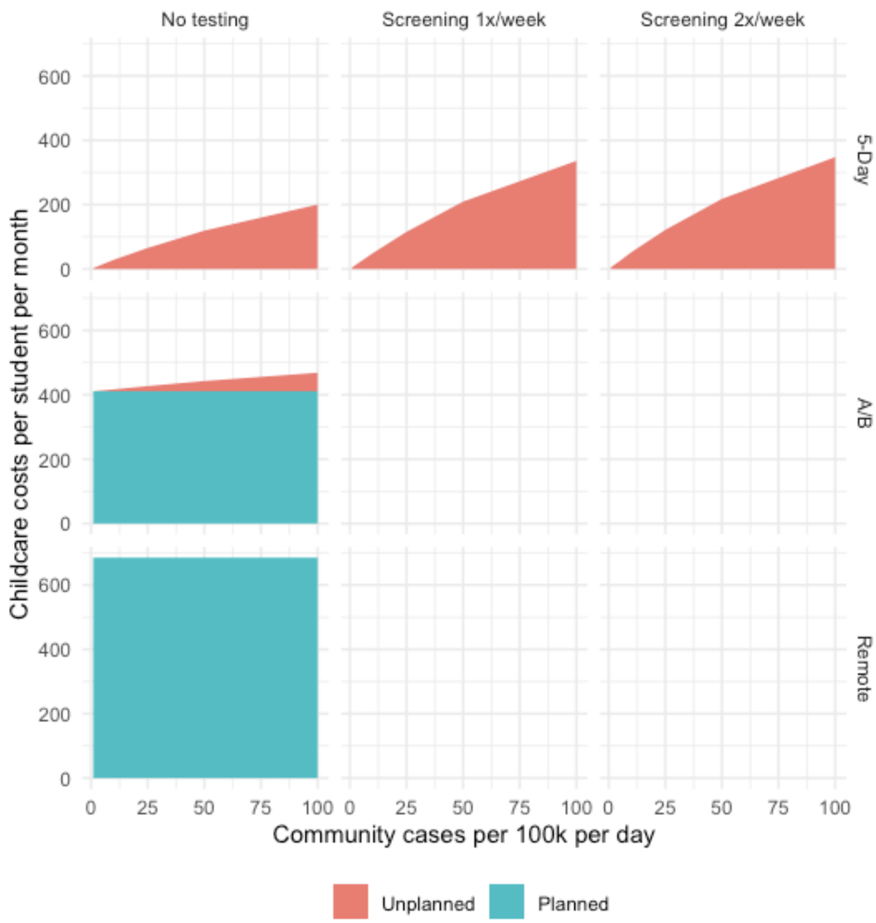


Fig S7. Costs associated with rapid antigen screening tests (weekly tests at $12 per test, PCR confirmation of positive results with same one-day turnaround, 0.5% false positive rapid tests, no change in sensitivity for acute infection) compared to those of schedule-based mitigation and of full-time in-person attendance without asymptomatic screening.

