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THE RELATIONSHIPS BETWEEN CLASSROOM AIR QUALITY AND CHILDREN'S PERFORMANCE IN SCHOOL

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ABSTRACT

The data from published studies were used to derive systematic relationships between learning outcomes and air quality in classrooms. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, rating schemes, and tests used to assess progress in learning including end-of-year grades and exam scores were used to quantify learning outcomes. Short-term sick leave was also included because it may influence progress in learning. Classroom indoor air quality was characterized by the concentration of carbon dioxide (CO_2). For psychological tests and school tasks, fractional changes in performance were regressed against the average concentrations of CO_2 at which they occurred; all data reported in studies meeting the inclusion criteria were used to derive the relationship, regardless of whether the change in performance was statistically significant at the examined levels of classroom air quality. The analysis predicts that reducing CO_2 concentration from 2,100 ppm to 900 ppm would improve the performance of psychological tests and school tasks by 12% with respect to the speed at which the tasks are performed and by 2% with respect to errors made. For other learning outcomes and short-term sick leave, only the relationships published in the original studies were available. They were therefore used to make predictions. These relationships show that reducing the CO_2 concentration from 2,300 ppm to 900 ppm would improve performance on the tests used to assess progress in learning by 5% and that reducing CO_2 from 4,100 ppm to 1,000 ppm would increase daily attendance by 2.5%. These results suggest that increasing the ventilation rate in classrooms in the range from 2 L/s-person to 10 L/s-person can bring significant benefits in terms of learning performance and pupil attendance. The results provide a strong incentive for improving classroom air quality and can be used in cost-benefit analyses.

KEYWORDS

Children; Learning; Cognitive performance; Elementary schools; Carbon dioxide

1. INTRODUCTION

Classrooms are places where children spend a large part of their waking hours to gain new knowledge and develop various skills and abilities. Research has documented that the indoor environmental quality in elementary school classrooms is often inadequate [1–3]. This has been demonstrated to have negative consequences for the learning process [4,5]. In previous work by Wargocki et al., it was shown that the temperature in classrooms has a strong impact on learning [6]. The present work examined how the performance of schoolwork is affected by poor classroom air quality.

Several studies have shown that classroom air quality may compromise the cognitive skills and abilities of pupils, as they cannot concentrate or are distracted from the work that they are supposed to do [7–11]. These effects have significant socioeconomic consequences [4] and impact their quality of life, e.g. by increasing stress on parents, who must take the day off when children must stay at home due to sickness [4,12]. Moreover, when classroom air quality is poor, the working conditions for teachers are degraded. This can result in reduced learning performance because the teachers' ability to teach effectively is reduced. This may also increase the sick-leave taken by teachers. As a result, further economic losses are to be expected.

To estimate the size of the effect of classroom air quality on student performance and sick-leave, relationships between classroom air quality and learning performance outcomes that summarize published data would be useful. Such relationships do not exist at present specifically for learning performance outcomes. However, some studies have established relationships between indoor air quality and cognitive performance, and they are summarized below. In these studies, the ventilation rate (outdoor air supply rate) was used as a metric of indoor air quality, with the presumption that a higher ventilation rate corresponds to improved indoor air quality. Different outcomes were used to describe cognitive performance, ranging from neurobehavioral tests examining abilities to performance of different cognitive tasks to regular office work.

Seppänen et al. developed a relationship between ventilation rate and cognitive performance representing mainly office work [13]. It shows that doubling the ventilation rate would improve performance by about 1.5%. The relationship is based on the results obtained from nine studies. They were performed in call centres [14–18] where average handling, talk, or wrap-up time was used as the performance outcome; in laboratories using simulated office work tasks such as typing and proof-reading as the performance outcomes [19,20]; and in a school where neurobehavioral cognitive tests were used to measure effects on the performance of pupils [8]. Consequently, this relationship does not specifically address the effects of classroom air quality on learning as it is based on data from different studies that primarily investigated the effects of indoor air quality on office-type work.

A few studies performed in schools used performance outcomes relevant for learning, such as school work consisting of arithmetic and language-based tasks or the results of annual tests measuring progress in learning, to create a relationship between performance outcomes and air quality [4,21]. Wargocki and Wyon obtained a relationship predicting a 14% increase in the performance of pupils when the outdoor air supply is doubled [4]. Haverinen-Shaughnessy et al. derived a relationship showing an improvement in students' mean mathematics score by 0.5% for each 1 L/s per person increase in ventilation within the range of 0.9-7.1 L/s per person [21]. These studies did not integrate the results from multiple experiments as was the case when deriving the relationships of Seppänen et al. [13] but used only the results obtained in their own measuring campaigns. Alfano et al. [22] proposed a relationship between school performance and ventilation rates based on the results from a few studies performed in schools in Denmark [23], the UK [24], the Netherlands [25] and the USA [26], which used selected school work and psychological tests as the outcomes describing the effects on learning. The relationship that was obtained was similar in shape to the one that Seppänen et al. obtained for office work [13] and showed that doubling the outdoor air supply rate would improve performance by 7% to 8%. This relationship was not published in the peer-reviewed literature but appeared in the REHVA Guidebook 13 [22].

Other relationships have been derived to predict how changing the ventilation rate will affect the prevalence of illness and sick-leave. One of the first was developed by Fisk et al. [27]. It shows a 10% reduction in respiratory illness and sick-leave rates when the air change rate is doubled [27]. Only limited data were available to produce this relationship from studies performed in medical barracks [28], nursing homes [29], jails [30], and offices [31]. One of the predictions derived by Fisk et al. [27] was made using a theoretical model based on the Wells-Riley equation, which describes the effect of ventilation on the transmission of infectious respiratory diseases [32]. The relationship derived by Fisk et al. [27] was based on outcomes such as respiratory diseases, influenza, pneumococcal disease, and short-term sick leave, and so does not specifically predict the sick leave taken by pupils in schools. Another relationship was created by Mendell et al. [12]. They derived a relationship between classroom ventilation and the short-term sick leave taken by pupils in US elementary schools using their own long-term measurements in schools in California [12]. The relationship predicts that increasing the outdoor air supply rate by 1 L/s per person reduces the sick-leave of pupils by about 1.4% to 1.8%.

The present work was conducted to estimate the magnitude of the effects on learning and sick-leave that can be expected as a result of changes in classroom air quality based on the results of studies published in archival journals. The objective was achieved by, firstly, summarizing the existing data on the effects of air quality in classrooms on learning outcomes and short-term sick leave taken by elementary school pupils, and, secondly, by using these data to develop relationships describing how classroom air quality affects learning outcomes.

2. METHODS

The scientific literature was surveyed using major electronic databases to find studies reporting measurements of indoor air quality in classrooms, learning outcomes, and short-term sick leave. Ventilation rates and concentration of carbon dioxide (CO_2) were used as proxies for classroom air quality. Only studies reporting measurements in elementary schools (primary, middle, and/or secondary schools) were selected, i.e. for students no older than 18-19 years old. Data from colleges and universities were excluded. Laboratory studies were not considered either and none was found.

Diverse learning outcomes were considered, including typical schoolwork tasks such as arithmetical calculations and reading and comprehension exercises, psychological tests measuring cognitive skills and the abilities needed to perform school work such as tests measuring concentration, memory and response time, results of aptitude and national tests examining progress in learning, the results of midterm and final exams, and end-of-year grades. Studies reporting short-term sick leave rates were also included. Subjectively rated performance was not considered a valid metric of learning outcome therefore no studies using this metric to characterize learning outcomes were included. Proxies for reduced performance such as the prevalence and intensity of acute health symptoms, especially fatigue, difficulty in concentrating, sleepiness, or headaches were not considered to be sufficiently valid predictors of learning outcomes. Perceived disobedience, behavioural changes and reported discomfort in the classroom environment were not accepted as valid predictors of learning outcomes.

Results from studies reporting both cross-sectional and intervention experiments were included. Similar inclusion criteria were used previously by Wargocki et al., who developed a relationship between classroom temperature and children's performance in school [6].

Information obtained from each study included: the study location, type of study, the number of subjects, CO_2 concentration measures, type of performance metric used for estimating learning outcomes, and the main results. These data were tabulated and are presented in Table 1, and in Tables A.1 and A.2 in the Supplementary Material.

Because many studies reported measurements of CO_2 but did not measure or report ventilation rates (ventilation rates were predominantly calculated using measured CO_2 concentrations) it was decided that CO_2 concentration would be used as a metric of indoor air quality.

All results reported in the studies identified in the literature survey were used regardless of whether changes in learning outcomes as a result of changes in classroom air quality were statistically significant or not. The same approach was used before by Wargocki et al. [6].

