Quantitative relationships between classroom CO_2 concentration and learning in elementary schools

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ABSTRACT

The data from published studies were used to build relationships between learning outcomes and air quality in classrooms. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, ratings schemes and tests used to assess progress in learning including end-of-year grades and exam scores were considered to represent learning outcomes. Indoor air quality was characterized by concentrations of carbon dioxide (CO_2). Short-term sick leave was included as well because it can influence learning. For psychological tests and school tasks, fractional changes in performance were regressed against the average concentrations of CO_2 at which the changes were recorded; all reported data were used regardless of whether the change was statistically significant. For other learning outcomes and absence rates, the relationships created by original studies were used. The results predict that reducing CO_2 concentration from 2,000 ppm to 1,000 ppm (equivalent to about 2.5 times higher outdoor air supply rate) would improve performance on psychological tests and school tasks on average by 12% (as regards the speed at which the teasks are performed) and by 3% (as regards errors made while performing the task. The performance on rating schemes will be improved by 1.3%. This change and will increase the number of pupils passing exams by 12%and is further estimated to result in about 6 out of 100 pupils improving their performance and to reduce absence by 0.5 day per student in a 200 days long school year.

KEYWORDS

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

1 INTRODUCTION

Research has documented that classroom environmental quality in elementary schools, where children spend large part of their waking hours (ca. 14%), is often inadequate (Daisey et al., 2003; Toftum et al., 2015), and that this has significant consequences for learning process (Wargocki and Wyon, 2013; 2016). When air quality is suboptimal in classrooms, cognitive skills and abilities of pupils are compromised as, among others, they cannot concentrate and/or are distracted from the work that they are supposed to do (Myhrvold et al., 1996; Myhrvold and Olsen, 1997; Coley et al., 2007; Ribic, 2008; Bako-Biro et al., 2012). As a result, the optimal and effective learning process is disturbed, which has consequences for learning performance outcomes, teachers work in suboptimal environment that do not support learning, and parents are distressed, troubled or must take the leave from work because children have stay home, all having significant socio-economic implications (Wargocki et al., 2014).

A quantitative relationship showing the potential size of the effect of changes in indoor air quality on cognitive performance exists, but it was not developed specifically for the effects on learning performance; it integrates data from studies investigating the quality of indoor environment on primarily office-type work (Seppänen et al., 2006). The relationship shows that performance would improve by 1-3% for each 10 L/s per person increase in outdoor air supply rate (over the range of ventilation rates that were on average between 7 and 55 L/s per person).

Fisk et al. (2003) used the available and rather limited data on the link between absence rates and ventilation to develop a relationship predicting illness or sick leave prevalence as a function of air change rate. They showed that doubling ventilation rate would produce roughly a 10% reduction in the absence rate.

A few studies performed in schools that measured performance outcomes relevant for learning have attempted to create a relationship between temperature or air quality in classrooms to the performance of school work (Wargocki and Wyon, 2012; Haverinnen-Shaughnessy et al., 2015; Mendell et al., 2013). These studies indicated that improvement in learning outcomes was about 5-15%, but unlike the analyses of Seppänen et al. (2006), they used only the results that had been obtained in their own measuring campaigns. Integration of results from a few studies in an attempt to create a relationship between school performance and ventilation was reported in the REHVA Guidebook (Alfano and Bellia, 2010). They showed that the effect of doubling ventilation rate would result in about 7-8% higher performance.

It is fair to say that no dedicated quantitative relationships between air quality and learning performance outcomes have yet been developed that systematically analyze and integrate the results obtained in many studies. The present work was consequently undertaken to fill this gap. The specific objective was to develop quantitative relationships that associate carbon dioxide (CO_2) as a proxy of air quality with learning performance outcomes and absence rates in elementary schools using all available information in the published archival literature. CO_2 concentration was used rather than the other measures of air quality or ventilation rates as it was frequently measured to describe air quality or ventilation efficiency in classrooms.

2 RESULTS

The archival literature was surveyed to find the articles reporting studies on learning performance outcomes and classroom conditions. Articles published from 1996 until the end of 2016 were included, i.e. covering and summarizing half a century of research on this topic. To be selected, the articles had to report both measurements of air quality in classrooms and measurements of cognitive performance of pupils. Only studies performed in elementary schools (primary, middle and/or secondary schools) were accepted.

Diverse measures of cognitive performance were accepted including psychological tests measuring cognitive skills and abilities to perform school work, the tasks typical of schoolwork, results of aptitude and national tests examining progress in learning, and the results of midterm and final exams, as well as end-of-the year grades. Studies reporting absence rates in relation to classroom conditions were included as well. Papers reporting cross-sectional and intervention studies were included.