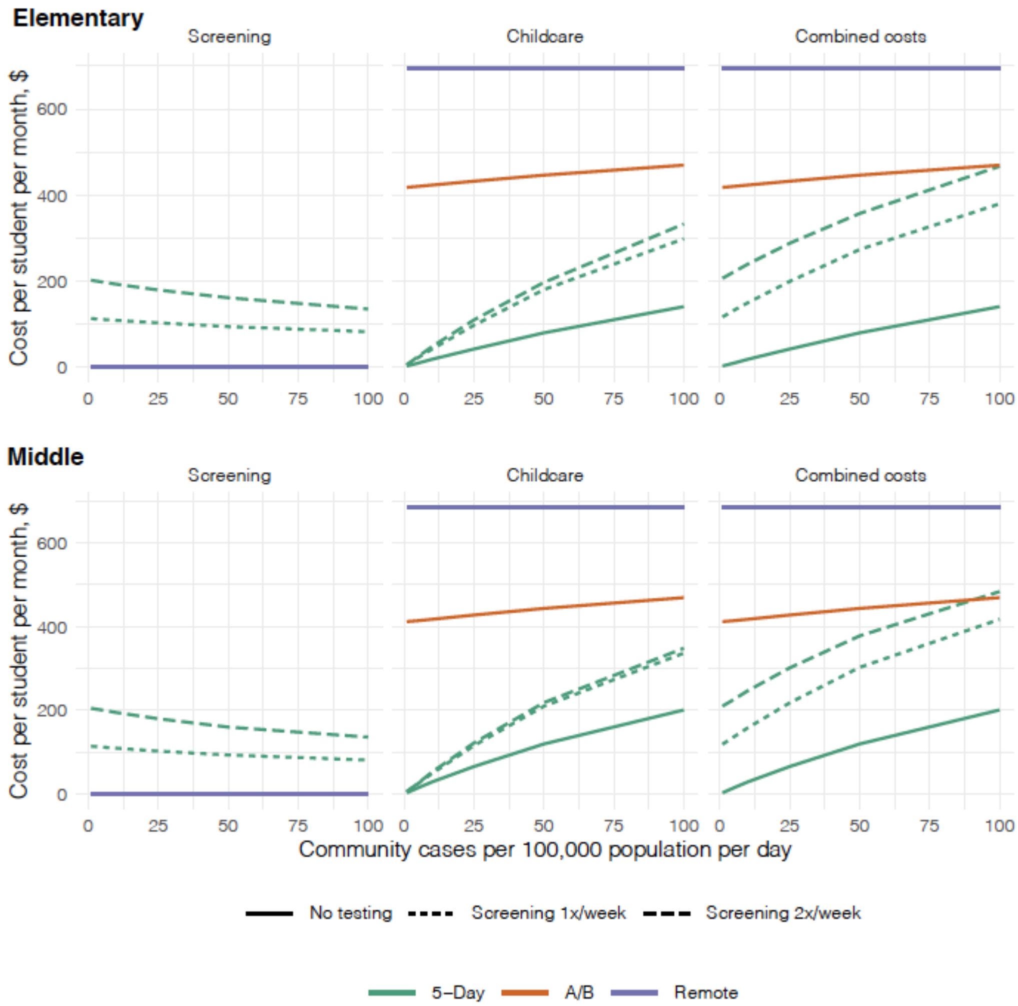


Fig S8. Cost-effectiveness of rapid screening (cost per infection directly averted among students and staff), comparing weekly screening to full-time attendance without screening, under the same rapid screening assumptions as in Figure S7.

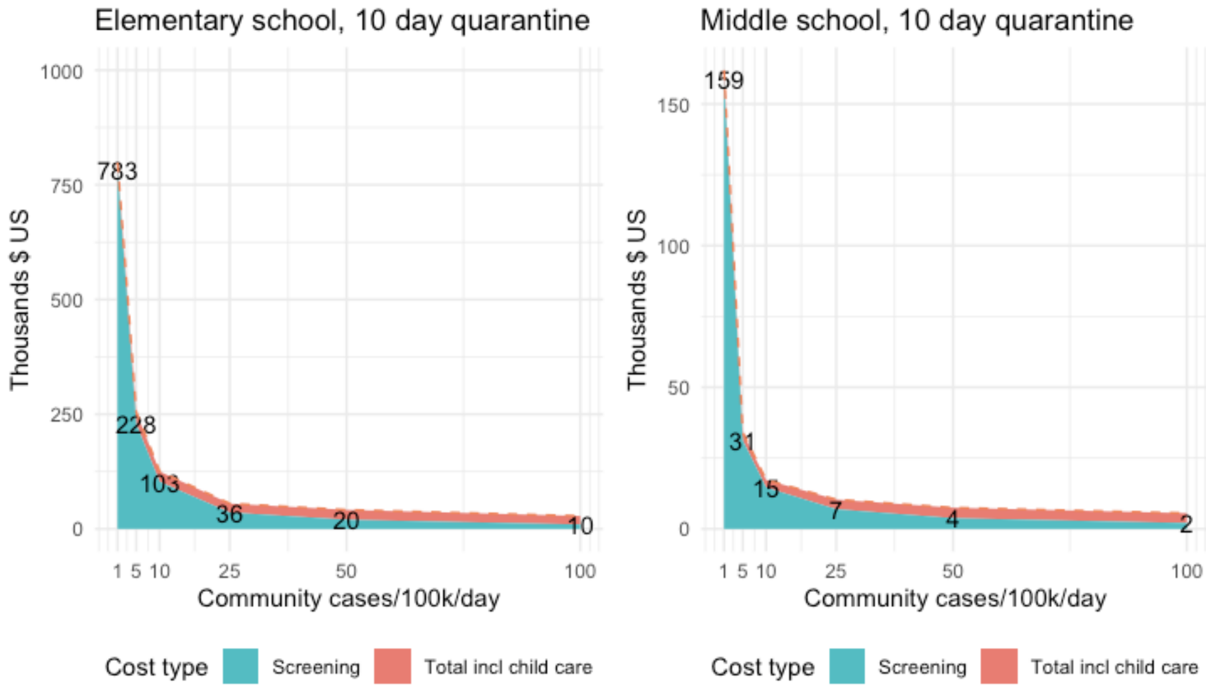


Fig S9. Cost effectiveness of weekly screening in middle school with 50% vaccination coverage of students (and 90% of teachers and staff).

