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Research Report

Student close contact behavior and COVID-19 transmission in China's classrooms

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Abstract

Classrooms are high-risk indoor environments, so analysis of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission in classrooms is important for determining optimal interventions. Due to the absence of human behavior data, it is challenging to accurately determine virus exposure in classrooms. A wearable device for close contact behavior detection was developed, and we recorded >250,000 data points of close contact behaviors of students from grades 1 to 12. Combined with a survey on students' behaviors, we analyzed virus transmission in classrooms. Close contact rates for students were 37 ± 11% during classes and 48 ± 13% during breaks. Students in lower grades had higher close contact rates and virus transmission potential. The long-range airborne transmission route is dominant, accounting for 90 ± 3.6% and 75 ± 7.7% with and without mask wearing, respectively. During breaks, the short-range airborne route became more important, contributing 48 ± 3.1% in grades 1 to 9 (without wearing masks). Ventilation alone cannot always meet the demands of COVID-19 control; 30 m^3/h/person is suggested as the threshold outdoor air ventilation rate in a classroom. This study provides scientific support for COVID-19 prevention and control in classrooms, and our proposed human behavior detection and analysis methods offer a powerful tool to understand virus transmission characteristics and can be employed in various indoor environments.

Keywords: COVID-19, children health, school pandemic prevention, close contact behavior, ventilation

Significance Statement

To obtain the actual close contact behaviors of students and COVID-19 transmission characteristics in classrooms, we developed a wearable device for close contact behavior detection based on semisupervised learning and deployed it in a sample field trial in school classrooms. We found that the close contact behaviors of students can markedly affect the transmission of SARS-CoV-2 and that students in the lower grades had higher close contact rates and greater virus transmission potential. The calculated dominant virus transmission routes and required outdoor air ventilation rates differ from previous assumptions, suggesting that current approaches need to change to better mitigate virus transmission in school classrooms.

Introduction

The COVID-19 pandemic has evolved into a global public health threat with associated economic and social burden (1). Classrooms should receive more attention since they are where virus transmission frequently occurs, since students spend long periods in class and have frequent close contacts, and indoor ventilation is frequently insufficient (2, 3). In fact, many documented cases of COVID-19 spread occurred in classrooms and schools (4). Most governments temporarily closed schools at various times during the pandemic to prevent the spread of the virus, impacting >90% of students worldwide (5).

Close contact is usually defined as any full or partial face-to-face interaction between individuals within 1.5 m, which occurs frequently between people (6). In this study, we defined close contact as a full or partial face-to-face (e.g. face-to-side/back) interaction (with or without conversation) within 1.5 m and the angles of the exhaled jet. This has a direct impact on exposure to infectious pathogens, so understanding the characteristics of close contact behaviors is essential for evaluating the

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potential for virus transmission in specific environments (6). To the best of our knowledge, no previous studies have focused on infection spread via the close contact route in classrooms (7), mainly due to the absence of reliable and convenient equipment to record human close contact behavior (8).

We developed a wearable device that could detect and record close contact behavior and used it for a sample field trial in school classrooms to record students' close contact behaviors. The sample subjects included both male and female students from grades 1 to 12. This study is the first to use a wearable device to record the real-time close contact behaviors of students from all grades, including interpersonal distance, facial orientation, and relative position of the students. Combing these behavior data with the aerodynamics of exhaled particles, we could quantitatively assess severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) spread in classrooms (e.g. the relative contribution of each transmission route). In addition, students' knowledge of SARS-CoV-2 was obtained from a questionnaire survey and compared with our calculated results. Finally, we investigated the efficacy of preventative interventions and suggest appropriate mitigation measures (e.g. outdoor air ventilation rate). This work is useful for understanding students' close contact behaviors, SARS-CoV-2 transmission characteristics, and effective epidemic prevention strategies in classrooms, which is critical for reopening and managing schools during an airborne virus pandemic.

Materials and methods

Surveying human behavior

For this research, we developed a wearable device for recording close contact behavior and used it in a sample field trial in school classrooms. The device is composed of a depth sensor, a portable power source, and a microcomputer. The frame rate of the device is 1/6 s, and the resolution for distance detection is 1 mm. The horizontal angle of view is −45.6 to 45.6° with an accuracy of 0.142°/pixel, and the vertical angle of view is −32.6 to 32.6° with an accuracy of 0.136°/pixel. This detection range can cover the jet angle from breathing and talking (9). The device was supplied by a power source with 10,000 mA and 64-Gb memory card (Fig. S1). It could continually detect human close contact behaviors for at least 12 h, and the location and interpersonal distance between experimenter and target can be determined.

