A ventilation intervention study in classrooms to improve indoor air quality: the FRESH study

Jeannette TM Rosbach1,2, Machiel Vonk2*, Frans Duijm2, Jan T van Ginkel3, Ulrike Gehring1 and Bert Brunekreef1,4

Abstract

Background: Classroom ventilation rates often do not meet building standards, although it is considered to be important to improve indoor air quality. Poor indoor air quality is thought to influence both children’s health and performance. Poor ventilation in The Netherlands most often occurs in the heating season. To improve classroom ventilation a tailor made mechanical ventilation device was developed to improve outdoor air supply. This paper studies the effect of this intervention.

Methods: The FRESH study (Forced-ventilation Related Environmental School Health) was designed to investigate the effect of a CO2 controlled mechanical ventilation intervention on classroom CO2 levels using a longitudinal cross-over design. Target CO2 concentrations were 800 and 1200 parts per million (ppm), respectively. The study included 18 classrooms from 17 schools from the north-eastern part of The Netherlands, 12 experimental classrooms and 6 control classrooms. Data on indoor levels of CO2, temperature and relative humidity were collected during three consecutive weeks per school during the heating seasons of 2010–2012. Associations between the intervention and weekly average indoor CO2 levels, classroom temperature and relative humidity were assessed by means of mixed models with random school-effects.

Results: At baseline, mean CO2 concentration for all schools was 1335 ppm (range: 763–2000 ppm). The intervention was able to significantly decrease CO2 levels in the intervention classrooms (F (2,10) = 17.59, p < 0.001), with a mean decrease of 491 ppm. With the target set at 800 ppm, mean CO2 was 841 ppm (range: 743–925 ppm); with the target set at 1200 ppm, mean CO2 was 975 ppm (range: 887–1077 ppm).

Conclusions: Although the device was not capable of precisely achieving the two predefined levels of CO2, our study showed that classroom CO2 levels can be reduced by intervening on classroom ventilation using a CO2 controlled mechanical ventilation system.

Keywords: Ventilation, Schools, Carbon dioxide, Indoor air quality, Intervention

Background

Children spend much of their time in schools; it is the indoor environment where they spend most of their time besides in their home. It is therefore important that schools have a good indoor air quality (IAQ). Classroom ventilation was already recognised as an important determinant of indoor air quality in the beginning of the 20th century [1]; however, even recent studies showed that classroom ventilation rates do not meet building standards. Two studies performed in The Netherlands in 2007 showed that more than 80% of the schools exceeded CO2 levels of 1200 parts per million (ppm) during classroom occupation [2,3], which in The Netherlands is the advised maximum CO2 concentration for classrooms [4,5].

Poor IAQ has found to be associated with a negative impact on health [6,7]. However, these reviews mainly focussed on office buildings and their occupants. Daisy et al. [8] reviewed the literature published until 1999 with a specific focus on schools. With respect to ventilation, most studies merely investigated the amount of ventilation and conclude that ventilation is inadequate in many classrooms, which may possibly lead to health related symptoms. As of 1999, Daisy et al. [8] found two studies that specifically looked at the relationship between
ventilation and the prevalence of health related symptoms. However, the results of these two studies were inconsistent and thus the authors stress the need of more studies looking into the relationship between IAQ in schools and health. The recent review of Sundell et al. [9] looked into the available literature until 2005 and discussed five articles that have studied the school environment. They concluded from these studies that lower ventilation rates are associated with increased absenteeism and more respiratory symptoms in school children, but emphasise that there is too little data available to make firm conclusions. Furthermore, they also stressed the need for more studies on the relationship between ventilation and health, especially in buildings other than offices. Since 2005, more studies on the relationship between ventilation of schools and health have been published, for example two articles relating ventilation rates in schools to illness absenteeism of the students [10,11]. Both of these studies found that lower ventilation rates are associated with higher absenteeism. Another study, on the effect of the implementation of a new ventilation system in schools, found that after installation less asthmatic symptoms were reported and exposure to airborne pollutants decreased [12].

Apart from the effects of IAQ on health, research has also focussed on the effects of ventilation on human performance. Mendell and Heath [13] reviewed the literature available until 2003 on the possible effects of poor IAQ on students’ performance and concluded that there is suggestive evidence for an association between ventilation levels and the attention and performance of students, two prerequisites of an efficient learning process. Since this review, various papers have been published regarding this topic. An observational study reported an association between classroom ventilation rates and students’ achievements on a standardised academic performance test. Based on their study the authors suggest a linear relationship between poorer classroom ventilation and lower academic achievement [14]. Four studies have used an experimental design [15–18]. Findings of these studies are inconsistent, but comparisons of the studies are difficult due to differences in study design and outcome parameters.

