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Estimating aerosol transmission risk of SARS-CoV-2 in New York City public schools during reopening

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ABSTRACT

The objective of this study was to estimate the risk of SARS-CoV-2 transmission among students and teachers in New York City public schools, the largest school system in the US. Classroom measurements conducted from December 2017 to September 2018 were used to estimate risk of SARS-CoV-2 transmission using a modified Wells-Riley equation under a steady-state conditions and varying exposure scenarios (infectious student versus teacher, susceptible student versus teacher, with and without masks). We then used multivariable linear regression with GEE to identify school and classroom factors that impact transmission risk. Overall, 101 classrooms in 19 schools were assessed, 86 during the heating season, 69 during cooling season, and 54 during both. The mean probability of transmission was generally low but varied by scenario (range: 0.0015–0.81). Transmission rates were higher during the heating season ($\beta=0.108$, $p=0.010$), in schools in higher income neighborhoods (>80K versus 20K–40K $\beta=0.196$, $p<0.001$) and newer buildings (<50 years $\beta=0.237$, $p<0.001$; 50–99 years $\beta=0.230$, $p=0.013$ versus 100+ years) and lower in schools with mechanical ventilation ($\beta=0.141$, $p=0.057$). Surprisingly, schools located in older buildings and lower-income neighborhoods had lower transmission probabilities, likely due to the greater outdoor airflow associated with an older, non-renovated buildings that allow air to leak in (i.e. drafty buildings). Despite the generally low risk of school-based transmission found in this study, with SARS-CoV-2 prevalence rising in New York City this risk will increase and additional mitigation steps should be implemented in schools now.

1. Introduction

As fall 2020 began, schools around the U.S. reopened for in-person learning after having closed last spring when the COVID-19 epidemic took hold within the country (Bushwick, 2020). While some of the hardest hit areas, like New York City, were able to control and reduce the very high rates of transmission, morbidity, and mortality, this success was only won with the implementation of widespread work-at-home orders and shutdown of all nonessential work that could not be conducted from home. This shutdown included the migration of in-person learning in schools to online learning platforms (Cowley et al., 2020). Now that New York City is beginning to re-open, COVID-19 cases are rising again. From a seven-day average peak of >5000 cases per day in April 2020, the weekly average number of new cases in New York City decreased to <250 per day in August; yet in September, the weekly

average began to rise again, reaching 411 new cases on September 29th (New York City Department, 2020a), only a few days before all students were slated to return to in-person learning on October 1, 2020 (New York City Department, 2020b).

According to data collected at the beginning of October, approximately 50% of New York City's public school student population had enrolled in remote learning (Chang et al., 2020). However, as of October 26th, only a little over a quarter of students had attended any in-person classes (Shapiro, 2020). For those students accessing in-person learning, the New York City Department of Education (NYCDOE) has drafted a comprehensive school reopening plan, which includes several mechanisms to reduce the likelihood of SARS-CoV-2 (the virus responsible for causing COVID-19) transmission (New York City Department, 2020c). This plan includes policies to promote social distancing, such as alternating online and in-person learning to reduce crowding, assignment of

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students to cohorts that stay in one classroom all day with teachers moving room-to-room for classes instead of students to limit mixing patterns, repurposing the cafeteria to increase classroom space, and having students eat lunch at their desks. In addition, mask wearing and remaining at least six feet apart while inside school buildings is mandated for all staff, students, and essential visitors, and hand sanitizer, soap, and disinfectants made available. Random temperature checks are also planned, performed by designated staff, such as nurses present in every school. Further, schools are deep cleaned nightly using electrostatic disinfectant sprayers approved by the U.S. Environmental Protection Agency (EPA) (i.e., List N disinfectants (A. <https://www.epa.gov>, 2020)), and HVAC systems are being repaired or upgraded, including upgrading central HVAC system filters from MERV 8 to MERV 13 (Chang et al., 2020). At the time of writing this manuscript in early November 2020, the filters had not yet been upgraded in most schools. These repairs and upgrades are much needed, with about 5% of New York City classrooms recently determined to need repairs to the ventilation systems, though detailed airflow information was not provided (Chang, 2020).

The Centers for Disease Control and Prevention (CDC) suggests that the primary form of SARS-CoV-2 transmission is through airborne respiratory droplets that are passed from person-to-person during close contact (defined as being within six feet of an individual with COVID-19 for 15 min or more over a 24-hour period, with infectiousness thought to start two days before illness onset or first possible positive test result), or via contaminated surfaces (i.e. fomites) that spread when a person touches that surface and subsequently touches their eyes, nose, or mouth (Centers for Disease Contr, 2020a). Several COVID-19 outbreaks have originated in indoor environments where individuals were in close proximity with one another for extended periods of time or where airflow might have facilitated the spread of respiratory droplets over larger distances than might normally occur. Examples of these outbreaks include in a restaurant in China where airflow from the air-conditioning system appears to have spread the virus farther than would be expected through normal person-to-person droplet transmission (Lu et al., 2020), and, in the U.S., a number of COVID-19 clusters have similarly been linked to indoor dining in restaurants or bars (Foster and Mundell, 2020). Clusters among church attendees have also been reported both in China (Yong et al., 2020) and the U.S. (Conger et al., 2020) On October 5th, the CDC reported on its website that COVID-19 can occasionally be spread via aerosol transmission under certain conditions (Centers for Disease Contr, 2020b). There is increasing evidence that aerosol transmission likely occurs, particularly in indoor settings with poor ventilation, and aerosol transmission of related viruses, such as SARS-CoV and MERS-CoV, has been documented (Tang et al., 2020). Under experimental conditions, SARS-CoV-2 in aerosolized form may remain viable for up to 3 hour (van Doremalen et al., 2020), and while real-world evidence for airborne transmission of SARS-CoV-2 is still being evaluated, it seems increasingly likely (Lednický et al., 2020; Morawska and Cao, 2020; Augenbraun et al., 2020; Riediker and Tsai, 2020; Jayaweera et al., 2020).

