SARS-CoV-2 testing strategies to contain school-associated transmission: model-based analysis of impact and cost of diagnostic testing, screening, and surveillance

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Abstract

Background: In March 2021, the Biden administration allocated $10 billion for COVID-19 testing in schools. We evaluate the costs and benefits of testing strategies to reduce the infection risks of full-time in-person K-8 education at different levels of community incidence.

Methods: We used an agent-based network model to simulate transmission in elementary and middle school communities, parameterized to a US school structure and assuming dominance of the delta COVID-19 variant. We assess the value of different strategies for testing students and faculty/staff, including expanded diagnostic testing ("test to stay" policies that take the place of isolation for symptomatic students or quarantine for exposed classrooms); screening (routinely testing asymptomatic individuals to identify infections and contain transmission); and surveillance (testing a random sample of students to signaling undetected transmission and trigger additional investigation or interventions).

Main outcome measures: We project 30-day cumulative incidence of SARS-CoV-2 infection; proportion of cases detected; proportion of planned and unplanned days out of school; and the cost of testing programs and of childcare costs associated with different strategies. For screening policies, we further estimate cost per SARS-CoV-2 infection averted in students and staff, and for surveillance, probability of correctly or falsely triggering an outbreak response at different incidence and attack rates.

Results: Accounting for programmatic and childcare costs, "test to stay" policies achieve similar model-projected transmission to quarantine policies, with reduced overall costs. Weekly universal screening prevents approximately 50% of in-school transmission, with a lower projected societal cost than hybrid or remote schooling. The cost per infection averted in students and staff by weekly screening is lower for older students and schools with higher mitigation and declines as community transmission rises. In settings where local student incidence is unknown or rapidly changing, surveillance may trigger detection of moderate-to-large in-school outbreaks with fewer resources compared to screening.

Conclusions: "Test to stay" policies and/or screening tests can facilitate consistent in-person school attendance with low transmission risk across a range of community incidence. Surveillance may be a useful reduced-cost option for detecting outbreaks and identifying school environments that may benefit from increased mitigation.

Introduction

In K-12 education, COVID-19 poses risks to student and teacher health, school operations, and local communities. 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 opted for remote learning (1–3). However, virtual and hybrid models imposed substantial burdens, including educational and mental health risks for students, training and logistical challenges for teachers, and productivity or child-care costs for the working parents of younger students (4–10). 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 and reduced vaccine efficacy against new variants (11–16).

In March 2021, the Biden administration allocated $10 billion for diagnostic and screening tests in schools (17). Improvements in SARS-CoV-2 diagnostic technology and infrastructure – such as increased PCR testing capacity, lateral flow rapid antigen tests, and validations of specimen pooling – make frequent, widespread testing a viable option (18,19). A key question is how to best allocate this funding to maximize in-person educational time while both controlling COVID-19 transmission and managing financial and operational costs. Centers for Disease Control and Prevention (CDC) guidelines for school reopening divide testing into three categories (20). Diagnostic testing targets those showing symptoms of COVID-19 as well as close contacts of a diagnosed case. Screening entails routine asymptomatic testing of the full school population in order to identify active cases and prevent onward transmission. Last, surveillance testing involves sampling a fraction of the population in order to identify potential outbreaks and trigger additional public health responses (e.g., school-wide screening or school closures). At present, schools require guidance on how to best allocate resources toward different testing objectives.

In this manuscript, we address several questions regarding the role of testing in educational settings: First, to what extent can different testing strategies limit school-associated transmission of

SARS-CoV-2 while sustaining in-person learning? How frequent are quarantines arising from different strategies, and to what extent can testing of contacts avert days out of school? How do testing costs compare to the financial costs associated with school absences or closures? Last, how might these outcomes vary depending on local transmission risk? 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 (21). We use an agent-based simulation of COVID-19 transmission to compare outcomes associated with different testing strategies, with a particular focus on infections, in-person educational days, and costs.

Methods

We used a previously validated agent-based simulation model to estimate the effects of different testing strategies in elementary and middle schools in the US (Figure S1) (22). 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

For a simulated elementary school (638 students in grades K-5 and 60 staff) and middle school (460 students in grades 6-8 and 51 staff), we generated households from synthetic population data (23) and grouped students into fixed classroom cohorts with a primary teacher. In schools, individuals had sustained daily contact with their classroom cohort as well as additional interactions with other members of the school community. 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.

We assumed that elementary school students are half as susceptible and half as infectious as adults and that middle school students have similar susceptibility and infectiousness as adults (22,24–

28). In the base case, we assumed schools adopted high mitigation (i.e., masking, ventilation, and distancing) and calibrated the model assuming the delta variant is approximately twice as transmissible as wild type (29,30). We further assumed that 90% of teachers and staff and 50% of middle school students were vaccinated with an 80% efficacious vaccine (31,32). Further details of model structure, assumptions, and validation are described in (22) and the Supplement.

Testing strategies

Scenarios without testing

We first modeled three scenarios without school-based testing: 1) five-day in-person attendance (the base case, and also the schedule assumed for all testing scenarios), 2) a hybrid model in which half of each class attends school on Monday and Tuesday and the other half on Thursday and Friday (a strategy used in 2020-21) and 3) fully remote learning (a proxy for anticipated infection risk unrelated to in-person education). In these scenarios, we assumed that individuals with clinically-identifiable symptoms isolated and underwent testing outside of school on the day that symptoms appeared, that they received results within 48 hours, and that the entire classroom cohort of a diagnosed COVID-19 case was quarantined for 10 days (26). We assumed that isolation and/or diagnostic testing for symptoms caused by non-COVID etiologies occurred in 1% of students and staff each week (33).

Diagnostic testing

The “test to stay” strategy altered both how symptomatic students/staff are managed and how the school responds to diagnosed COVID-19 cases (34). Individuals with clinically identifiable symptoms remained at school and took a rapid test each day they had symptoms, isolating only after testing positive. Likewise, after exposure to a confirmed case, contacts remained in school and received a rapid test daily for one week (34). We assumed 80% test sensitivity during the infectious period and 100% specificity, following a second confirmatory test (35,36). We present both quarantine and test to stay for each of the five-day in-person scenarios modeled.

Screening and surveillance

Screening entailed weekly PCR screening (on Mondays) of all students and teachers, with 90% coverage, 90% sensitivity during infectiousness, and a 24-hour test turnaround time. Surveillance entailed weekly PCR testing (90% sensitivity) of 10-20% of the school population, randomly selected solely from unvaccinated individuals. Due to the small proportion of the school tested, if ≥1 case was detected during surveillance, 90% of the school was screened the following day, including vaccinated individuals. If further cases were found, the school changed to weekly school-wide (90% coverage) screening beginning the next Monday for the remainder of the month; otherwise, surveillance resumed as scheduled the following Monday. (Threshold selection is discussed further in the Supplement.)

Based on recent CDC guidance (16), we assumed that vaccinated individuals do not quarantine and are not included in surveillance. However, due to reduced vaccine efficacy with the delta variant and associated recommendations to test vaccinated contacts (16), we included them in “test to stay” measures and school-wide screening.

Costs

We based screening and surveillance costs on pooled PCR testing. We assumed separate anterior nasal swab specimens were collected from each person tested, samples from up to 8 specimens were pooled and run as a single PCR, and residual individual specimens were held for immediate testing when the corresponding pool was positive (Supplement). Costs of PCR testing were estimated at $40 per assay, plus an $8 per-person cost of labor and supplies for nasal swab collection (Table 1). Rapid testing for the “test to stay” scenario cost $6 per assay plus the same specimen collection costs as for PCR specimens. In a sensitivity analysis, we also considered rapid testing with confirmatory PCR for screening and surveillance. Costs of non-school-based diagnostic testing were excluded in order to focus on the tests costs incurred by the school; this exclusion will result in conservative estimates of the societal cost savings of the “test to stay” strategy.

In comparing the costs associated with remote learning to the costs of testing, we took a modified societal perspective that focused on childcare or parent productivity costs; educational and other student costs are likely to accrue, but difficult to estimate. For remote and hybrid education, we estimated the cost of a planned day of remote instruction based on the average cost of group childcare (Table 1). For unplanned days at home (i.e., while isolated due to COVID-19 diagnosis or symptoms, or quarantined due to COVID-19 exposure), we estimated costs based on the average child care worker's wages over a 7-hour day (37) 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 assumed that the average productivity loss of supervising at-home learning was comparable to childcare costs.

Outcomes

For each scenario, we ran the model 1000 times for 30 days each, and estimated the following outcomes over a 30-day period: average cumulative true incidence of SARS-CoV-2 infection among staff and students (not counting secondary transmissions to household members or community contacts), cumulative case detection (as a proportion of all students and staff and as an absolute number with confirmed infection during the month), detection fraction (the ratio between cases detected and true infections), 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). We performed one-way sensitivity analyses for multiple parameters to evaluate uncertainty in the number of infections (among students and teachers) prevented by weekly screening. The model was implemented in R 4.0.2. Model code is publicly available as an R package at: https://github.com/abilinski/BackToSchool2.

Results

Effect of in-person school attendance on COVID-19 incidence

Figure 1 and Table S1 show 30-day incidence, case detection, and school attendance outcomes of different testing scenarios. At the elementary school level, compared to fully remote instruction, 5-

day in-person attendance with no in-school testing was associated with a 40% projected increase in COVID incidence among students (mean 1.9 additional infections per school per month) at a community notification rate of 10/100k/day and a 38% increase (8 additional infections per school per month) at 50 community notifications/100k/day (Figure 1A). If students with known exposures were allowed to stay in school with daily testing (the “test to stay” strategy), slightly more transmission occurred; e.g., a 43% increase over the remote-instruction baseline, at 10 community notifications/100k/day.

In the middle school where students were more susceptible and more infectious, in-person attendance had greater potential to increase transmission, although 50% student vaccination kept it partially in check. Compared to remote instruction, 5-day middle school attendance (with quarantine of known close contacts) increased incidence by 72% (3 added infections per school per month) at a community notification rate of 10/100k/day and by 60% (10 added infections per school per month) at 50 community notifications/100k/day (Figure 1E). As in the elementary school, the “test to stay” strategy increased transmission slightly compared to the remote-only baseline; e.g. from a 72% increase with quarantine to an 82% increase with test-to-stay at 10 community notifications/100k/day.

In comparison, a hybrid (A/B) schedule could prevent much of this excess transmission by reducing the number and duration of contacts, but with the downside of ≥60% remote instruction (Figure 1, gray lines).