Three different relationships were developed for various outcomes describing children's performance, one using data on typical schoolwork, one using data from final exams and one using the results for sick-leave.

The analytical approach used to develop the relationships when data on learning performance were available was the same as was used by Seppänen et al. [13, 33] and Wargocki et al. [6]. The fractional change in performance (λ) was first calculated for each performance outcome using the results from the studies identified in the literature survey, which are summarized in Table 1. The fractional change described the change in performance per 100 ppm change in CO_2 concentration.

School performance outcomes were reported in the studies in the form of absolute and relative values. Equation 1 was used to estimate the fractional change (λ) for those results presented in terms of absolute change, while for the results reported as percentages (or as relative change) the fractional change (λ) was calculated using Equation 2, as follows:

$$\lambda = \left[\frac{P(C_L) - P(C_H)}{P(C_H)} \Big/ (C_H - C_L) \right] \cdot 100 \quad (1)$$

where P (C_L) is either the speed at which the task was performed or reaction time at the lower CO_2 concentration, and P (C_H) is either the speed at which the task was performed or reaction time at the higher CO_2 concentration, C_L represents the lower CO_2 concentration and C_H the higher CO_2 concentration at which performance was measured in ppm.

$$\lambda = \frac{P(C_L) - P(C_H)}{C_H - C_L} \cdot 100 \quad (2)$$

where P (C_L) is the accuracy expressed as the percentage of errors made at the lower CO_2 concentration, and P (C_H) is the accuracy expressed as the percentage of errors made at the higher CO_2 concentration, C_L represents the lower CO_2 concentration and C_H the higher CO_2 concentration at which performance was measured.

To ensure that the assumption of linearity was maintained, the midrange fractional change λ at the midpoint of the range of CO_2 concentrations over which the effect on performance was measured (λ_{mid}) was calculated following the method and equation proposed by Seppänen et al. [33].

$$\lambda_{mid} = \frac{\lambda}{1 + 0.005\lambda (C_H - C_L)} \quad (3)$$

where λ is the fractional change in performance calculated per 100 ppm. C_L again represents the lower CO_2 concentration and C_H the higher CO_2 concentration.

The calculated fractional changes in learning outcomes at the midrange (λ_{mid}) were regressed against the average CO_2 concentration estimated from the range of CO_2 concentrations for which λ_{mid} values were calculated. Fractional polynomials were used to determine the best fit [34]. The 95% confidence intervals were estimated using the equation for the variance of a fitted value proposed in this publication

The performance of schoolwork at any specific CO_2 concentration relative to the performance at a reference CO_2 concentration was calculated and used to produce relationships between CO_2 concentration and learning performance outcomes. A reference CO_2 concentration of 900 ppm was selected because the lowest average CO_2 concentration for which the fractional change in performance was available was 890 ppm. The performance measured at 900 ppm was assumed to be 100%. Independently of this assumption the relationships were extrapolated to lower levels of CO_2 to predict the magnitude of effects of air quality on performance below a concentration of 900 ppm. The highest average CO_2 concentration for which the fractional change in performance was available was 2,100 ppm so this was taken to be the upper limit at which the relationships are valid.

A bootstrapping method was used to estimate the 95% confidence interval bands for the above relationships [35]. One thousand random samples were created following recommendations by Field [36] and the curves that best fitted these samples were estimated using the functional form of the regression line describing the relationships between the fractional change in performance and the CO_2 concentration. Using these curves, the performance was estimated for all CO_2 concentrations between 900 ppm and 2,100 ppm for which the relationships were valid with a step of 100 ppm producing 1000 performance estimates for each CO_2 concentration level. These data were used to calculate the 2.5th percentile and the 97.5th percentile which were used to fit the curves and assumed to represent the 95% confidence interval.

The fractional changes in performance could only be calculated for the typical schoolwork tasks and psychological tests. For the results of aptitude and national tests examining progress in learning, which consisted of the percentage of pupils passing the results of midterm and final exams or the results of these exams, the relationships developed by the studies providing data on this matter were used. The relationships showed how learning performance changed with varying ventilation rate. They were plotted for the range of ventilation rates for which they were valid. Then, assuming CO_2 produced in classrooms to be 0.0039 L/s per person [49], the value found in the studies from which the data were obtained, the CO_2 concentration was calculated and the relationships were re-plotted using CO_2 concentration as the independent variable. It should be noted that the original studies did not measure ventilation rates directly but calculated them from measured CO_2 concentration either at steady state or close to steady-state. For the range of CO_2 over which all relationships were valid, the weighted effect on learning performance was calculated using the number of classrooms as a weighting coefficient. The weighted performance was used to produce the final relationship. A confidence interval was not estimated for this relationship due to the limited amount of data.

In the case of the relationship between sick-leave and classroom air quality the approach using fractional change also could not be used. Because the relevant studies on this matter presented the relationships between sick-leave and either ventilation or CO_2 in the classrooms, a similar approach was used as in case of the relationship for aptitude tests and final exams. As in the case of the relationship for performance, a confidence interval was not estimated due to the limited amount of data.

3. RESULTS

Twenty studies identified in the literature survey met the inclusion criteria described above in the Methods section. They are summarized briefly in Tables 1 and 2. More details on these studies can be found in the Supplementary Material in Tables A1 and A2. The studies were published between 1996 and 2015. They are therefore from nearly two decades of research on the effects of classroom air quality on learning performance outcomes for children in elementary schools. The studies were carried out in >760 schools, >2,000 classrooms, and over 15,000 subjects were involved.

Please insert Table 1 somewhere here

Please insert Table 2 somewhere here

In most of the studies, classroom air quality was characterized in terms of the measured concentration of CO_2. In a few cases, outdoor air supply rates were also provided. Outdoor air flow rates were either measured directly or calculated from the measured concentrations of CO_2. In the latter case, either peak concentrations of CO_2 were used or a mass-balance model was used and fitted to the build-up of CO_2 concentrations in classrooms. The measurements of CO_2 concentration were obtained in the classrooms while they were occupied.

The measured CO_2 concentrations were between 600 ppm and 4,300 ppm. The studies reported either average daily, weekly, or peak levels of CO_2. Interventions to change classroom air quality involved either opening/closing windows and doors or using existing ventilation systems or a purpose-built mobile ventilation system [11,37].

All studies were performed in temperate climates; no study was performed in tropical or subtropical climatic zones. They were performed both in both heating and non-heating seasons.

Four studies reported the results of national aptitude tests or exams and three reported absence rates while nine provided sufficient data to calculate the fractional change in performance as a function of changes in air quality.

The relationship between CO_2 concentration and the observed fractional change in speed or reaction time is shown in Figure 1a. A similar relationship for the fractional change in accuracy is shown in Figure 1b. Data from 35 tasks were used to develop the relationships between speed or reaction time and CO_2 concentration, while data from 37 tasks were included when accuracy was the outcome. The figures show how the fractional change would vary as a result of changes in the average CO_2 concentration. They show that the relative change in performance outcomes was higher, i.e. the absolute fractional change λ_{mid} was higher, at the lower average CO_2 concentrations. It additionally indicates that the change in performance outcomes was not constant. The line showing the upper 95% confidence level in Figure 1a suggests that the estimated effects on performance at concentrations of CO_2 >1,600 ppm may not be significant at $p = 0.05$ because $\lambda_{mid} = 0$ falls within the confidence interval. In the case of Figure 1b this occurs for CO_2 concentrations >1,500 ppm.

Please insert Figure 1a somewhere here

Please insert Figure 1b somewhere here

The regression lines shown in Figures 1a, and 1b were used to produce the relationships shown in Figures 2a and 2b. The relationship in Figure 2a indicates that reducing classroom CO_2 concentration from 2,100 ppm to 900 ppm can be expected to increase the speed or reduce the time needed to perform school tasks or cognitive tests measuring aspects of ability to perform schoolwork by about 12%. Most of the improvement, 11%, occurs when CO_2 concentration is changed from 1,500 ppm to 900 ppm. The relationship in Figure 2b indicates that reducing classroom CO_2 concentration from 2,100 ppm to 900 ppm can be expected to improve the accuracy with which children perform school tasks or cognitive tests measuring different abilities to perform schoolwork by 2%.