The ease of airborne transmission through droplets and possible aerosolization of SARS-CoV-2 is a concern, especially in schools as children may find it challenging to follow social distancing and mask-wearing rules (Pinsker, 2020). Further exacerbating this concern is the fact that a high proportion of school employees and people living with school-age children in the U.S. have risk factors that put them at increased risk for serious COVID-19 illness, such as being age >65 years, obese, or having a chronic health condition such as diabetes, cancer, or lung, kidney, or heart disease. In fact, 42% of school employees (teachers, teaching assistants, administration, and facilities staff) in the U.S. have one or more risk factors for severe COVID-19 illness and 58.7% of school-age children live in a household with at least one adult at high-risk (Selden et al., 2020). Furthermore, while young children appear to be less likely to become severely ill with COVID-19 themselves, the number of pediatric cases in the U.S. was already increasing

before school re-openings, doubling from 200,000 on July 9th to over 406,000 on August 13th (Bushwick, 2020). Recent reports of a severe multisystem inflammatory syndrome in children associated with COVID-19 illness (MIS-C) (Godfred-Cato et al., 2020) further raises concerns. On October 3rd, the first student attending in-person classes in a New York City public school tested COVID-19 positive, leading to the quarantine of six teachers and seven students from that school (Edelman, 2020).

Previous investigators have concluded that carbon dioxide (CO₂) concentrations, when used as a proxy for ventilation rates, can indicate the potential presence of airborne SARS-CoV-2 (Bhagat et al., 2020) and, subsequently, the risk of aerosol transmission in confined, indoor spaces (Harrichandra et al., 2020). The objective of this study was to estimate the risk of SARS-CoV-2 transmission among New York City public school students and teachers under steady-state conditions using previously collected classroom CO₂ concentrations. While three modes of transmission (1. contact via fomites, 2. Person-to-person via respiratory droplet transmission and 3. Aerosol [droplet nuclei] transmission) are all probable routes of transmission contributing to the spread of the COVID-19 pandemic, the focus of the current study is the potential aerosol transmission of SAR-CoV-2 in New York City public school classrooms.

2. Methods

2.1. Recruitment

Classroom data were collected as part of a larger indoor air quality (IAQ) survey. Recruitment of schools occurred from December 2017 through October 2018 with the assistance of the United Federation of Teachers (UFT), the teachers' union representing New York City public school teachers. The UFT provided schools with an explanatory summary of the study and expected commitment from teachers and schools. Approximately 30 schools volunteered to participate, however, only 19 schools, grades 1–5, were deemed eligible. For a school to be eligible it needed to be an elementary school with the Principal agreeing to participate and have at least 5 teachers from grades 3rd through 5th volunteering. Only elementary schools were eligible for the study rather than middle or high schools because elementary school teachers tend to stay with their students in the same classroom for most of the day. For schools that participated, the Principal provided written consent and selected five or six classrooms for CO₂, temperature, and relative humidity (RH) measurement.

Data collection were conducted twice to evaluate the effects of ambient conditions on IAQ, once in during the winter months (heating season), which was from December 2017 to March 2018, and once during the spring-early fall (cooling season), which was between April 2018 and September 2018, with equivalent methods used for both time periods. In total, 101 classrooms in 19 schools were assessed with 86 classrooms sampled during the heating season and 69 sampled during the cooling season. Fifty-four classrooms were assessed during both seasons.

2.2. Environmental monitoring

Onset HOBO MX1102 (Cape Cod, MA) data loggers were used to measure CO₂ (accuracy of ±50 ppm), temperature (accuracy of ±0.21 °C), and RH (accuracy of ±2%) data throughout the study periods. The MX1102 uses a non-dispersive infrared (NDIR) self-calibrating CO₂ sensor technology and integrated temperature and RH sensors. The HOBOMobile® App and HOBOWare software were used to configure the data loggers and download the data. The battery powered data loggers remained in the classroom for a week, after which they were retrieved by the technician. Most classrooms were sampled for the week; those that were sampled for less than one week were due to either school holiday, teacher sickness, field trip, and/or other scheduling

issues.

