Original Article

Testing mobile air purifiers in a school classroom: Reducing the airborne transmission risk for SARS-CoV-2

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ABSTRACT

Airborne transmission of SARS-CoV-2 through virus-containing aerosol particles has been established as an important pathway for Covid-19 infection. Suitable measures to prevent such infections are imperative, especially in situations when a high number of persons convene in closed rooms. Here we tested the efficiency and practicability of operating four air purifiers equipped with HEPA filters in a high school classroom while regular classes were taking place. We monitored the aerosol number concentration for particles > 3 nm at two locations in the room, the aerosol size distribution in the range from 10 nm to 10 µm, PM_{10} and CO_2 concentration. For comparison, we performed similar measurements in a neighboring classroom without purifiers. In times when classes were conducted with windows and door closed, the aerosol concentration was reduced by more than 90 % within less than 30 minutes when running the purifiers (air exchange rate 5.5 h^{-1}). The reduction was homogeneous throughout the room and for all particle sizes. The measurements are supplemented by a calculation estimating the maximum concentration levels of virus-containing aerosol from a highly contagious person speaking in a closed room with and without air purifiers. Measurements and calculation demonstrate that air purifiers represent a well suited measure to reduce the risks of airborne transmission of SARS-CoV-2 substantially. Staying for two hours in a closed room with a super infective person, we estimate that the inhaled dose is reduced by a factor of six when using air purifiers with a total air exchange rate of 5.7 h^{-1}.

1. Introduction

Currently the transmission risks for viruses of the type SARS-CoV-2 pose a substantial challenge for all situations where people gather in closed rooms, be it in schools, shared offices, meeting rooms, restaurants, bars, etc. Especially in schools, where presence is obligatory and a high density of people in a room is frequently reached, a high level of responsibility rests with the authorities to ensure a safe environment for the school students and teachers.

Currently three transmission pathways are mainly considered important for Covid-19: direct transmission by droplets, airborne transmission by virus-containing aerosol particles and transmission via fomites (Tellier, 2020). The direct infection by droplet transmission is well established as a transmission pathway for SARS-CoV-2. Here it is assumed that large droplets (usually defined as droplets larger than 5 µm) are transferred from one infected person to another, for example, through droplets emitted during coughing, sneezing or speaking. The droplets are assumed to be large enough that they sediment to the ground quickly and that these droplets do not travel more than 1.5 or 2 m horizontally. Morawska and Milton, 2020, recently compiled the evidence for the airborne transmission. Their paper was accompanied by an open letter signed by 237 scientists supporting the view that the airborne transmission did not receive sufficient attention so far. The scientific evidence in favor of the airborne transmission pathway includes, for example, the description of infections that occurred over distances of many meters, such as several infections that occurred in a restaurant in China (Li et al., 2020). Furthermore, aerosol samples containing viable SARS-CoV-2 were collected 4.8 m away from a Covid-19 patient in a hospital ward (Lednicky et al., 2020). Van Dormalen et al., 2020, showed that SARS-CoV-2 remains viable in aerosols with a half-life of 1.1 hours, and some virus remained viable for more than 3 hours. Despite of the mounting evidence in favor of airborne transmission an exact delineation of droplet and airborne transmission pathways is difficult (Tellier et al., 2019, Beggs, 2020; Jayaveera et al., 2020). For most infections it is not possible to reconstruct the exact details of the transmission. It is by now well-known that infected persons frequently stay completely asymptomatic or develop only mild symptoms that are not associated with a potential Covid-19 infection.

Furthermore, infected persons are highly contagious shortly before symptoms of the disease occur (pre-symptomatic). Currently there are no well-established numbers to quantify the fraction of infections that are caused by the different pathways of infection (Jayaweera et al., 2020). These fractions are also expected to change depending on the effectiveness of measures and precautions that are introduced to reduce the transmission. Furthermore, the exact definition of the involved particle and droplet sizes for each transmission pathway is under debate (Beggs et al., 2020). Additionally, it is not known how many virus-containing aerosol particles have to be inhaled by a susceptible person to trigger an infection. Jayweera et al., 2020, states in this respect that "there has been no discernible evidence on the minimum infectious viral load for COVID-19 pandemic, but many researchers speculate that a few hundreds of SARS-CoV-2 virus would be enough to cause the disease among susceptible hosts (Beggs, 2020; SMC, 2020)".

People emit substantial amounts of aerosols and droplets when speaking, which could potentially contain the virus (Asadi et al., 2019; Asadi et al., 2020; Stadnytskyi et al., 2020). The amount of emitted aerosol particles increases with loudness. Furthermore, it was found that so-called super-emitters exist: 20% of the tested persons emitted far more particles than the average (8 out of 40 persons, Asadi et al., 2019). This lead to the hypothesis that these super-emitters could also act as super-spreaders that are responsible for clusters with many infections occurring at single events (Asadi et al., 2020). Asadi et al., 2019, observed that on average 4 particles per second are emitted when a person speaks in a loud voice. These particles have an average size of about 1 µm. It is not well known, in how far these particles emitted during speaking can contain viruses if the speaker is infected with SARS-CoV-2. Lelieveld et al., 2020, argue that in case of super infective emitters about 30% of the particles <5 µm contain virus RNA. But this number is currently not well-established. Stadnytskyi et al., 2020, report higher aerosol emissions from speaking than Asadi et al., 2019. When saying the words „stay healthy", it was estimated that at least 1000 droplet cores that contain virions are emitted per minute with an average diameter of about 4 µm. This would correspond to 16,6 virion-containing particles per second. The differences might be explained by the particularly high aerosol emissions when pronouncing the "th" in "stay healthy".

In schools and universities talking with a loud voice for longer periods during classes and lectures occurs very frequently. Therefore, the aerosol transmission pathway could be of special importance. Longer periods of loud speaking by an infected asymptomatic or pre-symptomatic teacher, professor or student could lead to a high level of virus-containing aerosol particles in closed, unvented or insufficiently vented rooms even without coughing or sneezing. Simulations by Beggs, 2020, show that speaking in an office room can lead to similar levels of virus-containing aerosols as occasional coughing, and these levels could be high enough so that sufficient virus-containing particles are inhaled by other persons in the same room to cause an infection.

For a relative humidity far below 100 % droplets emitted during speaking will lose a large fraction of their water content rapidly and much smaller droplet cores will remain. Droplet cores with sizes below about 10 µm will remain airborne for minutes to hours and these particles are transported in a room by thermal convection, turbulence and other air movements. Therefore, the particles are distributed throughout a classroom within minutes and they can accumulate in a closed room over hours.

Mobile air purifiers offer the possibility to reduce the aerosol load in closed rooms substantially. If the air in a closed room is drawn continuously through a filter, the risk of an infection from virus-containing aerosols will be reduced. The volume passing through the purifier should be as high as possible to eliminate any virus-containing particles as fast as possible. Volume flow rates where the room volume is exchanged four to ten times per hour can be realized in classrooms without high technical efforts and costs.

The experiments conducted in this study will test if air purifiers offer an efficient and realistic way to reduce the aerosol load during day-to-day operation in a high school classroom. The reduction of all aerosol particles will also lead to a reduction of potentially virus-containing aerosols. The risk of infection through inhaled aerosol particles would therefore also be reduced.

So far, only a few investigations on the operation of air purifiers under real life conditions exist. Küppers et al., 2019, study their performance in an office room environment. To our knowledge the present investigation represents the first report of air purifier testing under the conditions of a classroom environment.

Especially in a densely seated classroom it is necessary to take precautionary measures to prevent aerosol infections with SARS-CoV-2. This can be achieved by frequent venting by opening the windows or by filtration with air purifiers. Many schools (at least in Germany) are not equipped with pre-installed ventilation systems. Venting is usually done by opening the windows during the breaks. By venting, the room air is diluted and exchanged with outside air within a few minutes. The exact exchange rates depend on numerous conditions such as wind speed and direction, temperature difference between outside and inside air, window size, etc. The venting reduces the infection risks considerably, but during winter time it does not seem realistic to vent every classroom several times per hour, each time for 5 to 10 minutes, as officially recommended by the German commission for indoor air hygiene (Birmili et al., IRK, 2020). This would lead to uncomfortably cold classrooms, substantially increased heating costs and high CO_2 emissions from the additional heating.