Please insert Figure 2a somewhere here

Please insert Figure 2b somewhere here

Four cross-sectional studies correlated standard test scores and examination results with measured CO_2 concentration. None of them except Mendell et al. [12] measured performance outcomes concurrently with CO_2 concentration or ventilation rate. The concentration of CO_2 was measured for a period of a week and assumed to represent typical conditions for the entire school year. No direct measurements of ventilation rates were made in any the studies. CO_2 concentrations were measured and ventilation rates were estimated from these measurements. The relationship summarizing the results from these four studies is shown in Figure 3. It indicates that reducing classroom CO_2 from around 2,400 ppm to 900 ppm can be expected to improve children's performance of national tests by about 5%. The largest change in performance occurred when CO_2 concentration changed from 1,600 ppm to 900 ppm.

Please insert Figure 3 somewhere here

Figure 4 shows how daily attendance would change as a result of changes in the concentration of CO_2. Because Mendell et al. [12] derived a linear function describing the relationship between ventilation rate and sick leave, a nonlinear (logarithmic) function between sick leave and CO_2 concentration was estimated using their data, and it was then converted into a discrete variable before a linear function was fitted. This was done to match their results with the relationships developed by Shendell et al. [38] and Gaihre et al. [39]. To obtain the relationship shown in Figure 4, the effects on daily attendance in the three studies from which data were available [12, 38, 39] were weighted and averaged. The relationship is valid for CO_2 concentrations between 1,000 ppm and 4,100 ppm. Reducing the concentration of CO_2 in this range would increase daily attendance by 2.4%.

Please insert Figure 4 somewhere here

4. DISCUSSION

The present work sought to systematically compare and integrate the currently available evidence on the effects of indoor air quality in school classrooms on learning outcomes that had been obtained in different studies using diverse methods. It provides a crude estimate of the influence of classroom air quality on the performance of pupils in schools. Student performance was characterized by the ability to perform schoolwork, exams and aptitude tests, and student well-being was characterized by sick-leave. Studies in elementary and secondary schools were included. Because there is no accepted metric of indoor air quality, a proxy for air quality was used. Usually, ventilation rates or the concentration of CO_2 are used as a proxy for indoor air quality. In the present work the latter was used. In other words, in the realtionships presented, CO_2 concentration is not a concencentration of pure CO_2 but represents certain ventilation with outdoor air under specific occupancy in classrooms. The decision to use CO_2 was warranted by the data available to create the relationships. Because most studies relevant for the purpose of the present work reported the concentration of CO_2 and did not measure the ventilation rate directly, it was decided to create relationships between the measured concentration of CO_2 and learning outcomes. CO_2 concentration is a commonly used air quality metric, so this choice seems both logical and likely to be of the most practical use in school building operation. CO_2 is produced by people during the metabolic processes, so CO_2 concentration can be used to indicate momentary/interim air quality when people are present indoors. CO_2 concentrations can vary depending on the number of people, their metabolic rate, duration of occupancy, the ventilation rate, and air mixing. In the present work the concentration of CO_2 in the relationships should be interpreted as the steady-state level. Since classrooms with pupils of the same age range were selected it can be assumed that their CO_2 emission rates were not very different from study to study although some degree of variation in these emission rates cannot be excluded.

Although some studies show that pure CO_2 may affect decision-making performance, the performance of commercial airline pilots, or proof-reading as summarized by Fisk et al. [40], other studies have not found similar results. The relationships derived here should not be interpreted as showing how pure CO_2 affects performance. CO_2 in the present work is used only as a marker of air quality in the classroom that indicates changes in the concentrations of many other pollutants, most of them bioeffluents as these are the dominant air pollutants in occupied classrooms [41]. Zhang et al. [42] proposed tentative dose-response relationship between the level of bioeffluents (described by the level of CO_2) and different adult human outcomes. They proposed that at bioeffluent levels corresponding to CO_2 concentrations >1,800 ppm the exposure to bioeffluents is likely to elicit acute health symptoms and cause negative effects on cognitive performance. The present results for the response of school age children show that these effects can occur at even lower levels. The reason for this difference should be investigated in future experiments but it can be hypothesized that it is due to the fact that exposure in classrooms entails exposure not only to bioeffluents but also to other pollutants [41], while the relationship proposed by Zhang et al. was only for bioeffluents.

The relationships presented in Figures 2 to 4 can be used only when the following assumptions are satisfied. Firstly, they are valid for the steady-state or near steady-state concentrations of CO_2, as argued above. Secondly, air mixing in the classrooms must be good. Thirdly, the metabolic rate of pupils must correspond to sedentary activity. Finally, they are valid only in the range of CO_2 concentrations between 900 ppm and 1,900 (speed and accuracy of schoolwork), 900 ppm and 2,400 ppm (national and aptitude tests) or 1,000 and 4,200 ppm (sick-leave or school attendance). If these assumptions are not met, the use of the relationships created in the present work may yield inaccurate predictions. In particular, the relationships should not be applied to dynamic or variable conditions.

It was decided to use 900 ppm, the lowest average CO_2 concentration for which the fractional change in performance was estimated, as the reference CO_2 concentration at which performance is 100%. Whether further reductions in CO_2 concentration would produce additional improvement in the performance clearly requires further study, but seems likely. For example, an analysis by Jacobs et al. suggests that the performance of schoolwork would further increase by reducing CO_2 concentrations below 900 ppm [43]. Moreover, a CO_2 concentration of 900 ppm corresponds to about 10 L/s per person while published research results suggest that cognitive performance can improve with an increase in ventilation rates up to 15 L/s per person [44] and even to 25 L/s per person [45,46]. A ventilation rate of 25 L/s per person corresponds to CO_2 concentration of around 600 ppm. An extrapolation of the present relationships from CO_2 at 900 ppm to CO_2 at 600 ppm would predict an additional increase in performance of 10% as depicted in Figs 2a, 2b, 5a, 5b. It might also be that the expected improvement in performance with increased ventilation rate would continue until classroom CO_2 concentration reached the outdoor level of 400 ppm, but such a change would require a massive increase in ventilation rates that would be technically challenging to implement and difficult to justify economically.

For CO_2 concentrations higher than 2,100 ppm, the performance of schoolwork may further decrease with increasing CO_2 levels, but there are no data in the present analysis to prove that this is the case. On the other hand, it may be hypothesized that CO_2 concentrations close to 2,000 ppm define such poor air quality that a further increase in CO_2 would not lead to a further reduction in performance. A CO_2 concentration of 2,100 ppm corresponds to a very low ventilation rate (around 2 L/s per person). In Denmark, a CO_2 concentration of 2,000 ppm is considered as an action level at which improvements to classroom ventilation must be made [47] and the present results indicate that this level can be considered as a ceiling limit of exposures that have an adverse effect on learning. According to Fanger [54], 2 L/s per person would cause only about 45% of occupants to be dissatisfied with the indoor air quality on entering a classroom, so in terms of subjective perception a further degradation of air quality at lower ventilation rates/higher CO_2 concentrations seems possible. ISO Standard 17772-1 [56] recommends that the minimum ventilation rates should not be lower than 4 L/s per person following the recommendations of HealthVent project [57].

When developing their relationships between ventilation and office work, Seppänen et al. used arbitrarily selected weighting coefficients to account for the differences between the methods used to measure performance [13,48]. The use of these coefficients had in their analysis some, but not a large, effect on the shape of the relationship and the magnitude of the effect on performance as a result of changing ventilation rate. In the present work, no weighting coefficients were used to adjust for the differences in tasks and tests used to measure school work. This was because Wargocki et al. [6] found no evidence in the literature that would justify the use of any type of weighting and argued that each measure relates to different aspects of cognitive performance and that they may all be important for efficient and effective learning [6].

The present relationships were developed using data from children attending primary or high schools (6 to 19 years old) so they should not be applied to other educational settings, e.g. to university students or adults participating in continuing education nor for children of kindergarten age. Performance was assessed by psychological tests examining the ability to perform schoolwork or representative of schoolwork as learning outcomes. Absence rates, although they may have a negative effect on learning for pupils unable to compensate for having taken sick leave, cannot be regarded as performance outcomes and should be evaluated separately.

It is relevant to ask whether the learning outcomes used to create the relationships presented in Figures 2a and 2b represent the actual effect on learning as measured by the national tests, end of year grades, or examination results (Figure 3). Because the psychological tests and tasks measuring schoolwork are usually short, it may be argued that they only present the immediate or short-term effect of classroom conditions on performance, while other tests predict better the cumulative effect of the conditions in classrooms on learning outcomes. Whether this is the case should be be examined more carefully in future experiments. Meanwhile, comparing the magnitude of the effects shown in Figures 2 and 3 it may be concluded that the performance of schoolwork slightly overestimates the magnitude of the effects of air quality on national tests and school-leaving examinations.