The levels of CO2 that exist indoor have long been thought to have no direct impact on occupant’s health or performance [19], but to be primarily an indicator of the level of ventilation. It has been hypothesised that the observed associations between ventilation levels and health or performance result from the fact that ventilation does not only affect the level of indoor CO2, but also levels of other pollutants in the indoor environment that are able to cause these adverse effects [20]. However, Satish et al. [20] conducted a laboratory experiment on the direct effects of CO2 at normally occurring indoor concentrations on human decision making. Their study suggests that, compared to CO2 concentrations of 600 ppm, at 1000 ppm and 2500 ppm a reduction in decision-making performance occurs. This may indicate the importance of considering CO2 in itself as an air pollutant. However, they stress that confirmation of their findings is needed.

Since there is still a need for more experimental evidence with respect to the relationship of classroom ventilation and its effect on both respiratory health and cognitive performance, the FRESH study (Forced-ventilation Related Environmental School Health) was designed. The aim of this study is to investigate whether an intervention can be used to improve classroom IAQ by increasing classroom ventilation and whether this intervention affects children’s cognitive performance and/or respiratory health. In this paper, we focus on the performance of the ventilation system in terms of achieved classroom CO2 concentrations.

**Methods**

**Study design**

The FRESH study has been designed as an intervention study with two experimental groups and one control group. Differences between the two experimental groups were created using a cross-over design. Data collection for this study took place at 17 primary schools during the heating seasons (October–April) of 2010–2011 and 2011–2012. In the first school year, ten schools participated, in the second year eight. One school participated in both the first and the second year, but with a different student population. With this exception, per school, one classroom was studied, with repeated measurements during three consecutive weeks. The first week served as baseline period, with measurements of normally existing CO2 levels and ventilation according to the teachers own preference. In the following two weeks, in the 12 intervention classrooms the concentrations of CO2 were maintained at pre-set levels of 800 and 1200 ppm, established with a mobile, custom-made mechanical ventilation device. During these weeks, the teachers were asked not to ventilate the classroom by opening doors or windows. In the six schools that acted as the control group, no intervention on ventilation took place. In these classrooms, CO2 levels were monitored and teachers were allowed to ventilate as they preferred.

**Participating schools**

In total 18 classrooms (7th grade children, ages 10–11 years) from 17 different schools were investigated in the FRESH study. These schools were all located in two regions in the north and north-eastern part of The Netherlands with comparatively low concentrations of ambient air pollutants (Zwolle and Groningen). Each region provided nine classrooms for the study. In the Zwolle region it was more difficult to find schools willing to participate, so that
in the second year of the study, one school (but with a different student population) participated again. Schools were randomly selected, excluding those that were within 250 m of a busy road or highway. A total of 80 schools were asked to participate before the planned number of 18 classrooms was achieved (23% response). Many schools that did not participate in the study valued the FRESH study as important, but were too busy to take part in the (relatively invasive) FRESH study. Schools were randomly allocated to the three study arms, but were allocated to the control arm when for practical reasons it was not possible to install the ventilation system (4 schools). The exact size of the classrooms has not been measured, but classrooms in The Netherlands measure approximately 50 m². The average number of students in the studied classrooms was 26, per classroom one teacher was present. All studied classrooms relied on natural ventilation through opening doors and windows to provide fresh air. Table 1 provides more information on the schools.

Intervention
In 12 schools we changed the classroom ventilation, using a specially designed and installed mechanical ventilation device. Based on a design of providing a stable ventilation flow with an adjustable outdoor air supply rate, this device consisted of an exterior constant flow fan (LAAHP12, Shandong LARK Central Air Condition Co., China) placed outdoors. Within the device outdoor air was mixed with indoor air derived from the classroom via the return system. The mixing ratio between indoor and outdoor air was depended on the setting of the targeted CO₂ concentration and was adjusted by means of a valve in the inlet of the outdoor air supply system. The mixture of indoor and outdoor air was than heated before being introduced into the classroom with a flow of approximately 1400 m³/h. Simple ducting (diameter 355 mm) lead the air without filtering into the building through a tailor made window pane. In the classrooms, the air was distributed through a flexible, perforated fabric air sock. A non-flexible duct was used for air exhaust. Both the air sock and exhaust duct were attached to the ceiling of the classroom. In Figure 1 the ventilation device and the installation within a classroom are shown.

