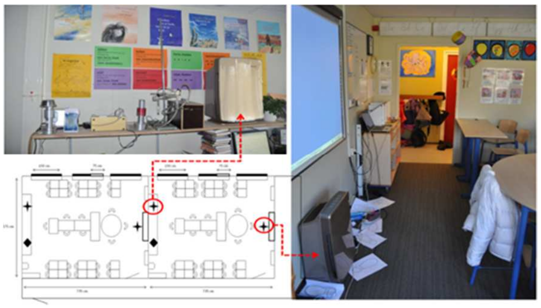
Environmental Science Processes & Impacts

Table of content entry

Sentence highlighting the novelty of the work:

In situ testing in a primary school classroom showed that combining air filtration with a carpet reduced particulate matter concentrations.

Color graphic (8 x 4 cm):



Environmental impact statement

Public schools often rely only on natural ventilation. If the air exchange rate is low, air pollutants from indoor sources will accumulate. Outdoor air pollutants may infiltrate and also contribute to poor indoor air quality. This may cause respiratory problems in children. In these schools compact air filtration units may capture both airborne particles and gas phase pollutants. If combined with a dust reducing carpet resuspension of large particles may also be reduced. We used a cross-over design to study the effect of combining these technologies. During teaching hours concentrations of airborne particles were reduced 27-43% during. In an unoccupied setting during the weekend this reduction was 51-87%. An influence on gas phase air pollutants could not be demonstrated.

INFLUENCE OF COMBINED DUST REDUCING CARPET AND COMPACT AIR FILTRATION UNIT ON THE INDOOR AIR QUALITY OF A CLASSROOM

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Running head: influence of carpet and air filter on classroom air quality

ABSTRACT

Primary schools mostly rely on natural ventilation but also have an interest in affordable technology to improve indoor air quality (IAQ). Laboratory tests show promising results for dust reducing carpets and compact air filtration systems but there is no information available on the performance of these interventions in actual operating classrooms. An exploratory study was performed to evaluate a combination of the two systems in a primary school. Measurements of PM-10 and PM-2.5 were performed by filter sampling and aerosol spectrometry. Other IAQ parameters included black smoke (BS), volatile organic compounds (VOC), nitrogen dioxide (NO_2) and formaldehyde. Both interventions were introduced in one classroom during one week, using another classroom as a reference. In a second week the interventions were moved to the other classroom, using the first as a reference (cross-over design). In three remaining weeks the classrooms were compared without interventions. Indoor IAQ parameters were compared to the corresponding outdoor parameters using the indoor/outdoor (I/O) ratio. When the classrooms were occupied (teaching hours) interventions resulted in 27-43% reductions of PM-10, PM-2.5 and BS values. During the weekends the systems reduced these levels by 51-87 %. Evaluations using the change in I/O ratios gave comparable results. Levels of VOC, NO_2 and formaldehyde were rather low and a contribution of the interventions to the improvement of these gas phase IAQ parameters was inconclusive.

Key words: black smoke, compact filtration unit, formaldehyde, particulate matter, nitrogen dioxide, school, technology intervention, volatile organic compounds

INTRODUCTION

Population-based studies have shown that urban air pollution has an impact on morbidity and mortality. Specifically children suffer from more respiratory complaints and lung function decrements.[1-8] There is some discussion about the relative contribution of outdoor air and indoor air pollution to these health effects.[9-11] The concentration of air contaminants may be higher outdoors than in a classroom.[12-14] A commonly used assumption is that components of outdoor air penetrate into buildings and have an impact on indoor air quality (IAQ).[10,15] Children spend 5-6 hours per school day in a school indoor environment, and consequently the impact of air pollution on children's health can be significant given the relative high levels of some health relevant IAQ parameters.[16-18]

Relatively few school buildings are equipped with a HVAC system or similar air treatment system with a high quality filter to remove outdoor air pollutants before supplying the air to the indoor environment. In the Netherlands such systems are present in less than 40 % of the primary schools.[18]

Retrofitted HVAC installations or standalone air cleaning filters have shown to reduce PM-related indicators of IAQ of schools near high traffic roads.[13,19] However, most schools do not have the means to install this sophisticated but expensive technology. Therefore, we assessed technologies with a high benefit-cost ratio that can be used temporarily; in anticipation of a structural improvement of an existing building or in anticipation of the school moving to a new building with a state-of-the-art HVAC system. The technologies described in this paper have been previously tested in a laboratory setting with promising results for homes.[20-21] This paper describes an exploratory study to evaluate the impact of a combination of two affordable technical systems on some relevant IAQ indicators and discusses whether it is useful to set up a large scale study in primary schools.

MATERIALS AND METHODS

Selection of the interventions

Suppliers of clean air technologies in The Netherlands were pre-selected, based on information available on the Internet. Only technologies applicable in large rooms such as classrooms were considered and suppliers were invited to provide technical documentation. Six suppliers were selected to demonstrate their products and provide references of schools already using these systems. Suppliers of affordable solutions (in the range of € 500-1000 per classroom per year, based on depreciation of the initial investment in 4 years, including maintenance) were shortlisted. From all provided affordable technical solutions, a dust reducing carpet and a compact air filtration unit were selected by IAQ experts of the Public Health Service Gelderland-Midden, Province of Gelderland and Radboudumc. The dust reducing carpet was the Airmaster® produced by Desso in Waalwijk, The Netherlands. The selected air filtration unit was a Philips AC4091 produced by Philips, Drachten, The Netherlands. Tables S1 and S2 in the Supporting Information provide technical descriptions of these interventions and also provide information on the available results of laboratory tests. We expected that combining the dust reducing carpet with air filtration would lead to a better result than either of the two interventions alone. It was hypothesized that coarse particles would be less resuspended from the carpet and that the fraction of particles too small to be deposited by gravity would be effectively removed by air filtration. In this way the two technologies together would be effective over a much wider range of particle-size than expected for each of the technologies, separately.