Note that we will not study the role of face masks as a measure to reduce the transmission of aerosols or droplets. For a discussion of this subject, see, e.g., Drewnick et al., 2020, or, Lelieveld et al., 2020. Furthermore, we will only study the role of air purifiers for the aerosol transmission pathway. It should be noted that in cases of a direct droplet or aerosol transfer between two persons in close proximity ('face-to-face') the transmission risks cannot be substantially reduced by the operation of air purifiers that are located at some distance in the same room.

In this study we investigate if the operation of mobile air purifiers in classrooms can reduce the aerosol load fast, efficiently and homogeneously. A simple calculation is provided to estimate the average concentration of virus-containing aerosol in the closed room if an infected person is present that emits a high amount of virus-containing aerosol via speaking. Also the uptake of virus-containing aerosol via inhalation is estimated as a function of time. It is demonstrated that the uptake depends critically on whether or not air purifiers are operated in the room. Furthermore, we assess if the operation of air purifiers is hindered by other factors such as noise level or cleaning and maintenance of the purifiers.

2. Methods

This section describes the air purifiers that were used in our tests. Furthermore, the instrumentation for characterizing the aerosol is described, as well as the design of the tests that were conducted.

2.1. Air purifiers

The tests were performed with commercially available mobile air purifiers (Philips Model 2887/10), which are available as regular household appliances. The air purifiers are equipped with HEPA filters (High Efficiency Particulate Air Filter) that remove more than 99.95% of the particles in the size range of 0.1 to 0.3 µm according to the manufacturer (filter type H13). The volume flow through the purifier can be adjusted in five stages: "sleep", 1, 2, 3 und "turbo". Table 1 shows the measured volume flows for the higher flow regimes (stages 2, 3 or „turbo") that were used during our tests. To reduce the risks of aerosol transmission, the ventilation rate should be set as high as possible. Furthermore, we determined the energy consumption and the noise level during operation at these stages. The noise level was determined using a simple mobile phone app. We measured 1 m above the instrument but outside the main airflow exiting the instrument. The air purifier's dimensions are 24,0 cm x 35,9 cm x 55,8 cm.

The purifier includes a simple pre-filter for coarse dust and aerosol (metal screen with mesh width ~0,5 mm), an active charcoal filter with screens with mesh width of ~0,7 mm. Following the recommendation of the German commission for indoor hygiene we avoided air purifiers that rely on the use of ozone generators, ionizers, UV light, etc. (Birmili et al., 2020).

2.2. Instrumentation

Measurement of aerosol number concentration by condensation particle counters

For measuring the aerosol concentration several ultrafine Condensation Particle Counters (TSI, uCPC model 3776) were employed. The uCPCs allow a precise measurement over a wide range of particle concentrations (0.1 cm^{-3} to more than 100 000 particles cm^{-3}). Ultrafine particles starting from a size of 2.5 nm are detected. The sampling was performed directly from the room air without using any additional sampling lines. The uCPCs use butanol as the working fluid for growing the aerosol particles to sizes at which they can be detected optically. The exhaust air of the uCPCs was transferred to the outside by use of an exhaust line. The sample flow was set at 1,5 l/min. The measurement uncertainty is about ±5%.

Measurement of aerosol size distribution and total aerosol mass (PM_{10})

The aerosol size distribution is measured over a wide range from 10 nm to 10 µm by applying a combination of a Scanning Mobility Particle Sizer (SMPS, consisting of an electrostatic classifier TSI model 3082 with Differential Mobility Analyzer TSI model 3080 and uCPC TSI model 3776) and an Optical Particle Sizer (OPS, TSI model 3330). The SMPS measures the aerosol size distribution in the size range 10 to 300 nm. The OPS measures the size distribution in the size range from 300 nm to 10 µm applying 16 size bins. The approximate total mass (PM_{10}) is derived from the size measurements and assuming a mean particle density of 1.2 g/cm^3.

CO_2-sensor

A CO_2 sensor (NDIR) is used for monitoring the CO_2 mixing ratio (Trotec model BZ30). The sensor measures the CO_2 mixing ratios in the range from 0 to 10 000 ppm CO_2. The uncertainty is given by the manufacturer as ±75 ppm. The instrument also records the temperature and relative humidity.

2.3. Measurement Site

A sketch of the placement of the air purifiers and the measurement instruments in the classroom is shown in Figure 1. The classroom (room B109 of Leibnizschule Wiesbaden) is located in the second floor. It has a length of 8.24 m, width of 6.18 m, a ceiling height of 3.66 m and a total volume of about 186.4 m^3. Small additional recess volumes from the door and window area were not considered. At the window front two rows of windows are located. Up to five windows of size 0.70 m x 1.36 m were fully opened for venting the room. In addition, the door (0.93 m x 1.99 m) was fully opened when venting. The room offers 27 places for the school students and a place for the teacher. For our tests, also a scientist was present to conduct and monitor the measurements. Three or four air purifiers were operated in the room simultaneously. For some of our measurements air purifier #2 (see Figure 1) was turned off. At the back side of the room the uCPC, SMPS, OPC and the CO_2-sensor were placed on a table. The second uCPC was operated on a desk located next to the teacher's desk at the front side of the room. The air purifiers were placed directly on the floor and were distributed across the room as indicated in Figure 1.

For comparison we also conducted measurements in a neighboring classroom (B110), but without operating any air purifiers. Here the air was monitored continuously with a uCPC and an OPS. The room dimensions were very comparable (8.25 m x 6.32 m x 3.69 m, total volume ~192.4 m^3). This room also has six windows of which up to five were fully opened for venting. Also in this class typically 27 students, one teacher and one scientist were present.

The two rooms are oriented perpendicular to each other, resulting in a difference between the rooms as the windows of the room without air purifiers were facing towards a busy road, while the windows of the other room opened towards a quiet side way of this road. Consequently, aerosol number and mass concentrations in the room facing the street were higher most of the time, even when purifiers were turned off in the other room.

3. Results

Figure 2 shows a typical measurement of the total aerosol number concentration (uCPC), the number concentration of large particles (0.3 to 10 µm, OPS), and the total aerosol mass (PM_{10}, OPS) for the two rooms during a school lesson with windows and doors closed. The total number concentration in the room without purifiers decreases slowly over time and is reduced by about 30% at 12:06 when a window is opened and additional particles enter the room from the outside. The decrease in particle concentration while the room is closed is mainly caused by diffusion of the particles to the surfaces in the room, as well as coagulation processes and sedimentation losses. A fraction of this decrease is also caused by the respiration of the 29 persons in the room as a fraction of the aerosol particles is inhaled and deposited in the upper and lower respiratory tracts of the people in the room. The overall reduction was also found to vary from lesson to lesson (with the time constant of the exponential decay varying between 47 and 71 minutes) mainly because the loss processes are dependent on the particle size, the humidity in the room, the charging state of the aerosol, the presence of electrostatically charged surfaces in the room, and other factors.

The aerosol concentration decreased considerably more in the room with the air purifiers. The four purifiers were operated at stage 3 yielding a total volume flow of 1026.4 m^3/h and an air exchange rate of 5.5 h^{-1}. The aerosol concentration decreased by more than 95% within 37 minutes following an exponential decay rate. Both uCPCs measured almost identical values (red and black line in Figure 2a). This shows that the room is well mixed and the reduction of particles in the room is very homogeneous. This was very reproducible and we did not notice any parts of the room to be excluded from the action of the four purifiers. The total number concentration as well as the total mass from the OPS measurements in the two rooms are shown in the lower panels of Figure 2. The number concentration of particles in the range 0.3 to 10 µm decreases exponentially with a similar time constant as the total number concentration measured by the uCPC while in the room without purifiers the total number of particles measured with the OPC remains almost constant.