More details on the detection devices can be found in our previous study (8).

Our sampling period was 2022 March 1 to 18, in Taizhou Minxing School, one of the largest private schools in Jiangsu Province, China. The Taizhou Minxing School has ∼150 classes with >5,000 students from grades 1 to 12. Twenty-four students (12 males and 12 females, two per grade) were selected as device wearers. They were asked to sit in the middle of the classroom (overcoming the influence of seat distribution according to students' behavior) and to wear the device and act normally (information on the classrooms is shown in Tables S1 and S2). Each subject was sampled for 55 min (45 min during class and 10 min during breaks). To minimize the influence of other factors on human behavior (e.g. personal focus), we only sampled in the second and third classes for the core subjects (Chinese, Math, and English) in the morning (9:15 AM to 10:50 AM). This experiment was approved by the Ethics Committee of Zhejiang University (No. IIT20220116B).

Finally, the sample results including recorded images of close contact behaviors [interpersonal distance, face orientation, relative position (horizontal and vertical), close contact rate, and number of people per close contact] were automatically processed by semi-supervised learning (Text S1). We averaged the values of 6 students from each three-grade group, to represent their close contact behaviors to obtain the human behavior data for four groups (grades 1–3, 4–6, 7–9, and 10–12).

Field measurement of outdoor air ventilation rate

In addition to the close contact route, long-range airborne transmission also played an important role in the spread of SARS-CoV-2, especially in those indoor environments with poor ventilation (10). Outdoor air ventilation is critical for reducing indoor virus transmission, especially via the long-range airborne route. In this study, we measured outdoor air ventilation rates in classrooms, using CO_2 as the tracer gas. Fine temporal resolution monitoring of CO_2 concentrations (ppm) was done, inside and outside the selected classrooms, using an indoor environmental monitoring instrument (iBEM). The details of this process can be found in Text S2.

Questionnaire survey

We also conducted an on-site questionnaire survey of students in grades 1 to 12, from 2022 March 1 to 18, at the Taizhou Minxing School. The survey was designed to obtain their personal information (gender and grade), behavior during classes and breaks such as talking rate (the ratio of the time a person spends talking, to the length of class or break), and knowledge of COVID-19. The questionnaire can be found in Text S3.

Evaluation of the virus transmission potential

The respiratory actions, such as breathing and talking, of an infected person can release droplets that contain infectious pathogens, and exposure to these droplets may lead to infection. There are various definitions for the transmission routes of respiratory pathogens. In this paper, three transmission routes were considered (Figs. 1 and S2): short-range inhalation, large droplet deposition, and long-range inhalation. The former two routes are often referred as close contact transmission.

The exposure mechanism for large droplet transmission refers to the deposition of large droplets on the lip/eye/nostril mucosa of another person in close proximity (11). Short-range airborne refers to the direct inhalation of fine droplets and droplet nuclei. The exposure mechanism of these two transmission routes are determined by interpersonal distance, facial orientation, and relative position (horizontal and vertical). For long-range airborne transmission, droplets $<5\,\mu$m and not inhaled during close contacts are considered, as they can follow the airstream and travel long distances after being exhaled (12).

In this research, the probability of infection P and the number of infection cases C are used to evaluate the virus transmission potential, which can be calculated according to the dose–response model, the details of which can be found in Fig. S3, Text S4, and Table S1.

Results

Human behavior characteristics during classes and breaks

We analyzed the close contact behavior of students from grades 1 to 12 during classes and breaks, based on the collected 251,558 data points of close contact events. The close contact rate,