Selection of the school

In the pre-selection of the schools, CO_2 was used as criterion to evaluate ventilation. Schools in the province of Gelderland with indoor air concentrations during teaching hours in excess of 1 400 ppm in one or more of the classrooms were pre-selected. This represents the 98th percentile of schools with insufficient ventilation. Fourteen schools in the province of Gelderland with poor natural ventilation performance were selected and these schools received a letter with information about the study and an announcement of a short interview by telephone to find out about the interest of the school to participate. Based on this interview three schools were short-listed and visited by the research team. Finally, a primary school in Arnhem was selected for this study. The authors submitted a short request to the ethics committee to find out if medical ethics approval should be considered. The committee advised not to submit a formal request because no personal information is collected and because of the very limited role of the children and teachers in the study.

Study design

The study was planned in a cross-over design over a period of five weeks (Figure 1). During the first, third and fifth week, two classrooms were compared in the baseline setting (without interventions). Air sampling was performed in unoccupied classrooms during four periods of two days (weekends) and in occupied classrooms during periods of five days (teaching hours). In the second week the combined interventions of dust reducing carpet and air filtration was introduced in classroom A on Friday afternoon for a period of 7 days. In the fourth week the combined interventions were introduced in classroom B on the same day and for a similar period of time. The other classroom was used as a reference. All indoor and outdoor air sample collection was synchronized for comparison.

School

The school was a semi-permanent one-storey building, consisting of wooden floors, walls and a flat wooden roof (Figures S1-S2). This building was a satellite to a double storeyed permanent main (stone) building located in a quiet residential setting with no large connecting roads within 300 m from the school. The semi-permanent building provides space to four classrooms that can be reached from the main entrance via a corridor along the longest side of the building (Figures S1-S2). In addition to the classrooms, there is a toilet and a storage room. The two classrooms that were selected for this study were adjacent and were used by two groups of 10-12 year old children, grades 7 and 8. During the teaching hours, each of the two classrooms (floor surface 735 x 575 cm and height 260 cm) was occupied by 27 children and a teacher. This corresponds to an average available surface of 1.5 m^2 per person. In each classroom there were three windows with ventilation grids for natural ventilation. Only the middle window (127 x 55 cm) could be opened (see Figure S2). Convector heaters were present on one side of each classroom below the window. The two classrooms were identical in geometry and also in lay-out (see Figure 2).

Because of the high occupancy, the ventilation grids and the window were continuously left open (day and night) and also during the weekend when the roller shutters were closed. In addition, the door to the corridor was open most of the time. The exchange rate was well below 1 h^{-1} and could not be exactly quantified because of the low air exchange rate caused by the low outdoor wind speed (see Supporting Material for a description of the weather conditions). The low ventilation rate caused the carbon dioxide concentrations to go up during the lessons to a median of 1 500-2 100 ppm (see Supporting Material Tables S4-S5 for day average carbon dioxide concentrations

Interventions

On Friday of study week 1 and 3 at 4:00 pm the interventions were installed in the classroom. The Airmaster® carpet tiles were taped on the existing linoleum floor, covering the entire floor surface, using two-sided adhesive tape that would allow removal of the tiles without a trace. During the week (on Tuesday and Thursday) the carpet was vacuumed by the researchers using a vacuum cleaner provided with the carpet, according to instructions given by Desso. Two air filtration units were placed (Figure S2). Both units were fitted with a complete set of new filters. The first air filtration unit was placed on the floor in front of the classroom and a second unit was placed on a shelf in the back of the classroom at 150 cm from the floor. For this study the units were operating continuously (day and night) at a capacity of 270 m^3/h (setting ‘4’, see Table S2). This setting was chosen in agreement with the teachers to keep noise levels under the general background noise level of 30-35 dB(A) in an unoccupied classroom.

IAQ parameters

Air temperature, relative humidity and levels of CO_2 were continuously monitored using Atal air quality monitoring equipment (type EX-EA80, Purmerend, The Netherlands). Concentrations of PM-10 and PM-2.5 were determined by drawing air through a Harvard impactor at a flow of 10 L/min, using an air suction pump (Air Diagnostics and Engineering, Naples, ME, USA).[22] PM was collected on PTFE-coated membrane filters (Gelman Science, Ann Arbor, MI, USA). The filter loads were determined gravimetrically and will be presented as PM-10 (grav) and PM-2.5 (grav). PM concentrations were also continuously measured using a type 1.109 aerosol spectrometer (Grimm Aerosoltechnik, Ainring, Germany). Three spectrometrically measured fractions were aggregated and will be reported as: PM-10 (spec), PM-2.5 (spec) and PM-1.0 (spec). Measurements of VOC were performed using an adsorbent tube with activated charcoal (SKC, Eighty Four, PA, USA), according to NIOSH method 1500. Formaldehyde was collected on adsorbent tubes loaded with 2,4-dinitrophenylhydrazine (DNPH)-impregnated silicagel (SKC, Eighty Four, PA, USA) according to NIOSH method 5700. For both VOC and aldehyde measurements, air sampling pumps (Buck VSSTM-5, Orlando, Florida, USA) were operated at a flow rate of 200 mL/min. NO_2 was collected using Palmes diffusive samplers.[23]

Outdoor air quality parameters

For temperature, relative humidity, VOC, NO_2 and formaldehyde, the same methods were used as indoors. For outdoor measurement of air concentrations of PM-10 and PM-2.5 beta attenuation monitoring (BAM) was used (BAM-2010 air sampler with a BX-802 PM-10 head and a BX-808 PM-2.5 cyclone supplied by Met One Instruments, Grants Pass, OR, USA). As this equipment arrived two days later these measurements were started with a delay on Wednesday, November 3rd.