Altogether 16 studies were identified (Table 1). Five studies measured performance using psychological tests, four measured performance of schoolwork, five reported the results of aptitude and national tests or exams, and three studies reported absence rates as a function of classroom air quality. Classroom air quality was approximated by measuring carbon dioxide (CO_2) concentrations and in few cases also outdoor air supply rates achieved by controlling the dedicated ventilation systems or by calculating them using the measured CO_2 levels (peak concentrations were used or the mass-balance model was fitted). Average daily, weekly or peak levels of CO_2 in ppm were reported. All measurements were performed in classrooms normally used by pupils during regular lessons. No study was performed in the tropical or subtropical climatic zones although air conditioning was part of the systems used to support classroom conditions in some schools. All studies were performed with elementary school children typically in the 4^{th} to 6^{th} grade (primary school children).

Table 1. Studies included to develop the relationship and the measures used to examine the effect on cognitive performance

Psychological tests	Myhrvold et al. (1996) Myhrvold and Olsen (1997) Coley et al. (2007) Ribic (2008) Bakó-Biró et al. (2012)
School tasks	Bakó-Biró et al. (2007) Wargocki and Wyon (2007a) Wargocki and Wyon (2007b) Petersen et al. (2015)
Standard tests and rating schemes	Shaughnessy et al. (2006) Haverinen-Shaughnessy et al. (2011) Gaihre et al. (2014) Haverinen-Shaughnessy et al. (2015) Mendell et al. (2015)
Absence rates	Shendell et al. (2004) Mendell et al. (2013) Gaihre et al. (2014)

Following the analytical approach used by Seppänen et al. (2006), for each individual task and test, the fractional change in performance was calculated per 100 ppm change in CO_2 concentration for the examined range of CO_2 concentrations. The fractional changes were calculated separately for the speed at which the tests were performed or the reaction time, if it was reported, and accuracy describing the percentage of errors committed; all data were included indpendently of whether the changes reached statistical significance in the original studies. The mid-range fractional changes in performance of psychological tests and the performance of school tasks were regressed against the average CO_2 concentration calculated based on the range of CO_2 concentrations for which they were calculated; linear regression was used. Using this fit, the relationships were produced between CO_2 and the performance metric. The developed relationships show thus diminution in performance from what is assumed to be the optimal performance.

To derive the relationship between CO_2 and the performance of tests examining progress in learning, the relationships developed in original studies were used: the median slope was calculated to determine the mean effect of changes in ventilation rate.

The relationship between absence rate and classroom conditions was derived using the changes in absence rates as a function of CO_2 reported in the original studies. The median reported change was used to develop the final relationship. Using the relationship between absence rate and classroom CO_2 concentration the number of days absent from school per pupil was estimated. It was assumed that there are 200 schooldays in a school year, which is the length of school year in Denmark.

In case the data on means and standard deviations were reported by the studies included in the present analyses, Cohen's effect size d was calculated, as well (Cohen, 1988). Cohen's d provides a standardized difference; therefore, it allows comparison of effects obtained in different studies with diverse populations having different size of populations even when measuring scales are not the same. Cohen's d provides additional and supplementary information on the magnitude of effect on performance not in form of the effect size expressed as percentage loss in performance but in form of number of pupils that would be affected by the change in classroom CO_2 concentration.

3 RESULTS

3.1 Effects on performance of psychological tests and school tasks

Figures 1 and 2 show the relationships between the concentration of CO_2 and the performance on psychological tests and school tasks. Since the highest average CO_2 concentration based on which the relationships were established was 889 ppm, it was decided not to extend the relationship to lower CO_2 concentrations. It was admitted that with the proposed analytical approach the shape of the relationship in this range cannot be validated and justified and simply will not be credible. The highest average concentration was around 2,000 ppm. Cohen's d could be calculated based on the data from the studies of Coley et al. (2007) and Wargocki et al. (2007a,b). Median d for the effects on speed at which the tasks were performed was 0.21.This corresponds to 6 pupils performing less well out of 100.