All schools had a coordinator who assisted in scheduling classroom assessments and delivering instructions to the teachers and installing measurement instruments. Five or six classrooms in two schools were typically scheduled for IAQ per week. The technician delivered the data loggers to the school on Friday, prior to the start of the upcoming school week. The technician manually calibrated the data loggers, following the manufacturer's instructions. Equipment calibration was performed outdoors near the school but away from any combustion sources, including vehicles. The data loggers were activated immediately prior to being dropped off in the specific classroom and the display screen on each data logger was turned off. The data loggers were placed on the teacher's desk and were not moved for the duration of the assessment. While in the classroom, the display screens on the data loggers were turned off to ensure that the teachers would not be able to view the measurements. The area of the classrooms were obtained from NYC DOE facilities data.

Teachers were asked to complete a questionnaire regarding the conditions of their classroom at the end of the week. The questionnaire asked about the number of students in the class, their grade, and if classroom windows were operable.

2.3. Estimation of outdoor airflow rates

We were unable to directly measure outdoor airflow rates. Therefore, we estimated outdoor airflow rates per person using Equation 6 from ASTM standard D6245-18 and shown as Equation (1) below (American Society for Testing and Materials, 2018). CO₂ concentrations were averaged by day when the class was in session. Daily averages were subsequently averaged by week. The CO₂ generation rate was averaged for males and females aged 6 to <11 years performing sedentary activity and 410 ppm was the average measured outdoor CO₂ concentration. To determine the total outdoor airflow rates, V_O was multiplied by the number of students and teacher in the room.

$$V_o = \left(\frac{N}{C_s - C_o} \right) \times 10^6 \quad \text{Eq. 1}$$

Where: V_O = outdoor airflow rate per person (m³/hour-per person)
 N = CO₂ generation rate per person (0.01026 m³/hour)
 C_S = CO₂ concentration in the space (ppm)
 C_O = CO₂ concentration in outdoor air (410 ppm)

2.4. Risk of aerosol transmission

In order to estimate the risk of aerosol transmission of SARS-CoV-2 in the confined indoor spaces of New York City schools, we used the Wells-Riley equation (Riley et al., 1978) which was designed to quantitatively assess the airborne risk of measles transmission during an outbreak in New York State in 1974. This model was based on the 'quantum of infection' concept first introduced by William Firth Wells in 1955 to signify the smallest dose of any infectious agent to cause infection in 63% of susceptible hosts (Wells, 1955).

The probability of infection (P) in a room that has achieved a steady-state concentration is shown in Equation (2) (i.e., the Wells-Riley equation) with modifications to include sink mechanisms including losses from particle deposition and viral inactivity (Sze To and Chao, 2010).

$$P = 1 - e^{\left(-\frac{R \cdot I \cdot IR \cdot t}{Q + V \cdot \lambda + k} \right)} \quad \text{Eq. 2}$$

Where: P = probability of transmission.
 R = fraction of particle penetration through a face mask.
 I = number of infected individuals (assumed as one [1] in this study)
 Q = quanta generation rate (quanta/hour)
 IR = inhalation rate (m³/hour)

t = period of time (min)
 Q = outdoor airflow rate (m³/hour)
 λ = viral inactivation loss (constant)
 k = gravitational settling loss (constant)
 V = room volume (m³)

In addition to elimination through exhausted air, airborne droplets can be removed by viral inactivation (λ) and gravitational settling (k). Buonanno, Stabile, Morawska (Buonanno et al., 2020) derived the value of k from a previously calculated settling velocity of particles (Chattoutsidou and Lazaridis, 2019). Viral decay was based on SARS-CoV-2 halflife (van Doremalen et al., 2020). The values of k and λ for virus removal were expressed as increased ventilation in the room with k being 0.24 air changes/hour (ACH) and λ being 0.63 ACH. The number of ACH was multiplied by the volume of each classroom and added to the total outdoor airflow rate. Room area was obtained by the NYCDOE, so room volume was estimated by multiplying area by an assumed ceiling height of 3.04 m. The duration of exposure was 6.3 hours, which is the length of a New York City school day (United Federation of Teac, 2020).

The risk of aerosol transmission can further be reduced by the wearing of face masks by both infected and susceptible individuals. As noted above, use of face masks by all individuals in New York City public school is required, although how strongly this rule is enforced for children is unknown. For the purpose of this study, the term 'face mask' generally encompasses N95 (or similar) respirators, surgical masks, and homemade fabric/cloth masks or other face coverings. However, it should be noted that the efficacy of face masks depends on the type. In fact, various forms of face masks have been found to reduce the transmission of respiratory viruses by 60%–80%, and these viral transmission rates can be further reduced when face masks are worn in conjunction with adherence to social distancing protocols (Fennelly and Nardell, 1998; Nazaroff et al., 1998; Liang et al., 2020; Nicas, 1996). In this paper, a conservative value of a 30% reduction in viral transmission from face mask-use by a susceptible individual was used since children may have difficulty wearing a face mask all day or it may not properly fit their face. In fact, van der Sande et al. (2008) demonstrated that children are significantly (p<0.001) less protected from exposure than adults when wearing face masks, regardless of the type (cloth face covering v. surgical mask v. filtering facepiece respirator) (van der Sande et al., 2008). In order to account for an infected child wearing a face mask, the quanta generation rate (q) was reduced by 30%. To be conservative, a 30% reduction in exposure and generation for teachers was also used.