The total aerosol mass is reduced from about 35 $\mu g/m^3$ at the beginning of the lesson to about 6 $\mu g/m^3$ after about 37 minutes, while the total mass stays fairly constant in the room without purifiers. Note that a window was opened for about 1 minute at 12:06, leading to an increase in particle mass and total particle number concentration. The particle mass and particle number of larger particles measured with the OPS is systematically higher in the room without purifiers, as explained above.

Figure 3 shows a composite plot of uCPC measurements from various school lessons in a closed classroom. All measurements were normalized to a starting level of 10 000 particles cm^{-3}. The blue line shows a typical slow decrease when no purifiers are used. The decays of the total particle number concentration for the tests with air purifiers are highly reproducible for the different air exchange rates with 3 and 4 air purifiers. A halving of the particle concentration is reached in 10.0, 7.0 or 5.4 minutes (green, black and red lines, respectively), depending on the total flow of the purifiers.

Figure 4 shows the measurements of the SMPS instrument for particle sizes between 10 and 300 nm. The concentration levels (indicated by the color coding) decrease markedly for all sizes over time. Similarly, for all size bins measured with the OPS, the size resolved particle concentrations are decreasing evenly over time (Figure 5). The homogeneous reduction with respect to all particle sizes is confirmed by the fact that the mean particle size stays constant at a value of ~0.4 µm (pink dashed line).

Overall it can be stated that the use of air purifiers with HEPA filters decreases the aerosol load strongly within the time intervals between venting by opening the windows. The homogeneous reduction of all particle sizes indicates that, in case of an infectious person being present in the room, also the virus-containing aerosol particles emitted by this person from speaking or breathing will be reduced in the room air.

Estimation of the effect of air purifiers for airborne virus transmission

The decrease of the aerosol concentration in the classroom as described above is not directly comparable to the situation of aerosol emissions by an infective person that might be causing an infection of other persons through airborne transmission. An infective person in a closed room that is continuously speaking acts like a continuous point source of aerosol particles containing virus RNA. In order to make an assessment of how the concentration of RNA-containing aerosol particles changes in a closed room with and without air purifiers, we perform a calculation with simplifying assumptions. We assume an infected pre-symptomatic or asymptomatic person at a stage when he/she is highly contagious, e.g., in the hours before symptoms occur. This person is assumed to be frequently talking with a loud voice (e.g., a teacher, lecturer or a student reading or presenting). In order to make our calculation comparable to a very similar approximation that was very recently released as a preprint via MedRxiv by Lelieveld et al. (2020), we base our calculation on the same assumptions. Note that several of these assumptions are currently highly uncertain for SARS-CoV-2 and may change in the future. Especially the amount of RNA-containing particles that form an infectious dose as well as the fraction of exhaled particles that contain virus RNA are uncertain.

Following the arguments of Lelieveld et al., 2020, we assume an infectious dose D50 of 316 particles as the amount of virus RNA that has to be inhaled by a host to cause an infection with 50% probability. Furthermore, we assume that aerosol particles are deposited in the respiratory system of the host with 50% probability. Breathing and speaking by an infective individual releases 0.06 and 0.6 particles cm^{-3}, respectively, into the exhaled air (Asadi et al., 2019; Stadmytsky et al., 2020; Lelieveld et al., 2020). These assumptions describe rather the case of a super emitter (highly contagious, speaking a lot, emitting a high amount of particles with virus-RNA) compared to a more average case of an infected student that is not talking for a large fraction of the time. The speaking/breathing ratio is assumed to be 0.1 and the respiration rate per person is 10 liters per minute. We assume the concentration of virus RNA present in the exhaled particles to be 5×10^8 per ml for a 'highly infective' and 5 10^9 ml^{-1} for a 'super infective' person (Lelieveld et al., 2020). The particles are exhaled with an average wet diameter of 5 µm when exiting the mouth, but due to the rapid evaporation at lower humidity the particle size quickly reduces to 1-2 µm. The 1/e-lifetime for viable SARS-CoV-2 in aerosol is assumed to be 1,7 hours (van Dormalen et al., 2020). With these assumptions Lelieveld et al., 2020, derive an emission of 68 400 particles per hour from the emitting person and about 3 % of the particles emitted during breathing and speaking contain virus RNA for the highly infective person, and about 30 % contain virus RNA for the super infective one, respectively. For a classroom of 180 m^3 volume with a low air exchange rate of 0.35 h^{-1} and without face masks being used, their model can then be used to calculate a steady-state concentration of RNA-containing aerosol of 0.012 l^{-1} for the highly infective case and 0.12 l^{-1} for the super infective case, respectively. For the highly infective case, a susceptible person in the room for 2 hours will take up a dose of 7.6 RNA-containing particles, representing a 1.7% risk of becoming infected. In a room with 25 persons, this leads to an overall risk of 33% that at least one of the other 24 persons becomes infected. For the super infective person with the very high viral load of 5×10^9 ml^{-1} in the emitted particles, the dose acquired in 2 hours changes to 75.9 RNA-containing particles, the individual infection risk increases to 15% and the risk that at least one person in the room becomes infected increases to 98%. All the details of the assumptions, parameters and equations used are discussed in Lelieveld et al., 2020.

We performed a similar calculation as derived here from the spreadsheet of Lelieveld et al., 2020, as we assumed the situation of a classroom for two hours without any ventilation and compared it to a situation with air purifiers running (air exchange rate 5.7 h^{-1}). Similar to Lelieveld et al., 2020, we did not perform a detailed flow calculation of the air movements, turbulent mixing and dilution processes, etc. Instead, we assume an instantaneous homogeneous mixing of the emitted aerosol in the room, which seems to be a justifiable assumption based on the regularly almost identical concentration measurements of the two uCPCs located at very different positions in the room (cf. Figure 1, Figure 2, and the experiments described below). We assume the room to be closed for 2 hours without venting by opening the windows and doors. For the typical classroom we also assume a volume of 180 m^3 and a volume flow rate of the four air purifiers totaling 1026 m^3/h and assuming a 100% filter efficiency. The concentration of virus-RNA containing aerosol particles for the case of a super-infective person (same assumptions as Lelieveld et al., 2020) is shown in Figure 6. We compare the situation with and without operating the air purifiers. It can be seen that a steady state concentration of about 0.01 particles per liter is quickly reached when the air purifiers are switched on, while without purifiers the concentration increases steadily reaching and 0.11 l^{-1} after 2 hours. The inhaled dose for a susceptible person in the room increases over time. It reaches a value of 68 virus RNA units after 2 hours. With the purifiers running, the inhaled dose is 11 particles after 2 hours. These results are very comparable to the calculations obtained from the model by Lelieveld et al., 2020. As our results for the concentration levels and inhaled dose are within about ±10% of the results calculated with the model of Lelieveld et al., we assume that the infection risks stated above can also be applied for our results.

After 2 hours, the concentration of aerosol particles containing virus RNA in the room is about 10 times higher 'without purifiers' compared to 'with purifiers'. The difference between the two cases increases over time and it becomes larger if higher ventilation rates of the purifiers are realized. Similarly, the difference between the inhaled dose increases over time. After one hour the difference between the cases with and without purifiers is a factor of 3.5 and it becomes a factor of 6.2 after 2 hours.

This estimate is thought to illustrate the profound differences in a room without ventilation vs. a room equipped with purifiers with HEPA filters. Although several of the numbers used for this estimation are uncertain, we expect the finding to be robust that the difference in concentration levels and inhaled dose between 'with' and 'without' purifiers increases over time. The longer other susceptible persons are in a closed room together with an infective person, the higher the risks of airborne transmission even if the persons are separated by more than 2 m distance.