Transmission impact of weekly screening and surveillance

Weekly screening of all students and teachers, with isolation of the identified cases and quarantine of their unvaccinated classroom contacts, eliminated a large proportion of the incremental transmission associated with school attendance. In a community with 10 notifications/100k/day, weekly screening averted 57% of excess incidence relative to remote learning in both the elementary and the middle school. The number of infections that screening could prevent among students and teachers increased roughly in proportion to the community incidence (Figure 1 A and E, and Table S1).

At low community incidence, weekly surveillance (focusing on the unvaccinated, and converting to school-wide testing if a case is detected in surveillance) achieved a large transmission benefit relative to the number of students undergoing surveillance (Figure 1 A and E green lines, and Table 1S). For a middle school in a community with 10 notifications/100k/day, weekly 20% surveillance averted 34% of the excess transmission associated with school attendance, more than half of the 57% averted by weekly universal screening of 90% of students and educators/staff; a switch from 20% surveillance to screening the entire school was required in fewer than one third of the simulations while maintaining only 20% surveillance for the full month in more than two thirds of simulations (Figure 1 and Figure S2). At high levels of community incidence, surveillance achieved nearly the same transmission benefit as universal screening, but this impact was attributable to a high probability of detecting multiple cases and therefore converting to universal screening (reaching 99.9% probability at 100 community notifications/100k/day) (Figure S2, left panel). Across all scenarios, the probability of no in-school transmission when screening was triggered was below 25%, decreasing with increased community incidence (Figure S2, middle panels).

As in the no-screening scenario, a “test to stay” strategy after case detection slightly diminished the transmission benefits of screening or surveillance. As an example, with “test to stay” instead of quarantine for an elementary school and 10 community notifications/100k/day, weekly screening prevented 46% rather than 57% of excess transmission, and weekly 20% surveillance prevented 17% rather than 25% (Figure 1 A, comparing dashed and solid lines).

Case detection and in-person learning days lost from screening and surveillance

At the elementary level, when the community notification rate was 10 cases/100k/day, weekly screening increased the detection fraction from 23% to 66%, and weekly 20% surveillance increased it from 23% to 39%. Despite the corresponding reduction in the absolute number of infections, the number of absolute cases detected increased (by more than a factor of two, for weekly screening), and the days spent in isolation or quarantine increased by a similar factor (Figure 1B, 1C, 1F, 1G). In an elementary school with weekly screening, the result was an average of 0.6 quarantine/isolation days per student per month at 10 community notifications/100k/day and 2.6 quarantine/isolation days per student per month at 50 community notifications/100k/day (Figure 1C). In middle school, quarantine of only unvaccinated students more than offsets the higher transmission, resulting in slightly fewer isolation or quarantine days per student than in the elementary school (Figure 1F-G).

A “test to stay” strategy had the benefit of far fewer days spent in isolation and quarantine, averaging <0.2 days per student per month, even at the highest modeled rates of community transmission and paired with maximal case detection through weekly screening.

Costs

Testing and childcare costs over the 30-day period were estimated for each strategy (Figure 2, breakdowns in S3-S6). When no pooled screening tests were positive and all students and staff were in attendance, weekly screening cost approximately $69 per student per month (requiring, for example, 3,141 specimen collections and 465 PCR tests per month in the elementary school). At higher incidence, the testing costs of weekly screening remained roughly stable (with the increasing cost of deconvoluting positive pools partially offset by the reduced screening days due to quarantine); costs of surveillance approached those of screening as positive surveillance tests and subsequent conversion to weekly screening become common above community notification rates of 10 to 25/day (Figures S3-S4).

Accounting for childcare during isolation and quarantine, the societal costs associated with weekly screening in an elementary school ranged from <$100 per student per month at community notification rates ≤5/100k/day, to $429/student/month at a community notification rate of 100/100k/day (Figure 2, top-right panel). A “test to stay” strategy increased testing costs by an amount proportional to the community incidence (e.g., by 27% at a community notification rate of 25/100k/day), but reduced the combined costs of testing plus child care at all community notification rates (Figure 2, dotted lines). In comparison, the cost of childcare exceeded $400/student/month for a hybrid schedule and exceeded $600/student/month for a fully-remote schedule at all incidence levels. The estimated costs of a rapid antigen screening strategy were similar to those of pooled PCR screening (Figure S7).

Cost per infection averted

We estimated the cost of screening or surveillance per infection averted among students and teachers/staff, when compared to the same full-time in-person attendance without school-based testing (Figure 3). In the elementary school, combined costs per infection directly averted were between $4,000 and $20,000 (depending on the community incidence and the use of quarantine or test-to-stay) at community notification rates of ≥25 cases/100k/day; costs rose to approximately $50,000 per infection averted at 10 cases/100k/day and $500,000 per infection averted at 1 case/100k/day. In a middle school with a strategy of screening and quarantine, the greater risk of transmission reduces the costs of per infection averted by approximately half compared to the elementary school, despite the comparative inefficiency of screening vaccinated students: for example, $25,000 at 10 cases/100k/day (Figure 3).

Sensitivity analysis

The infections averted by screening increased with higher true community COVID-19 incidence (including either higher community notification rates or lower community case detection rates) as well as with higher in-school attack rates (which could reflect weaker mitigation measures or greater variant transmissibility) (Figure S10). Correspondingly, higher attack rates reduced the cost of screening per infection averted by at least half in both settings (Figure S9). Screening later in the week or with a less sensitive test decreased impact slightly. Increasing testing frequency to twice per week increased the number of averted infections by <25% (Figure S10). For surveillance, reducing the fraction tested to 10% rather than 20% each week reduced impact but still allowed a response to large outbreaks; for example, it reduced the proportion of school-associated transmission prevented from 34% to 27% in a middle school at 10 community notifications/100k/day. Surveillance was more beneficial as the in-school attack rate increased (Figure S2).

Discussion

Our work highlights that carefully designed COVID-19 testing can support safe school reopening and help maintain 5-day in-person education across a large range of community case rates. In particular, we underscore the importance of considering multiple dimensions of cost in school reopening plans. While school-based testing programs will increase expenditures, whether borne by school systems or supported by 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 as well as costs associated with lost educational time.

Gains are particularly pronounced for expanded diagnostic testing, or “test to stay,” programs. We project that testing to stay results in only minor increases in transmission, even at the highest community case notification rates and with conservative assumptions about test sensitivity. Such estimates are consistent with a recent randomized controlled trial of “test to stay” programs in the United Kingdom, which were layered on top of twice-weekly screening programs (38). We further find that “test to stay” strategies have lower societal costs than quarantine-based strategies and could maintain student absences to less than 0.2% of school days. Given the current dominance of highly transmissible variants, an additional benefit of “test to stay” strategies is the option to adopt a broad definition of “close contact” without associated loss of school time.

We also provide information about the benefits and costs of two additional testing strategies: screening and surveillance. While previous analyses have documented that weekly screening can help control transmission, this analysis adds the finding that under conservative assumptions, 5-day in-person learning with screening is cost-saving from a societal perspective, compared to the hybrid or remote models often used in 2020-21 (39–41). Cost savings persist across levels of community transmission up to 100 cases/100k/day, even when improved case detection from the screening program increases the time that students spend in quarantine.

In 2020-21, screening was implemented in countries Germany, Austria, Norway, and the United Kingdom (18–22), as well as some US states (42,43), but its role in the coming year remains debated. We find that the value of 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, and the properties of emerging variants of concern. As a result, screening capacity may be useful as an “insurance policy” to maintain in-personal instructional time if cases remain high during fall 2021, and would be most efficiently targeted toward older students, areas with low vaccination coverage, and settings where adherence to mitigation precautions is low or unknown.

In estimating impacts of testing on transmission, we did not include the downstream infections averted beyond students and staff, the medical costs associated with COVID-19 infection, or many other dimensions of cost (e.g., educational). Our estimates of cost per infection averted are therefore likely to be conservative, and when interpreting them, a school community’s willingness to pay per averted case should be affected by onward transmission risk. For example, setting the value per statistical life of $8 million (44), a common measure of willingness to pay, communities would be willing to invest $48,000 to avert a downstream infection in an unvaccinated person aged 50-64 and $720,000 per infection averted in those over 65 (45). Other important planning inputs might include local hospital capacity and any increased pediatric risks that may be associated with new variants. However, the availability of external federal funding may render the financial costs of testing less consequential for districts than logistical and practical considerations (19).

For districts concerned about in-school transmission, but without the capacity to perform regular screening, weekly surveillance of 10-20% of the school population may offer a middle ground.

Surveillance (with the subsequent conversion to weekly screening when cases are identified) can reduce the risk of large outbreaks, is unlikely to falsely trigger burdensome interventions, and may allow schools to save money on testing when local incidence is low. However, surveillance of a small portion of the school population is likely to miss early outbreaks and requires regularly adapting school procedures. For these reasons, the benefit of surveillance strategies is largest when local testing is sparse (making it difficult to know how community case incidence maps to school incidence), when local incidence is rapidly changing, or when there is high uncertainty in the school attack rate. Beyond transmission impacts, both screening and surveillance also provide real-time information about case incidence in the school community, and may have value even at low incidence levels by providing reassurance to educators and parents concerned about in-person full-capacity attendance with the delta variant.

There are a number of limitations to this analysis. Guidance is still evolving in terms of who is a “close contact” in the context of new variants and which interventions are recommended for vaccinated individuals. Costs and benefits of testing strategies may change as recommendations evolve, but the ratio of testing compared to childcare costs should remain similar. In addition, 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 (19). Nevertheless, this work highlights that flexible and strategic testing can help ensure stable 5-day in-person education during the 2021-22 school year.