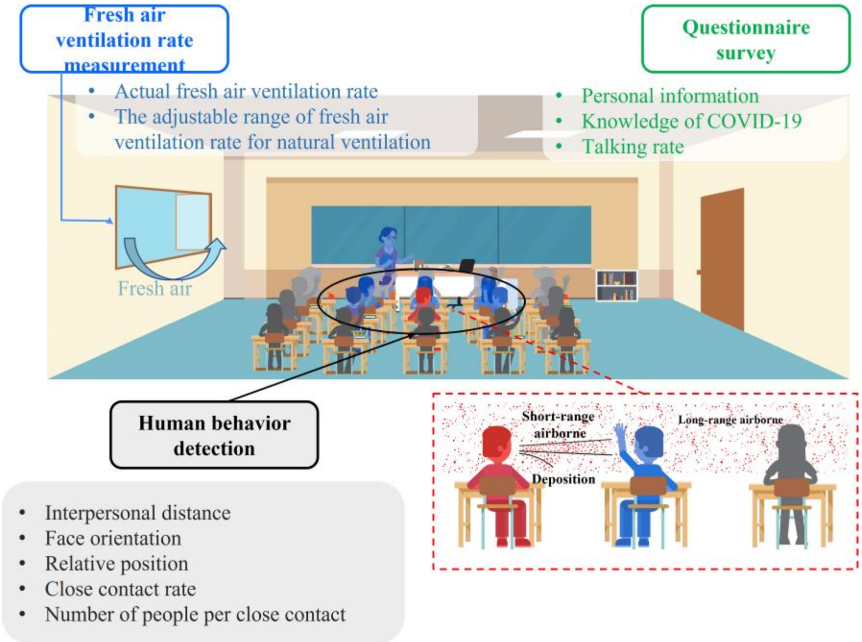

Fig. 1. Potential transmission routes of SARS-CoV-2 in the classroom and our research methods.

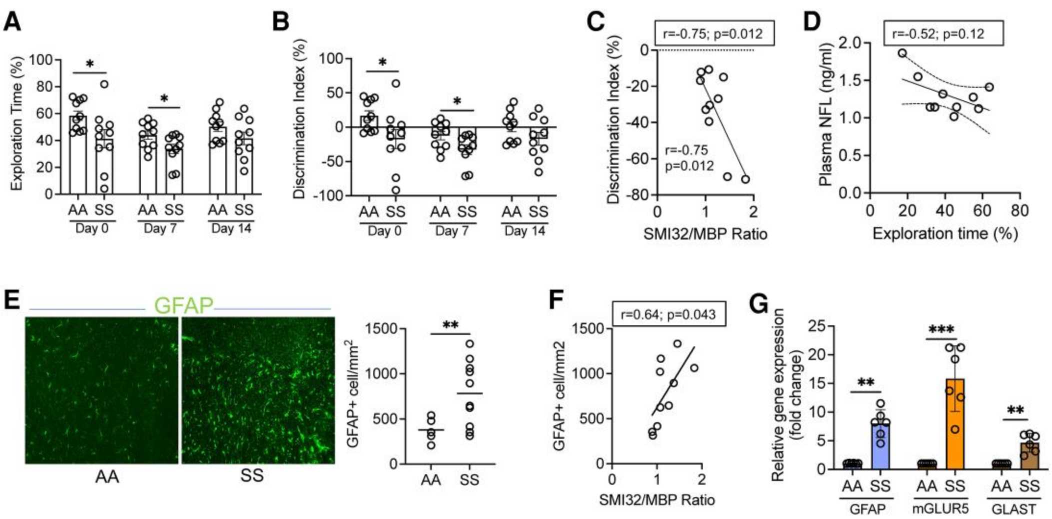

Fig. 2. Close contact–related behavior data in classrooms. A) Probability distribution of interpersonal distance and face orientation (F-F, face to face; F-S, face to side, F-B, face to back); B) probability distribution of relative horizontal and vertical angles by grade; C) talking rates during classes with different subjects and breaks by grade.

interpersonal distance, face orientation, and relative position were selected as key parameters (Figs. 2 and S4).

Close contact rates are higher during breaks than during classes, and younger students usually have higher close contact rates, the close contact rates are 48.6, 45.6, 32.8, and 21.8% during classes and 60.5, 59.9, 43.5 and 28.4% during breaks for grades 1–3, 4–6, 7–9, and 10–12, respectively (Fig. S4). During classes, face to back is the main orientation for close contacts because students usually face the blackboard and teacher. The probability of face-to-back close contact increases with grade level, and accounts for 67.8, 75.7, 82.3, and 84.6% of close contacts for grades 1–3, 4–6, 7–9, and 10–12, respectively. Face-to-face contacts were only 11.3, 8.1, 2.9, and 2.8% for grades 1–3, 4–6, 7–9, and 10–12, respectively. During breaks, face to face was dominant, accounting for 52.9, 51.5, 45.6, and 40.9% of close contacts, for grades 1–3, 4–6, 7–9, and 10–12, respectively.

In general, the distribution pattern of relative position is similar for students in different grades. The absolute horizontal relative angles were usually concentrated between 5 and 35° during classes, and 15–25° was the dominant relative angle range. During breaks, the absolute horizontal relative angles were usually concentrated between 5 and 25°, and 5–15° was the dominant relative angle range. The vertical relative angle was usually concentrated between −5 and 25° during both classes and breaks, with relatively few vertical angles being less than −5°, mainly due to the seating arrangement based on the height of students, with students in the back seats generally being taller than those in front.