To confirm the validity of our estimation experimentally we performed a set of test measurements in a seminar room (128 m^3 volume) without people. Here we placed an aerosol generator in the middle of the room, producing a constant output of NaCl solution droplets. We then ran two experiments monitoring the number concentration of particles >3 nm with 3 uCPCs at different locations in the room and measuring the particle concentration >300 nm with 2 OPS instruments. In the first experiment all windows and the door were closed, we removed the pre-existing particles in the room by operating several air purifiers down to a total level <100 particles per cm^{-3} and then we switched off the purifiers and started the aerosol generator remotely. We observed the steady increase of particle concentration in the room over a period of 50 minutes. In the second case we continued to operate 3 purifiers when switching on the aerosol generator. The results are shown in Figure 7. When assuming a constant emission from the aerosol generator of 1.8 million particles per second, then the measured concentrations in the room are well described by the simple model for both cases, with and without the purifiers running. Especially in the case without purifiers the circulation and mixing in the room is not as strong and the uCPC measurements show differences in the concentration levels, indicating that the room air is not well-mixed throughout. Nevertheless, all three uCPCs measure the strong increase over time and the model describes the increase well. Although the emissions by the aerosol generator are orders of magnitude higher than the emissions by a person from speaking, these experiments show that the basic assumptions of a nearly well-mixed room are approximately correct, even in a case when the room is not actively ventilated.

4. Further considerations

4.1 Carbon dioxide

Typical CO_2 mixing ratios as measured during a school lesson with closed windows and doors are shown in Figure 8. The CO_2 mixing ratio increases by 48 ppm per minute. At the end of the lesson a value above 2700 ppm is reached. It was repeatedly observed that even after several minutes of venting the room with open windows, the CO_2 concentration did not fall below 1000 ppm. Therefore, already at the beginning of the lesson, the mixing ratio in the room was around 1000 ppm. The current recommendation by the German Environment Agency is that rooms should be vented at concentrations above 1000 ppm and have to be vented at values above 2000 ppm, as such high values cause headache and tiredness (UBA, 2009). For classrooms with a high density of persons this implies that also during lessons venting has to take place. This is independent of the use of air purifiers.

4.2 Positioning of the air purifiers

When installing and positioning the air purifiers, several aspects should be considered. When just a single purifier is installed, the positioning should ideally be at a central place in the room (Kähler et al., 2020). If several purifiers are installed, the instruments should be distributed evenly in the room. Küpper et al., 2019, show that also a placement in the corners is possible as long as the flows towards the air intake and from the clean air outlet are not obstructed. Especially any blocking of free circulation, e.g. by placing the air purifier underneath a table, is reducing the efficiency of the purifier substantially. Obviously all safety aspects need to be considered, for example, emergency exits must not be blocked when installing the mobile air purifiers.

4.3 Noise levels

Besides the simple measurement of the noise levels (Table 1) we also conducted a survey among the school students and teachers. Care had to be taken that the noise level from the aerosol measurement instruments did not influence the impression of the noise level from the air purifiers. Therefore, we conducted some lessons with the purifiers switched on but without aerosol measurements. The results of the anonymous survey are shown in Figure 9. During the lesson before the survey was conducted four purifiers were operated at stage 3. The students (age 14 to 15) did not consider the noise level as disturbing. From the 26 students that participated in the survey, 58% felt "not disturbed at all", 27% felt "not disturbed" and 15% were neutral with respect to the noise level. From the 6 teachers that participated in the survey, 1 felt "strongly disturbed", 2 felt "somewhat disturbed", 1 was neutral, 1 felt "not disturbed" and 1 was "not disturbed at all". Only a very small number of teachers was included in the survey, so these numbers might not be significant, but the noise produced by the purifiers at the necessary high ventilation rates needs to be considered carefully before the procurement of purifiers.

4.4 Cold drafts

None of our surveys revealed that the students or teachers were disturbed by cold drafts or the enhanced air circulation in the room. Here it should be noted that the tests were conducted during a phase of relatively high outside temperatures of 22 to 29 °C. As the purifiers blow the filtered air directly upwards, also persons that are seated close to a purifier are usually not affected by strong drafts.

4.5 Cleaning and maintenance

When running the air purifiers for a longer time (e.g., several hours of daily operation for several months during winter) a proper and regular cleaning and maintenance needs to be included. A visual inspection of the filters at the end of one week of operation in a classroom showed that the pre-filter and the active charcoal filter already had aggregated substantial amounts of coarse dust (Figure 10). No deposits were visible on the HEPA filter from inspection with the naked eye. Many of the commercially sold air purifiers issue a warning signal when the filters need to be cleaned or exchanged. Nevertheless, the filters should only be cleaned or exchanged by trained personnel, and safety precautions need to be observed as the aerosol deposited on the filters may still contain infectious aerosol. Here it seems advisable that the filters are just exchanged in the classroom and cleaned at a different place. If the HEPA filters are protected from the coarse dust (>10 µm), the HEPA filters should be operational for many months. Note that the commercial purifiers tested here did not contain proper pre-filters to fully retain the coarse dust particles >10 µm. Ideally two additional pre-filter stages with filter classes F7 and F9 should be included in a proper purifier system.

4.6 Co-Benefits

As our measurements demonstrate, operating air purifiers continuously in a classroom also reduces the amount of particulate matter ($PM_{2.5}$ and PM_{10}) considerably. The WHO recommends that the average exposure levels to $PM_{2.5}$ should be below 10 µg/m^3 because higher exposure increases the risks of ischaemic heart disease, chronic obstructive pulmonary disease, lung cancer, cerebrovascular disease leading to stroke, and various other diseases. Long-term exposure to high levels of $PM_{2.5}$ reduces the life expectancy considerably and such high PM levels are among the leading health risk factors in many parts of the world (Lelieveld et al., 2019). Therefore, the average $PM_{2.5}$ levels that students and teachers are exposed to should be kept below 10 µg/m^3. Installing air purifiers would greatly help to reduce the average exposure to $PM_{2.5}$. Similarly, exposure levels to various airborne allergenes would be reduced.

5. Summary and Conclusions

Air purifiers can reduce the aerosol load in a classroom in a fast, efficient and homogeneous way. In situations when windows and doors are closed for a longer period of time a large reduction in the inhaled dose of particles containing virus RNA is achieved and therefore the risk of aerosol infection is lowered. Staying for two hours in a closed room together with a super infective person, we estimate that the inhaled dose via airborne transmission is reduced by a factor of six when using air purifiers with an air exchange rate of 5.7 h^{-1}. The air purifiers should be equipped with HEPA filters (H13 or H14). A high air exchange rate of 4 to 10 h^{-1} should be applied. In order to achieve high air exchange rates and homogeneous mixing in the entire room it can be of advantage to install several smaller purifier units. In addition to the HEPA filters, the purifiers need to be equipped with pre-filters to remove the coarse dust efficiently and the pre-filters need to be cleaned or exchanged regularly. If applied in school rooms, the noise levels from operating the air cleaners need to be considered. While large ventilation rates are desirable, the noise level needs to be sufficiently low in order to not disturb the ongoing classes.

In summary, the operation of mobile air purifiers in classrooms seems technically feasible. In order to reduce the risks of aerosol transmission for SARS-CoV-2 air purifiers are an important additional measure of precaution, especially in cases where no fixed ventilation systems are installed and when windows cannot be opened. The implementation and maintenance costs need to be compared to the substantial advantages of reducing the amount of infections and Covid-19 cases, the reduced needs for contact tracing and the avoidance of major disruptions caused by school closures. Nevertheless, air purifiers do not replace other measures for the reduction of transmission such as wearing face masks, hygiene measures and social distancing. The purifiers should be considered as efficient additional measures. An important co-benefit of a standard operation of air purifiers is that average levels of particulate matter (PM) are considerably reduced leading also to a long-term health benefit.

Rooms with a high density of people require frequent ventilation to reduce the CO_2 mixing ratio. CO_2 monitors should be used in order to ensure that CO_2 limits are not exceeded and that ventilation measures are sufficient to reduce the CO_2 levels in the room.

While our study focuses on school classrooms, these results can in principle be transferred to similar situations in closed rooms that are occupied by more than a single person, such as meeting rooms, restaurants, bars, shared offices, waiting rooms and others.