2.5. Estimation of quanta generation rate

Buonanno et al. (2020) conducted a relatively rigorous mass balance analysis (Equation (3)) to estimate q for SARS-CoV-2 during various expiratory activities (e.g., breathing, speaking) based on the hypothesis that respiratory droplets produced by an infected individual contain the same concentration of infectious particles as sputum. The investigators estimated that q for SARS-CoV-2 ranged from 10.5 to 1030 quanta/hour, depending on activity level and expiratory activity (Buonanno et al., 2020).

$$q = c_v \times c_i \times IR \times \sum_{i=1}^4 (N_i \times V_i) \quad \text{Eq. 3}$$

Where: c_v = viral load in sputum (10⁹ RNA copies/mL)
 c_i = conversion factor between one infectious quantum and the infectious dose in RNA copies/mL (0.02)
 IR = activity level- and age-specific inhalation rate (m³/hour)
 N_i = expiratory activity-specific droplet concentration (particulates/cm³ of air) for four different particulate size distributions based on mid-point diameters (Table 1)
 V_i = spherical droplet volume (cm³)
 As a plausible, upper-bound scenario for a classroom setting, 'speaking' was selected as the expiratory activity of interest, which

Table 1

Expiratory activity-specific droplet concentrations for four different particulate size distributions.

Particulate Size Distributions ^a	Droplet Volume (cm ³)	Expiratory Activity (particulates/cm ³ of air)		
		Voiced Counting	Speaking ^b	Unmodulated Vocalization
<i>d</i> ₁ (0.80 μm)	2.68E-13	0.236	0.494	0.751
<i>d</i> ₂ (1.8 μm)	3.05E-12	0.068	0.104	0.139
<i>d</i> ₃ (3.5 μm)	2.24E-11	0.007	0.073	0.139
<i>d</i> ₄ (5.5 μm)	8.71E-11	0.011	0.035	0.059

^a Based on mid-point diameter values provided by Buonanno et al. (2020).

^b Defined as the mean value between voiced counting and unmodulated vocalization (Buonanno et al., 2020).

Buonanno et al. (2020) defined as the mean droplet concentration value between voiced counting and unmodulated vocalization. Importantly, the IR values utilized by Buonanno et al. to calculate q were specific to adults (Buonanno et al., 2020). To calculate a child-specific quanta generation rate for use in the current risk assessment, we used the mean IR for a child (males and females combined) aged 6 to <11 years during sedentary/passive activity of 0.29 m³/hour, as recommended by the U.S. Environmental Protection Agency (child-Specific Ex, 2008). A study by Walsh et al. (2020) suggests that there is no significant difference between viral loads of SARS-CoV-2 in children (aged ≤18 years) versus adults (Walsh et al., 2020). Therefore, the default value of 10⁹ RNA copies/mL for the viral load in children’s sputum was used. If anything, viral load may increase with age (Walsh et al., 2020), in which case the default c_v value for children used in this study would be an overestimate and subsequently produce a higher (more conservative) estimate for q. Using Equation (3), a quanta generation rate of 29.6 quanta/hour for SARS-CoV-2 was calculated for a child aged 6 to <11 years during sedentary/passive activity. For adults, we used a quanta generation rate of 142 quanta/hour and an IR of 0.96 m³/hour that was previously calculated by Buonanno et al. (2020)

2.6. Statistical analyses

Data analyses were conducted using SAS statistical software (version 9.4, Cary, NC). If continuous predictor variables were missing, they were substituted with the median of all reported values for the variable; missing categorical variables were substituted with the mode for the variable. We describe the risk probability by school characteristics (n=19) overall and stratified by risk level, which was defined as high for schools with a rate of child-to-child transmission with mask wearing above the median for all schools and low for those below the median. A Wilcoxon signed-rank test was used to determine significance of differences in risk level by school characteristics for continuous variables and a Fisher’s exact test was used for categorical variables. The variables examined included season of measurement (cooling only, heating only or both), NYC borough in which the school was located, median household income of the neighborhood the school served, age of the school building, whether the school had mechanical ventilation, whether the classroom sampled had no windows or if the windows it had would not open, the size of the classroom sampled (m²), and the number of students in the classroom sampled.

Continuous variables were assessed for normality using a Kolmogorov–Smirnov test and if determined not to be normally distributed were log-transformed to achieve normality. To control for classroom effects, paired t-tests were used to investigate whether CO₂, temperature, RH, outdoor airflow, and probability of transmission differed significantly by assessment during the heating versus cooling season.

We used univariate, multivariate with all variables described above in Table 2 included, and a backwards stepwise multivariable linear regression to assess the association between school and classroom variables and student to student transmission without mask wearing. Since

Table 2

Bivariate analyses of school and classroom characteristics by transmission risk from child-to-child with mask wearing.