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Table 1: Model parameters

	Estimate	**Sources/Notes**
Key transmission model parameters (see (22) for full list and sources)		
Duration of infectiousness	Lognormal (5, 2)	Calibrated to match serial interval (46,47). This ensures that early high transmissibility is captured, though a long tail of reduced infectiousness likely exists. (See sensitivity analyses.)
Classroom adult-adult symptomatic daily attack rate	2% (1% or 4% in sensitivity analysis)	Daily transmission rate between two unvaccinated adults during shared full-day contact The model further adjusts for reduced elementary school students susceptibility (RR=0.5) + infectiousness (RR=0.5); asymptomatic middle school students + adults (RR=0.5). See (22) for details
Relative attack rate for random school contacts (vs. classroom)	0.13	Based on 45 minutes/day of exposure
Household attack rate	20%	(48,49)
Probability of fully asymptomatic disease	20%, children (elementary + high school) 40%, adults	(24,25,28,50)
Probability that disease has clinically recognizable symptoms	20%, children (elementary + high school) 40%, adults	(50,51)
Presymptomatic period (days)	Normal (1.2, 0.4)	(52)
School size	Elementary: 638 students, 60 teachers/staff, 30 classes Middle: 460 students, 51 teachers/staff, 21 classes	(53)
Community COVID-19 notification rate	Varied between 1 and 100 diagnosed cases per 100,00 population per day	

Case detection ratio in community	1/3	Older US modeling estimate and current UK surveillance estimate (54,55) There is some evidence that this may be low in the current wave of infections; surveillance or screening can help to ascertain the true value.
Vaccine effectiveness	80%	(31,32)
Teacher vaccination uptake	90%	(56), assuming full completion of regimens among those who received their first dose by April + 10% additional uptake
Testing parameters		
PCR		
Sensitivity of PCR testing during infectious period for screening + surveillance	0.9	(57–60). Combined with 90% screening uptake, 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
School-based screening test turnaround time	1 day	
Time from symptom onset to result of community-based diagnostic tests	2 days	
Duration of isolation after COVID-19 diagnosis	10 days	(61)
Duration of quarantine after COVID-19 exposure	10 days	(61)
Rapid testing		
Sensitivity of rapid test during infectious period for test-to-stay	0.8	Estimates of culturable infections from (35) for asymptomatic individuals; for symptomatic children from (62); see further discussion in (36)
School-based test-to-stay turnaround time	15 minutes (same-day isolation of positive cases)	
Costs		
Cost per PCR run (per 8-sample pool, and per individual in pool for	$40	Consistent with prices paid by early adopters (63), Massachusetts school testing, and some types of Medicare reimbursement (64)

testing after a positive pooled result)		
Cost per rapid test run	$6	Assumes 50% discount from retail prices per documented bulk rates (65), consistent with other analyses (66)
Added cost per specimen collected (both PCR and rapid)	$8	(67)
Cost per planned day at home	$35.50	Based on group childcare costs for pre-kindergarten (68); summertime childcare costs for school-aged children are similar (69)
Cost per unplanned day at home	$85.90	Based on childcare worker wages (37)

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 (panels B and F) divided by true cumulative incidence (panels A and E).

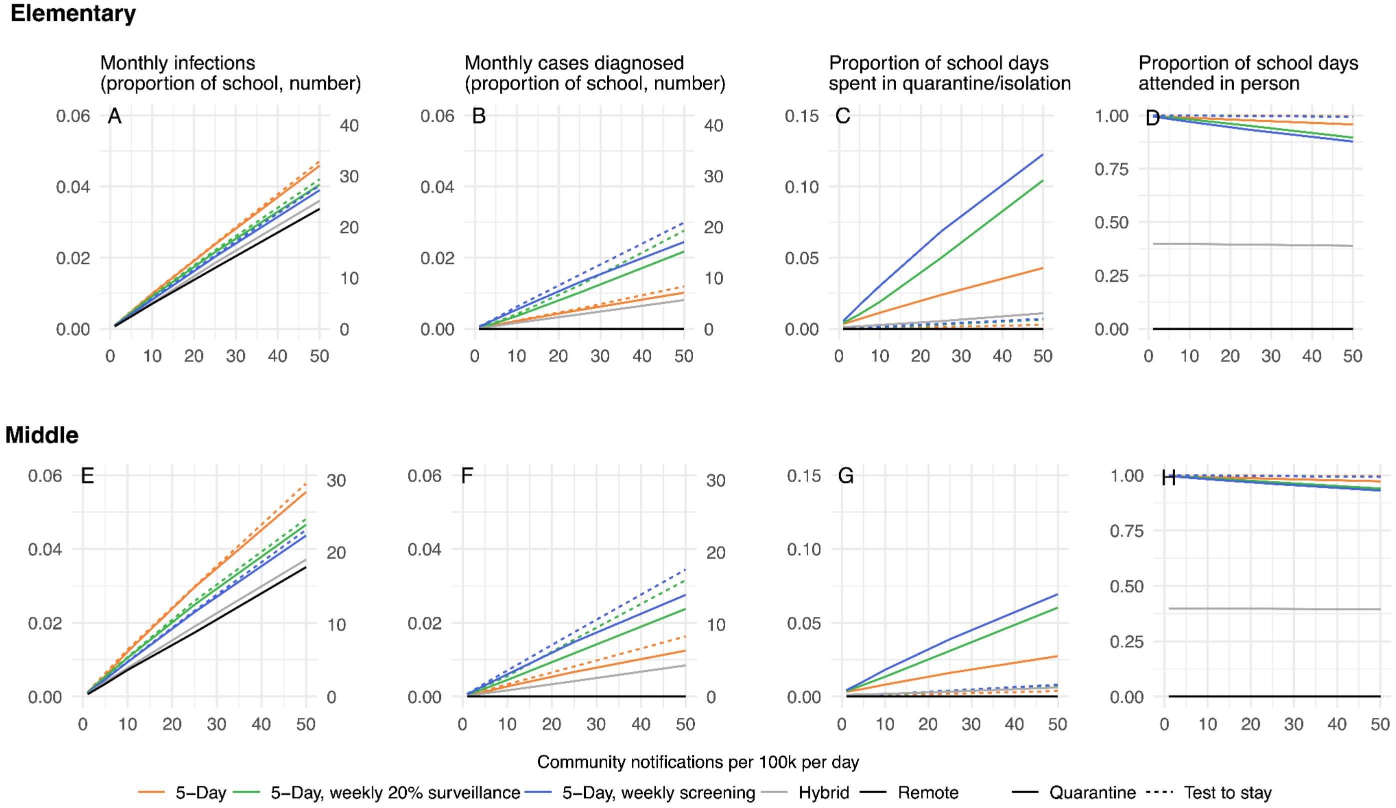


Figure 2: Costs associated with in-school COVID-19 testing and/or out-of-school childcare for different risk-reduction strategies, at varying community notification rates.

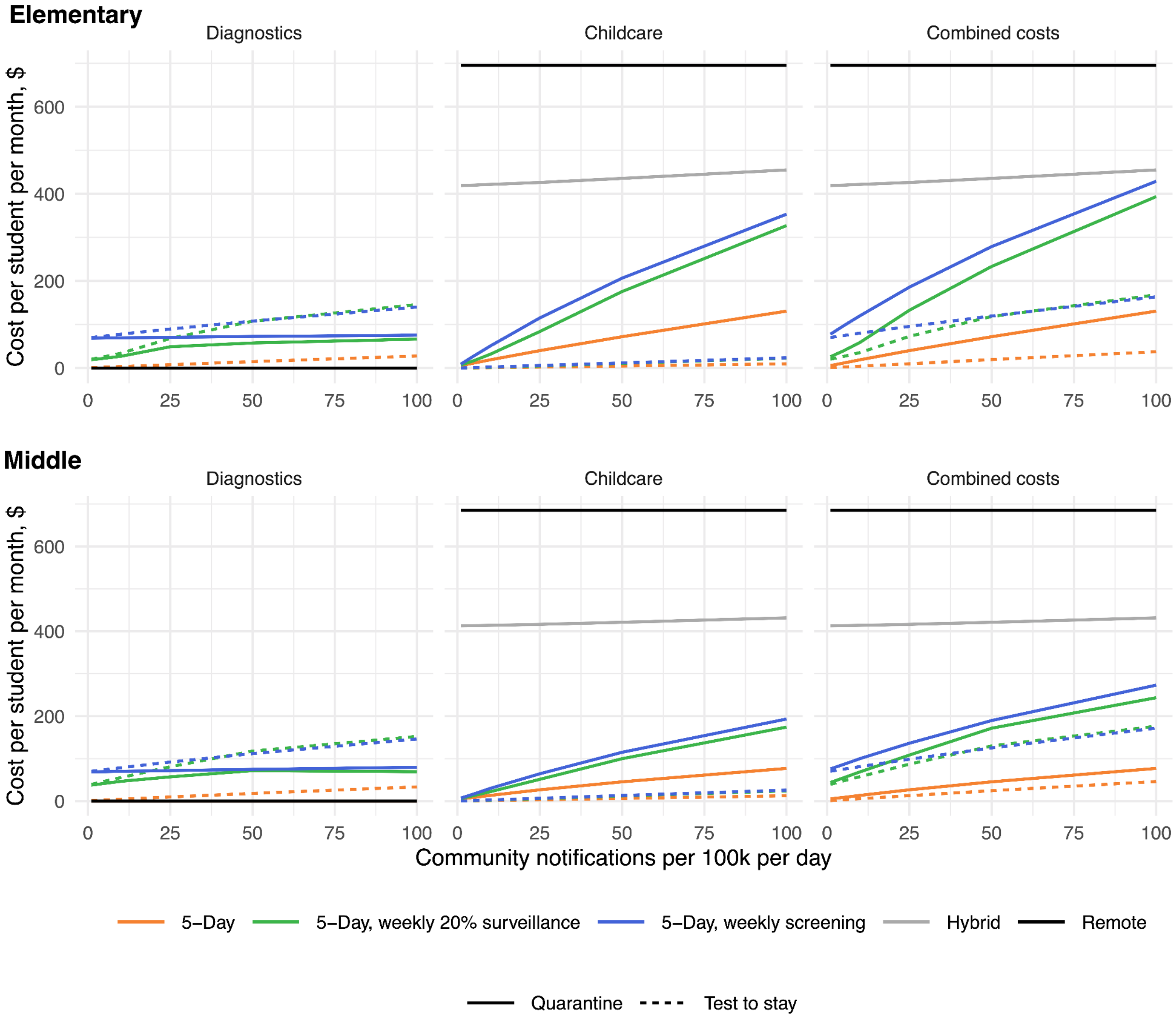
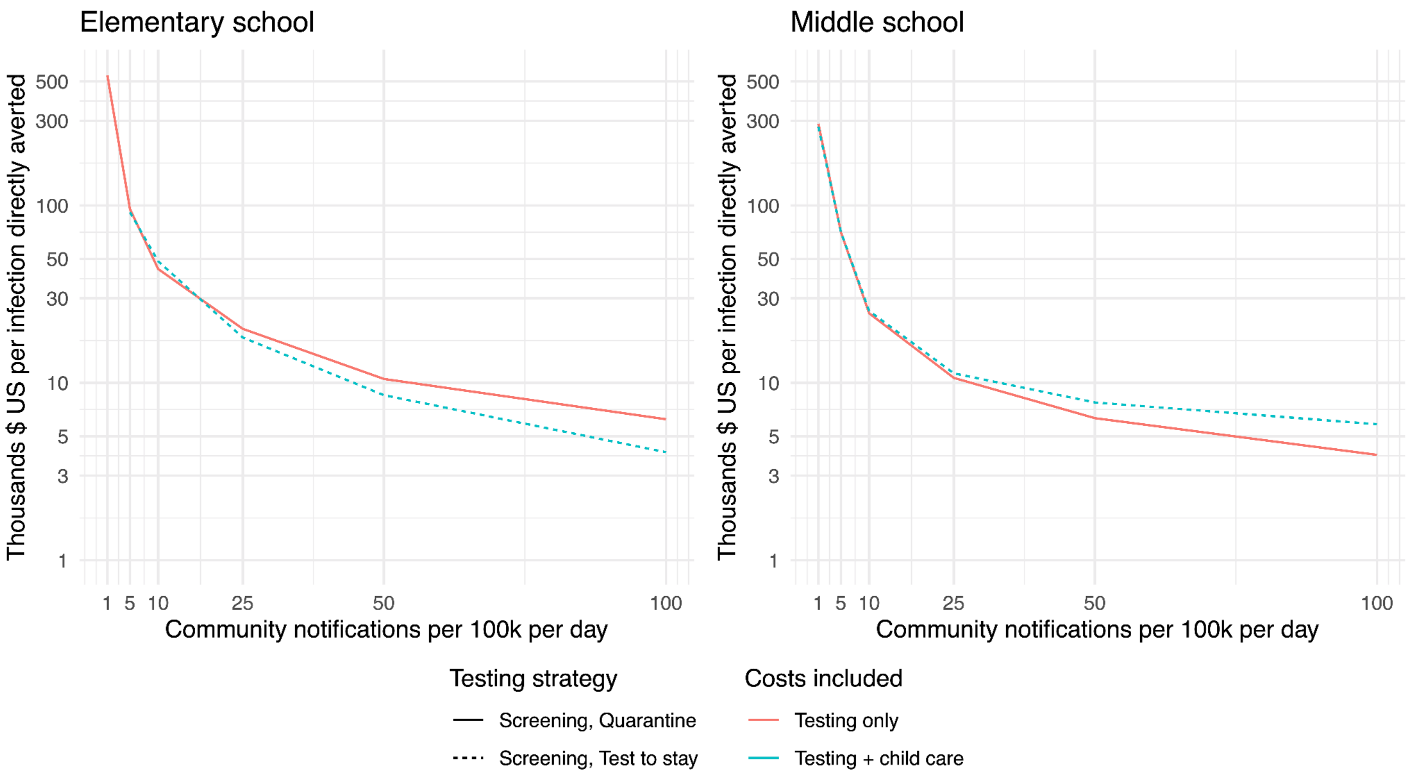