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Captions

Table 1: Technical properties of the air purifiers (Philips 2887/10) operated at a range of volume flows.

Figure 1: Sketch of the classroom indicating the position of the air purifiers (#1 to 4) and the measurement instrumentation at two locations A and B.

Figure 2: Top panel: Measurement of the total aerosol number concentration in the classroom with air purifiers (red and black line) and in the room without purifiers (blue line). Four air purifiers were operated at stage 3 during a lesson with windows and doors closed. A window was briefly opened in the room without purifiers at 12:06 for ~1 minute, when additional particles flowed in from outside. Particle concentrations are averaged over 1 minute intervals. Middle panel: Number concentration of larger particles (0.3 to 10 µm, OPS measurement) in the classrooms with (red) and without (blue) air purifiers. Bottom panel: The particle mass concentration PM_{10} in the rooms with and without air purifiers. Values are more scattered due to low counting statistics for the largest particles that contribute most to the derived mass concentration.

Figure 3: Reduction in aerosol particle concentration in a closed classroom without air purifiers (blue line) and with 3 or 4 air purifiers operating at stage 3 (3×257 m^3/h per purifier, green lines; 4×257 m^3/h per purifier, black lines) or stage "turbo" (4×365 m^3/h, red line). Data are normalized to a starting value of 10 000 particles cm^{-3}. Data are displayed for the time intervals until door or windows were opened again.

Figure 4: Measurement of the particle size distribution in the size range 10-300 nm as a function of time in the room with air purifiers. Red and yellow colors indicate high concentrations while green and blue colors indicate low concentrations. Particles <300 nm are filtered effectively and homogeneously.

Figure 5: Total (black line) and size resolved decrease of particle concentrations for seven aerosol size bins of the OPS in the size range 0.3 to 5 µm. The mean particle diameter (dashed pink line) remains constant, indicating that all sizes decrease at the same rate.

Figure 6: Estimated concentration of aerosol particles containing virus-RNA in a closed classroom (180 m^3), in which we assume that a super infective person emits on average 19 particles per second, e.g. through loud speaking and breathing (red line without purifiers, blue line with purifiers) with an air exchange rate of 5.7 h^{-1}. The dashed lines show estimates of the inhaled dose of virus-RNA units that is taken up by a person in the same room for two hours.

Figure 7: Left panels: Measurement of particle increase in a closed room without people, with and without purifiers. An atomizer is operated as a continuous particle source of NaCl solution droplets. 3 uCPCs and 2 OPS instruments measured at different positions in the room. Assuming an emission rate of 1.8 million particles s^{-1} a good agreement is reached between the model calculations and the measurements. Right panel: Sketch of the position of the aerosol generator (red), the three uCPC and OPS instruments (blue) and the position of the air purifiers (green) in the seminar room.

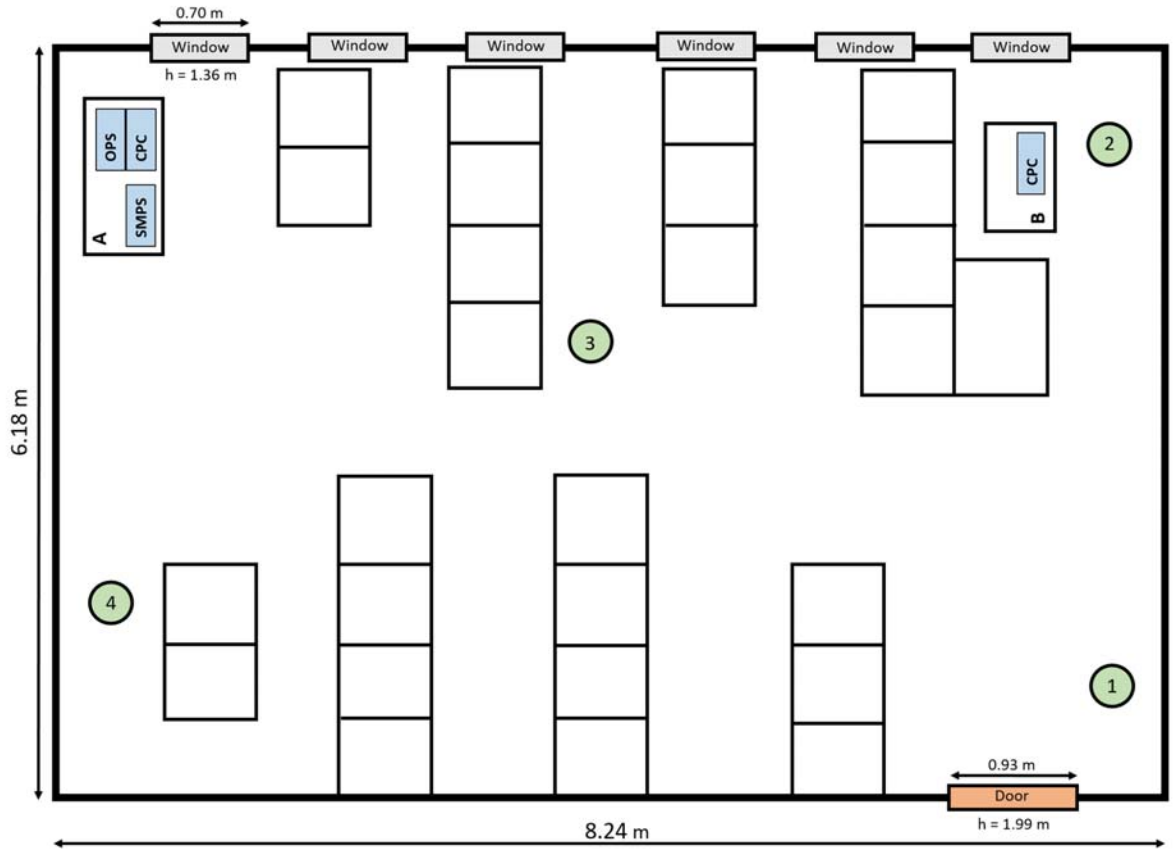
Figure 8: CO_2 mixing ratio as measured in class during a school day. Even after venting the room for several minutes with door and windows wide open, CO_2 levels do not drop below 1000 ppm. With classes proceeding in the closed room, CO_2 levels quickly rise to mixing ratios of 2500 to 2800 ppm at the end of the lesson.

Figure 9: Results of the survey among students (left, n=26) and teachers (right, n=6) on disturbances by the noise levels produced by the purifiers when running four purifiers at stage 3 (total volume flow of 1026 m^3/h, air exchange rate of 5.5 h^{-1}).

Figure 10: Pre-filter (left), active charcoal filter (middle) after one week of operation in the classroom. Coarse dust, hairs and fluff can be discerned. No deposits of particles could be discerned by eye on the HEPA-Filter (right). Sections that appear darker are due to the illumination.