Gravimetrical and chemical analysis.

PM-10 and PM-2.5 filter loads were determined gravimetrically, following 24 h of adjustment to the conditions of the weighing room at the Institute of Risk Assessment Sciences of the University of Utrecht, The Netherlands.[24-25] Blank filters were used to adjust for modifying factors in the weighing process. Black smoke (BS) was determined for PM-10 and PM-2.5 and is reported as BS (PM-10) and BS (PM-2.5). The BS values were determined by light absorption of the surface of the loaded membrane filters using an EEL Reflectometer model 43 (Diffusion Systems, London, United Kingdom) as described by Fischer and co-workers (2000)[26] and expressed in 10^{-5} m^{-1}. VOCs were quantified using an in-house developed and validated method. Prior to analysis, activated charcoal tubes were extracted with carbon disulfide. Each extract was analyzed using gas chromatography with flame ionization detection (GC-FID). The used analytical method allowed single-run identification and quantification of over 180 different compounds. Quantification was based on compound-specific relative response factors. The recovery upon carbon disulfide extraction was pre-assayed for each compound. From the results of the VOC-analysis, the sum of all detected and quantified substances was calculated as total VOC (TVOC) in mg/m³. Each sample was injected simultaneously on two capillary analytical columns (60 m) with different polarity (SPB-1 and WAX10, Supelco Inc., Bellefonte PA, USA), using split injection. For the analysis of formaldehyde the 2,4-DNPH-formaldehyde complex was analyzed by HPLC with UV-detection. NO_2 was extracted with Saltzmann reagent and analysed by UV-vis spectrometry. A more detailed description of the analysis of VOC, formaldehyde and NO_2 can be found in Scheepers and co-workers (2011).[18]

Calculations and data analysis

All air sampling in the occupied setting was related to the time periods, corresponding to the teaching hours during week days (8:00 am – 3:00 pm). In the unoccupied setting during the weekend days, the same time interval was selected using timers on the pumps of VOC, formaldehyde and PM. From the continuously logged data registered for temperature, relative humidity, CO_2 and for the logged data in the aerosol spectrometer, the same time intervals were selected, using the internal time registration of these instruments. For PM-10 and PM-2.5 filter samples, a time-weighted average was calculated based on the gain in filter weight. PM-concentrations from the aerosol spectrometer data and the percent changes of all relevant air quality indicators were calculated as previously reported:[18]

Relative changes of all air quality indicators were determined by calculation of the difference in air concentration C_1 in the classroom with no intervention and the concentration C_2 in the classroom with interventions divided by C_1, and multiplied by 100. When both classrooms were compared without interventions the lower value was substracted from the higher value:

$$\text{Change in IAQ parameter} = \frac{(C_1 - C_2)}{C_1} * 100\ \% \qquad (1)$$

Indoor/outdoor (I/O) ratios were calculated for each IAQ parameter, based on the outdoor and indoor arithmetic means, calculated over time-intervals between 8:00 am and 3:00 pm of weeks or weekends. The I/O ratios for different days were therefore aggregated by calculation of arithmetic means and standard deviations, separately over the weeks and weekends, for both studied conditions (with and without the combined interventions). I/O ratios in the baseline and intervention setting were compared in a two-sided Student's t-test, following log-transformation of the data.

From the I/O ratios, the relative change in each of the IAQ parameters was calculated, comparing the condition with and without interventions in both occupied and non-occupied settings, separately, first for classrooms A and B, separately, and also by aggregating the results from both classroom for both conditions studied. The change in I/O ratio for the classroom with no intervention r_1 and for the classroom with intervention r_2 was calculated as:

$$\text{Change in I/O ratio} = \frac{(r_1 - r_2)}{r_1} * 100\ \% \qquad (2)$$

Activity patterns and air exchanges

During the entire study a researcher was observing the activity patterns and kept a journal to register the number of occupants and their activities. The teacher was asked not to use open fire (e.g. candles) or organic solvents (e.g. glue) in the classroom during the study period. In all studied settings (unoccupied and occupied, during intervention and non-intervention periods) the level of natural ventilation was kept the same (grids of windows opened, one window opened, door opened). On Wednesday afternoon after the last lessons the air exchange rate was estimated using carbon dioxide as a tracer. The gas was dispersed using a fire extinguisher and homogenized using a ventilator. An initial carbon dioxide level of approximately 10.000 ppm was monitored until it decreased to the background, using an infrared spectrophotometer (Miran 1A, Foxboro Instruments, Plano, TX, USA).. The air exchange rate was calculated assuming an exponential decrease.[18]

RESULTS

The results will be presented expressed as changes in IAQ parameters and also by I/O ratios. Both comparisons from a nonoccupied (weekend) to an occupied setting (teaching hours) as the comparison of no intervention (native) to intervention (introduction of combined carpet and air filtration) will be discussed.

Changes in IAQ parameters

The relative changes calculated from the comparison of classroom A and B in the unoccupied and occupied settings (using equation 1) are presented in Figure 3. The unoccupied setting showed that the classrooms are very similar with respect to particle-related IAQ parameters, with relative changes from classroom A to B of -9.6 to 11.6% for all measured PM-related parameters (PM-10 (grav), PM-2.5 (grav), PM-10 (spec), PM-2.5 (spec) and PM-1.0 (spec), as well as BS (PM-10) and BS (PM-2.5). Introduction of the combined interventions in classroom A (second weekend) and classroom B (fourth weekend) showed a consistent influence of the interventions on the PM-related IAQ parameters with an average relative change ranging from -51.0% to -87.1% in the unoccupied setting (Table S6). As shown in Figure 3 the contribution of the interventions to all PM-related IAQ parameters were close to reaching statistical significance at $p < 0.05$. However, the statistical significance for the changes in PM-10 (grav), PM-2.5 (grav) and BS (PM-10) could not be evaluated because only one observation in the baseline setting was available (see Tables S4-S5).