Using CO_2 concentrations to estimate ventilation rates, the relationships presented in Figures 2a and 2b were transformed to relationships between ventilation rates and learning outcomes (Figures 5a and 5b). This was achieved using a simple mass balance approach for which some assumptions must to be made. Firstly it must be assumed that the air in a classroom is well mixed, which is a fair assumption considering that classrooms are populated by many pupils who create mixing both by their movements and by the impact of their thermal plumes. Another assumption concerns the generation rate of CO_2 of the pupils and teacher in a classroom. In the present calculations, 0.0039 LCO_2/s per person was assumed for pupils and 0.0052 LCO_2/s per person for an adult teacher [49]. Similar assumptions were made in some of the studies used in the present work [21,50]. Finally, an assumption concerning outdoor CO_2 concentration must be made. In the present calculations, it was assumed to be 400 ppm. With these assumptions, the CO_2 concentrations in Figures 2a and 2b were converted into ventilation rates, and the Figures 5a and 5b were created. They suggest that doubling ventilation rates would be expected to increase the speed at which the tasks that represent schoolwork and tests examining the ability to perform schoolwork are performed by 7%, while a 1% decrease in the error rate would be expected. In addition, Figure 5a provides an explanation of why the largest increase in learning outcome performance measures shown Figure 2a was observed between CO_2 levels of 1,500 ppm and 900 ppm. This range of CO_2 corresponds to a large increase in ventilation rates, from about 4 L/s per person to about 10 L/s per person, while the remaining range of CO_2 concentrations for which the relationship in Figure 2a was created, i.e. between 2,100 ppm to 1,500 ppm, corresponds to a relatively small change in ventilation rates from about 3 L/s per person to 4 L/s per person. Over the latter range, a relatively small change in the performance of learning outcomes was observed. Figure 5a also shows that most of the available data on learning performance are for ventilation rates below 10 L/s per person.

Please insert Figure 5a somewhere here

Please insert Figure 5b somewhere here

Figure 5a indicates that performance can be expected to increase by 7% when the ventilation rate is doubled. A similar effect was predicted by Alfano et al., who combined learning outcomes from different studies as previously noted in the Introduction section [22]. A smaller effect was predicted by Seppänen et al. [13] and a larger one by Wargocki and Wyon [4], also as noted in the Introduction section. The former study showed that doubling of ventilation rate can be expected to increase the performance of office work by 1.5% and the latter that doubling of ventilation rate can be expected to increase the speed at which schoolwork is performed by 14%. The latter study did not find that ventilation rates had a significant effect on errors, which is consistent with the results presented in Figure 5b. Comparing the results from these different studies, it may be concluded that the effects of air quality on learning outcomes are about five times higher than its effects on the performance of office work. It seems likely that fewer opportunities to adapt and the higher sensitivity of children to reduced air quality in classrooms provide an explanation of this difference.

As in Figures 5a and 5b, Figures 6 and 7 show the relationships between ventilation rates and the performance of national tests and on pupils' daily attendance. They show that increasing ventilation rates from 2 to 7.5 L/s will improve pupils' performance in national tests by 5%. Likewise, Figure 7 shows that doubling ventilation rates from 2 to 4 L/s per person will increase children's daily attendance by 1% and that an additional 0.5% would be expected if ventilation rates were doubled again from 4 to 8 L/s per person.

Please insert Figure 6 somewhere here

Please insert Figure 7 somewhere here

The present results show that the effects of classroom air quality on performance in school are non-trivial and higher than the effects of office air quality on the performance of office work. The socio-economic consequences of the observed effects are expected to be high, but there are only a few published economic analyses on this topic. A hypothetical analysis of the socio-economic benefits resulting from improving classroom air quality in Danish schools showed that increasing ventilation rates from 6 L/s per person to 8.5 L/s per person would increase Denmark's Gross Domestic Product (GDP) by €173 million per annum. These economic benefits would be the result of the increased productivity of better educated pupils after completing their education and entering the work force, reduced costs due to earlier completion of school, and savings due to reduced sick leave for teachers [51]. The relationships developed in the present work provide a persuasive argument for decision-makers and regulators to revise codes and standards so that the pupil, the teacher, and the optimal learning environment will always remain in focus independently of whether the aim is to design, renovate or operate school buildings. They can form the basis of cost-benefit analyses similar to the one presented by Wargocki et al. [51].

The present results focus on learning outcomes for pupils, but it is likely that poor classroom air quality will also have negative effects on teachers. It has recently been shown that the frequency of voice disorders reported by teachers in classrooms in Finland is increased by poor classroom air quality [55], although whether this is a direct effect on the vocal chords or is caused by teachers having to raise their voices because pupils become more unruly when their performance is negatively affected by poor air quality could not be determined. Negative effects on teachers will contribute to an overall decrease in learning outcomes. However, there are no studies that demonstrate the effect of classroom air quality on teaching performance. Such evidence would be useful and should be considered as a future research priority. Before data are available, it would be reasonable to assume that the performance of teachers in schools will be affected by reduced air quality to at least to the same extent as the performance of employees in office buildings, as summarized by Wargocki and Seppänen [52].

Together with a recently developed relationship between classroom temperature and the performance of schoolwork [6] the present results show clearly that both thermal conditions and indoor air quality in classrooms are essential determinants of learning that should not be neglected when actions to improve learning are considered. It is unknown whether the magnitudes of improvements in the performance of schoolwork would be additive when both classroom temperatures and air quality are improved concurrently, as there are almost no data on the combined effects of the different parameters of indoor environmental quality on performance. Additive effects have been suggested [53], but more results are needed to support or reject this hypothesis. Data on combined effects would be useful as they would provide a rational basis for how resources for improving the quality of classroom environments could be most effectively distributed and used. Until more data are available, it would be prudent to make a conservative assumption and use the larger of the effects on performance when ventilation rate and temperature change simultaneously, as previously proposed by Wargocki and Seppänen [52].

5. CONCLUSIONS

Relationships were developed between the classroom air quality in elementary and secondary school classrooms and learning outcomes. Air quality was assessed in terms of CO_2 concentration and ventilation rate. The relationships predict how the performance of schoolwork and of national learning tests were affected by changing classroom air quality, using multiple metrics. The metrics for schoolwork included the ability to perform arithmetic calculations, the performance of language-based tasks requiring reading skills and comprehension, and psychological tests examining concentration, memory and response time. National learning tests included the percentage of students passing the tests and the actual results of such tests. The relationships obtained indicate that reducing the CO_2 concentration in classrooms from 2,100 to 900 ppm would increase performance speed by 12% and accuracy by 2%. Reducing the CO_2 concentration from 2,400 ppm to 900 ppm would improve the performance of national tests and school-leaving examinationss by 5% and reducing CO_2 from 4,200 ppm to 1,000 ppm would increase children's daily attendance by 2.5%. In terms of ventilation rates these results suggest that increasing ventilation rates in L/s per person from 2 to 7.5 will improve pupils' performance in national tests by 5%, and children's daily attendance by 1.5%. These effects are not negligible and are higher than the effects found for office work performed by adults under similar conditions. These results should be taken into account when any investments whose purpose is to promote learning in schools are under consideration. It is anticipated that reducing the negative effects of poor classroom air quality would lead to considerable socio-economic benefits and to an improved quality of life for pupils in primary and secondary education.

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Table 1. Summary of studies examining the effect of indoor air quality on learning outcomes

Study	Year	Location	Season	Type	Population (schools)	Population (pupils)	Age of pupils	CO_2 averaging in the original study (exposure metric)	Measured CO_2 concentrations: range or levels (average concentration) (ppm)	Learning outcomes
Myhrvold et al. ❸	1996	Norway	Winter	Measurements before and after the intervention	22 classooms in 5 high schools	550	15-20	Mean concentration during school-day	600-3800 (2200)	Psychological tests
Myhrvold et al. ❶	1997	Norway	Winter	Measurements before and after the intervention	35 classrooms in 8 high schools	600	16-19	Mean concentration during school-day	735-1515 (1125)	Psychological tests
Shaughnessy et al. ❷	2006	USA (Midwest)	Winter and spring	A cross-sectional study in one school district	54 classrooms in 54 high schools	N.A.	10	Average peak CO_2 concentration (used to calculate ventilation rates)	765-5200 (2982)	Standard tests or rating schemes
Coley et al. ❶	2007	England	Summer	Measurements with windows open and closed	1 classroom in 1 elementary school	18	10-11	Concentration at the onset of the test period	700- 2900 (1800)	Psychological tests
Bakó-Biró et al. ❶	2007	England	N.A.	Field intervention. Ventilation rates were changed	2 classrooms in 1 elementary school	40	9-10	Mean concentration during the test period	650-1850 (1250)	School tasks
Wargocki and Wyon ❶	2007	Denmark	Late summer (August, September)	Field intervention. Ventilation rates were changed	2 classrooms in 1 elementary school	44	10-12	Weekly average (when pupils were present)	775- 1000 (888)	School tasks
Wargocki and Wyon ❶	2007	Denmark	Winter (January)	Field intervention. Ventilation rates were changed	2 classrooms in 1 elementary school	44	10-12	Weekly average (when pupils were present)	925- 1280 (1102)	School tasks