Table 1: *Technical properties of the air purifiers (Philips 2887/10) operated at a range of volume flows.*

ventilation flow stage	volume flow	noise level (1 m above purifier)	power consumption
2	186.7 m^3/h	~39 dB	9.2 W
3	256.6 m^3/h	~48 dB	16.9 W
„turbo“	365.2 m^3/h	~54 dB	42.8 W



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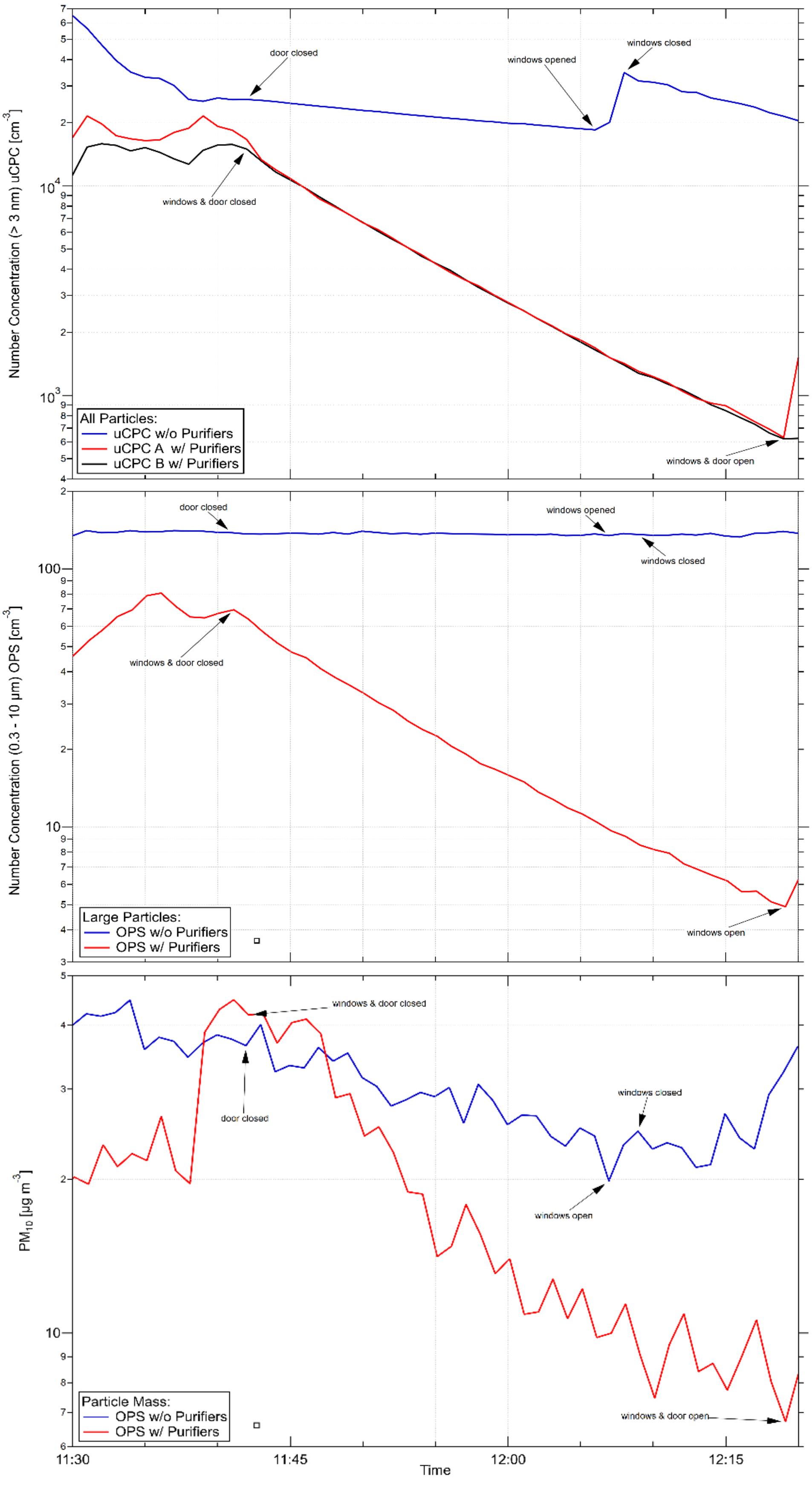
Number Concentration (> 3 nm) uCPC [cm^-3]
door closed
windows closed
windows opened
windows & door closed
windows & door open
All Particles:
uCPC w/o Purifiers
uCPC A w/ Purifiers
uCPC B w/ Purifiers
Number Concentration (0.3 - 10 µm) OPS [cm^-3]
door closed
windows opened
windows closed
windows & door closed
windows open
Large Particles:
OPS w/o Purifiers
OPS w/ Purifiers
PM10 [µg m^-3]
windows & door closed
door closed
windows closed
windows open
windows & door open
Particle Mass:
OPS w/o Purifiers
OPS w/ Purifiers
11:30
11:45
12:00
12:15
Time

Figure 2

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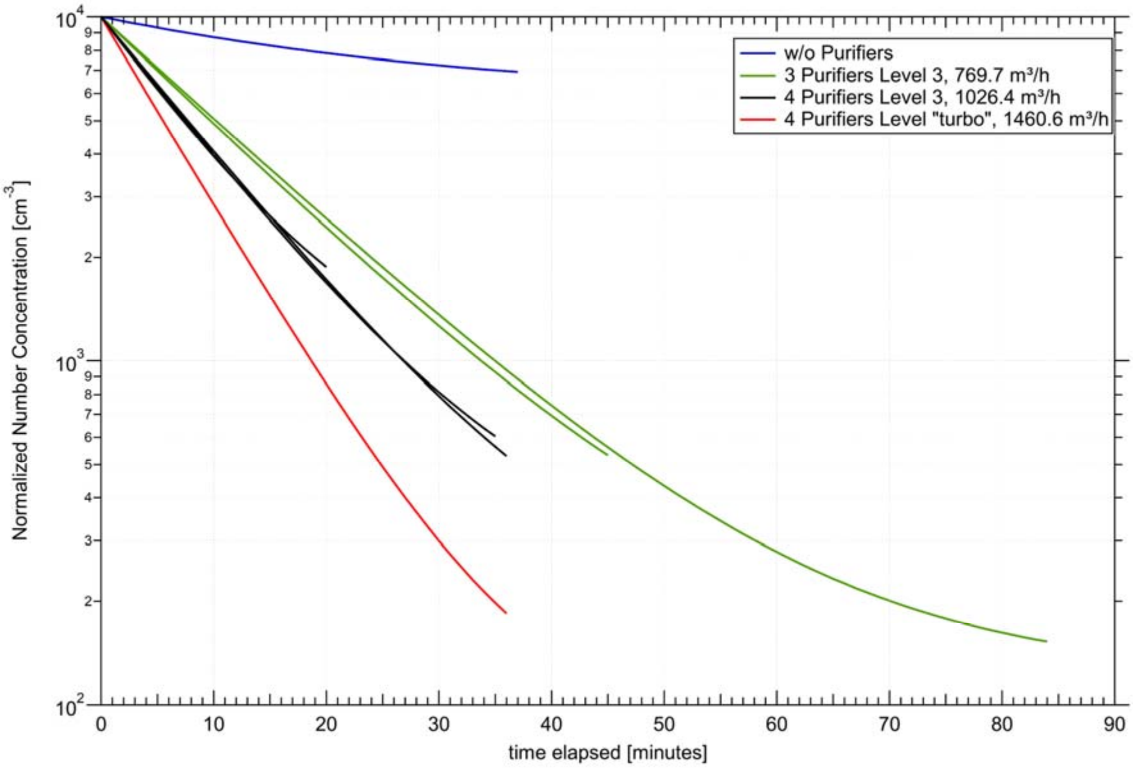