As shown in Figure 3 the observations in the presence of the combined interventions showed a pattern that was similar to the baseline, with corresponding effects in the same direction (VOC, formaldehyde) or in the opposite direction for NO_2 (changing from a reduction to an increase). In other words, for VOC, formaldehyde and NO_2 our results indicated that for these IAQ parameters in the nonoccupied setting the classrooms A and B were very different. In our study, the following VOC were detected in both classrooms: acetonitrile, ethanol, n-heptane, limonene, 2-methylbutane, methylcyclohexane, iso-propanol, n-pentane and toluene.

In the occupied setting (teaching hours) the relative changes for particulate matter (PM)-related IAQ parameters at baseline showed much more variation (up to 20 % for PM-10 (grav)).

In the occupied setting the changes were approximately twofold smaller compared to the influence of the interventions in the unoccupied intervention setting, ranging from -27.4% to -42.7%. The performance of the combined interventions resulted in reductions of around 30% for PM-10-related IAQ parameters (27.3%, for PM-10 (grav), 32.9 % for PM-10 (spec) and 36.0% for BS (PM-10)) and reductions of around 40 % for PM-2.5-related parameters (40.5% for PM-2.5 (grav), 41.8% for PM-2.5 (spec) and 42.7 % for BS (PM-2.5)) and PM-1.0 (spec) of 40.0%. This suggests that the interventions are somewhat less effective in reducing coarse particles (PM-10) compared to finer fractions (PM-2.5 and PM-1.0). In accordance with this, the PM-10 (grav) and PM-10 (spec) results did not indicate a statistical significant change attributable to the interventions (p-values of 0.637 and 0.144, respectively), whereas all the measured IAQ parameters related to the fine fractions PM-2.5 and PM-1.0 and both BS (PM-10) and BS (PM-2.5) showed an effect that was tested statistically significant at $p < 0.05$ (Table S6).

The results of VOC, formaldehyde and NO_2 at baseline again suggest that classrooms A and B cannot be compared for these IAQ parameters, also in the occupied setting. Similar to the unoccupied setting there was no net effect that could be attributed to the combined interventions because for these parameters the variation between the classrooms were of a similar magnitude in the baseline setting as during the periods of intervention in both occupied and unoccupied settings.

I/O ratios

For weekend days the average I/O ratios in the baseline setting indicated that indoor levels for all studied IAQ parameters in the classrooms were higher indoors than outdoors (I/O ratio > 1), except for formaldehyde and for VOC in classroom B (Figure 4a and Table S7). From unoccupied hours to teaching hours, this pattern changed for all PM I/O ratios, shifting values < 1. For VOC (classroom B) formaldehyde and NO_2 no change is observed. In the unoccupied setting, introduction of the combined interventions reduced the I/O ratios for PM-10 and PM-2.5, ranging 0.30-0.48, to average values for both classrooms, ranging 0.05-0.13. These changes were statistically significant at $p<0.05$ for all PM-related IAQ parameters.

In the occupied setting (Table 4b and Table 7) the results of PM-2.5 indicated a shift from an I/O ratio of around 1.00 (1.06-1.17) to values below 0.50 (0.48 for spectrometry and 0.43, based on gravimetry). This relative change corresponds to a statistical significant reduction of the I/O ratio of approximately 60 % ($p<0.01$). For PM-10 the I/O ratio ranged from 2.91 to 4.33 at baseline. The combined interventions had an impact but the I/O ratios for PM-10 still remained well above unity (means of 1.62 for spectrometry and 1.49 for gravimetry). Nevertheless, the relative change in the I/O ratio (calculated using equation 2) for PM-10 showed reductions of 53% for the gravimetric measurement and 60% for the spectrometric measurement ($p=0.015$ for both parameters). For formaldehyde and NO_2 the occupied setting did not indicate a consistent influence of the combined interventions. For VOC a shift to a negative I/O ratio is observed for classroom A but not for classroom B.

DISCUSSION

This study describes the IAQ effects of a combination of two interventions when applied in an occupied primary school classroom., using a crossover design. In addition, measurement were performed in an unoccupied setting over the weekend. The study shows a reduction of 27-43 % in particulate air pollution during teaching hours, and a 51-87 % effect during weekends. For gaseous air pollution components no conclusive effect was found. Earlier studies on the influence of technology interventions on IAQ in schools were (only) based on a comparison of I/O-ratios at baseline and intervention settings in the same classroom.[13,18-19] In this study we evaluated the influence of technology interventions by comparing two different classrooms. The classrooms were first compared in a native situation (baseline). Next, the combined interventions were introduced in one classroom and an identical measurement program was conducted in this classroom and in a second (reference) classroom at the same time. In a second study period, the interventions were moved to the second classroom, using the first classroom as a reference. With this cross-over study design it was possible to standardize for the influence of general indoor and outdoor factors such as the influence of weather conditions, temporal changes in the general outdoor air quality and other (unknown) factors changing over the study period.