Variable	All schools	High transmission risk schools (>median rate)	Low transmission risk schools (≤median rate)	P-value
Total, n (%)	19 (100)	9 (47.4)	10 (53.6)	
Sampling season, n (%)				
Heating	19 (100)	9 (47.4)	10 (53.6)	
Cooling	15 (78.9)	7 (46.7)	8 (53.3)	
Both	15 (78.9)	7 (46.7)	8 (53.3)	
Location, n (%)				
Bronx	4 (21.0)	0 (0)	4 (100)	0.056 ^a
Brooklyn	5 (26.3)	2 (33.3)	3 (66.7)	
Manhattan	3 (15.8)	3 (100)	0 (0)	
Queens	5 (26.3)	2 (33.3)	3 (66.7)	
Staten Island	2 (10.5)	2 (100)	0 (0)	
School has mechanical ventilation, n (%)				
Yes	7 (36.8)	3 (42.8)	4 (57.2)	1.000 ^a
No	12 (63.2)	6 (50.0)	6 (50.0)	
Age of school, n (%)				
≥100 years old	5 (26.3)	1 (20.0)	4 (80.0)	0.364 ^a
50–99 years old	9 (47.3)	6 (66.7)	3 (33.3)	
<50 years old	5 (26.3)	2 (40.0)	3 (60.0)	
Median household income (\$) in neighborhood school serves, n (%)				
20K- ≤40K	9 (47.3)	4 (44.4)	5 (65.6)	0.182 ^a
>40K- ≤80K	5 (26.3)	1 (20.0)	4 (80.0)	
>80K	5 (26.3)	4 (80.0)	1 (20.0)	
Total classroom, n (%)	155 (100)	74 (47.7)	81 (52.3)	
Classrooms sampled by season, n (%)				
Heating	86 (55.5)	40 (46.5)	46 (53.5)	
Cooling	69 (44.5)	34 (49.3)	35 (50.7)	
Both	54 (34.8)	26 (48.1)	28 (51.9)	
Classroom size (m ²)				
Mean (SD)	57 (14)	55 (16)	58 (16)	0.640 ^b
Median (Range)	56 (10–100)	56 (10–100)	56 (41–100)	
Average number of students per class				
Mean (SD)	23 (8.3)	23 (9.5)	23 (7.2)	0.821 ^b
Median (Range)	24 (4–50)	26 (4–50)	24 (8–32)	
Classrooms with no windows or broken windows, n (%)				
Yes	18 (17.8)	11 (61.1)	7 (38.9)	0.298 ^a
No	83 (81.2)	37 (44.6)	46 (55.4)	

^a Fisher’s exact test.

^b Wilcoxon signed-rank test.

a subset of classrooms were sampled twice, during both the heating and cooling seasons, we adjusted for the correlated nature of the data due to repeated measurement using general estimating equations. All independent variables in the initial model entered the backwards stepwise regression and were removed one-by one based on the criteria of p<0.10 for inclusion in the final model. Variables that remained in the final model were checked for two-way interactions separately (none were significant). Least square means were used to determine covariate-adjusted mean.

3. Results

Table 2 shows the characteristics of the participating schools. Over the course of the study, 101 unique classrooms were sampled from 19 schools, with 54 classrooms sampled both during the heating and during the cooling seasons. Most schools were in the boroughs of Queens and Brooklyn (52%) and a plurality (47%) were in neighborhoods with a median household income between \$20,000 and \$40,000 per year. More than half of the schools were almost 100 years old with an average building age of 83 years. Only 37% of schools had mechanical

ventilation, which includes all schools built after 1939, and 18% had no windows or windows that were broken and would not open. The average classroom size was 56 m² and the mean number of students per classroom was 23, but there was large variation (range: 9–30 students).

There were no significant differences in school characteristics (p>0.20) by transmission risk level, but the association with borough of school location was borderline significant (p=0.056) with the schools in Manhattan and Staten Island all in the high-risk group while those in the Bronx were all in the low-risk group. Neighborhood income was also of borderline significance (p=0.182) with schools in the highest income category more likely to be at high risk (80.0%) compared to those in the middle-income (20.0%) and low-income (44.4%) groups.

Classroom CO₂ concentrations, percent RH, and temperature are described in Table 3. Carbon dioxide concentrations did not differ significantly (p=0.325) by round, but RH (p<0.001) and temperature (p=0.038) were significantly lower in the heating season compared to the cooling. On average classrooms tended to be 20% less humid and about 1 °C cooler in the heating season.

The mean outdoor airflow differed significantly (p=0.048) between heating versus cooling season sampling, with the outdoor airflow in classrooms doubling during the cooling season (1100 m³/hour) compared to the heating season (560 m³/hour). This increase in outdoor airflow during the cooling season was seen in both classrooms with mechanical ventilation and those without (i.e., natural ventilation). Classrooms in schools located in neighborhoods with highest median household income had the lowest outdoor airflow rate (390 m³/hour) compared to schools located in neighborhoods with the middle (1200 m³/hour) and lowest (830 m³/hour) median household income. Classrooms with broken windows or no windows had less outdoor airflow in the cooling season, but approximately the same amount during the heating season (Table 4).

The mean probability of transmission varied widely depending on who was infected (from a student or teacher), to whom the infection was transmitted (to a student or teacher), and whether everyone in the classroom was wearing a mask or no one was wearing a mask (probability of transmission range: 0.0015–0.81). Consistent mask wearing was associated with lower transmission rates (with mask range: 0.0015–0.55; without mask range: 0.0031–0.81). When mask wearing was consistent, mean transmission was highest from teacher to student (0.20) compared to student to teacher (0.14) and student to student (0.046). As might be expected, when masks were not worn, mean transmission across all dyads was increased, with a similar pattern of higher transmission from teacher to student (0.35), student to teacher (0.26), and student to student (0.091). Mean transmission probabilities were consistently higher in the heating season compared to the cooling season (heating season range: 0.011–0.70; cooling season range: 0.0015–0.81; p-values comparing heating and cooling season all <0.05) (Table 5).