The device was CO₂ controlled, using a real-time, self-calibrating CO₂ sensor (Telair 6613 CO₂ module, GE Measurement & Control, USA) to adjust the amount of outdoor air supplied, in order to achieve a target steady-state CO₂ concentration in the classroom. This CO₂ sensor was located at one of the walls of the classroom, at approximately 1.5 m from the floor, where possible not close to windows and doors. By means of the recirculation and constant air flow blinding of students, teachers and field investigators to the level of outdoor air supply was established. As classrooms in The Netherlands have approximately the same size, one single ventilation flow was chosen (approximately 1400 m³/h) that was enough to realise the targeted CO₂ concentration without creating disturbingly high air flows within the classroom.

For this study, pre-set levels of 800 and 1200 ppm CO₂ were defined. The lower level represents the level

| School | n students | Study region | Condition | Study period |
|--------|------------|--------------|-----------|--------------|
| E1     | 31         | Zwolle       | Intervention 1 (800–1200) | Jan 2011 |
| E2     | 27         | Zwolle       | Intervention 1 (800–1200) | March 2011 |
| E3     | 22         | Zwolle       | Intervention 1 (800–1200) | Nov 2011 |
| E4     | 30         | Groningen    | Intervention 1 (800–1200) | Jan 2011 |
| E5     | 27         | Groningen    | Intervention 1 (800–1200) | Jan 2012 |
| E6     | 25         | Groningen    | Intervention 1 (800–1200) | March 2012 |
| E7     | 23         | Zwolle       | Intervention 2 (1200–800) | Feb 2012 |
| E8     | 23         | Zwolle       | Intervention 2 (1200–800) | March 2012 |
| E9     | 22         | Zwolle       | Intervention 2 (1200–800) | Jan 2012 |
| E10    | 23         | Groningen    | Intervention 2 (1200–800) | Nov 2010 |
| E11    | 29         | Groningen    | Intervention 2 (1200–800) | March 2011 |
| E12    | 29         | Groningen    | Intervention 2 (1200–800) | Nov 2011 |
| C1     | 36         | Zwolle       | Control    | Oct 2010 |
| C2     | 25         | Zwolle       | Control    | Jan 2011 |
| C3     | 22         | Zwolle       | Control    | March 2011 |
| C4     | 28         | Groningen    | Control    | Jan 2011 |
| C5     | 18         | Groningen    | Control    | March 2011 |
| C6     | 29         | Groningen    | Control    | March 2012 |
advised by the joint Dutch Municipal Health Services. The upper level represents the basis on which Dutch Building Regulations have formulated the minimal achievable air flow for the design of new schools [4,5]. To maintain a cross-over in the design, in half of the classrooms, we started ventilating at 800 ppm, the other six schools started with a setting of 1200 ppm. In the third week of the study, the ventilation regime changed.

To prevent thermal discomfort and create a more or less stable classroom temperature, the device was equipped with an air pump able to both heat and cool the outdoor air before it was introduced into the classrooms. Classroom temperature was set at 21°C, to minimize differences between the schools. Based on measurements of a real-time temperature sensor (located at the same position as the CO₂ sensor) cooling or heating of the supplied air was adjusted according to the classroom temperature. As the experiment was carried out in winter seasons, classroom temperature was higher than outdoor temperature. Even though no measurements were performed of the exact temperature of supplied air, it is to be expected that this air was heated. When classroom temperature exceeded 21°C, colder air was supplied to lower the indoor temperature. Furthermore, the system was designed to maintain system noise below 35 dB (A). This value has shown to be the threshold for annoyance and disturbance [21].

**Indoor measurements**

During the study weeks, each classroom was equipped with two data loggers (GRP-300 Pro (ATAL, The Netherlands) in study region 1 and ATV-IAQ set (ATAL, The Netherlands) in study region 2) for CO₂, temperature and relative humidity. These data loggers were calibrated each year by the manufacturer. The loggers were positioned as much as possible at the height of the desks of the pupils and on the opposite sides of the classroom. Log interval was 4 minutes. From the two data loggers the average was taken to represent classroom CO₂, temperature and relative humidity. All data reported in this paper are restricted to periods of actual classroom occupation excluding breaks and periods when students were elsewhere (e.g. gym).

**Outdoor measurements**

The selected schools were not located to obvious sources of CO₂, therefore no continuous measurements of outdoor CO₂ concentrations were performed. To get an indication of outdoor CO₂ concentrations, short time frame measurements of approximately 5 minutes were performed just...
outside the school building, using the same type of CO₂ data loggers that were used for indoor measurements. Measurements took place at the beginning and end of each week. Data on 24 h-average outdoor temperature and relative humidity were obtained from the two weather stations (Eelde and Hoogeveen) of the Royal Netherlands Meteorological Institute closest to the study regions.