Indoor and outdoor air quality

Variability in PM-10 values was large due to episodes of elevated air pollution resulting from stagnant weather conditions (Figure S3 and a description of the weather conditions in the Supporting Material). With an average of 44.3 μg/m^3 calculated from all of the day averages, the PM-10 value at the school location exceeded the EU air quality guideline for PM-10 of 40 μg/m^3 (year-average). The pattern of PM-10 and PM-2.5 corresponds well to the registration of PM-10 at a nearby regional air monitoring station no. 738 at Wekerom-Riemsterdijk, 30 km NW from the study location. However the average PM-10 concentration at this regional study of 36.2 µg/m^3 was lower than the average PM-10 and very similar to the PM-2.5 concentration measured at the school (study period average of 36.2 µg/m^3). That the PM-2.5 concentrations were close to air levels of PM-10 during most of the days, indicated that particulate air pollution is driven by fine rather than coarse particles with only a minor contribution from local sources.[27] Fine particles can effectively penetrate the indoor environment and likely influenced indoor air levels in this study.[15] BS values derived from PM-10 and PM-2.5 were very similar, presumably because the soot component absorbing the light is primarily present in the submicron particle fraction.[25-26]

Interventions

Based on the volume of the classrooms, the capacity of the air filtration units would theoretically be sufficient to treat the air 4.8 times every hour. However, the air filtration unit was designed for a residential setting and not intended for use in classrooms with such high occupancy. The presence of so many persons per m^2 and the low air exchange rate caused extremely high PM-levels, resulting in the pre-filter to become clogged on Thursday of the first intervention period (study week 2). The problem could be solved by cleaning of the pre-filter according to instructions given by the supplier (see Table S2). Visual inspection of the carpet also showed deposition of debris, indicating heavy soiling during the teaching hours. Due to these ‘heavy duty’ conditions it is not surprising that the overall effectiveness observed in this study of 30-60 % is much lower compared to the results obtained under laboratory conditions (reporting overall effectiveness of 80-85% or higher, see Tables S1 and S2).

I/O ratios

I/O ratios are useful to take into account the changes in general outdoor air quality. It is difficult to judge to what extent indoor or outdoor pollutants contribute to the overall risk of respiratory health.[28] Some studies suggest that health complaints in children aggravate such as in asthma, specifically related to school indoor air quality. [29-30] Results of Ebelt and co-workers (2006) indicate that also cardiovascular health effects are associated with PM-10, PM-10-2.5 and PM-2.5 of outdoor origin and not of indoor origin. [11] Koenig and co-workers (2005) observed similar effects of outdoor-generated PM-2.5 vs. indoor generated PM-2.5 on a biomarker of inflammation (exhaled NO) in children with asthma.[10]

The I/O ratios observed in this study are in line with results reported in previous studies that characterized an unoccupied classroom as a relative clean indoor environment where pollutants are mostly originating from outdoor air by the introduction of untreated (natural) ventilation air.[10,21,18,31-32]

From the unoccupied setting in the weekends to the occupied setting during the teaching hours, the I/O ratios for PM-10 were increased by tenfold (from 0.24-0.42 to 2.9-4.3), suggesting that occupancy is a driving factor of indoor PM-10 levels. Compared to PM-10 the increase for PM-2.5 was only 2-3 fold (from 0.36-0.48 to 1.1-1.2) due to higher penetration of PM-2.5 in the unoccupied setting) and a smaller contribution of resuspension in the occupied classroom.

In the occupied setting pollutants such as PM-10 are resuspended from floors causing I/O ratios to go up to levels between 1 and 10.[16,19,21,33-35] Most of the PM-10 originates from indoor sources[35] and consists of earth crust materials, detrition of building materials and chalk[15,31,33]. This coarse particle fraction may also contain bio-allergens such as skin flakes, molds, insect and mite debris or pollen which have an allergenic and pro inflammatory potential and may contain endotoxins. [9,36-37] A recent study in The Netherlands suggests that levels of allergens from animals are higher in schools than in a home environment.[38] Removing indoor-generated coarse particles may therefore be in the interest of the occupants. In the occupied setting VOC concentrations varied over two orders of magnitude and were strongly influenced by the contribution of ethanol (total VOC was 0.10-2.1 mg/m^3 and total VOC without ethanol ranged from 0.03 to 0.20 mg/m^3). The levels in classroom B were higher compared to classroom A but no specific substances were identified to explain these differences**.** The shift in the I/O ratio from 0.1 in classroom A to 10 in classroom B (Figure 4b) is likely due to indoor conditions related to occupancy and activities (e.g. differences in personal care products by occupants and/or differences in cleaning activities). Other studies reported increased I/O ratios from an unoccupied setting (weekend) to an occupied setting (teaching period).[19,35,39-40] Of the observed VOC ethanol is likely to be primarily of endogenous origin since it was high in all week samples and much lower in weekends. The detection of ethanol, isopropanol and limonene in two weekends may be related to their use in cleaning.[41-42] The observation of limonene in all occupied periods may also be explained from the use of personal care products.[41] Only few substances were detected simultaneous in indoor and outdoor air (n-pentane, 2-methylbutane and xylene), indicating their possible outdoor origin.

Effect of combined interventions

The influence of the combined technology interventions on IAQ parameters was calculated in two ways: by comparison of the levels of IAQ parameters from the two classrooms in a cross-over design and by comparing I/O ratios over the study periods with and without the interventions installed. This cross-over strategy has the advantage that the measurement of the general outdoor quality is not required for the calculation of the relative changes, assuming that the influence of this factor will be the same for each of the two classrooms (IAQ parameters were measured simultaneously). To avoid a systemic contribution of the room and its occupants, the classrooms were compared in a cross-over design (interventions were moved from classroom A to classroom B). An intrinsic weakness of the cross-over approach is that two different classrooms with different groups of occupants are compared. In this study the classrooms could be well compared because they were exact copies in terms of building materials used, furnishing and lay-out (Figure 1). They also had the same geographical orientation and similar ventilation practice and a similar number of occupants. Nevertheless, variability can still occur due to differences in the occupants of the classroom and their behaviour and activity patterns. In our study we concluded that the two classroom settings were sufficiently similar in PM-related IAQ parameter levels and their I/O for the purpose of studying the contribution of technology interventions.