The final stepwise multivariable regression model of the probability of student to student transmission without a mask is presented in Table 6. Adjusting for other significant covariates, there was a 28% increase in the probability of transmission in the heating season compared to the cooling season (beta=0.108; p<0.001; mean transmission probability 0.078 vs 0.061). Building age was also significantly associated with transmission with the probability higher in the newest schools (beta=0.237; p=0.095; mean transmission probability=0.083) and middle-age schools (beta=0.230; p=0.013; mean transmission

Table 3
Classroom CO₂ concentrations, temperature, and RH.

Variable	Heating season				Cooling season				P-value for paired T-test
	Mean	Median	Std	Range	Mean	Median	Std	Range	
CO ₂ (ppm)	980	890	310	510–1900	990	800	460	430–2200	0.325
RH (%)	31	30	8.9	8.7–56	53	52	12	26–82	<0.001
Temperature (°C)	23.4	23.4	1.9	19.6–29.5	24.2	24.1	1.3	21.7–27.7	0.038

Table 4
Mean outdoor airflow stratified by round.

Variable	Mean (SD) outdoor airflow (m ³ /hour)			P-value for paired T-test
	Overall	Heating season	Cooling season	
Overall	820 (1600)	560 (420)	1100 (2300)	0.048
Median household income (\$)				
20K- ≤40K	830 (1200)	600 (390)	1120 (1800)	0.495
>40K- ≤ 80K	1200 (2600)	690 (560)	2000 (3800)	0.035
>80K	390 (250)	370 (210)	420 (300)	0.616
HVAC				
Yes	940 (2200)	570 (520)	1400 (3200)	0.027
No	740 (1100)	550 (360)	1000 (1500)	0.557
Classrooms with no windows or broken windows				
Yes	660 (580)	560 (500)	800 (700)	0.101
No	840 (1700)	560 (420)	1200 (2500)	0.836

probability=0.082) compared to schools over 100 years old (mean transmission probability=0.048). Classrooms without mechanical ventilation had significantly higher probability of transmission (beta=0.013, p=0.057, mean transmission probability: 0.081 vs 0.059). Classrooms in the highest income category had a significantly higher probability of transmission (beta=0.196, p<0.001, mean transmission probability=0.099) compared to schools in the lowest (mean transmission probability=0.063).

4. Discussion

Our findings suggest that the risk of SARS-CoV-2 transmission upon the introduction of one infectious person into the classroom is fairly low under the assumption of sedentary to low-activity levels, and this is even lower with consistent mask-wearing (student-to-student transmission risk=0.046). Risk is higher when adults are the susceptible group considered (student to teacher risk=0.14) or infectious (teacher to student risk=0.20) individuals considered. The NYCDOE began resuming in-person learning in mid-September and even though, at the time this paper was prepared, only a little over a quarter of students had attended any in-person classes (Shapiro, 2020), with approximately one million combined students and teachers, the New York City public school system is by far the largest in the U.S. and represents a substantial population at risk for COVID-19 infection. However, currently available data from the New York State Department of Health (NYSDOH) suggests that public schools are not seeding COVID-19 outbreaks to the extent initially anticipated. According to school district-reported data, 324 students and 367 teachers/staff have tested positive for COVID-19 as of October 23rd; and while the total number of tests performed to date were not reported, approximately 1800 to 5700 daily tests were conducted between October 13th and October 23rd in New York City (New York State, D-19, 2020). Additional data as of October 25th from laboratories reporting to the NYSDOH suggest that 2436 individuals aged 5–17 years have tested positive for COVID-19 out of 132,587 tests conducted (New York State, D-19, 2020). These relatively low positive COVID-19 pediatric case

Table 5
Probability of transmission by exposure scenario and season.

Exposure Scenario	Overall		Heating season		Cooling season		P-value for paired T-test comparing heating to cooling season
	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	
Student to student without mask	0.091 (0.050)	0.085 (0.0031–0.29)	0.094 (0.044)	0.086 (0.021–0.22)	0.088 (0.057)	0.077 (0.0031–0.29)	0.032
Student to student with mask	0.046 (0.026)	0.042 (0.0015–0.15)	0.048 (0.023)	0.043 (0.011–0.12)	0.044 (0.030)	0.039 (0.0015–0.15)	0.033
Student to teacher without mask	0.26 (0.13)	0.25 (0.010–0.68)	0.27 (0.11)	0.26 (0.069–0.56)	0.25 (0.14)	0.23 (0.010–0.68)	0.027
Student to teacher with mask	0.14 (0.076)	0.13 (0.0051–0.42)	0.15 (0.067)	0.14 (0.034–0.33)	0.14 (0.086)	0.12 (0.0051–0.43)	0.031
Teacher to student without mask	0.35 (0.16)	0.35 (0.015–0.81)	0.37 (0.14)	0.035 (0.098–0.70)	0.33 (0.18)	0.32 (0.015–0.81)	0.025
Teacher to student with mask	0.20 (0.10)	0.19 (0.0074–0.55)	0.20 (0.089)	0.19 (0.049–0.44)	0.19 (0.11)	0.17 (0.0074–0.55)	0.029

Table 6
Multivariate analyses of log-transformed probability of student to student transmission without a mask by major predictors.