Ethical approval
The study design and protocols have approved by the ‘Central Committee on Research involving Human Subjects’ (CCMO, The Hague) on February 23, 2010 and is registered under number 120620026.

Statistical analysis
The data were analysed using PASW Statistics 18 and SAS 9.2. Significance was tested against an $\alpha = 0.05$. The effect of the intervention, as well as differences between the two settings of the intervention (800 ppm and 1200 ppm) were tested by means of mixed models with random school intercepts to take into account the dependency of the repeated measurements performed in the same classrooms.

Results
Mean indoor CO₂ concentrations, temperature and relative humidity during classroom occupation per school per week are presented in Tables 2, 3 and 4.

During the first week (baseline) mean classroom CO₂ concentration was 1335 ppm (sd = 325) with a range of 763–2000 ppm. In the classrooms allocated to become intervention schools, mean CO₂ concentration was 1399 ppm (sd = 350), the control classrooms had an average CO₂ concentration of 1208 ppm (sd = 244). Only two classrooms (E10 and C5) had mean CO₂ concentration lower than 800 ppm at baseline, and another five classrooms had mean CO₂ concentrations lower than 1200 ppm.

In the second week, we started the intervention in 12 classrooms. In those 12 classrooms, on average we decreased mean CO₂ with 491 ppm compared to baseline (sd = 324, range: -1085–124 ppm). With the setting of the ventilation set at 800 ppm, the average CO₂ concentration was 841 ppm (sd = 65) with a range of 743–925 ppm. When set at 1200 ppm, the average CO₂ concentration was 975 ppm (sd = 73, range: 887–1077 ppm). In the control classrooms, during the second and third week, CO₂ concentrations ranged from 740 to 2328 ppm, with an average mean CO₂ concentration of 1350 ppm (sd = 486). Figure 2 displays the boxplot of CO₂ concentrations per condition per week. The P98 results confirm that the ventilation device was able to maintain a maximum level of 1200 ppm CO₂, whereas it was more difficult to keep CO₂ levels below 800 ppm (Table 2).

Table 5 provides the results from our mixed model analysis. From this analysis we can conclude that

| School | Condition | n | mean | sd | P98 |
|--------|-----------|---|------|----|-----|
| E1     | Intervention 1 (800–1200) | 344 | 1365 | 531 | 2991 |
| E2     |           | 352 | 1337 | 460 | 2351 |
| E3     |           | 286 | 1143 | 398 | 2052 |
| E4     |           | 215 | 1648 | 353 | 2395 |
| E5     |           | 347 | 1466 | 330 | 2322 |
| E6     |           | 255 | 2000 | 602 | 3321 |
| E7     | Intervention 2 (1200–800) | 356 | 1323 | 291 | 1963 |
| E8     |           | 354 | 1049 | 158 | 1313 |
| E9     |           | 265 | 1763 | 423 | 2507 |
| E10    |           | 222 | 763  | 131 | 1153 |
| E11    |           | 367 | 1762 | 625 | 3064 |
| E12    |           | 347 | 1171 | 213 | 1553 |
| C1     | Control   | 380 | 1393 | 483 | 2446 |
| C2     |           | 342 | 1176 | 289 | 1694 |
| C3     |           | 351 | 1112 | 333 | 1789 |
| C4     |           | 350 | 1389 | 425 | 2264 |
| C5     |           | 353 | 779  | 177 | 1166 |
| C6     |           | 282 | 1399 | 311 | 1975 |
### Table 3 Mean indoor temperature (°C) per school per week