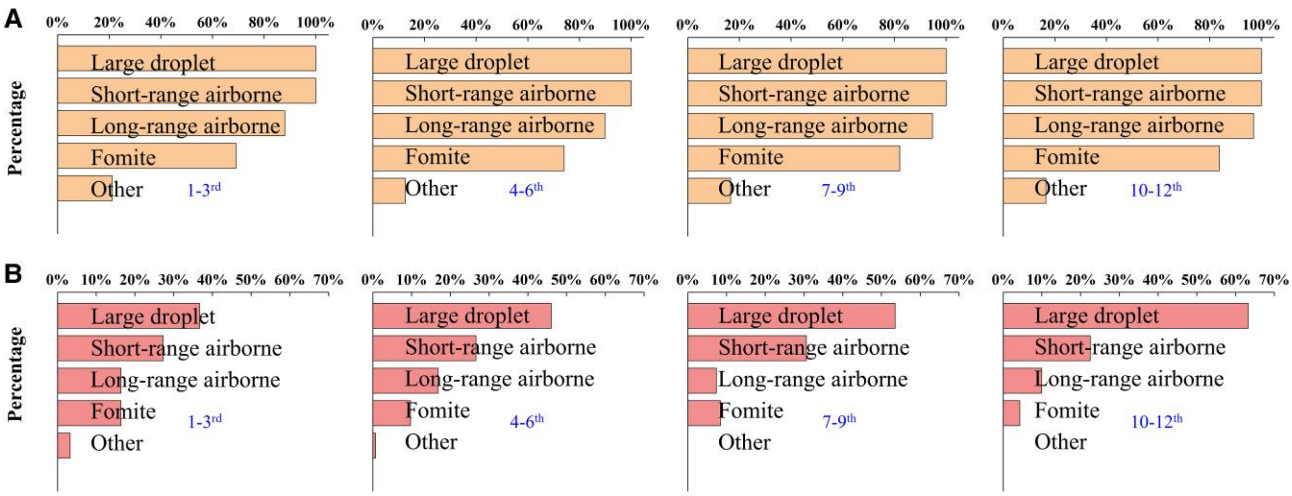

Fig. 3. Students' responses regarding A) possible transmission routes and B) the dominant transmission route.

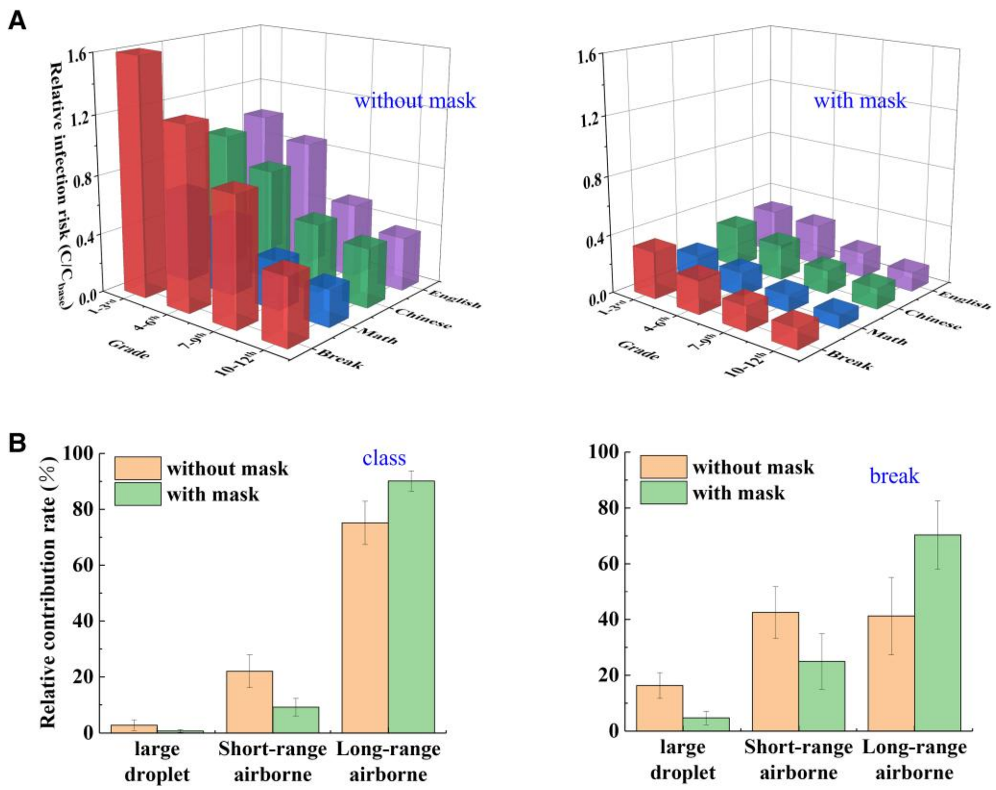

Fig. 4. Relative infection risk. A) Different grades and subjects; B) relative contribution rates of different virus transmission routes.