Variable	Univariate models		Multivariate model		Stepwise final model	
	Beta	P-value	Beta	P-value	Beta	P-value
Number of children	-0.013	<0.001	-0.013	<0.001	-0.012	<0.001
Area (m ²)	-0.006	<0.001	-0.005	<0.001	-0.005	<0.001
Round						
Heating	0.097	0.023	0.106	0.014	0.108	0.010
Cooling	-	-	-	-	-	-
Median household income (\$)						
20K–40K	-	-	-	-	-	-
>40K–80K	-0.092	0.1423	-0.107	0.171	-0.075	0.140
>80K	0.152	0.002	0.165	0.001	0.196	<0.001
Building age						
≥100 years old					-	-
50–99 years old	0.041	0.496	0.171	0.004	0.230	0.013
<50 years old	0.056	0.395	0.265	0.011	0.237	<0.001
School has mechanical ventilation						
Yes	-	-	-	-	-	-
No	0.020	0.699	0.156	0.039	0.141	0.057
Classrooms with no windows or broken windows						
Yes	-	-	-	-	NA	NA
No	-0.031	0.658	0.028	0.612	NA	NA
Location						
Bronx	-	-	-	-	NA	NA
Brooklyn	0.114	0.068	0.061	0.239	NA	NA
Manhattan	0.242	<0.001	0.140	0.029	NA	NA
Queens	0.043	0.541	0.115	0.239	NA	NA
Staten Island	0.338	<0.001	0.008	0.910	NA	NA

NA: Not applicable.

counts are consistent with our finding of generally low risk of transmission in school settings, especially with a successful multi-layered infection control program such as what has been implemented across New York City public schools. Indeed, using a modified Wells-Riley equation, Sun and Zhai suggested that, assuming 45 min of exposure in a classroom setting, SARS-CoV-2 transmission probabilities could be reduced by approximately 4% only by reducing occupancy density by half (Sun and Zhai, 2020). However, we want to emphasize that our estimates were based on the introduction of one infectious person into a classroom and the validity of this assumption of a low contact rate with susceptible will vary depending on the prevalence of the disease. Currently COVID-19 rates in New York City are fairly low (New York City Department, 2020a), especially in comparison with rates at the beginning of the epidemic. However, rates in New York City are on the rise (New York City Department, 2020a) and higher rates could lead to multiple exposures within the classroom setting, thus increasing transmission rates exponentially.

In addition to precautionary measures being taken by schools in New York City, such as social distancing and face mask-wearing (New York City Department, 2020c), the results of this study suggest that the rate of outdoor airflow in indoor classrooms is an important factor in SARS-CoV-2 transmission risk. Lower transmission risk was associated with having mechanical ventilation, as would be expected. Furthermore, we found significantly lower transmission risk associated with the oldest school age (>100 years), as well as with schools located in neighborhoods with lower household income. These schools (older and located in lower-income neighborhoods) are likely to be “leakier” than more recently constructed or recently renovated schools in higher-income neighborhoods, which were likely more purposefully designed and/or retrofitted to maximize energy efficiency by reducing infiltration of outdoor air and exfiltration of indoor air (Lawrence Berkeley National, 2020). While beneficial from an energy saving standpoint, newer and recently renovated schools likely have lower outdoor air exchange rates, which results higher SARS-CoV-2 infection transmission risk. This is one piece of good news for residents of the lower-income neighborhoods that have been hardest hit by this epidemic. However, the risk of transmission increases relative to the number of infected students and lower income neighborhoods have a larger number of cases within the community to potentially seed the classroom. For example, average student to student transmission probability while wearing a mask in the lowest median household income group was 0.045, which increases to 0.087 with two infected students, and 0.13 with three infected students.

Transmission risk estimates all increase during the heating season compared to the cooling season, presumably because of lower outdoor airflow rates as building occupants close windows and doors to the outside to retain heat. As the winter season approaches, this finding has important implications for school officials who may need to revise current infection control plans to account for seasonality. Officials may consider the possibility of allowing for windows and doors to remain open during the winter months while classrooms are occupied, to the extent possible, to allow for greater outdoor airflow, while simultaneously increasing indoor heat levels to retain occupant comfort. This simple, yet highly efficacious, infection control measure was also widely implemented in New York City buildings to reduce the transmission risk of the Spanish influenza virus during the early 20th century (Sisson, 2020).