Wargocki and Wyon ❶	2007	Denmark	Late summer (August)	Field intervention. Ventilation rates were changed	2 classrooms in 1 elementary school	48	10-12	Weekly average (when pupils were present)	900- 1125 (1012)	School tasks
De Gids et al. ❸	2007	Nederland	Spring	Field intervention. Ventilation rates were changed	Elementary school	47	10-11	N.A.	620- 2125 (1373)	Neuro- psychological tasks
Ribic ❶	2008	Austria	N.A.	Measurements with windows open and closed	6 classrooms in 2 high schools	152	15-16	Concentration at the onset of the test period	870- 3300 (2085)	Psychological tests
Ribic❶	2008	Austria	N.A.	Measurements with windows open and closed	6 classrooms in 2 high schools	152	15-16	Concentration at the onset of the test period	870, 4300 (2585)	Psychological tests
Haverinen-Shaughnessy et al. ❷	2011	USA (Midwest)	Winter and spring	Cross sectional study. Measurements with windows and doors open and closed	104 classrooms in 104 elementary schools	5178	10	Average peak CO2 concentration (used to calculate ventilation rates)	1000- 5200 (3100)	Standard tests or rating schemes
Bakó-Biró et al. ❶	2012	England	Autumn, winter, spring and early summer	Field intervention. Ventilation rates were changed	16 classrooms in 8 elementary schools	332	9-10	Mean concentration during the test period	950- 3000 (1975)	Psychological tests
Gaihre et al. ❸	2014	Scotland	Late spring (May-June)	Cross-sectional study	60 classrooms in 30 elementary schools	N/A	6-7, 10-11	Average: 1086 Min-Max: 595-2115		
Haverinen-Shaughnessy et al. ❷	2015	USA (Southwest)	Winter and spring (January to April)	Cross-sectional study	140 classrooms in 70 elementary schools	3019	10	Average peak CO2 concentration (used to calculate ventilation rates)	1000- 5200 (3100)	Standard tests or rating schemes

Mendell et al. ❷	2015	USA (California)	All seasons	Longitudinal 2-year long cross-sectional study in 3 school districts	150 classrooms in 27 elementary schools	5000	8-10	15 min moving average peak CO2 concentration (used to calculate ventilation rates)	965-1950 (1458)	Standard tests or rating schemes
Toftum et al. ❸	2015	Denmark	Fall and winter	Cross-sectional with retrospective data on test performance	820 classrooms in 389 elementary schools	N/A	8-16	N/A	400-4000 (2300)	Standard tests or rating schemes
Petersen et al. ❶	2015	Denmark	Autumn (September -October)	Field intervention. Ventilation rates were changed	4 classrooms in 2 elementary schools	40	10-12	Weekly average (when pupils were present)	880- 1510 (1195)	School tasks

❶ Data from this study was used to calculate fractional change in performance

❷ Data from this study was used to estimate the relationship between classroom air quality and performance of aptitude tests or and final exams

❸ Data from this study was not used to develop any relationship

Table 2. Summary of studies examining the effect of classroom air quality on absence of pupils

Study	Year	Location	Season	Type	Population		Age of pupils	CO_2 concentration (ppm)	Effect
					Schools	Pupils			
Shendell et al.	2004	USA	N/A	Cross-sectional	409 traditional and 25 portable classrooms in 22 elementary schools	N/A	6-12	Average: 580-1510 (above outdoors) Min-Max: 10-4230 (above outdoors)	1000 ppm increase in CO_2 corresponds to 0.5-0.9% decrease in annual attendance which is 10-20% relative increase in student absence
Mendell et al.	2013	USA (California)	All seasons	Longitudinal 2-year long cross-sectional study in 3 school districts	162 classrooms in 28 elementary schools	N/A	8-10	Median peak: 1140-2380 Min-Max peak: 654-2490	For an additional 1 L/s per person the absence rate reduced by 1.4-1.8%%
Gaihre et al.	2014	Scotland	Late spring (May-June)	Cross-sectional study	60 classrooms in 30 elementary schools	N/A	6-7, 10-11	Average: 1086 Min-Max: 595-2115	An increase of 100 ppm CO_2 estimated to produce an annual reduction of absence at 0.2% (range 0.04-0.4%) ($P<0.05$) which is about 0.4 days of absence less per year per 100 ppm

FIGURE 1a. Fractional change in speed at which tests and tasks were performed per change of 100 ppm at midrange (λ_{mid}) CO_2 concentration plotted against average CO_2 concentration over the range for which the fractional change was calculated. Negative values indicate reduced performance with increased CO_2 concentration. The regression (solid line) is shown with 95% confidence bands (dashed lines). Dots show the estimated λ_{mid} for individual tests or tasks (see Table A.1 in Supplementary Material for details). The form of the relationship is as follows: $\lambda_{mid} = 3.3E\text{-}05\ CO_2 - 0.0636$; where CO_2 is the average CO_2 concentration. $R^2 = 0.27$; $p < 0.001$.

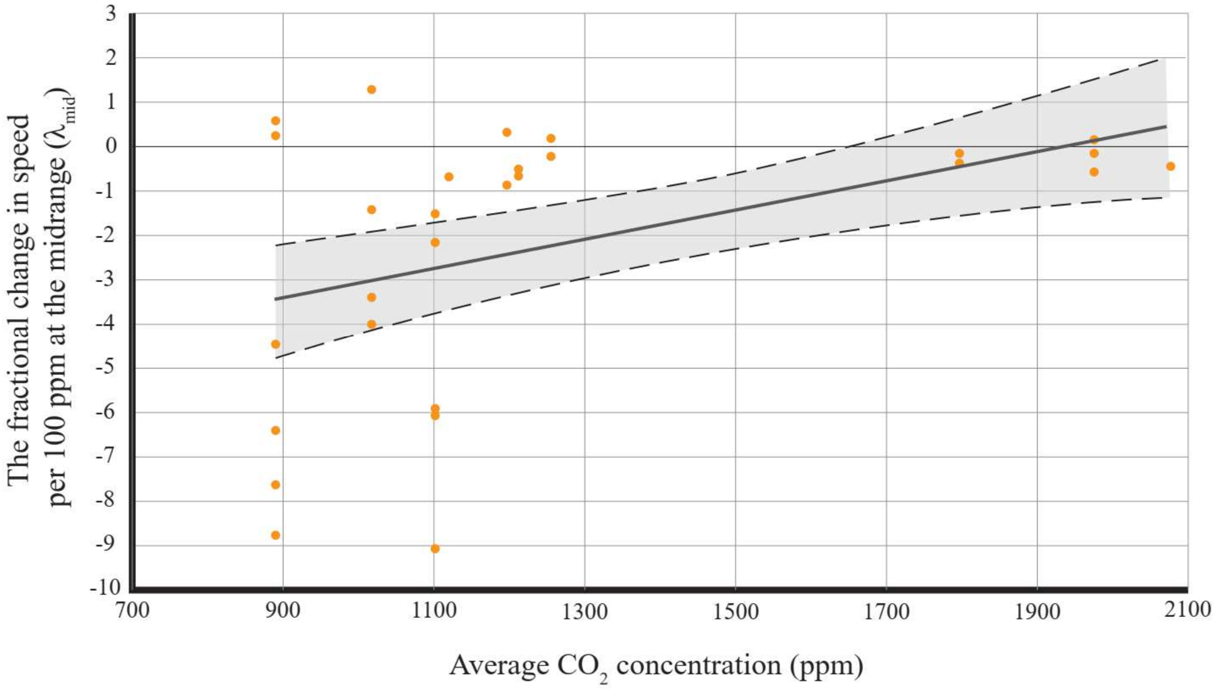

FIGURE 1b. The fractional change in accuracy with which tests and tasks were performed per 100 ppm at the midrange (λ_{mid}) CO_2 concentration plotted against average CO_2 concentration over the range for which the fractional change was calculated. Positive values indicate improved performance with reduced CO_2 concentration. Regression (solid line) with 95% confidence bands (dashed lines) are shown. Dots show the estimated λ_{mid} for individual tests or tasks (see Table A.1 in Supplementary Material for details). The form of the relationship is as follows: λ_{mid} = 5.5E-06 CO_2 – 0.0104; where CO_2 is the average CO_2 concentration. $R^2 = 0.10$; $p < 0.001$.