The second way of assessing the influence of the interventions was by the more commonly used calculation of the I/O ratios. This adjustment is important if results of measurements, taken on different days, are compared because the general outdoor conditions continuously change IAQ parameters. The advantage of this approach is that the I/O ratios themselves are informative. They can be compared to reported ratios in previous studies (see previous section). A limitation of using I/O ratios is that additional outdoor measurements, preferably at the study location, are required.

Despite these differences, the results of both approaches lead to similar conclusions for the research question studied. In the occupied setting the reduction in PM-10 was around 30%, whereas the change in the indicators of finer particles (PM-2.5, BS of PM-10, BS of PM-2.5 and PM-1.0) were close to 40 %. It is suggested that the coarse particles, if resuspended, go up and down and are not taken up by the airflow before being deposited again due to gravity. The finer fraction is more likely to remain airborne sufficiently long to be taken to the filtration unit and be removed from the air.[18]

For the gas-phase air pollutants an influence of the combined interventions could not be evaluated, mainly because of a too high variability in both indoor and outdoor air levels, combined with a too low number of observations. Such high variability in VOC was also observed in other recent work.[19] The I/O ratios for formaldehyde remained above unity, also during the weekends, confirming that this substance is primarily generated from indoor sources such as building materials and furniture.[43-44]

Method evaluation for follow-up studies

The strengths of this study were an extensive air sampling effort to characterize climate, ventilation and health-relevant IAQ parameters in time-synchronized campaigns in two different classrooms to find out if they can be compared. Most parameters were also determined outdoor at the study location, using the same or a very similar type of air monitoring equipment. The study design allowed evaluation of the combined interventions by comparison of the classrooms for their IAQ with and without the interventions and also by comparing the I/O ratios for the IAQ parameters of both classrooms. A further useful addition was the measurement of the IAQ parameters during the teaching hours (occupied setting) as well as the same clock-times on weekend days (non-occupied setting). This demonstrated the major impact of the users and their activities on the different IAQ parameters combined with the performance of the two technology interventions.

This study also has some limitations. It was only carried out during the cold season. Although the school personnel assured the researchers that the ventilation regime during the cold season was the same as during the summer, there may be many other seasonal factors such as the temperature and humidity conditions and the composition of outdoor air pollution. In this study we have not evaluated the performance of the technological interventions over a sufficient long period to be able to assess a possible decrease of the performance over time.

Earlier studies of the use of carpets in homes and offices showed that maintenance such as cleaning activities may have an influence on exposure of asthmatic patients to bioallergens and subsequent respiratory complaints.[45-46]

Another limitation of this study is that the results might be specific to the primary school selected for this study (building type, geographical and meteorological setting) and it is not certain if results obtained in this study can be applied to other schools in this or other climate zones. This exploratory study should therefore be followed-up by a study in cross section reflecting different types of school buildings.

This study did also not include any health-related endpoints. Nevertheless, the coherent influence on the studied PM-related air pollution parameters suggests that there might be a benefit for health, in particular for respiratory disease in children.[8] This should be confirmed in follow-up studies, involving a considerable number of schools that also take into account a wide range in building types and seasonal characteristics.

An obvious limitation of this study is that the influence of each of the interventions was not studied separately, but with the results presented in this paper it appears worthwhile to further study the impact of the dust reducing carpet and air filtration units, separately.

CONCLUSION

The combined use of an especially designed low dust carpet combined with two compact air filtration units has an impact on PM-related IAQ parameters that are considered to be relevant for the health of children. During teaching hours the observed reductions are reduced by 50 %, due to increased PM concentrations and changed air flow patterns as a result of occupancy. In future studies one method (either gravimetric or spectrometric determination) could be used to study the change in PM concentrations. The influence on gas-phase parameters could not be assessed due to a too large variability, which makes it difficult to compare the two classrooms and their respective I/O ratios. Due to these obstacles the outcome of this study regarding the influence of the combined interventions on VOC, formaldehyde and NO_2 is considered inconclusive.

This study also showed that relative changes in a cross-over design can be used to study effects of interventions on IAQ. This does not require simultaneous characterization of outdoor quality. If it is not possible to find classrooms that can be compared in a cross-over design changes in I/O ratios may also be used to study interventions. In this study the results observed in the cross-over design were similar to the results of I/O ratios.

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Week number	**44**		**45**		**46**		**47**		**48**
Research week	Week-1	Weekend-2	Week-2	Weekend-3	Week-3	Weekend-4	Week-4	Weekend-5	Week-5
Dates	1-4	5-6	7-11	12-13	14-18	19-20	21-25	26-27	28-2 dec
Classroom A		COMBINED INTERVENTION							
Classroom B						COMBINED INTERVENTION			

Figure 1: Schematic overview of the study period with the combined interventions crossing over from classroom A (2nd week) to classroom B (4th week).