Figure 3: Cost per infection directly prevented among students/staff, compared to a 5-day in-person schedule with no in-school testing and high mitigation. Plots show the incremental cost, per infection directly averted among students and staff. For testing costs (orange), we show the strategy of weekly screening in which exposed contacts quarantine at home (solid line), which dominates the "test to stay" strategy. By "dominates", we mean that if optimizing over test costs only, it is strictly higher value to quarantine contacts, rather than implement test-to-stay. Likewise, for combined costs of testing plus childcare (blue), we show the strategy of weekly screening with exposed contacts undergoing daily rapid tests to stay at school (dashed line), which dominates at-home quarantine. For alternative scenarios with rapid tests and/or lower in-school mitigation, see Figures S8 and S9.



SUPPLEMENT: SARS-CoV-2 testing strategies to contain school-associated transmission: model-based analysis of impact and cost of diagnostic testing, screening, and surveillance

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Model Structure

We assumed an SEIR model of COVID-19 transmission, using a previously published model (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). Based on data from household contact tracing studies, we further specified that, in absence of vaccination, children under 10 were 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 community per capita daily incidence assuming a 33% case detection rate. In vaccinated individuals, this risk was reduced by 80%; among unvaccinated adults, we upweighted community risk such that adults overall matched the community rate on average.

In scenarios without “test to stay”, 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 regardless of in-school screening practices.

For in-school testing, we assumed (a) specimens (e.g., anterior nasal swabs) were collected from each student and teacher, and (b) 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 (15,16) When a pooled specimen yielded a positive result, all individual specimens that had been included in the pool were immediately tested separately using PCR to identify the positive individual(s).

Model Parameterization and Calibration

Model parameterization is discussed at length in the Supplement of (1). Briefly, we first identified household attack rates (including differential susceptibility and infectiousness of young children) (17–19). We first adjusted these for the length of time spent in school and reduced infectiousness of asymptomatic individuals (9) to estimate attack rates with no or minimal mitigation. We then further adjusted them for a range of mitigation strategies. To partially validate our model, we compared our estimates of in-school attack rate and in-school R_t to those from empirical studies. We estimated in-school R_t with high mitigation and classroom quarantine and “bubbles” to be 0.2 for elementary schools and 0.64 in high schools, consistent with estimates from schools during 2020-2021 (e.g., (20)). Our estimates also reflect the wide range of attack rates across mitigation levels identified both in data directly from schools (21–23) and from household/population-level estimates (24,25), as well as the association between community incidence level and transmission risk (26).

We assumed that the delta variant is twice as transmissible than the wild type variant (27,28) and that this multiplicative increase is constant across levels of mitigation. The latter assumption is uncertain and requires further empirical evaluation in different contexts; for example, while it may be realistic with cloth masks, early anecdotal evidence from health care settings suggests that high filtration masks (e.g. N95, KN95) may protect nearly as well against the delta variant as they do against wild type. We also assumed that the delta variant has 80% vaccine efficacy, a decrease compared to the wild type (29,30). Some emerging estimates of vaccine efficacy are lower, potentially suggesting a conservative estimate of the value of screening.

For our base case, we assume high mitigation with the delta variant (R_t of approximately 0.4 in elementary schools and 1.2 in middle schools) to reflect the population of schools most likely to implement testing and likely ordering of interventions (e.g., testing will likely only be implemented in schools that have already implemented masking). We also present results with moderate mitigation, doubling the attack rate of the base case, to display the impact of testing in the context of reduced mitigation interventions in schools.

Surveillance Thresholds

Within a small school community, it is challenging to set an optimal threshold for triggering further investigation when conducting surveillance. We expect some COVID-19 cases to enter a school from the community *even if no transmission occurs within the school community*, and ideally the threshold for triggering additional testing should take this into account. However, when testing only a small fraction of the school (10-20%), the expected number of asymptomatic cases detected per testing episode, assuming no in-school transmission, is generally close to 0. In the paper, we chose a 1-case trigger threshold for 3 reasons:

1. At low-to-moderate community notification rates (1-25 cases per 100,000/day), no surveillance scenario with a threshold above 1 could detect even large outbreaks of at least 10 in-school transmissions with any regularity: the maximum probability of detection (i.e., maximum sensitivity) was 35% for a 2-case threshold at 25 cases per 100,000/day. By contrast, a 1-case threshold had a detection probability of 30-75% across 1-25 cases per 100,000/day, while maintaining low rates of false positive triggers.
2. In our model, there was generally at least some in-school transmission at high levels of community incidence, making threshold selection less of a concern, since false positives would be rare under any threshold. (For the same reason, surveillance testing as a method of detecting outbreaks is less useful at these levels, although a benefit remains if community case detection is low, which makes schools less likely to be aware of local incidence risks.)
3. If, in practice, a school calibrated the expected number of cases and associated threshold to the *observed* community incidence rate, this would be a significant underestimate (and for most community incidence levels we evaluated would be near 0). (However, it is not straightforward to correct for case detection, as there is no public, consistently-collected data source in the United States for estimating case detection rate, and most school leaders with whom we spoke would not be comfortable making such an estimate.[1])

Nevertheless, schools (or school districts more broadly) should adapt surveillance thresholds to meet their needs and level of caution. Our model is a st example over a single month for a single school. A

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[1] The common approach of comparing percent positivity from in-school testing to population testing is inappropriate, as community testing encompasses primarily exposed symptomatic individuals with a much higher probability of infection than randomly selected individuals.

longer-term strategy might include dynamic switching back to surveillance as well as stricter trigger thresholds when community incidence is high or when surveying large districts.

Fig S1. Model diagram

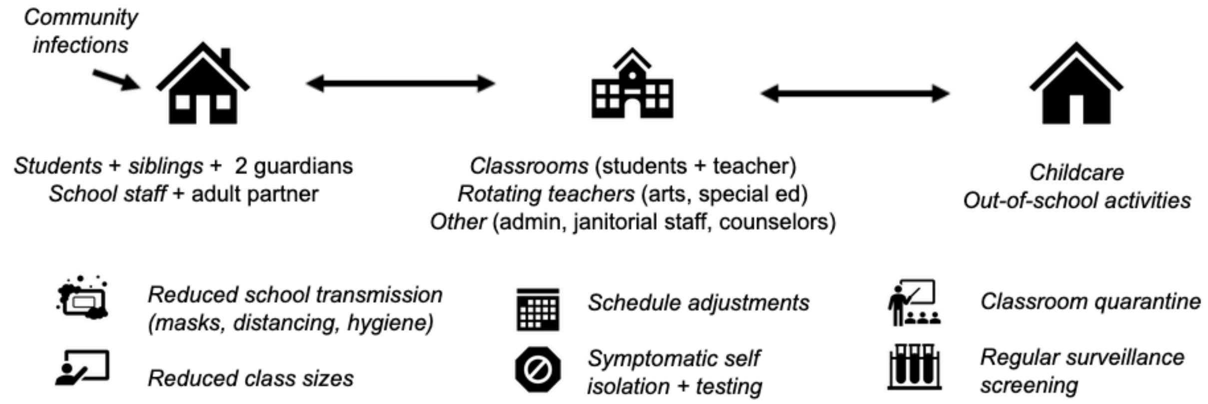


Fig S2. Surveillance characteristics. Color indicates the percentage of the school screened weekly (from unvaccinated individuals) under surveillance, while the line type indicates the transmission level. The left panels depict the probability of triggering screening. The middle panels depict the probability of in-school transmission, conditional on triggering screening ("true positives"). The right panels depict the probability of fewer than 3 in-school transmissions given no screening trigger ("true negatives").