While the probability of transmission of SARS-CoV-2 from student-to-student was generally low, it increased approximately three to four times for student-to-teacher and teacher-to-student transmission scenarios, respectively. This increased probability is a result of larger inhalation and quanta generation rates in adults compared to children. This is particularly concerning since a high proportion of adults working in schools (teachers and employees) have comorbid conditions or other risk factors that put them at increased risk for serious COVID-19 illness (Selden et al., 2020). One way to reduce transmission in the classroom without engineering controls, such as ventilation, would be to issue

teachers N95 filtering face piece respirators and ensure proper fit. One study found that at an inhalation rate of 1.8 m³/hour, N95 penetration of Bacillus subtilis phage and T4 viruses, which are similar in volumetric equivalent sizes to SARS coronavirus, were 0.58% and 0.23%, respectively. Assuming a conservative penetration rate of 5%, if teachers wore N95 respirators in the classroom, the overall mean probability of teacher to student transmission (while the student was wearing a cloth face mask) would reduce from 0.20 to 0.016 and student (with mask) to teacher from 0.14 to 0.011. Although the health risks of wearing N95 respirators are considered low, prior to receiving a respirator from an employer, an employee must fill out a medical questionnaire that is reviewed by a healthcare professional and undergo a follow-up medical examination, if deemed necessary (Department of Labor., 2020). Additionally, a respirator must be fit tested to ensure a proper seal between the facepiece and wearer (Department of Labor., 2020). While the additional regulatory requirements associated with respirator use by teachers may be burdensome for school districts, the severity of potential health effects among adults diagnosed with COVID-19 increases with age and comorbidity (Department of Health, 2020) and therefore the added protection is likely worth the investment.

In our probability estimates, we did not account for the additional reduction in transmission through air filtration in the ventilation system. Most HVAC system use filters with a low MERV rating that may not capture virus aerosols from the airstream. New York City public schools currently use a MERV rating of 8, which has a collection efficiency of 20% for particles in the size range of SARS-CoV-2. New York City has begun a process to update the filter to MERV rating of 13, which has a collection efficiency of 85% (The American Society of H, 2020). However, some HVAC systems may not be able to accommodate the increased pressure drop across the filter and replacing the filter may not be possible in all classrooms (The American Society of H, 2020). If schools cannot change the filter to a higher MERV rating, then air recirculation should be limited. We did not evaluate the effects of temperature and relative humidity on SARS-CoV-2 transmission risk in this study; however, mean temperatures of 23.4 °C and 24.2 °C, and mean relative humidity levels of 31% and 53% were measured during the heating and cooling seasons, respectively. While empirical evidence is still lacking, current evidence suggests that the viability of SARS-CoV-2 in the indoor air is likely diminished at high temperatures and relative humidity levels between approximately 40% and 60% (Quraishi et al., 2020; Ahlawat et al., 2020; Azuma et al., 2020; Clements et al., 2020). Surface viability of the virus may similarly be inactivated under these indoor conditions (Biryukov et al., 2020; Morris et al., 2020). Further, environmental data indicate that warm, humid climates tend to curtail the transmission of SARS-CoV-2, though other sociopolitical confounders (e.g., public health policies) must be considered (Mecenas et al., 2020; Huang et al., 2020; Liu et al., 2020). Thus, to the extent possible, New York City public schools should strive to maintain these indoor environmental conditions to further reduce SARS-CoV-2 transmission risk.

We acknowledge that our findings are likely an underestimation of the true impact of possible SARS-CoV-2 transmission tied to in-person learning in schools, as we do not include onward transmission to family members, nor do we consider bio-aerosols and surface contamination from toilet flushing in the absence of a lid (McDermott et al., 2020; Li et al., 1994). Many public toilets in the U.S. do not have lids (Chiueh, 2020) and more than half of New York City school bathrooms lack adequate ventilation (Carlson, 2020), so this could be an important source of school transmission outside of the classroom. On the other hand, not accounting for the possible reduction of risk from the filtration associated with ventilation systems, as described above, as well as our conservative estimate of the reduction in risk from consistent

mask-wearing (estimated at 30% due to unlikely consistency of use among children) may have led to an over-estimation of risk.

The small sample size of our study may limit the generalizability of the results. We only collected exposure measurements in 101 classrooms from 19 elementary schools located throughout New York City. The schools sampled in this study tended to be slightly older and largely located in lower income communities compared to other New York City elementary schools. Overall, there are 915 schools operated by the NYCDOE that enroll students in grades 1–5. Of these schools, 15.7% were at least 100 years old, 47.4% were 50–99 years old, and 36.8% were less than 50 years old. Additionally, about half of the schools in our study were located in neighborhoods with a median household income between \$20,000 to \$40,000, which is markedly lower than the median household income of New York City (\$63,998) (United States Census Bureau, 2020). Thirty-seven percent of schools in our study had mechanical ventilation; however, we do not have data on ventilation status or usage in other New York City elementary schools.

5. Conclusions

This study found generally low risk of SARS-CoV-2 transmission in New York City classrooms and risk was, surprisingly, lowest in older schools and those located in low-income neighborhoods, probably due to their lower air-tightness compared to newer or recently renovated schools. However, risk was higher for adults, who are more likely to experience severe illness when infected, than children and increases during the heating season, which we are approaching. In addition, risk will increase as the number of infectious individuals in the community served by the schools increases, and cases in New York City are on the rise. In order to reduce transmission risk, schools should increase outdoor airflow by increasing natural ventilation (open the windows); for schools with mechanical ventilation, low MERV rated filters should be replaced with higher rated filters and air recirculation should be limited. Finally, teachers should be fitted with N95 respirators as opposed to a cloth or surgical face mask.

Author statement

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Human subject

This work did not involve human subjects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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