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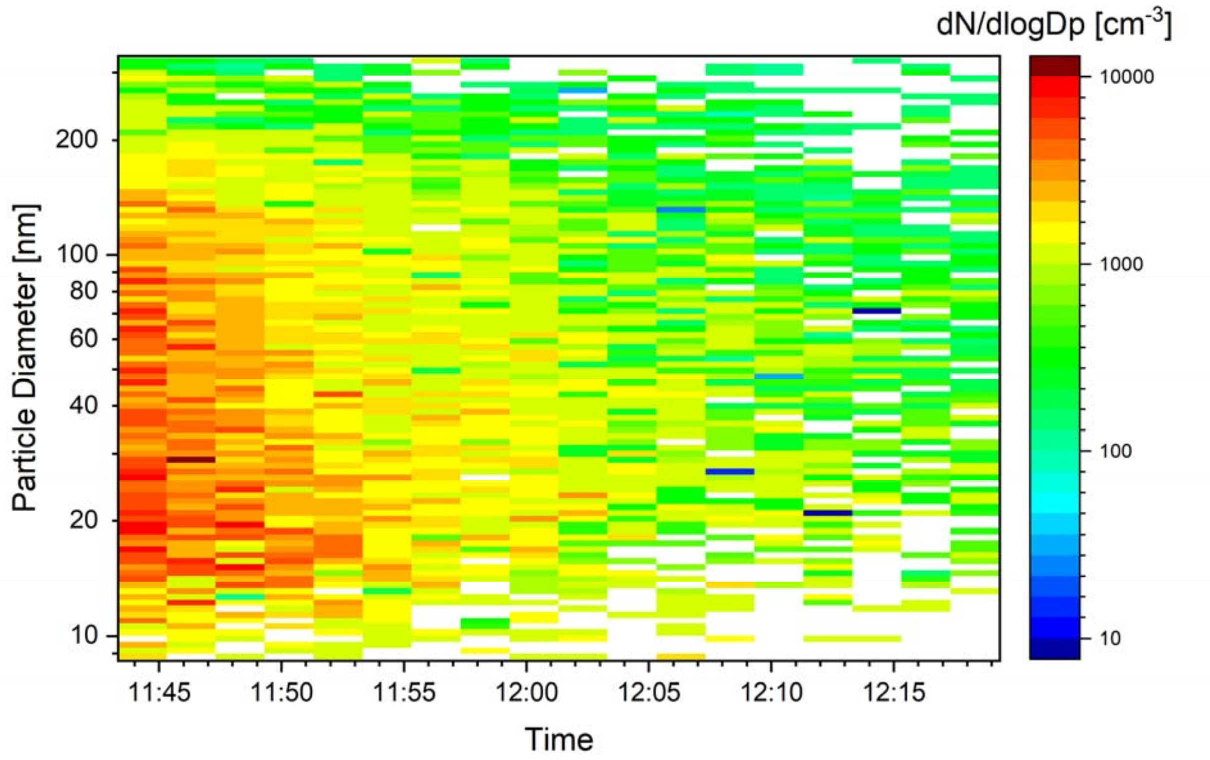

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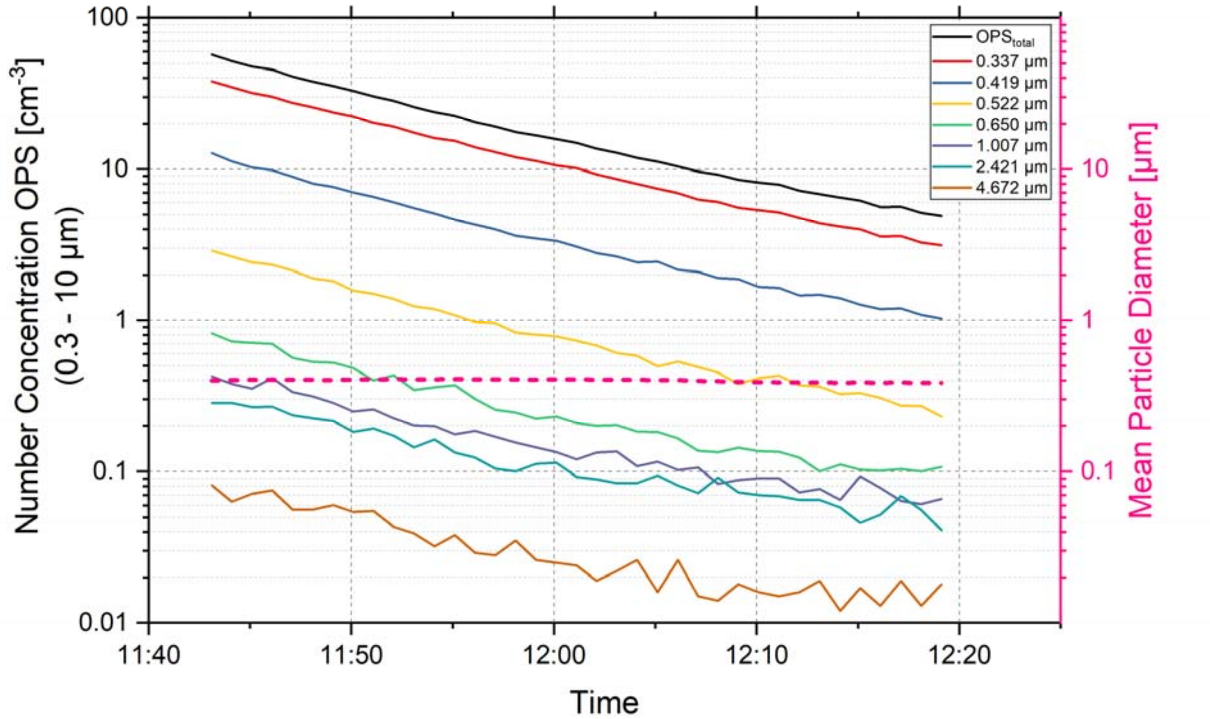

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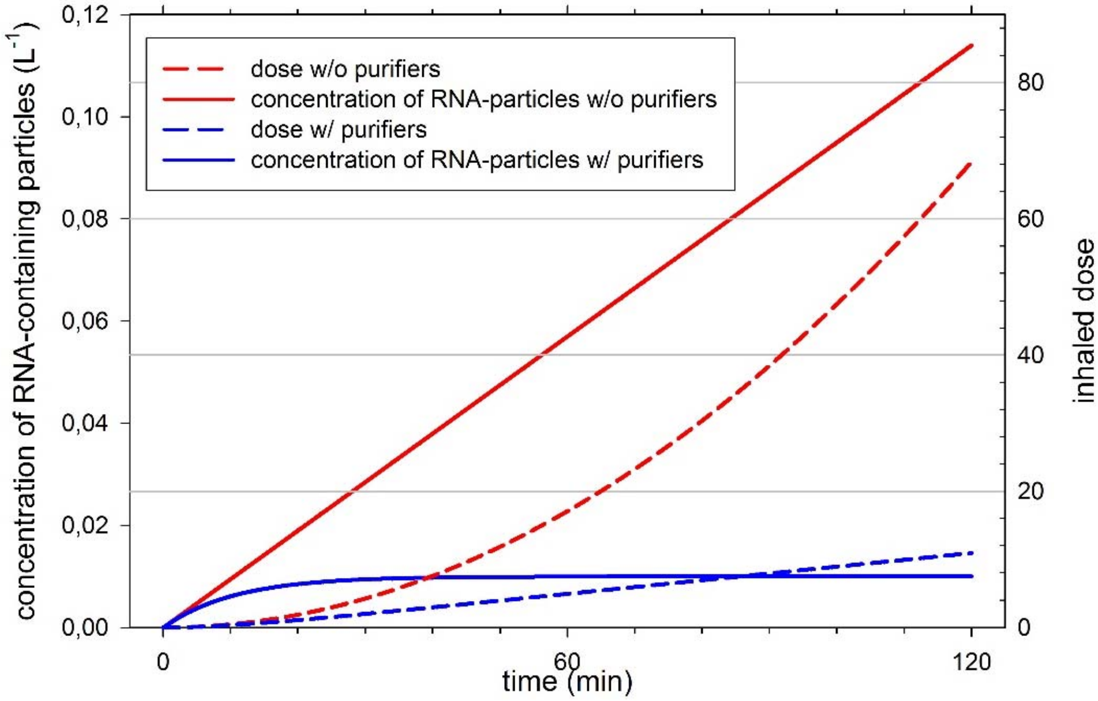