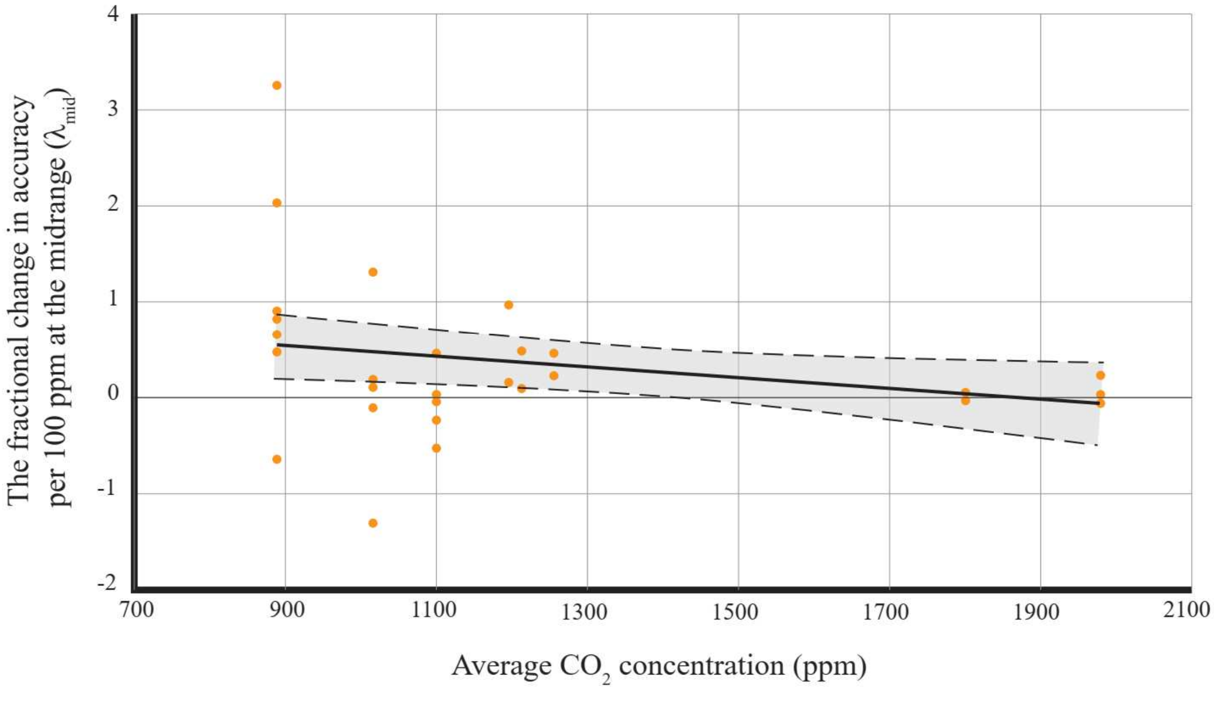

FIGURE 2a. Performance of schoolwork (speed or reation time) as a function of classroom CO_2 concentration derived using the relationship presented in Figure 1a; dashed lines show 95% confidence interval. Performance has been set arbitrarily to 100% at 900 ppm. The form of the correlation (solid line) is $y = 1.5E\text{-}07\ CO_2^2 - 0.0005\ CO_2 + 1.3002$; where CO_2 is the carbon dioxide concentration.The relationship was extrapolated beyond 900 ppm to predict potential effect at lower CO_2 concentration (dotted line for which no data were available.

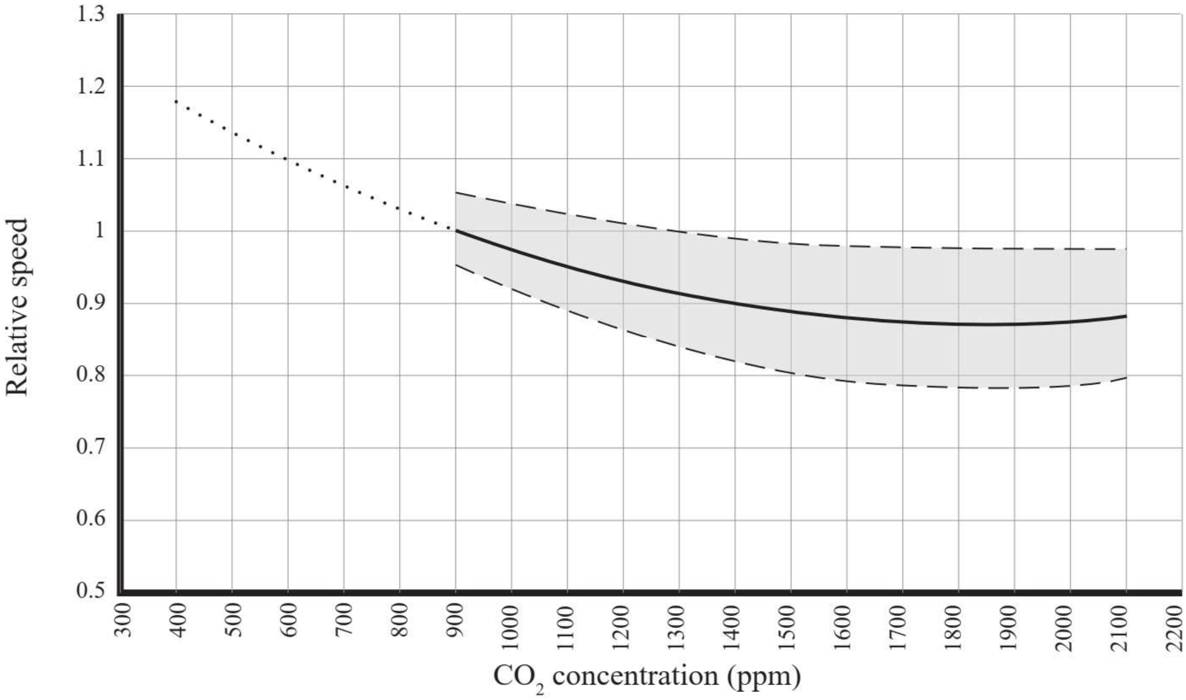

FIGURE 2b. Performance of schoolwork (accuracy) as a function of classroom CO_2 concentration derived using the relationship presented in Figure 1b; the dashed lines show the 95% confidence interval. Performance of 100% has been set arbitrarily at 900 ppm. The solid line is as follows $y = 2.7E\text{-}08\ CO_2^2 - 1E\text{-}05\ CO_2 + 1.0495$; where CO_2 is the carbon dioxide concentration. The relationship was extrapolated to below 900 ppm to predict potential effect at lower CO_2 concentrations (dotted line) for which no data were available.