| School | Condition          | Week 1          | Week 2          | Week 3          |
|--------|--------------------|-----------------|-----------------|-----------------|
|        |                    | n   | mean | sd  | n   | mean | sd  | n   | mean | sd  |
| E1     | Intervention 1 (800–1200) | 344 | 20.2 | 1.4 | 344 | 20.3 | 0.9 | 280 | 20.3 | 0.9 |
| E2     |                    | 352 | 21.1 | 1.1 | 345 | 19.1 | 0.8 | 290 | 19.1 | 0.8 |
| E3     |                    | 286 | 21.0 | 0.9 | 285 | 19.3 | 1.7 | 320 | 19.3 | 1.7 |
| E4     |                    | 215 | 19.2 | 1.1 | 312 | 18.5 | 1.2 | 350 | 18.5 | 1.2 |
| E5     |                    | 347 | 21.2 | 1.1 | 295 | 21.4 | 1.5 | 257 | 21.4 | 1.5 |
| E6     |                    | 255 | 20.4 | 1.0 | 270 | 20.2 | 0.5 | 297 | 20.2 | 0.5 |
| E7     | Intervention 2 (1200–800) | 356 | 21.6 | 0.9 | 356 | 20.4 | 1.0 | 356 | 20.4 | 1.0 |
| E8     |                    | 354 | 19.2 | 0.8 | 321 | 19.7 | 1.2 | 353 | 19.7 | 1.2 |
| E9     |                    | 265 | 21.8 | 1.5 | 301 | 20.8 | 1.9 | 336 | 20.8 | 1.9 |
| E10    |                    | 222 | 23.0 | 0.8 | 272 | 23.3 | 0.9 | 334 | 23.3 | 0.9 |
| E11    |                    | 367 | 20.9 | 1.1 | 352 | 20.8 | 1.3 | 336 | 20.8 | 1.3 |
| E12    |                    | 347 | 22.0 | 1.3 | 343 | 21.1 | 0.8 | 309 | 21.1 | 0.8 |
| C1     | Control            | 380 | 22.6 | 1.2 | 379 | 20.6 | 1.5 | 379 | 20.6 | 1.5 |
| C2     |                    | 342 | 21.2 | 0.8 | 342 | 20.7 | 0.6 | 342 | 20.7 | 0.6 |
| C3     |                    | 351 | 19.8 | 1.3 | 335 | 20.1 | 1.6 | 327 | 20.1 | 1.6 |
| C4     |                    | 350 | 20.9 | 0.6 | 340 | 21.8 | 0.8 | 340 | 21.8 | 0.8 |
| C5     |                    | 353 | 20.4 | 1.2 | 328 | 22.3 | 0.6 | 312 | 22.3 | 0.6 |
| C6     |                    | 282 | 19.7 | 1.0 | 344 | 20.1 | 1.0 | 336 | 20.1 | 1.0 |

### Table 4 Mean indoor relative humidity (%) per school per week

| School | Condition          | Week 1          | Week 2          | Week 3          |
|--------|--------------------|-----------------|-----------------|-----------------|
|        |                    | n   | mean | sd  | n   | mean | sd  | n   | mean | sd  |
| E1     | Intervention 1 (800–1200) | 344 | 33.6 | 6.4 | 344 | 38.0 | 11.7 | 280 | 30.3 | 4.0 |
| E2     |                    | 352 | 30.4 | 6.2 | 345 | 28.3 | 10.4 | 290 | 44.9 | 6.8 |
| E3     |                    | 286 | 54.4 | 5.6 | 285 | 41.5 | 7.6 | 320 | 32.0 | 8.6 |
| E4     |                    | 215 | 45.5 | 7.8 | 312 | 35.3 | 6.8 | 350 | 37.3 | 4.2 |
| E5     |                    | 347 | 49.8 | 6.2 | 295 | 30.7 | 4.0 | 257 | 32.7 | 3.2 |
| E6     |                    | 255 | 48.2 | 3.4 | 270 | 40.2 | 3.4 | 297 | 42.1 | 4.4 |
| E7     | Intervention 2 (1200–800) | 356 | 40.1 | 5.6 | 356 | 27.9 | 4.6 | 356 | 29.2 | 3.0 |
| E8     |                    | 354 | 42.7 | 3.9 | 321 | 42.4 | 3.7 | 353 | 40.4 | 3.0 |
| E9     |                    | 265 | 27.1 | 4.4 | 301 | 15.7 | 3.0 | 336 | 30.2 | 2.9 |
| E10    |                    | 222 | 48.7 | 4.0 | 272 | 31.4 | 2.9 | 334 | 32.6 | 1.6 |
| E11    |                    | 367 | 46.6 | 7.9 | 352 | 31.4 | 7.3 | 336 | 39.9 | 7.5 |
| E12    |                    | 347 | 53.8 | 4.7 | 343 | 41.9 | 4.8 | 309 | 33.0 | 5.9 |
| C1     | Control            | 380 | 62.3 | 2.9 | 379 | 54.6 | 4.5 | 379 | 55.0 | 2.2 |
| C2     |                    | 342 | 33.4 | 6.5 | 342 | 32.7 | 6.3 | 342 | 37.3 | 4.2 |
| C3     |                    | 351 | 42.3 | 4.3 | 335 | 43.7 | 6.5 | 327 | 47.0 | 6.3 |
| C4     |                    | 350 | 37.1 | 4.4 | 340 | 39.6 | 7.6 | 340 | 36.0 | 5.7 |
| C5     |                    | 353 | 35.9 | 4.1 | 328 | 35.8 | 6.9 | 312 | 40.1 | 5.3 |
| C6     |                    | 282 | 27.6 | 4.2 | 344 | 29.4 | 4.2 | 336 | 42.8 | 4.0 |
classroom CO₂ levels were statistically significantly decreased during the intervention (F (2,10) = 17.59, p < 0.001). Compared to baseline, the estimated mean decrease in CO₂ with the setting at 800 ppm was 558 ppm (SE = 97.8). For the setting of 1200 ppm, the estimated mean decrease was 424 ppm (SE = 97.8). The mean difference in decrease compared to baseline between the two settings of the intervention was 134 ppm (SE = 29.3, t (10) = 4.57, p = 0.001).