Using the questionnaire survey results, we summarize the talking rates of students in the different grades in Fig. 2C. During breaks and classes, the talking rate generally decreased with increasing grade. English, Chinese, and Math classes had average talking rates of 27, 25, and 15%, respectively.

Knowledge of SARS-CoV-2 transmission routes

In general, the threat of COVID-19 in students' subjective perception gradually decreased with increasing grade. Almost 40% of students in the first six grades believed that the risk of contracting COVID-19 in a classroom is high or very high, while half of students in grades 7 to 12 believed such a risk was intermediate (Fig. S5).

Almost all students believed SARS-CoV-2 can spread via large droplets and short-range transmission, and most students believed long-range airborne (90%) and fomite (70%) are also consequential. About half of the students believed that large droplets were the most important SARS-CoV-2 transmission route in classrooms, followed by short-range airborne transmission (27%). Less than 15% of the students believed that the long-range airborne transmission route was the most important. The detailed data is shown in Fig. 3 and Table S3.

Virus transmission characteristics for different transmission routes

The calculated infection risk for different conditions

In this section, we look at, and then analyze, several conditions classified by grade, period (class and break), and mask wearing. Details such as the protection efficiency of masks can be found in Table S4 and Text S5.

Due to a lack of information regarding the dose–response relationship of SARS-CoV-2, the *infection cases per hour* (C) cannot be accurately obtained. We took the C value for grade 1 to 3 students in English class who were not wearing masks (C_{base}) as a base line and employed C/C_{base} which indicates the number of additional dimensionless infections per hour, as an index of *relative infection risk* to analyze virus transmission potential for different conditions (Fig. 4A).

When not wearing masks, the relative infection risk in Chinese ($C/C_{base} = 0.64 \pm 0.21$), and English ($C/C_{base} = 0.68 \pm 0.25$) classes of the same grade students, was similar. Math classes, by contrast, had a relatively low transmission potential ($C/C_{base} = 0.42 \pm 0.14$), mainly due to the low talking rate. During breaks, the relative infection risk was more significant ($C/C_{base} = 1.03 \pm 0.42$). In addition, the relative infection risk among students decreased as their grade level increased, the C values for the grade 7–9 and 10–12 students were about 55 and 43% of that for primary school students (grades 1–6) during classes, respectively. During breaks, these values were 61 and 32%.

The mitigation effect of wearing masks decreased as grade level increased. Wearing masks during classes can reduce the relative infection risk to about 30, 32, 34, and 38% of their initial values for grades 1–3, 4–6, 7–9, and 10–12 grades, compared with not wearing masks. The protective effect of masks is more obvious during breaks, and the corresponding relative infection risks were 20, 19, 19, and 30% of those not wearing masks. The infection risk during breaks when wearing masks was about 107, 83, 97, and 99% of that during English classes for grades 1–3, 4–6, 7–9, and 10–12 grades, respectively. Math classes still had a relatively low transmission risk, which was 60–65% of the value in Chinese and English classes.

Relative contribution rates of different transmission routes

The relative contribution rates of virus transmission, with and without masks during classes and breaks, are shown in Figs. 4B