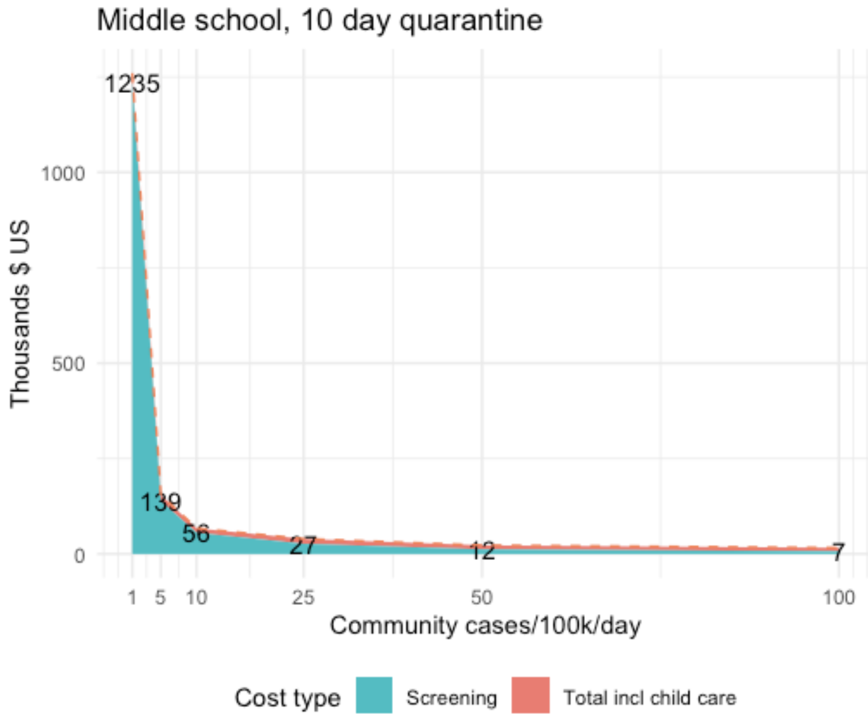
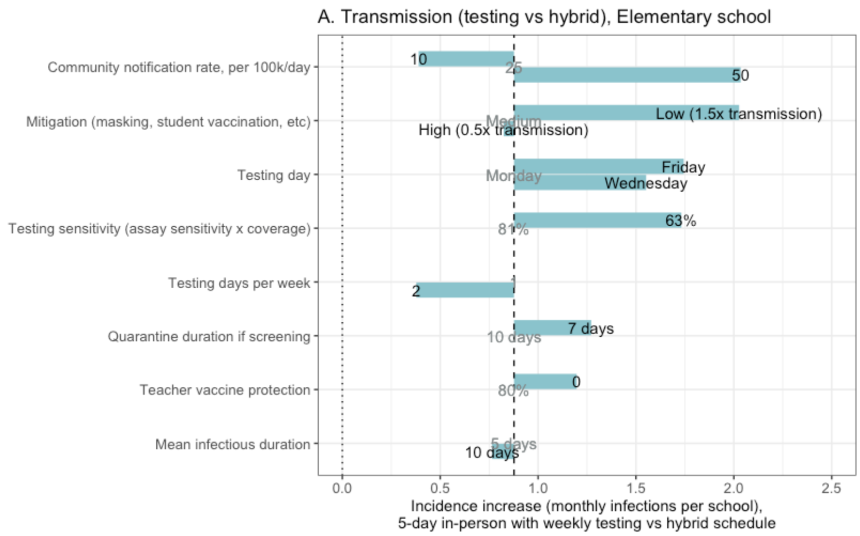