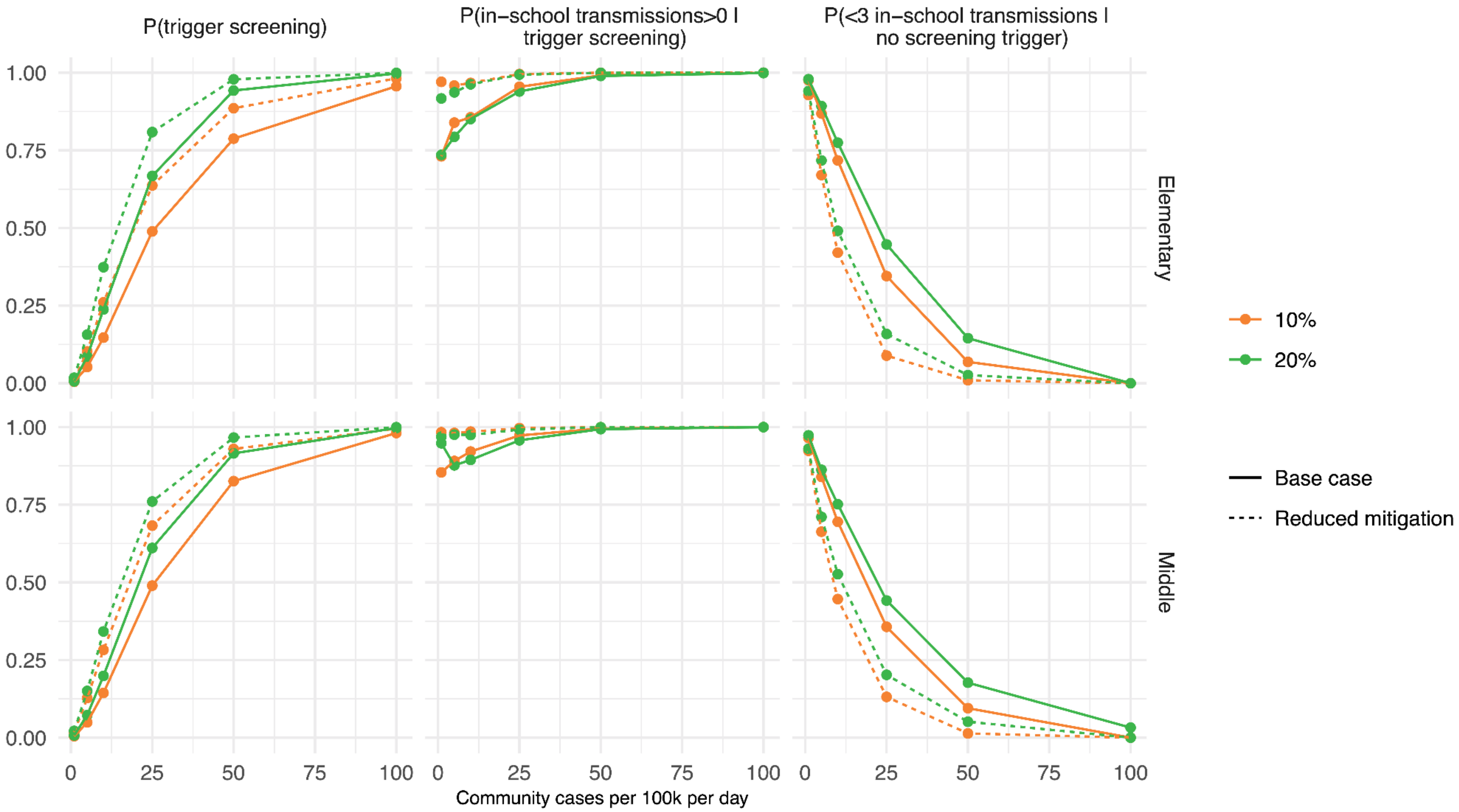


Fig S3. Testing costs, as dollars per student per month, in an elementary school. When exposed students quarantine at home, costs plateau at higher levels of incidence as classroom quarantines cause screening days to be missed; potential costs of community-based testing by exposed students or their contacts are not modeled. For a "test to stay" strategy that provides in-school rapid testing to symptomatic students and exposed contacts, testing costs increase as incidence rises.

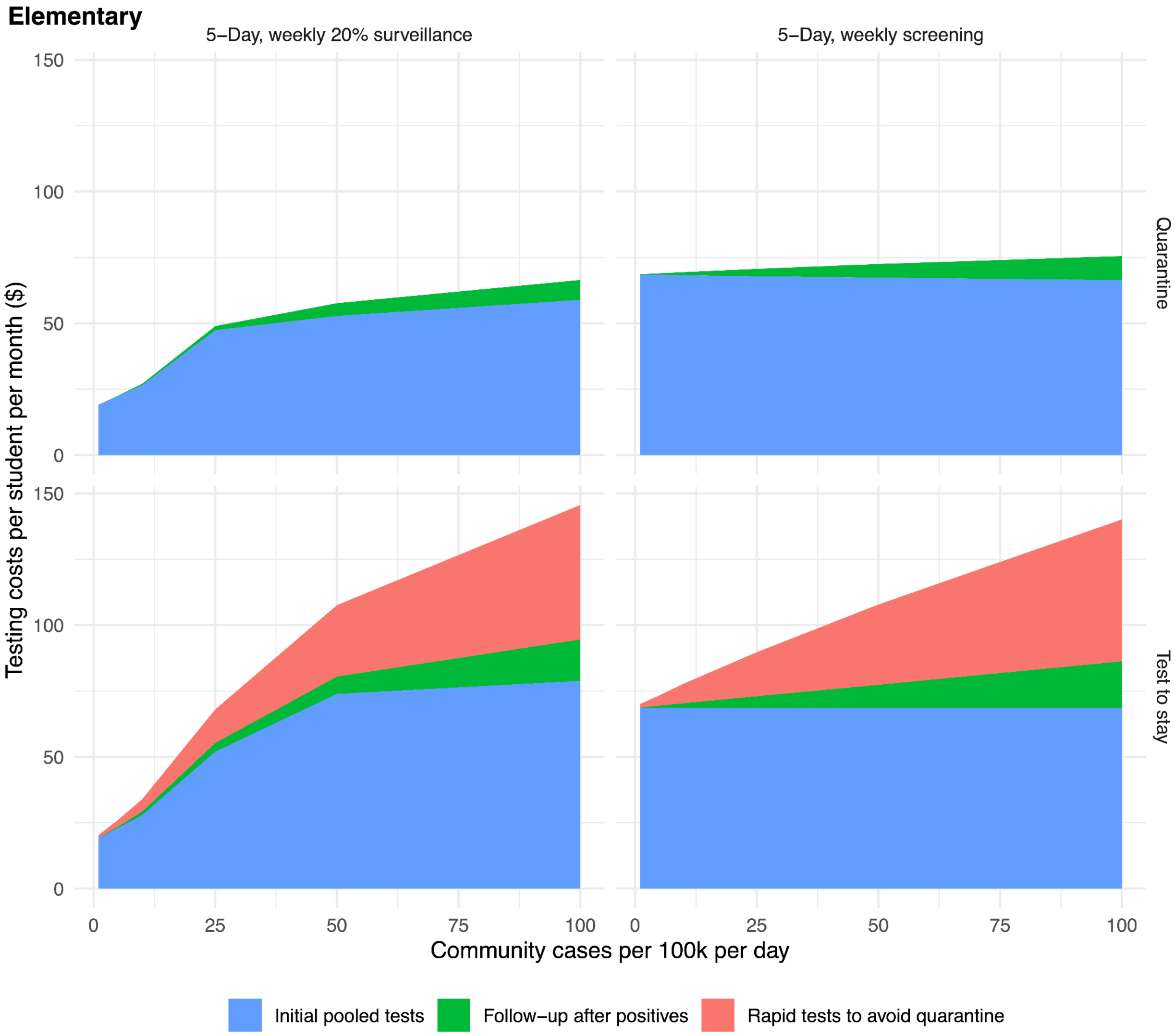


Fig S4. Testing costs, as dollars per student per month, in a middle school. When exposed students quarantine at home, costs plateau at higher levels of incidence as classroom quarantines cause screening days to be missed; potential costs of community-based testing by exposed students or their contacts are not modeled. For a "test to stay" strategy that provides in-school rapid testing to symptomatic students and exposed contacts, testing costs increase as incidence rises.