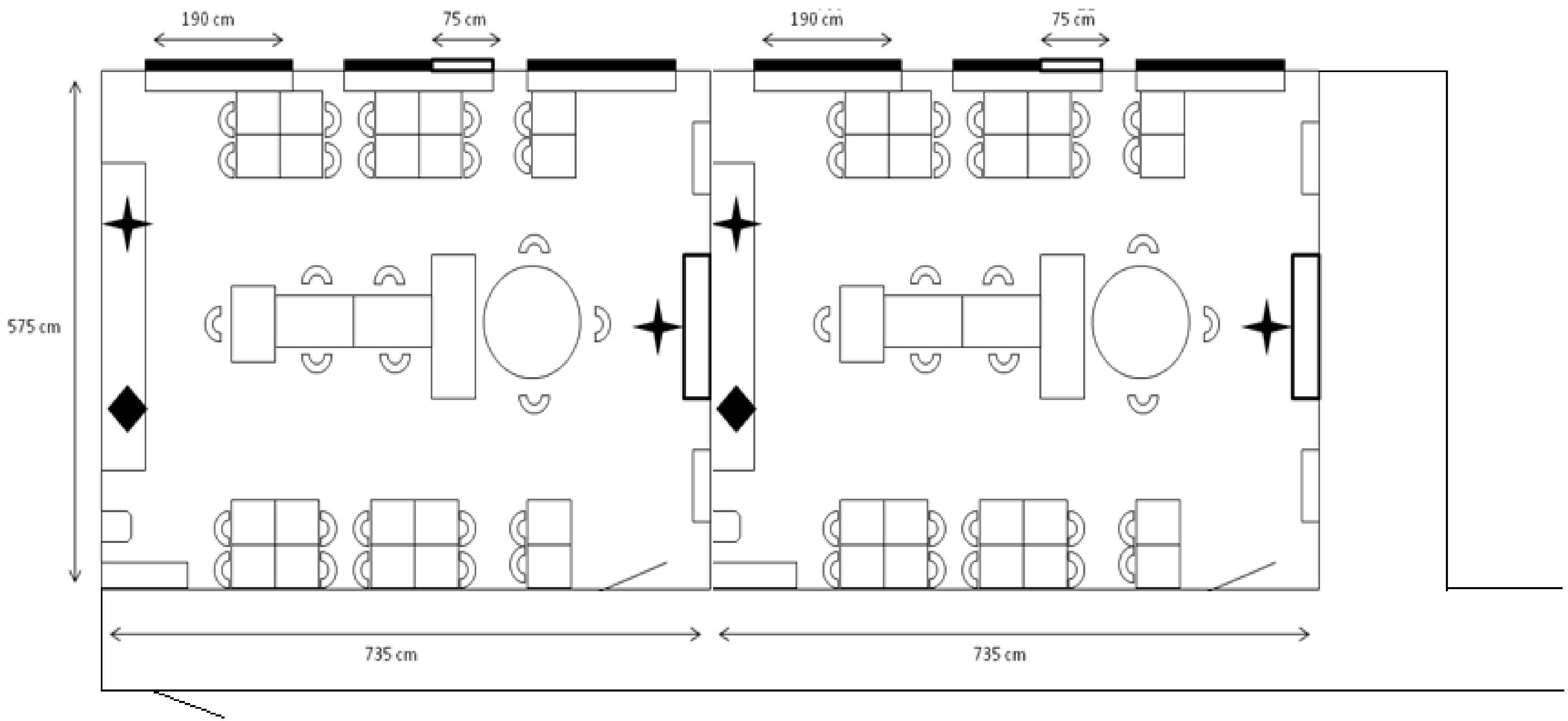
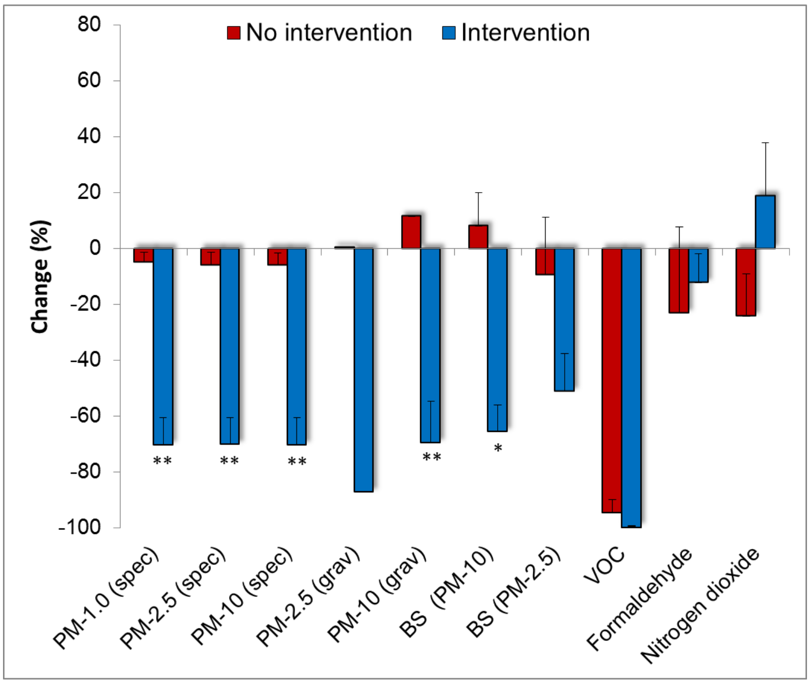
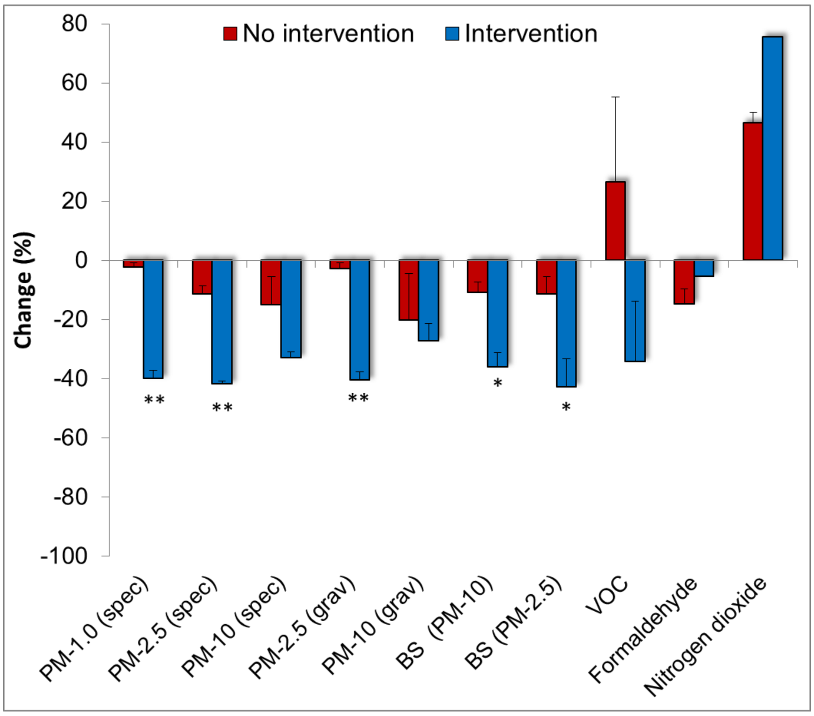