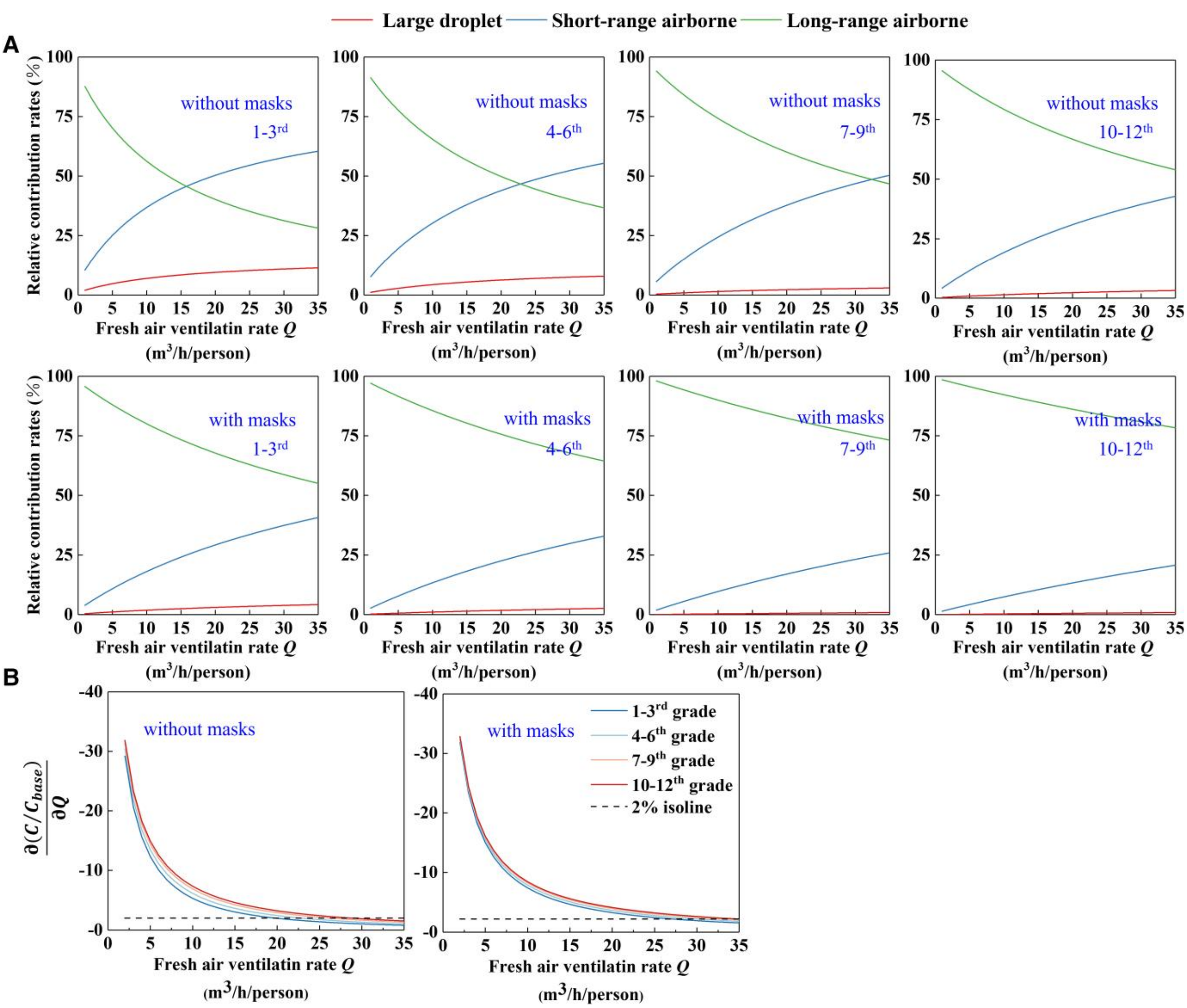

Fig. 5. A) Relative contribution for each transmission route at different outdoor air ventilation rates and B) the partial derivative of C/C_{base} with respect to the outdoor air ventilation rate.

and S7. Long-range airborne was the dominant route during classes when masks were not worn. The contribution rate of the long-range airborne route was greater with increasing grade level, and the short-range airborne and large droplet routes were lower.

During classes, the contribution rates changed little with grade level. The long-range airborne transmission route was dominant, accounting for roughly 75 (not masked) and 90% (masked). Short-range airborne was the second most important transmission route, accounting for about 22 (not masked) and 9% (masked). The large droplets transmission route contributed <3% of virus exposure.

During breaks and without masks, the contribution rates of each transmission route varied according to grade. For students in grades 1–3, 4–6, and 7–9, the short-range airborne transmission route was dominant, accounting for about 52, 46, and 45%, followed by the long-range airborne transmission route which accounted for 27, 35, and 38%, respectively. The long-range airborne transmission route was dominant for students in grades 10–12 at 64%, while short-range airborne and large droplets transmission routes accounted for 27 and 9%, respectively.

During breaks with masks, the long-range airborne transmission route was much more dominant as grade level increased, accounting for about 54, 63, 79, and 85% for grades 1–3, 4–6, 7–9, and 10–12, respectively, followed by the short-range airborne transmission route which accounted for 38, 31, 18, and 13%, respectively.

Analysis of the influence of ventilation rate

With an increasing outdoor air ventilation rate, the large droplet and short-range airborne transmission routes followed a gradually slowing upward trend in their relative contribution rates, while the long-range airborne transmission route was the opposite (Fig. 5). The key outdoor air ventilation rate (the rate at which the short-range airborne surpassed long-range airborne and becomes the dominant transmission route) for students from grades 1–3, 4–6, and 7–9 not wearing masks, were 15, 22, and 32 m^3/h/person, respectively. For the grade 10–12 students, the long-range airborne route was always the dominant transmission route regardless of whether masks were worn or not.