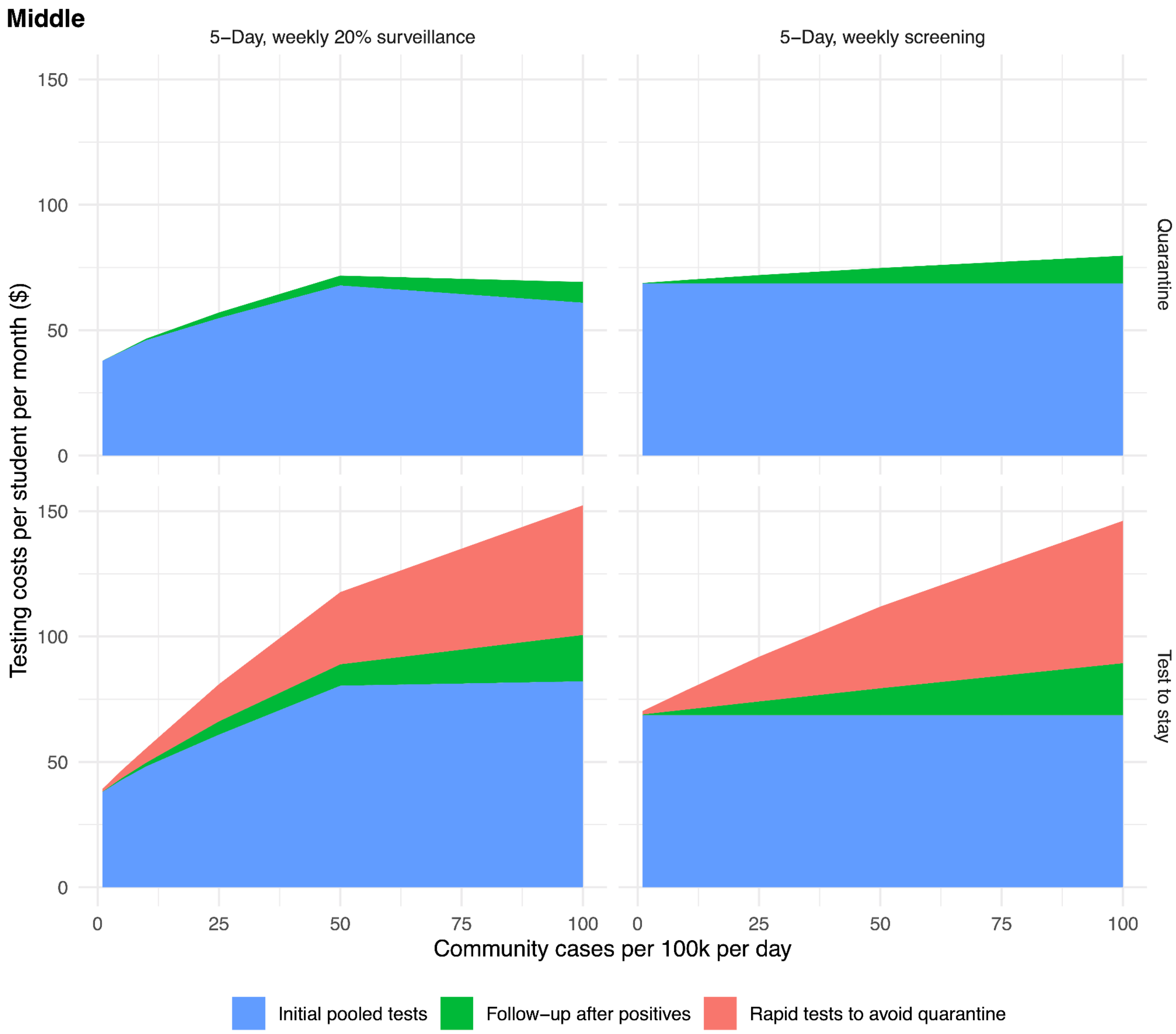


Fig S5. Childcare or parent productivity costs (elementary school). Planned costs reflect scheduled days of remote learning, and unplanned costs reflect days spent in isolation or quarantine. Rows reflect two different approaches to managing exposed contacts (quarantine for 10 days at home, top row; or staying at school with a week of daily rapid tests, bottom row). “Test to stay” is not modeled for Hybrid and Remote schedules.

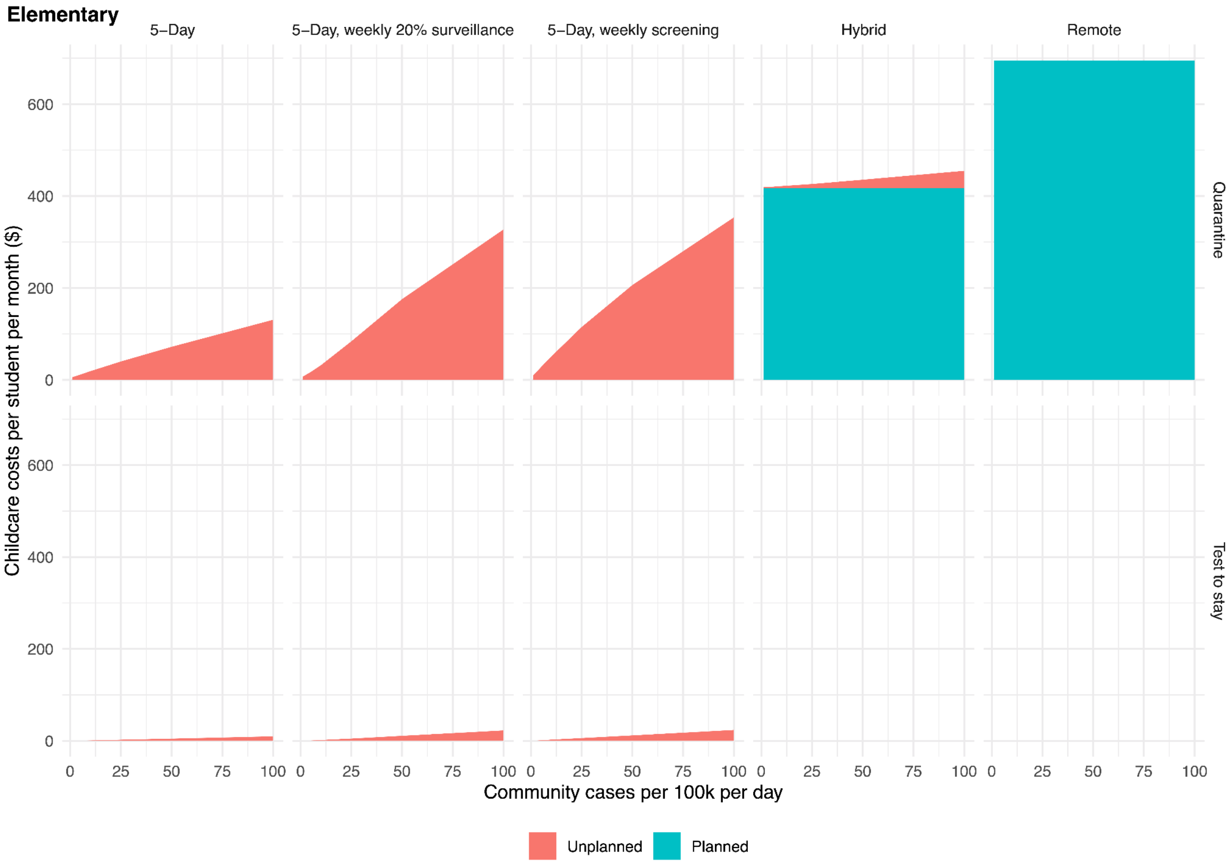


Fig S6. Childcare or parent productivity costs (middle school). We assume that for a combination of health and logistical reasons, full classrooms quarantine after exposure. If only unvaccinated students were asked to quarantine, then costs of 5-Day + Quarantine scenarios would be reduced.

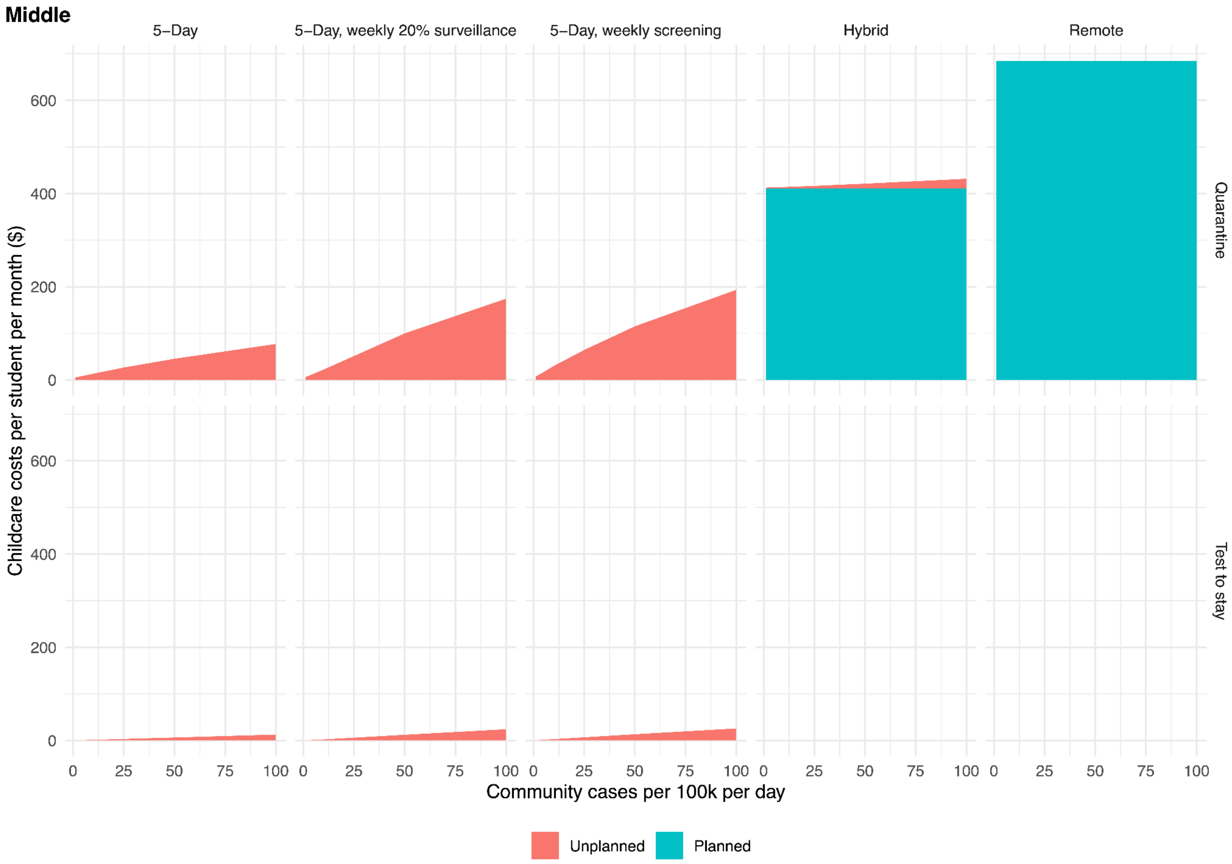


Fig S7. Costs associated with rapid antigen screening tests (weekly tests at $12 per test + $8 per sample collection, PCR confirmation of positive results with same one-day turnaround, 0.5% false positive rapid tests, no change in sensitivity for acute infection) compared to the costs of schedule-based mitigation and of full-time in-person attendance without asymptomatic screening.