The result of implementation of the ventilation intervention and its effect on the CO₂ in a classroom is illustrated in Figure 3. This graph displays the CO₂ concentration during the three weeks of the study in one of the experimental classrooms. The graph shows how in the first week, high CO₂ peak concentrations exist, which no longer occur during the second and third week. Also, it shows how the CO₂ concentrations are much more stable in the two intervention weeks. Furthermore, the graph shows the (slight) difference in CO₂ concentration during the second (ventilation set at 1200 ppm) and third (800 ppm) week.

The intervention was designed in such way that classroom temperature did not decrease as a result of supplying (cold) outdoor air. At baseline, average indoor temperature was 20.9°C (sd = 1.1, range: 19.2–23.0°C). In the intervention classrooms average temperature during weeks two and three was 20.6°C (sd = 1.0, range: 18.5–23.3°C), in the control classrooms average temperature was 20.9°C (sd = 1.2, range: 18.5–22.5°C). No significant effect of the intervention on classroom temperature was found (F (2,10) = 2.13, p = 0.170), nor on differences between the two intervention settings (Table 5).

Indoor relative humidity at baseline was 42.2% (sd = 9.9, range: 27.1–62.3%), in weeks two and three average relative humidity was 41.2% (sd = 8.0, range: 29.4–55.0%) in the control classrooms and 34.5% (sd = 6.6, range: 16.7–44.9%) in the intervention classrooms. This decrease in relative humidity due to the intervention appeared to be statistically significant (F (2,10) = 4.16, p = 0.049). No significant difference between the two intervention conditions was found (Table 5).

During the study, outdoor CO₂ concentration was on average 471 ppm (sd = 53, range: 350–660 ppm), mean outdoor temperature was 4.7°C (sd = 5.1, range: -12.7–16.9°C), and mean outdoor relative humidity was 87.1% (sd = 8.5, range: 54–100%).

### Table 5 Mean decrease of CO₂ (ppm), temperature (°C) or relative humidity (%) compared to baseline measurements

| Setting          | CO₂ (ppm) mean decrease | CO₂ (ppm) SE   | CO₂ (ppm) p       | T (°C) mean decrease | T (°C) SE | T (°C) p   | RH (%) mean decrease | RH (%) SE | RH (%) p  |
|------------------|-------------------------|----------------|-------------------|----------------------|----------|------------|----------------------|-----------|-----------|
| 800 ppm          | 558                     | 97.8           | <0.001            | 0.56                 | 0.35     | 0.144      | 8.5                  | 2.4       | 0.005     |
| 1200 ppm         | 424                     | 97.8           | 0.002             | 0.10                 | 0.35     | 0.784      | 9.3                  | 2.4       | 0.003     |
| Difference between 800 and 1200 ppm | 134                     | 29.3           | 0.001             | 0.46                 | 0.24     | 0.088      | 0.8                  | 2.3       | 0.734     |
Discussion

This study showed that it is possible to use a portable, tailor made mechanical ventilation device to improve outdoor air supply in schools during the heating season. In the classrooms where we intervened we found an average decrease of 491 ppm CO₂ with, however, little difference between the two experimental conditions. The target value of 1200 ppm was more than met, however the target value of 800 ppm proved to be more difficult to achieve. To what extent this is due to differences in CO₂ concentrations measured at the location of the system sensor and the location of our two data loggers we do not know as the system sensor was unable to log the CO₂ concentrations, nor was it equipped with a display enabling us to read measured CO₂ concentrations by the system sensor. Another possible explanation could be that the ventilation device appeared to have not enough capacity to lower CO₂ concentration to 800 ppm during classroom occupation. Technical specifications suggest that this should not have been the case, however, we did not measure true air displacement of our installation in the field as we focussed our study design on obtaining specific indoor CO₂ concentrations rather than on achieving specific ventilation rates.