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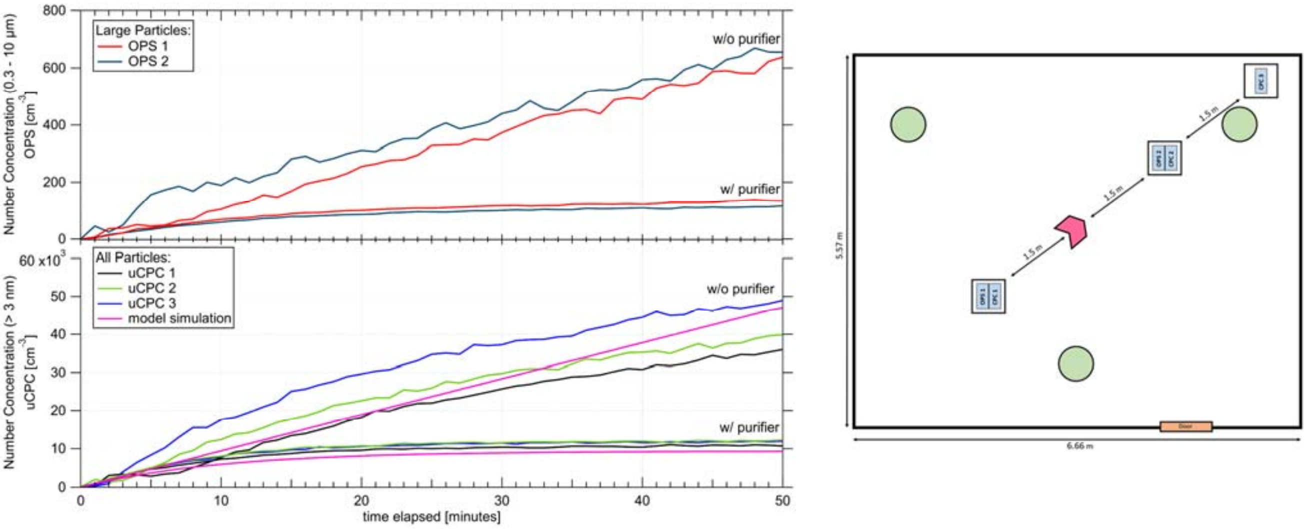

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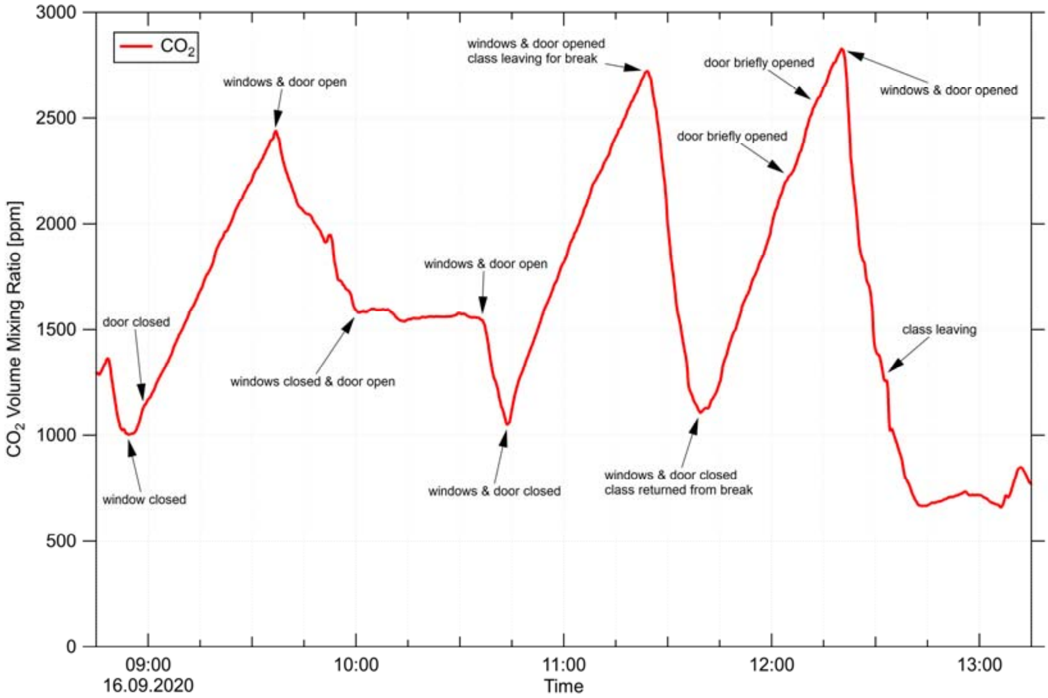

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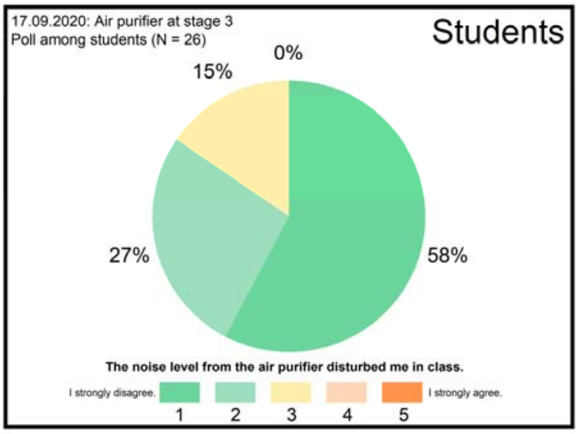

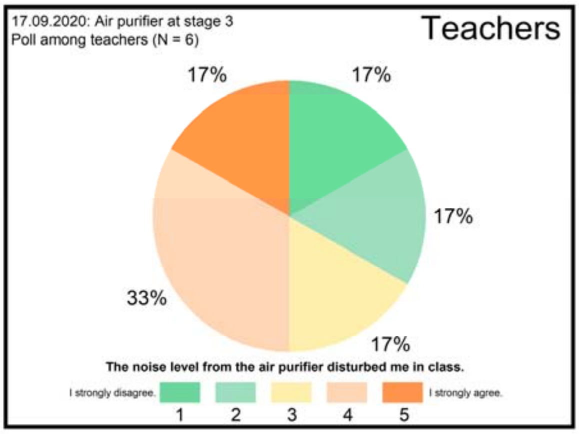

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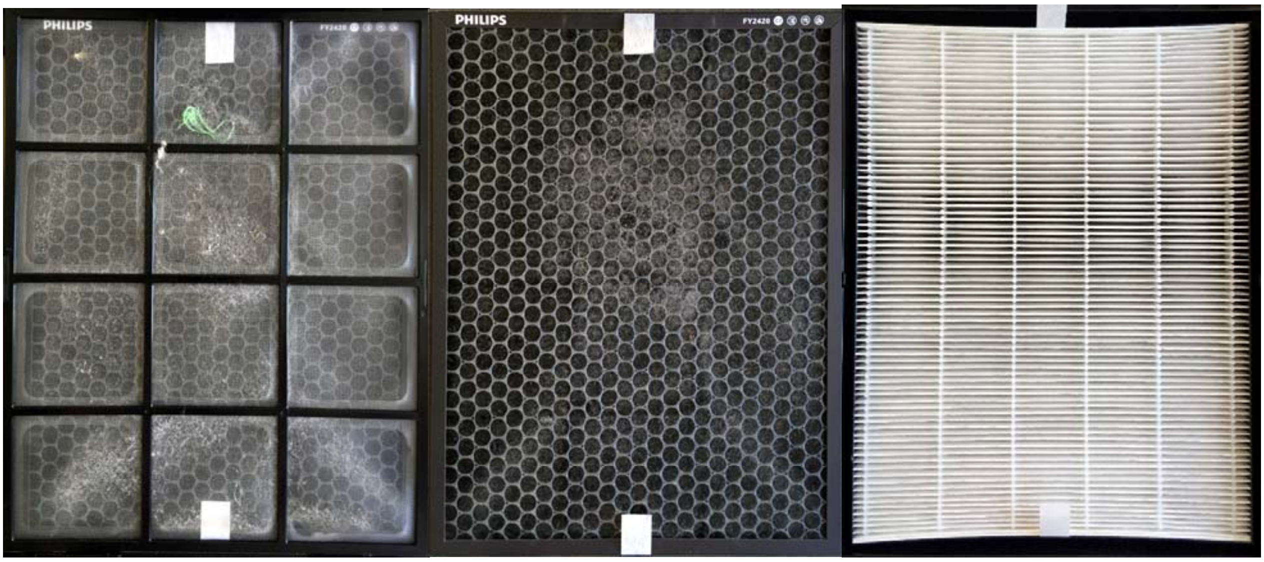

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