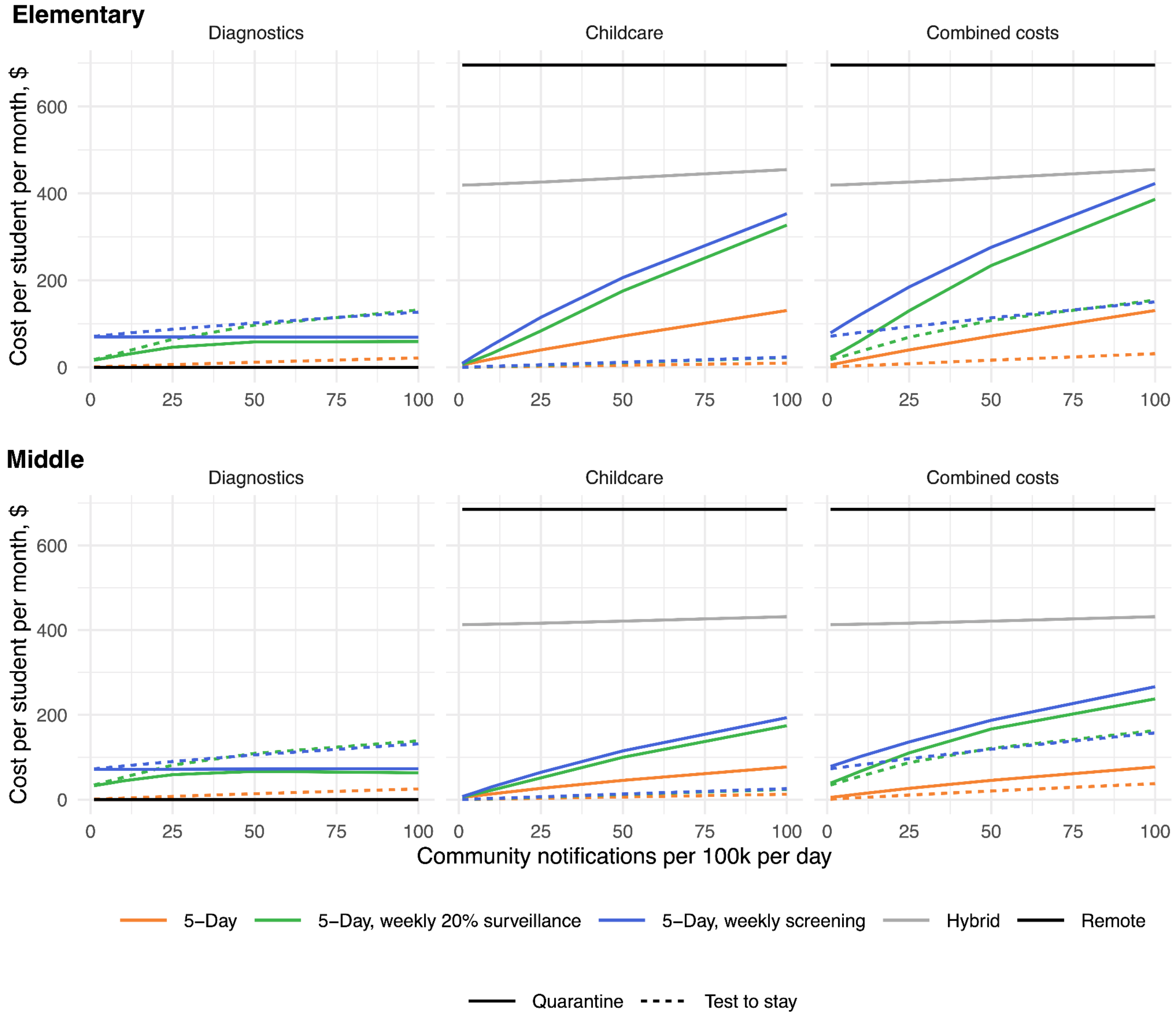


Fig S8. Cost-effectiveness of rapid screening (cost per infection directly averted among students and staff), comparing weekly screening to full-time attendance without screening, under the same rapid screening assumptions as in Figure S7. For testing costs (orange), we show the strategy of weekly screening in which exposed contacts quarantine at home (solid line), which dominates the "test to stay" strategy. By "dominates", we mean that if optimizing over test costs only, it is strictly higher value to quarantine contacts, rather than implement test-to-stay. Likewise, for combined costs of testing plus childcare (blue), we show the strategy of weekly screening with exposed contacts undergoing daily rapid tests to stay at school (dashed line), which dominates at-home quarantine.

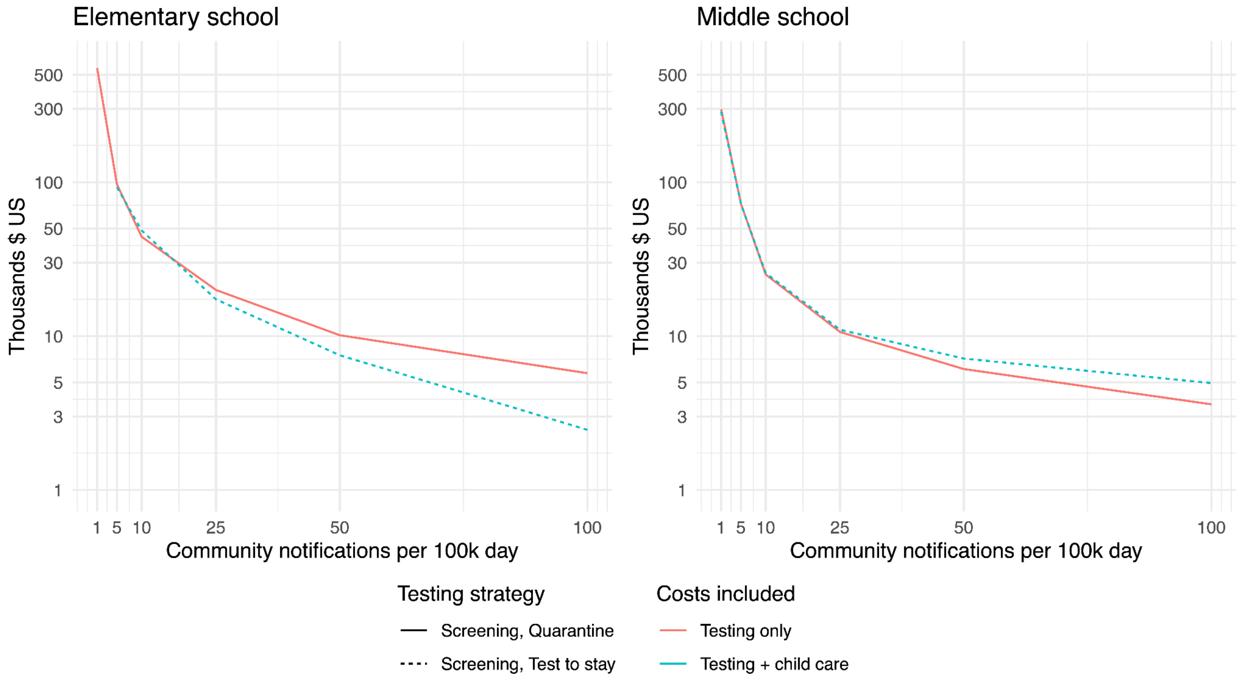


Fig S9. Cost-effectiveness of weekly screening (cost per infection directly averted among students and staff), comparing screening to full-time attendance without screening, assuming a two-fold increase in transmission rate over the base case (due to increased variant transmissibility or reduced in-school mitigation). For testing costs (orange), we show the strategy of weekly screening in which exposed contacts quarantine at home (solid line), which dominates the "test to stay" strategy. By "dominates", we mean that if optimizing over test costs only, it is strictly higher value to quarantine contacts, rather than implement test-to-stay. Likewise, for combined costs of testing plus childcare (blue), we show the strategy of weekly screening with exposed contacts undergoing daily rapid tests to stay at school (dashed line), which dominates at-home quarantine.

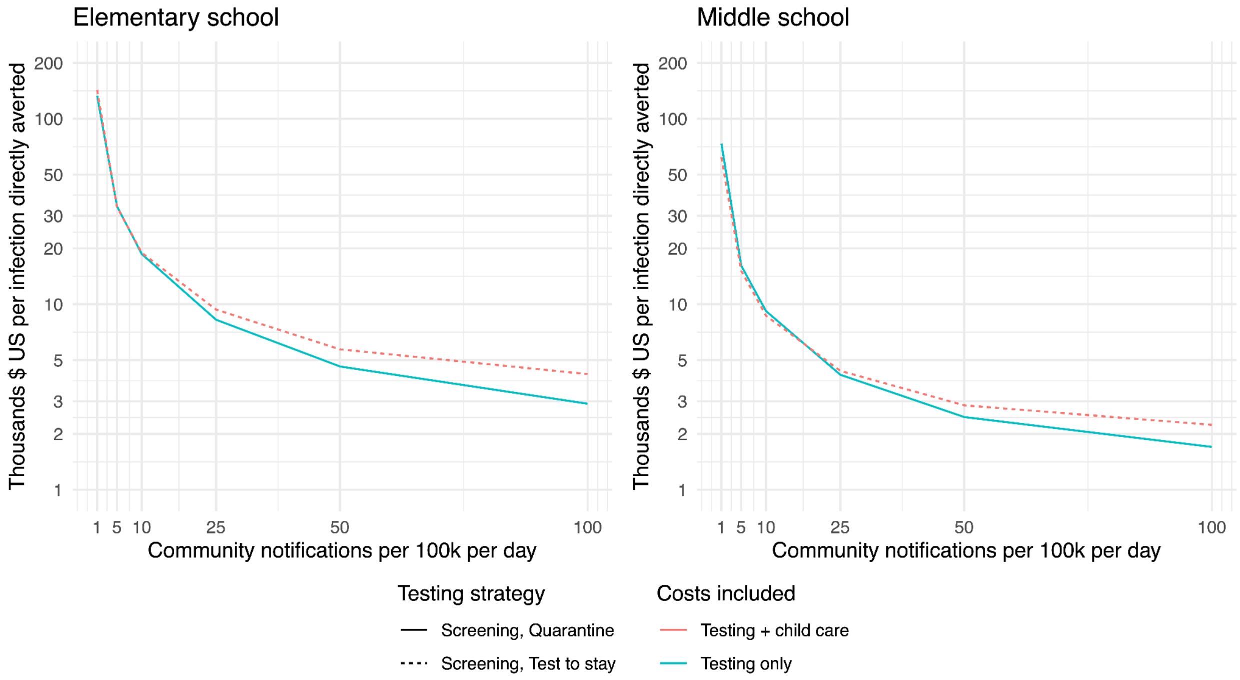
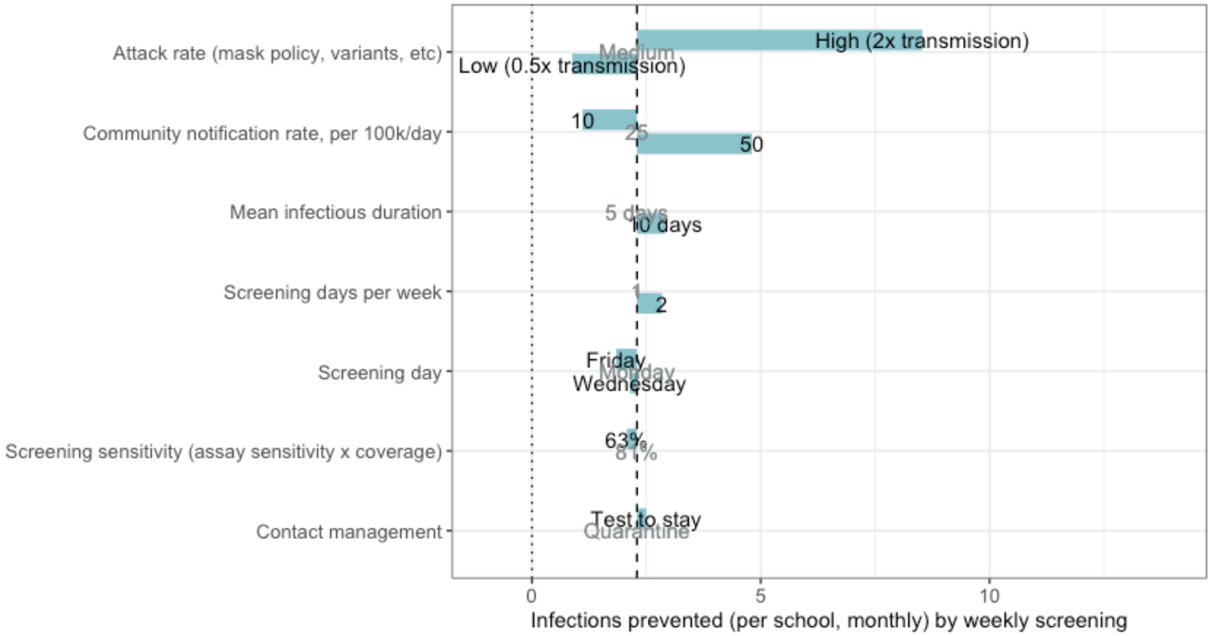