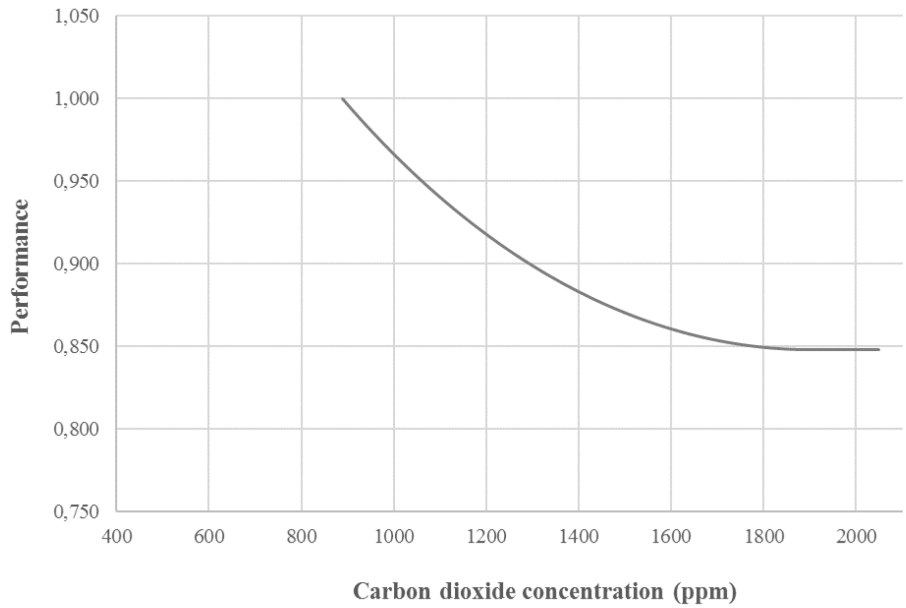

Figure 1: The performance of psychological tests and school tasks as a function of classroom CO_2 concentration; the performance was calculated based on the data showing speed and reaction time, at which the tests and tasks were performed by pupils.

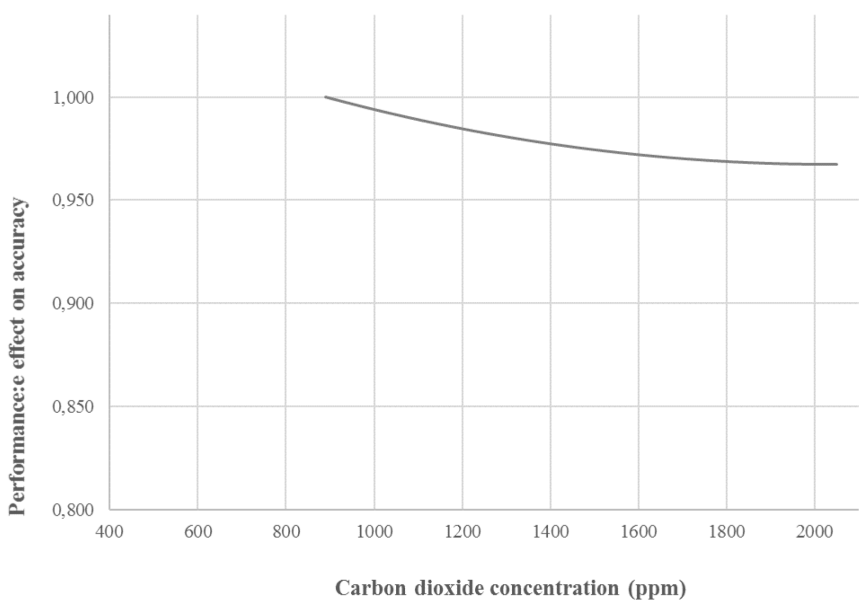

Figure 2: The performance of psychological tests and school tasks as a function of classroom CO_2 concentration; the performance was calculated based on the data showing accuracy, at which the tests and tasks were performed by pupils.

3.2 Effects on performance of standard rating schemes and final exams

Previous studies showed that the scores in math and English-art can be improved from 0.15% to 0.6% (median 0.375%) for each 1 L/s per person increase in classroom ventilation and that the percentage of students scoring satisfactorily or above (passing the tests) can increase by 2.7-2.9% for each 1 L/s per person higher classroom ventilation.

3.3 Absence rates

Three studies reported measurements of absence rates in relation to classroom ventilation. They show that 100 ppm lower concentration of CO_2 will reduce annual absence by 0.016% to 0.2% (median 0.07%) which corresponds to 0.03 to 0.4 days (median 0.14) per pupil per year with 200-day long school year.

4 DISCUSSION AND CONCLUSIONS

The present work is the first attempt to systematically summarize and compare current evidence on the effects of indoor environment in school classrooms on learning outcomes obtained in different studies using diverse methods. They show that there are significant economic benefits to gain if forceful actions for improving classroom environment and teaching conditions are executed.

The relationships developed in the present work can be used in cost-benefit analyses when seeking affordable and economically valid solutions that secure optimal conditions in elementary school classrooms. The results provide a powerful argument for decision makers and regulators to revise requirements in codes and standards so that the pupil, the teacher and the optimal learning environment will always remain in the center of attention independently of whether the aim is to design, renovate or operate the school buildings.

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