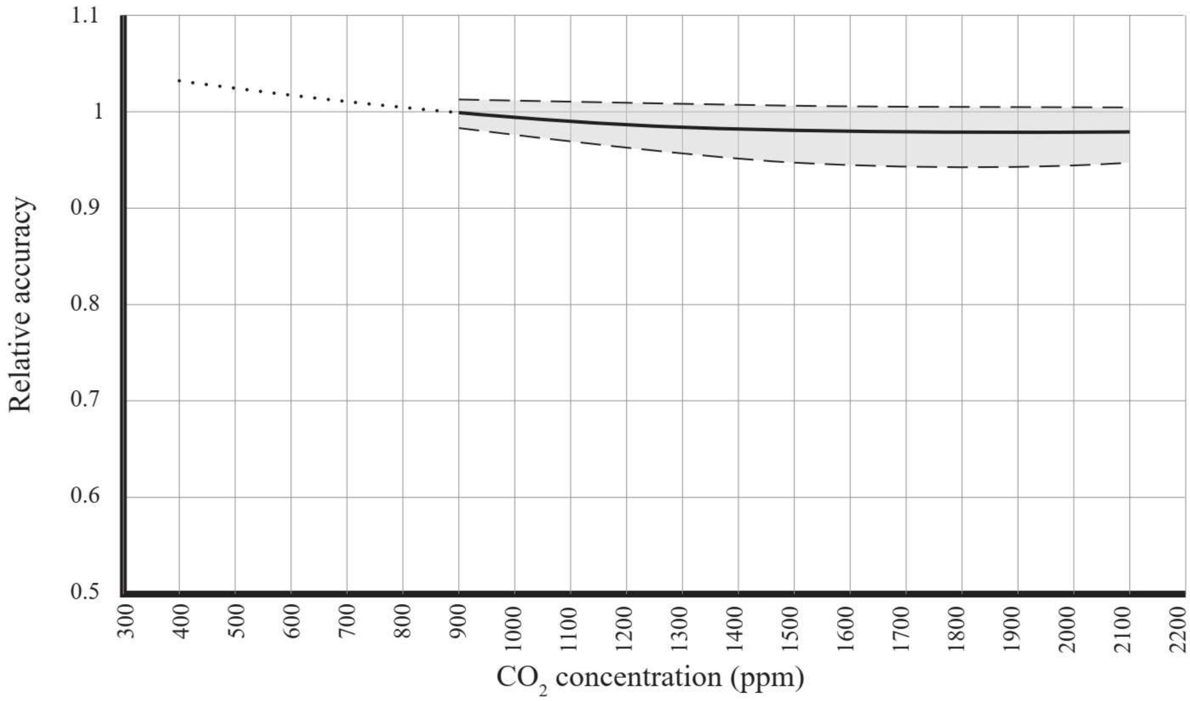

FIGURE 3. Performance on exams and national and aptitude tests as a function of classroom CO_2 concentration. Performance is the percentage of students passing or the score obtained (see Table 2 for details). The solid line is as follows y = -2E-11 CO_2^3 + 1E-07 CO_2^2 - 0.0003 CO_2 + 1.1665; where CO_2 is the carbon dioxide concentration.

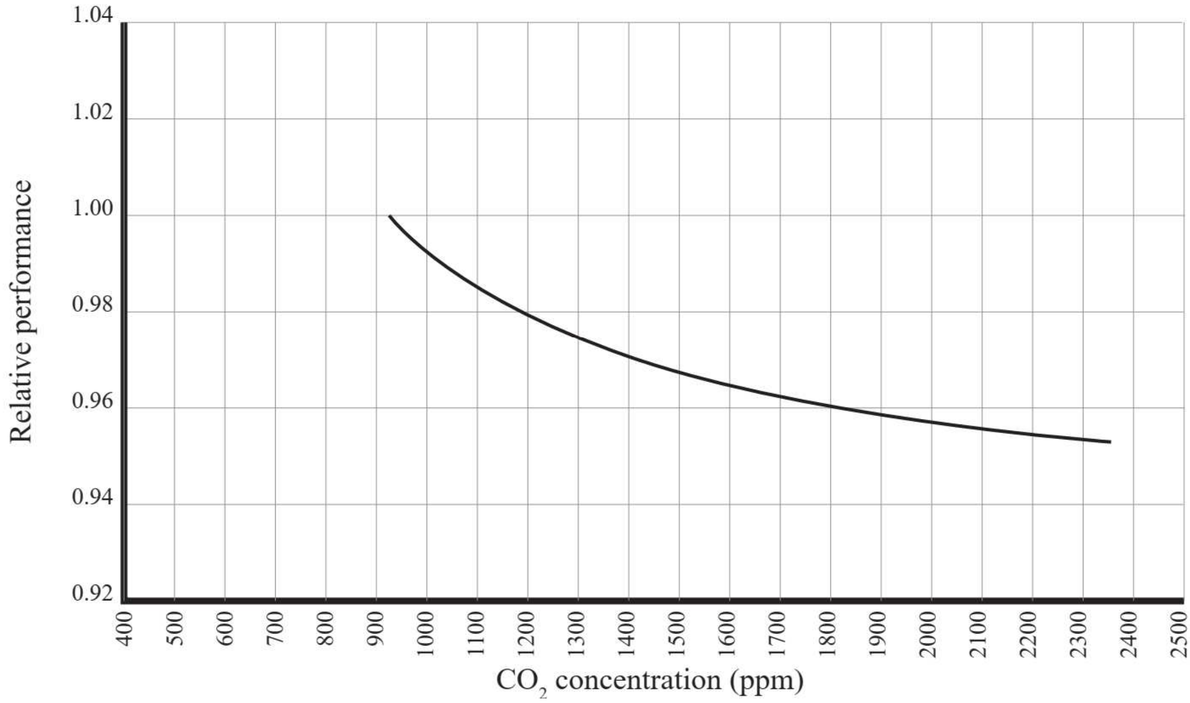

FIGURE 4. Pupils' daily attendance as a function of classroom CO_2 concentration. The solid line is as follows $y = -6E\text{-}13x^3 + 4E\text{-}09x^2 - 1E\text{-}05x + 1.0104$; where CO_2 is the carbon dioxide concentration.

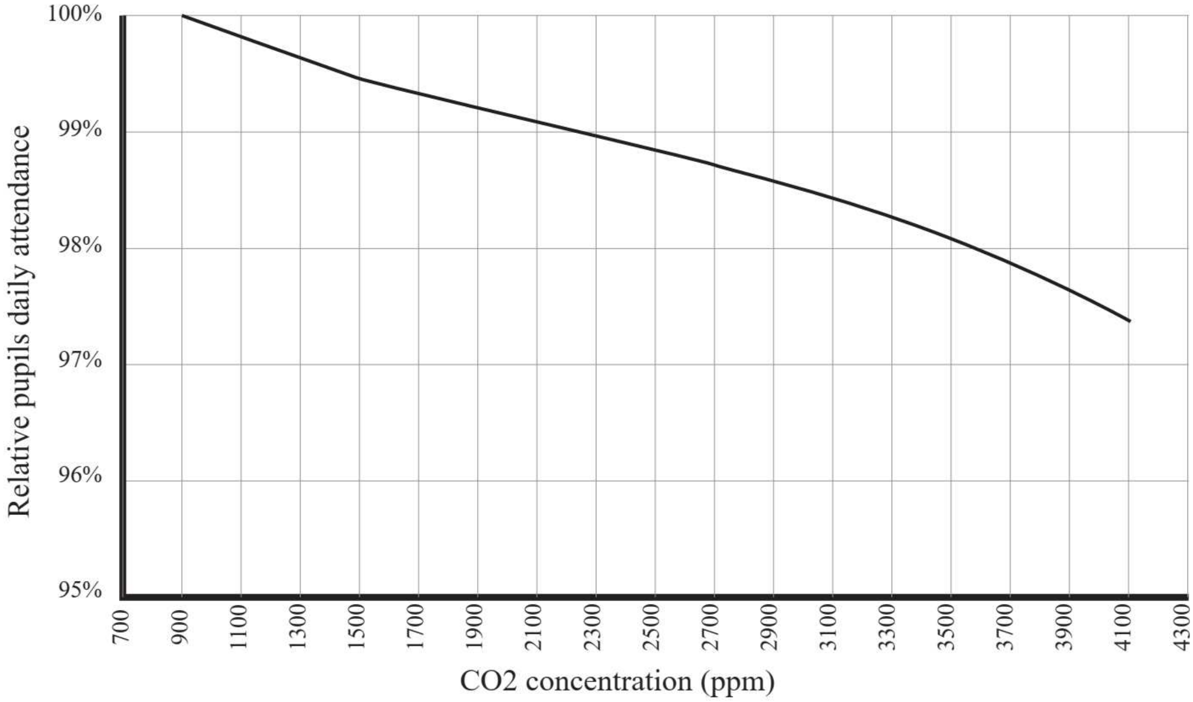

FIGURE 5a. Performance of schoolwork (speed or reation time) as a function of classroom ventilation rates (VR). The solid line show the relationship derived from the curve in Figure 2a using a simple mass balance model (see assumptions in the text). The function describing the relationship between relative performance and VR is y = 0.1062ln (VR) + 0.7683; where VR are the ventilation rates in L/s per person. The relationship was extrapolated to above 7.5 L/s per person to predict the potential effect at higher ventilation rates (dotted line) for which no data were available.