Fig S10. One-way sensitivity analyses, transmission effects of weekly screening. The outcome is the absolute difference in incidence (infections of students or teachers per school per month) between 5-day attendance with and without weekly screening, in an elementary (A) and middle school (B). The dotted horizontal line indicates the outcome when all parameters are at their base values (values indicated in gray text in the row where that parameter is varied).

A. Elementary school



B. Middle school

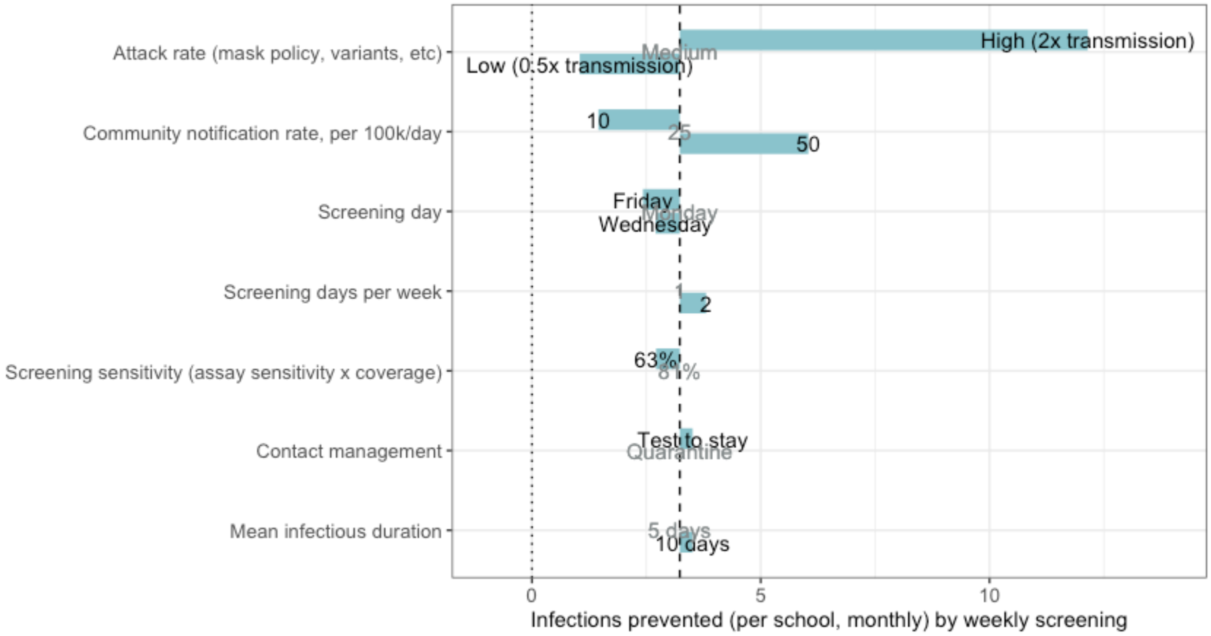


Table S1. Comparison of transmission, case-detection, operational, and cost outcomes between different schedules and screening frequencies

	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)	Testing costs ($ per student per month)	Testing + child care costs ($ per student per month)
Elementary school, community notification rate 10/100k/day							
5-Day, no screening, quarantine	0.01	0	0	0.23	0.989	0	19.03
5-Day, no screening, test-to-stay	0.01	0.0002	-0.06	0.23	0.999	3.47	4.36
5-Day, weekly 10% surveillance, quarantine	0.009	-0.0005	0.19	0.31	0.985	18.93	44.94
5-Day, weekly 10% surveillance, test-to-stay	0.01	-0.0002	0.06	0.35	0.999	24.25	25.56
5-Day, weekly 20% surveillance, quarantine	0.009	-0.0007	0.25	0.39	0.981	27.09	58.97
5-Day, weekly 20% surveillance, test-to-stay	0.009	-0.0005	0.17	0.44	0.999	33.98	35.59
5-Day, 1x/week screening, quarantine	0.008	-0.0016	0.57	0.66	0.97	69.42	120.26

5-Day, 1x/week screening, test-to-stay	0.009	-0.0013	0.46	0.73	0.999	77.81	80.25
5-Day, 2x/week screening, quarantine	0.008	-0.0019	0.69	0.77	0.968	124.19	178.24
5-Day, 2x/week weekly screening, test-to-stay	0.008	-0.0017	0.61	0.88	0.998	134.03	136.86
Hybrid	0.007	-0.0025	0.92	0.23	0.397	0	421.76
Remote	0.007	-0.0028	1	0	0	0	695.32
Elementary school, community notification rate 50/100k/day							
5-Day, no screening, quarantine	0.046	0	0	0.22	0.957	0	71.99
5-Day, no screening, test-to-stay	0.047	0.0013	-0.1	0.25	0.997	14.73	19.41
5-Day, weekly 10% surveillance, quarantine	0.042	-0.0034	0.28	0.45	0.912	46.65	194.49
5-Day, weekly 10% surveillance, test-to-stay	0.043	-0.0026	0.21	0.55	0.994	80.29	89.69
5-Day, weekly 20% surveillance, quarantine	0.041	-0.0054	0.44	0.54	0.896	57.65	233.33
5-Day, weekly 20% surveillance, test-to-stay	0.042	-0.0038	0.32	0.66	0.994	107.6	118.43
5-Day, 1x/week screening, quarantine	0.039	-0.0069	0.57	0.63	0.877	72.52	278.98

5-Day, 1x/week screening, test-to-stay	0.04	-0.0056	0.46	0.74	0.993	107.84	119.56
5-Day, 2x/week screening, quarantine	0.038	-0.0084	0.69	0.73	0.87	126.85	345.93
5-Day, 2x/week weekly screening, test-to-stay	0.039	-0.0064	0.53	0.89	0.992	169.93	183.79
Hybrid	0.036	-0.0099	0.81	0.22	0.389	0	435.62
Remote	0.034	-0.0121	1	0	0	0	695.32
Middle school, community notification rate 10/100k/day							
5-Day, no screening, quarantine	0.012	0	0	0.23	0.992	0	13.48
5-Day, no screening, test-to-stay	0.013	0.0006	-0.12	0.26	0.999	46.62	68.93
5-Day, weekly 10% surveillance, quarantine	0.011	-0.0013	0.27	0.34	0.989	4.47	5.76
5-Day, weekly 10% surveillance, test-to-stay	0.011	-0.0008	0.16	0.42	0.999	55.46	57.6
5-Day, weekly 20% surveillance, quarantine	0.011	-0.0017	0.34	0.43	0.987	23.84	42.07
5-Day, weekly 20% surveillance, test-to-stay	0.011	-0.0015	0.3	0.52	0.999	31.24	33.09
5-Day, 1x/week screening, quarantine	0.009	-0.0028	0.57	0.64	0.982	70.06	100.16

5-Day, 1x/week screening, test-to-stay	0.01	-0.0027	0.54	0.74	0.998	78.57	81.31
5-Day, 2x/week screening, quarantine	0.009	-0.0035	0.7	0.77	0.982	125.35	155.67
5-Day, 2x/week weekly screening, test-to-stay	0.009	-0.0031	0.62	0.9	0.998	135.35	138.51
Hybrid	0.008	-0.0044	0.89	0.22	0.398	0	413.93
Remote	0.007	-0.005	1	0	0	0	684.79
Middle school, community notification rate 50/100k/day							
5-Day, no screening, quarantine	0.055	0	0	0.22	0.973	0	45.46
5-Day, no screening, test-to-stay	0.058	0.0023	-0.11	0.28	0.996	71.78	171.71
5-Day, weekly 10% surveillance, quarantine	0.049	-0.0062	0.31	0.44	0.947	18.18	24.48
5-Day, weekly 10% surveillance, test-to-stay	0.051	-0.0049	0.24	0.59	0.993	117.73	129.93
5-Day, weekly 20% surveillance, quarantine	0.047	-0.0089	0.44	0.51	0.94	52.13	139.47
5-Day, weekly 20% surveillance, test-to-stay	0.048	-0.0073	0.36	0.66	0.993	92.72	104.17
5-Day, 1x/week screening, quarantine	0.044	-0.0118	0.58	0.63	0.931	74.8	189.83

5-Day, 1x/week screening, test-to-stay	0.045	-0.0103	0.5	0.76	0.992	111.96	125.28
5-Day, 2x/week screening, quarantine	0.041	-0.0148	0.73	0.75	0.929	131.25	248.46
5-Day, 2x/week weekly screening, test-to-stay	0.043	-0.0123	0.6	0.9	0.991	173.31	188.37
Hybrid	0.037	-0.0183	0.9	0.23	0.394	0	421.16
Remote	0.035	-0.0204	1	0	0	0	684.79

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