In all but one classroom, the intervention was able to decrease CO₂ concentration. The level of decrease varied per classroom, as this is related to CO₂ concentration measured at baseline. The highest decrease in CO₂ concentration was observed in school E6, where we lowered mean CO₂ concentration from 2000 ppm to 915 ppm. In one school CO₂ levels slightly increased after implementation of the intervention (school E10), this however was due to the high ventilation rate in the baseline week which produced low CO₂ concentrations that we did not need to lower further. In seven schools we found baseline CO₂ concentrations lower than 1200 ppm, in two schools the average CO₂ concentration in the first week was lower than 800 ppm. This number is higher than we had expected based on the studies from 2007 [2,3]. It is plausible that since 2007 ventilation behaviour in schools has improved. The study by Versteeg [2] resulted in media-attention and a political debate in the Dutch government. Moreover, it could well be that the participation in the FRESH study directly influenced the teachers’ (and pupils’) awareness of the importance of proper classroom ventilation, resulting in relatively low baseline CO₂ concentrations. The decreased relative humidity indoors during the intervention period may be explained by differences in outdoor and indoor temperature between baseline and intervention periods. Especially in cold climates, low indoor relative humidity is associated with increased ventilation rates [7].

Recently various other classroom ventilation intervention studies have been published, most of them predefined a contrast aimed to be achieved by the intervention. One of these studies, by Twardella et al. [16] adjusted the mechanical ventilation within 20 classrooms of six schools. They either up- or down-regulated the ventilation to achieve CO₂ levels of < 1000 ppm (‘better than usual’) or CO₂ concentrations of 2000 to 2500 ppm (‘worse than usual’). Each condition was implemented for 2 days. They report that it was difficult to regulate the ventilation in such way that the targeted CO₂ levels were achieved: only on half of the days of the ‘worse than usual’ condition CO₂ concentrations were higher than 2000 ppm and on 22 (of the 40) days of the ‘better than usual’ condition CO₂ concentrations were below 1000 ppm. Wargocki and Wyon [22] performed three experiments in which they also adjusted the existing outdoor air supply of the mechanical ventilation of schools by altering the fan capacity. They aimed on increasing ventilation rates from approximately 3 to 10 L/s per person. Using a general mass balance equation from measured CO₂ concentrations, they were able to estimate the actual effective ventilation rates. In the first experiment estimated mean effective ventilation rates were 4 L/s and 8.5 L/s per person, in the second experiment these ventilation rates were 3 L/s and 6.5 L/s per person and in the third experiment 5 L/s and 9.5 L/s per person. This shows that while they aimed for a threefold increase
of the ventilation rates, the estimated actual effective ventilation rates were doubled. Bakó-Biró et al. [15] intervened upon classroom ventilation using an installation similar to the one we used in the FRESH study. The biggest difference with our study is that they did not adjust ventilation to achieve predefined levels of CO₂, but used the installation to either supply fresh air or recirculate the indoor air in a blinded fashion. As this study aimed at comparing high and low levels of outdoor air supply, with their intervention set at recirculation, they were able to achieve big differences in CO₂ concentration between the two experimental conditions. In their study, Smidje and Norbäck were able to study the change in indoor air quality in schools that renewed their ventilation system [12]. They observed that air exchange rates improved, and that associated CO₂ concentrations decreased on average by 270 ppm due to a new ventilation system. Furthermore, they also reported a significant decrease in relative humidity in schools with a new ventilation system (-10%), compared to schools that did not change their ventilation system (-2%).

Conclusions
Various studies, including our own, show that intervening on classroom ventilation is effective if one wants to change indoor CO₂ concentrations. Furthermore, both our own study and the studies of Twardella et al. [16] and Wargocki and Wyon [22] show that field experiments are not comparable with laboratory experiments and that it can be challenging to execute the study as designed. Altogether, our study has shown that classrooms CO₂ levels can be significantly reduced by installing a CO₂ controlled mechanical ventilation system.

Abbreviations
IAQ: Indoor air quality; ppm: Parts per million; FRESH: Forced-ventilation related environmental school health (acronym for the study); m³/h: Cubic meters per hour; dBA: A-weighted decibels; L/s: Liters per second; sd: Standard deviation; SE: Standard error.

Competing interests
The authors declare that they have no competing interests.

Author's contributions
JTMR supported in the design of the study, led and participated in field work in one of the study regions, conducted data processing, analysis, and interpretation and drafted the manuscript. MV contributed to the study and intervention design, participated in data collection in one of the study regions and managed the overall project. MV furthermore helped draft the manuscript. JTVM contributed to the intervention design, participated in data collection in one of the study regions and reviewed the finalised manuscript. UG contributed to the statistical analysis and interpretation of the data and critically reviewed the manuscript. FD and BB conceived of and managed the project and helped prepare and critically review the draft. All authors have read and approved the final manuscript.