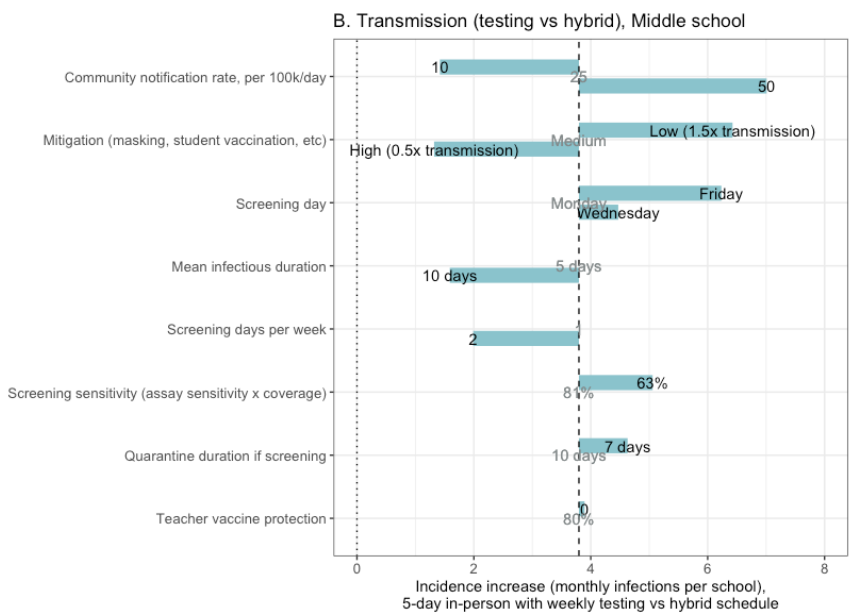
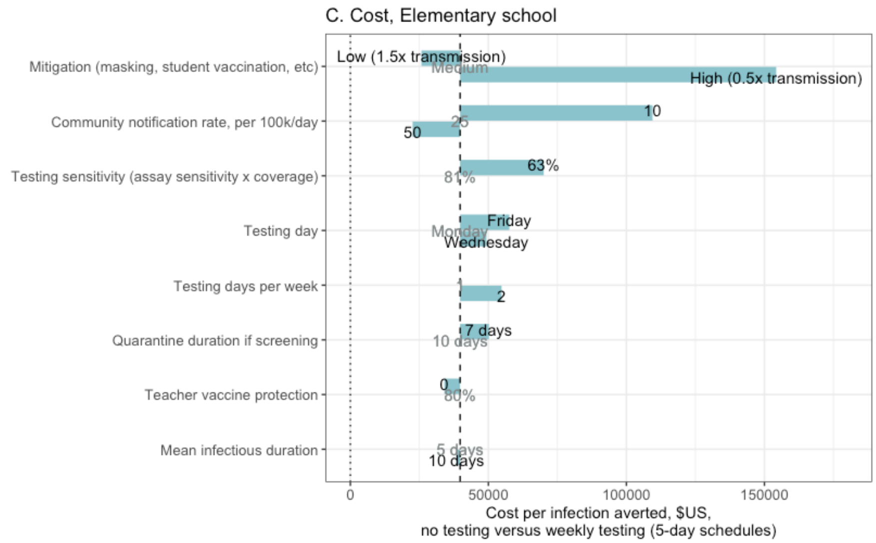