Figure 2: Lay-out of the two classrooms that were compared in a cross-over design. ◆ Air sampling equipment; ✦ Compact air filtration system; ▬ Closed window with ventilation grid; ▭ Opened window.

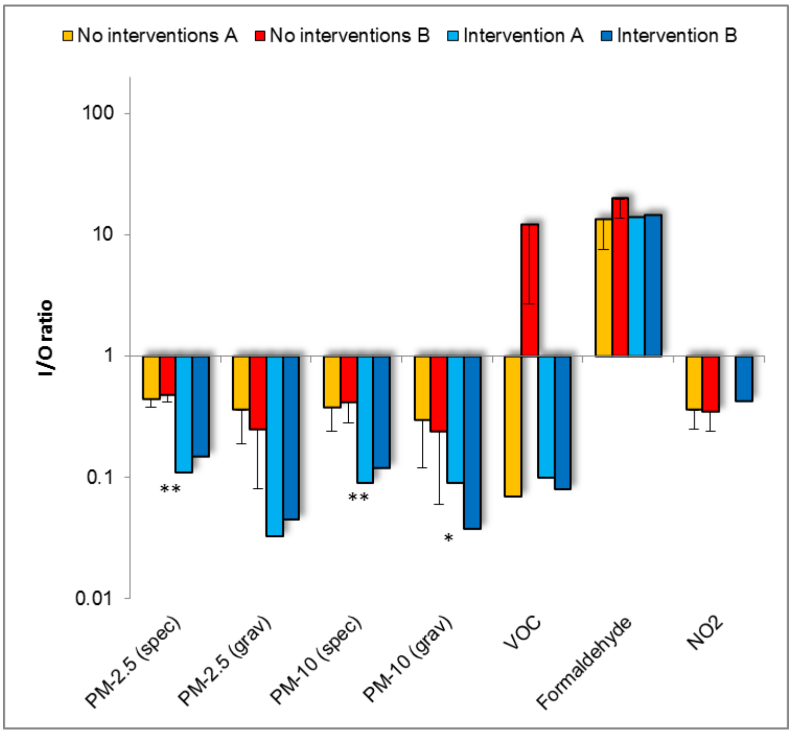


(a)

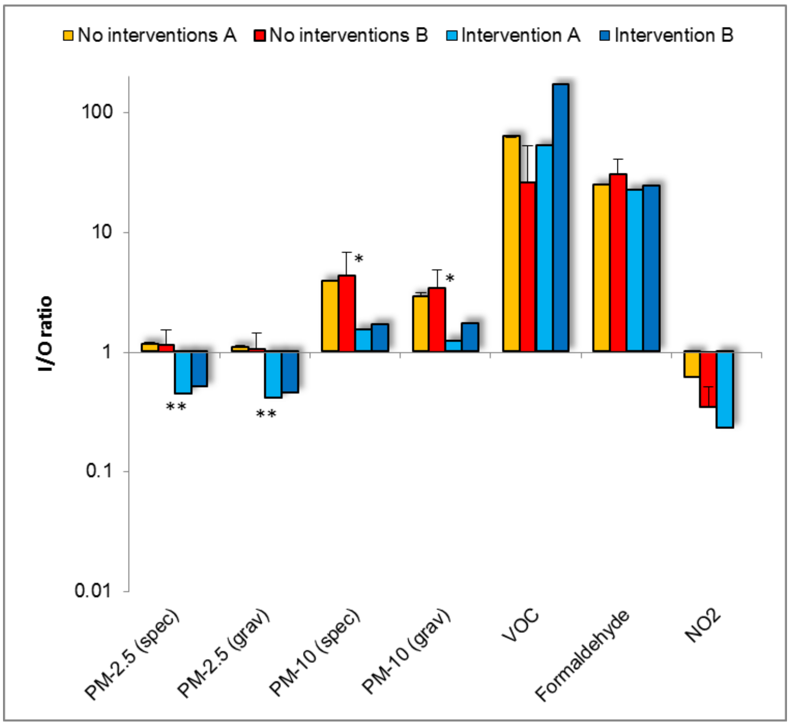


(b)

Figure 3: Change (AM ± SD) in IAQ parameters, based on the comparison of a classroom with and without the combined interventions in an unoccupied setting [weekend, (a)] and in an occupied setting [teaching hours, (b)]; * $p < 0.05$; ** $p < 0.01$. See the methods section for more information on the calculation of 'change' (equation 1).



(a)



(b)

Figure 4: Indoor/outdoor (I/O) ratios during weekend (a) and week (b) for combined intervention (single observations for classroom A and B, separately) and at baseline (AM ± SD of observations in three different periods). * $p < 0.05$; ** $p < 0.005$.