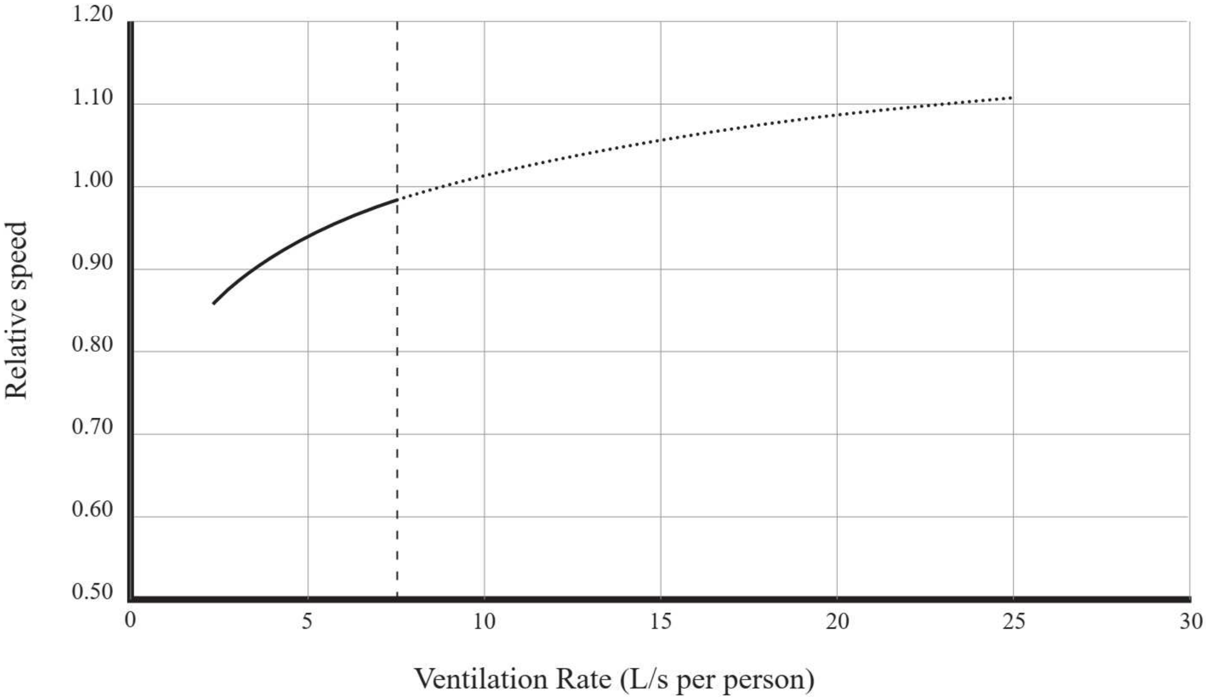

FIGURE 5b. Performance of schoolwork (accuracy) as a function of classroom ventilation rates (VR). The solid line is the relationship derived from the curve in Figure 2b using a simple mass balance model (see assumptions in the text). The function describing the relationship between relative performance and VR is $y = 0.0189\ln(VR) + 0.959$; where VR are the ventilation rates in L/s per person. The relationship was extrapolated to above 7.5 L/s per person to predict the potential effect at higher ventilation rates for which no data were available.

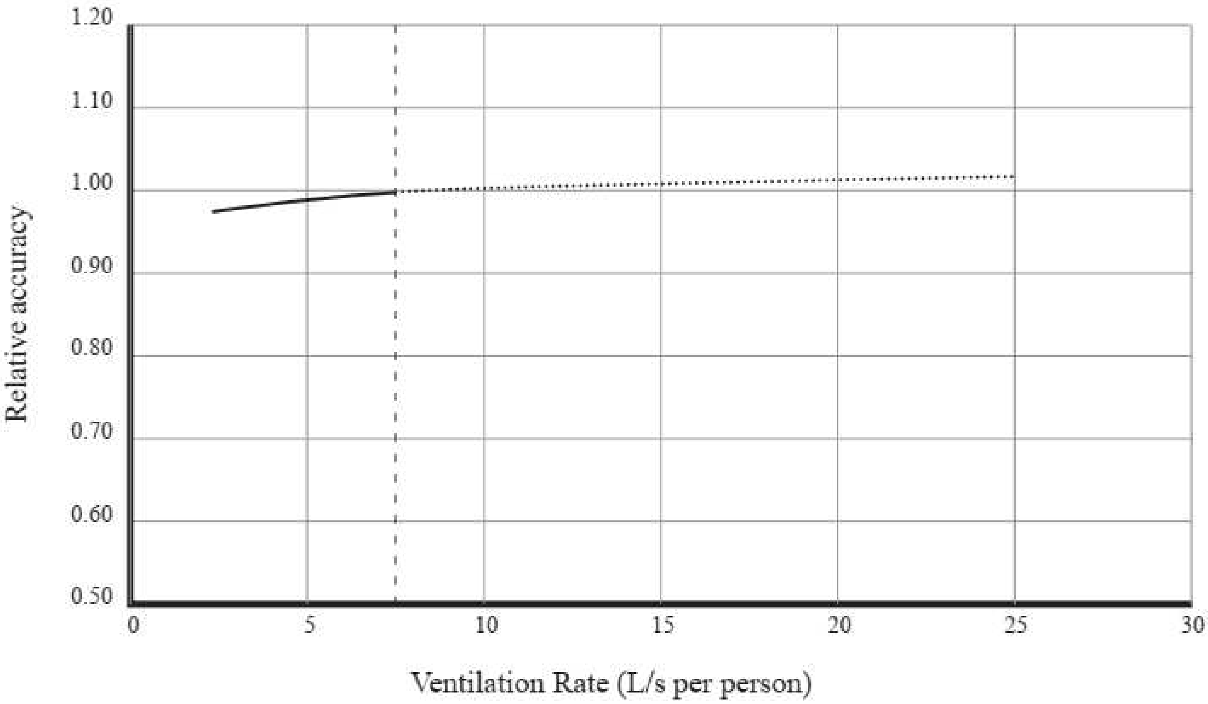

FIGURE 6. Performance of national and aptitude tests and exams as a function of classroom ventilation rates (VR). The solid line is the relationship derived from the curve in Figure 3 using a simple mass balance model (see assumptions in the text). Performance is the percentage of students passing or the score obtained (see Table 2 for details). The function describing the relationship between relative performance and VR is as follows y = 0.0086VR + 0.9368; where VR are the ventilation rates in L/s per person.

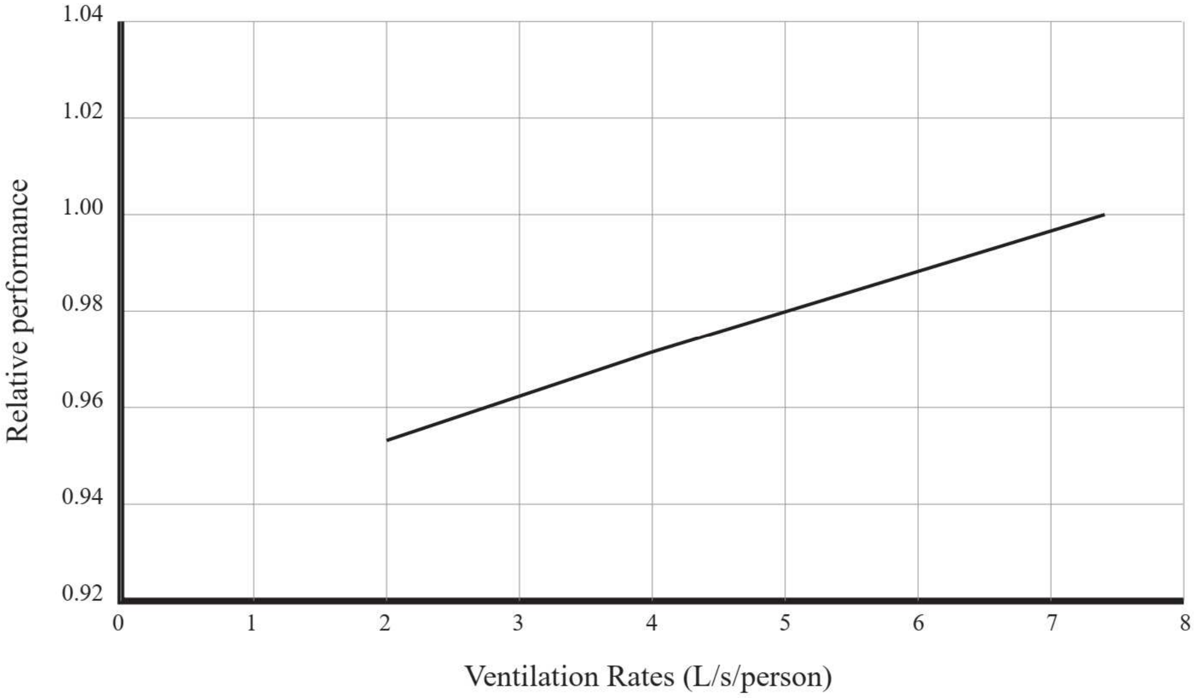

FIGURE 7. Pupils' daily attendance as a function of classroom ventilation rates (VR). The solid line is the relationship derived from the curve in Figure 4 using a simple mass balance model (see assumptions in the text).