Acknowledgements
The authors would like to thank all schools, and especially the teachers and students of our 18 classes, for their participation in the FRESH study. Furthermore, they thank all colleagues from the Municipal Health Services of Groningen and IJsselland for their support and their contributions to the field work. Gratitude is also expressed to the colleagues of Utrecht University. Financial support for this study was granted by The Netherlands Organisation for Health Research and Development (ZonMw).

Author details
1 Institute for Risk Assessment Sciences, Utrecht University, P.O. Box 80178, 3508 TD, Utrecht, The Netherlands. 2Department of Environmental Health, Municipal Health Services Groningen, P.O. Box 584, 9700 AN, Groningen, The Netherlands. 3Department of Environmental Health, Municipal Health Services IJsselland, P.O. Box 1453, 8001 BL, Zwolle, The Netherlands. 4 Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, P.O. Box 85500, 3508 GA, Utrecht, The Netherlands.

Received: 2 September 2013 Accepted: 12 December 2013 Published: 17 December 2013

References
1. Duftield TJ: School ventilation. Its effect on the health of the pupil. Am J Public Health 1927, 17:1226–1229.
2. Versteeg H: Onderzoek naar de kwaliteit van het binnenmilieu in basisscholen. The Hague: Ministerie voor Volkshuisvesting, Ruimtelijke ordening en Milieu; 2007: report B055.
3. Meijer G, Duijm F: Binnenmilieu van de openbare scholen in Groningen. Groningen: GGD Groningen; 2009.
4. Health Council of The Netherlands: Indoor air quality in primary schools. The Hague: Health Council of The Netherlands; 2010.
5. Habets T, Van Ass M, Duijm F, Geelen L, Hanss, L, Van Brederode N: GGD-richtlijn Beoordeling van ventilatie in scholen. Utrecht: GGD Nederland; 2008.
6. Mendell MJ: Non-specific symptoms in office workers: a review and summary of the epidemiologic literature. Indoor Air 1993, 3:227–236.
7. Seppanen OA, Fisk WJ, Mendell MJ: Association of ventilation rates and CO₂ concentrations with health and other responses in commercial and institutional buildings. Indoor Air 1996, 6:226–252.
8. Daisey JM, Argell WJ, Apte MG: Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. Indoor Air 2003, 13:53–64.
9. Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC, Samet JM, Spengler JD, Taylor ST, Weschler CJ: Ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 2011, 21:191–204.
10. Simons E, Hwang S, Fitzgerald EF, Kielb C, Lin S: The impact of school building conditions on student absenteeism in upstate New York. Am J Public Health 2010, 100:1679–1686.
11. Mendell MJ, Eliseea EA, Davies MM, Spears M, Lobbscheid A, Fisk WJ, Apte MG: Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. Indoor Air 2013, 23:515–528.
12. Smidje G, Norbäck D: New ventilation systems at select schools in Sweden: effects on asthma and exposure. Arch Environ Health 2000, 55:18–25.
13. Mendell MJ, Heath GA: Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor Air 2005, 15:27–52.
14. Haverinen-Shaughnessy U, Moschandreas DJ, Shaughnessy RJ: Association between substandard classroom ventilation rates and students' academic achievement. Indoor Air 2011, 21:121–131.
15. Bakó-Biró Z, Zementis-Croome D, Kochhar N, Awbi H, Williams M: Ventilation rates in schools and pupils' performance. Build Environ 2012, 48:215–223.
16. Twardella D, Matzen W, Lahre T, Burghardt R, Spiegel H, Hendromanso L, Frenzel A, Fromme H: Effect of classroom air quality on students' concentration: results of a cluster-randomized cross-over experimental study. Indoor Air 2012, 22:378–387.
17. Wargocki P, Wyon DP: The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257), HVAC & R Res 2007, 13:193–220.
18. Wargocki P, Wyon DP: The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257), HVAC & R Res 2007, 13:165–191.
19. Seppanen OA, Fisk WJ: Summary of human responses to ventilation. Indoor Air 2004, 14(Suppl 7):102–118.
20. Satish U, Mendell MJ, Shekhar K, Hotchi T, Sullivan D, Streufert S, Fisk WJ: Is CO₂ an indoor pollutant? Direct effects of low-to-moderate CO₂
concentrations on human decision-making performance. *Environ Health Perspect* 2012, 120:1671–1677.

21. Acoustical Society of America: Classroom Acoustics II: acoustical barriers to learning. Melville, NY: Acoustical Society of America; 2002.

22. Wargocki P, Wyon DP: Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Build Environ* 2013, 59:581–589.

doi:10.1186/1476-069X-12-110

Cite this article as: Rosbach et al: A ventilation intervention study in classrooms to improve indoor air quality: the FRESH study. *Environmental Health* 2013 12:110.