Specifically, $\frac{\partial(C/C_{base})}{\partial Q}$, the partial derivative of C/C_{base} with respect to the outdoor air ventilation rate Q, was used to represent the change in the relative infection risk with each additional 1 m^3/h/person of outdoor air ventilation. In other words, it can reflect the trend in the relative infection risk with increasing outdoor air ventilation rates (Fig. 5).

The relative infection risk declined with increasing outdoor air ventilation rate, but this trend gradually flattened out. The absolute value of $\frac{\partial(C/C_{base})}{\partial Q}$ changed little (≤2%) when the outdoor air ventilation rate exceeded 30 m^3/h/person. Above this point, continually increasing outdoor air does not reduce the infection risk effectively but consumes more energy. Therefore, we suggested a 30 m^3/h/person outdoor air ventilation rate in classrooms.

Based on our field measurements, the adjustable range of outdoor air ventilation during class is between 5 and 35 m^3/h/person, depending on different behaviors of opening doors and windows in classrooms (Fig. S6), which means that the required 30 m^3/h/person can be realized through natural ventilation alone. However, we found that the actual outdoor air ventilation rate during class was ~8 m^3/h/person, and the difference between grades was not significant, indicating that the classrooms are usually closed, which may lead to a high risk of COVID-19 transmission in schools.

Discussion

In this study, we monitored close contact behaviors of students from grades 1 to 12 during both classes and breaks, using wearable depth detection devices. Based on this identified close contact behavior and questionnaire survey data, we analyzed SARS-CoV-2 transmission via three routes (short-range airborne, large droplets, and long-range airborne) in classrooms by period (class and break), grade, and subject.

Indoor human behaviors have a direct impact on virus exposure in specific environments (6). Several previous studies have analyzed infection risk based on hypothesized human behaviors or on interpersonal distance alone, but this is oversimplified and unrealistic (13, 14). Radio frequency identification (RFID) is usually used to determine interpersonal distance; however, the spatial (1.5 m) and temporal (20 s) resolution are too coarse to meet our demands (15). In addition, other close contact parameters (e.g. facial orientation and relative position) can also dramatically affect virus exposure. To solve these difficulties, one study successfully used the video data from a restaurant associated with a COVID-19 outbreak to obtain close contact behaviors (16). However, video data for each indoor environment are not always available, and the accuracy of the data is limited since such an approach is subject to human error. Our wearable device that is based on depth image determination and semi-supervised learning can automatically obtain the close contact behaviors mentioned above, with fine spatial (1 mm) and temporal (1/6 s) resolution (8, 14). Therefore, our proposed human behavior detection method can overcome the shortcomings mentioned above.

Long-range airborne, short-range airborne, and large droplets are three main virus transmission routes (17), but few studies consider multiple transmission routes simultaneously, particularly based on real human behaviors. Therefore, it is not clear whether, or which, single route plays a key role in virus transmission, due to a lack of real behavior data (13). In addition, investigations of virus transmission in schools are often confined to class hours, and a single classroom, and generally ignore virus transmissions characteristics among students from different grades, during breaks, and in classes with different subjects (18).

Students from primary, middle, or high schools are between 7 and 18 years old, and their behavior and preferences vary widely. Current evidence suggests that younger children typically contribute less to virus transmission in the general population; however, it is not clear whether the same phenomenon holds in schools (19). Several researchers think that younger students are also less susceptible in schools, due to their smaller lung volume, lower aerosol emission height, and smaller and more sparse contact networks, according to cluster tracing data in Austrian schools from one study (2). However, Chinese students' behavior in schools may differ from Austrian students (Fig. S8). As no significant difference in viral load is observed across age groups (20), we found that Chinese primary school students suffered greater exposure to the virus due to their more frequent close contacts and higher talking rates, leading to the highest risk of infection. This is consistent with a cross-sectional analysis of SARS-CoV-2 infection in educational settings carried out in England (5). During the pandemic, schools were usually closed and offered online classes (10), with students not being able to return to school until the epidemic was completely controlled. Our findings suggest that primary school students should be the last batch of students to return to school from a virus transmission perspective. The typical schedule in Chinese schools is 45 min in class followed by 10-min breaks. Although the calculated number of infection cases during breaks is smaller than for during class, this is mainly due to the shorter time spent on breaks, because the virus transmission speed is actually much faster during breaks. Therefore, we think school administrators should take actions to control virus transmission during breaks, which seems to not have received much attention.