Fig S10. One-way sensitivity analyses. Panels A and B consider how individual parameter values or assumptions affect the difference in absolute incidence (infections per school per month) between asymptomatic screening and hybrid scheduling approaches in an elementary (A) and middle school (B). Panels C and D consider parameter sensitivity of the estimated cost per infection averted in an elementary (C) and middle (D) school. In each panel, the vertical dashed line shows the value of the outcome in the primary analysis. Text in gray along the dashed line indicates the values used in primary analyses, and black text on bars shows the one or two additional values that were explored for each parameter. Figures assume 90% teacher vaccination. For parameters other than the community notification rate, sensitivity analyses use a notification rate of 25 cases/100k/day.






C. Cost, Elementary school
Mitigation (masking, student vaccination, etc)
Low (1.5x transmission)
Medium
High (0.5x transmission)
Community notification rate, per 100k/day
10
25
50
Testing sensitivity (assay sensitivity x coverage)
63%
81%
Testing day
Friday
Monday
Wednesday
Testing days per week
1
2
Quarantine duration if screening
7 days
10 days
Teacher vaccine protection
0
80%
Mean infectious duration
5 days
10 days
0
50000
100000
150000
Cost per infection averted, $US,
no testing versus weekly testing (5-day schedules)

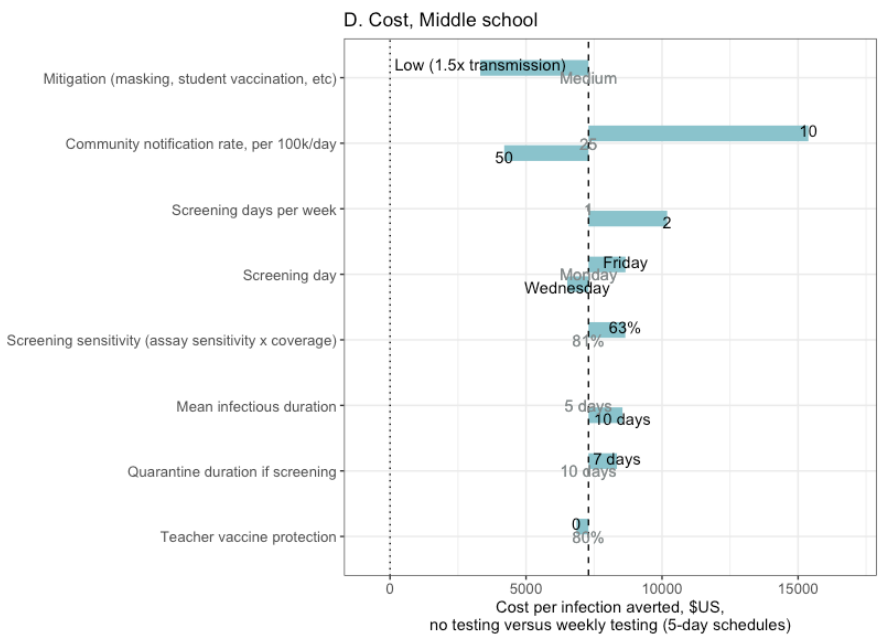

D. Cost, Middle school
Mitigation (masking, student vaccination, etc)
Low (1.5x transmission)
Medium
Community notification rate, per 100k/day
10
25
50
Screening days per week
1
2
Screening day
Friday
Monday
Wednesday
Screening sensitivity (assay sensitivity x coverage)
63%
81%
Mean infectious duration
5 days
10 days
Quarantine duration if screening
7 days
10 days
Teacher vaccine protection
0
80%
0
5000
10000
15000
Cost per infection averted, $US,
no testing versus weekly testing (5-day schedules)

Table S1. Comparison of transmission, case-detection, operational, and cost outcomes between different schedules and screening frequencies

	Infected (proportion of school per month)	Difference in proportion of school infected, per month vs full-time without screening	Proportion of incremental infections prevented (of difference between 5-day no screening and Remote)	Proportion of cases detected	In-person attendance (proportion of school days)	screening costs ($ per student per month)	Societal costs ($ per student per month)
Elementary school, community notification rate 10/100k/day							
5-day no screening	0.008	0	0	0.25	0.99	0	17
5-day 1x screening	0.007	-0.001	0.47	0.67	0.98	115	155
5-day 2x screening	0.007	-0.001	0.6	0.81	0.97	203	249
Hybrid	0.007	-0.002	0.73	0.25	0.4	0	423
Remote	0.006	-0.002	1	0.26	0	0	695
Elementary school, community notification rate 50/100k/day							
5-day no screening	0.04	0	0	0.25	0.95	0	79
5-day 1x screening	0.035	-0.005	0.54	0.65	0.89	108	288
5-day 2x screening	0.033	-0.007	0.76	0.77	0.88	181	378
Hybrid	0.032	-0.008	0.88	0.26	0.38	0	446
Remote	0.031	-0.009	1	0.26	0	0	695
Middle school, community notification rate 10/100k/day							
5-day no screening	0.018	0	0	0.23	0.98	0	28
5-day 1x screening	0.011	-0.007	0.67	0.6	0.97	114	163
5-day 2x screening	0.01	-0.009	0.77	0.72	0.97	202	254
Hybrid	0.008	-0.01	0.92	0.25	0.4	0	417
Remote	0.007	-0.011	1	0.25	0	0	685
Middle school, community notification rate 50/100k/day							

5-day no screening	0.078	0	0	0.23	0.93	0	119
5-day 1x screening	0.054	-0.024	0.57	0.58	0.87	110	320
5-day 2x screening	0.047	-0.032	0.74	0.71	0.87	182	399
Hybrid	0.04	-0.038	0.89	0.25	0.38	0	443
Remote	0.035	-0.043	1	0.26	0	0	685

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