Our study found that short-range airborne was dominant only during breaks when no masks were worn and that long-range airborne was dominant under all other conditions. Such results were different from students' understanding of COVID-19 transmission routes, as they generally believed that large droplets were the dominant route, which was consistent with university students and healthcare workers (21). In terms of the absolute extent of virus exposure for a single transmission route, short-range airborne is much greater than long-range airborne (22). However, since the possibility of close contact between students and an infector is lower than 5% during class (Fig. S9), this indicates that many more students are exposed via the long-range airborne route and that the total exposure of all students to the virus via short-range airborne was lower than for long-range airborne. The difference between students' understanding and the results may lead to increased risk because they may use less effective interventions.

Ventilation has long been recognized as one of the primary measures for indoor air quality control; however, the minimum ventilation requirements in the indoor environment to avoid infectious disease outbreaks are still unknown, due to the lack of sufficient data (23). Many studies have overestimated the role of ventilation in epidemic prevention and control because they tend to focus only on airborne transmission (24, 25). As we know, general dilution ventilation is ineffective for both short-range airborne and large droplet transmission routes, since an air speed of 2–20 m/s is involved in exhalation or coughing jets, while the typical air speed in a room due to dilution ventilation is only ~0.2–0.3 m/s (26). High outdoor air ventilation rates cannot always control infection risk to within a safe range but do consume extra energy. Therefore, the threshold required outdoor air ventilation rate in classrooms should be redefined taking into consideration all transmission routes and real indoor behaviors of students.

In China, the government appealed for a "dynamic zero COVID-19 strategy" which meant "moderate interventions to prevent COVID-19 spread during stable periods of the pandemic when the effective reproduction number is less than 1" (27). We should not try to reduce the risk of infection to zero at all costs, and other public health mitigation measures after an outbreak (extensive testing, tracing, and quarantining of exposed close contacts) should also be effectively implemented (7, 28). Therefore, taking epidemic prevention and control, as well as resource consumption into consideration, we recommend that 30 m^3/h/person be the reference outdoor air ventilation rate in classrooms. Such a ventilation rate is achievable during our experiment. Since the use of natural ventilation is dependent on outdoor weather conditions, air purifiers may be an effective supplementary measure to improve the dilution of indoor air contaminated with virus-laden aerosols (29), when natural ventilation fails to achieve the required ventilation rate. In addition, fresh air systems are recommended for the classroom if economic conditions allow, as they can ensure a stable ventilation rate at all times (30).

The current actual outdoor air ventilation rate is 8 m^3/h/person, which is far below the required value and does not even satisfy the requirements in corresponding national standards for indoor air quality [e.g. hygienic requirements for classroom ventilation in middle and primary school (GB/T 17226-2017)]. This may affect students' cognitive ability and, more seriously, enhance the spread of COVID-19. In addition, other pharmaceutical and nonpharmaceutical interventions such as vaccination, mask wearing, disinfection by ultraviolet (UV) light, and air purification should be implemented according to the diversity of schools and the uncertainty of practical operation in real life (31, 32).

Our developed wearable device can be used in various environments to collect people's close contact behaviors, and these data can be used to build databases of close contact behaviors that will be valuable in various research fields. For example, details of close contact behaviors can help reveal the dynamics of an epidemic at the population scale based on individual-level behavior, thus enhancing the understanding and prediction of epidemic patterns and improving intervention measures. The indoor settings of various hospital departments could be optimized through the study of close contact behaviors between healthcare workers and patients to have improved outcomes.

Our research has a number of limitations. First, behavior data of 24 students from different grades may be inadequate to represent all students. In future research, we will increase the detection time and number of participants to enrich our data to make the results more robust. Second, because a dose–response relationship for SARS-CoV-2 has not been ascertained (33), the absolute infection risk is difficult to assess. Third, teachers were not considered in our simulation, but they can also influence virus transmission in a classroom; we will fill this gap in further research. Finally, the virus concentration generated by infectors varies by individual, so we conducted a sensitivity analysis of virus concentration (viral RNA loads/μL) of SARS-CoV-2 in fine aerosols and large droplets generated by talking and breathing (Table S5).

Supplementary material

Supplementary material is available at *PNAS Nexus* online.

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Author contributions

Y.G. and N.Z. conceived and designed the study. Y.G., Z.D., X.L., and N.Z. contributed to the data collection, original draft, and formal analysis. Y.G., X.L., and N.Z. were responsible for data validation and verification. All authors contributed to reviewing and editing of the manuscripts.

Data availability

All data are included in this manuscript and its supplementary information files.

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