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A field study of the individual and combined effect of ventilation rate and lighting conditions on pupils' performance

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Abstract

A field lab study was conducted to determine how much the indoor climate parameters, ventilation and lighting, influence children's academic abilities. The study involved 92 children, aged 10-12 years, who over four weeks answered a questionnaire and three different performance tests, which measured their processing speed, concentration, logical reasoning and math solving abilities. An experimental design was constructed to test the effect of changing the lighting from constant warm light with 2900 K and 450 lux to a dynamic cool light with a maintained correlated colour temperature average of 4900 K and 750 lux. The change was tested at both low (3.9 l/s per person) and high ventilation rate (10.6 l/s per person). The results showed that processing speed (6.6%, $P < 0.001$), concentration (8.3%, $P < 0.001$) and math skills (11.8%, $P < 0.006$), improved the most in the combined scenario with high ventilation rate and dynamic cool lighting. The logical reasoning test did not show any significant changes. The questionnaire

results of the pupils' perception of the indoor environment suggested that they were satisfied in general, but the indoor environmental changes had only very limited effect on how they perceived the classroom. The combination of dynamic lighting and increased ventilation rate indicated a boosted positive impact on the speed and concentration of the children which means that future renovations would benefit from a holistic design including both of these factors.

Keywords: schools, ventilation, lighting, productivity, indoor climate

1 Introduction

The scientific evidence is growing that there are correlations between the indoor environment and people's health, well-being and cognitive performance. In the context of the cognitive process of learning, the indoor environment plays a key role in the pupil's abilities to absorb and process knowledge. This has sparked a number of studies trying to quantify the influence of different indoor environmental factors, like ventilation rate [1–4], natural light [5], artificial light [6,7], temperature [8] and acoustics [9–11].

Most of the body of scientific work on school children and performance is related only to one indoor climate parameter, but some researchers have taken a more holistic approach and even included classroom and school design [12–14]. The holistic approach by Barrett et al. [15] showed that pupil's learning progress in the UK can be attributed partly to the indoor climate (49%), partly to other "softer" values like classroom design (51%). Among the indoor climate parameters, Barrett ranked the lighting conditions to be most influential, both natural and artificial, then air quality, then temperature. In this study we focused on lighting conditions and ventilation rate as temperature is not controlled in a large share of schools, except through shading and ventilation rate. Lighting and ventilation are factors that

are often targeted during refurbishment, and the planning prioritization process will benefit from a deeper understanding of the individual and combined effect of these measures.

In terms of combined measures, Wargocki and Wyon [8] made a crossover study investigated the effect of raised ventilation rates and temperatures on pupils' performance in schoolwork. When increasing the ventilation rate from 5 L/(s person) to 10 L/(s person), the performance in four out of eight given tasks resembling schoolwork showed an improvement. The same result was shown for lowering the indoor air temperature from 25 °C to 20 °C. The improvement was mainly in terms of the speed at which the tasks were performed and there was almost no effect on the amount of errors made. Petersen et al. [4] made a similar study concerning only ventilation rate. It showed a significant increase in four out of four given tests in a double blind crossover intervention where the ventilation rate was increased from 1.7 to 6.6 L/s per person.

In terms of lighting conditions, several studies have shown that lighting affects people's health, mood, well-being and alertness. In terms of mood, Knez and Kers [16] found that young test subjects (about 23 years old) were inclined to keep their negative mood when subjected to correlated colour temperature (CCT) 3000K rather than 4000K at the illuminance intensity of approx. 500 lux.

Similar effects were found in a crossover experiment made by the Surrey Sleep Research Centre in 2008 [17] showing the effect of blue-enriched white light. During the experiment, half of the study group was exposed to normal white light (4000 K) while the rest was exposed to blue-enriched white light (17000 K). The 17000 K light source had a significant positive effect on the participants' alertness, mood, performance, evening fatigue, irritability, concentration, sleep quality and eye discomfort. A study by Mott [7] found that light qualities of illumination and colour temperature had a significant effect on 3rd graders' oral reading performance. The experiment involved 84 children who were exposed to either dynamic light, with an average maintained colour temperature of 6500 K and illuminance of 1000 lux, or normal light at 500 lux and with constant 3500 K. Slegers et al. [18] found evidence that dynamic

lighting had a positive effect on the pupil's concentration. The underlying hypothesis of dynamic lighting is that the circadian cycle of humans is influenced by the wavelengths and luminosity of the surrounding environment [19,20] and by mimicking the outdoor lighting conditions, dynamic lighting – also referred to as human-centric lighting – provides better well-being.

The majority of published work related to school children and performance focuses on only one indoor climate parameter at a time, but the indoor climate is multi-faceted. Thus, the purpose of this study is to gauge, by experimental design, both the *individual* and *combined* effect of two indoor climate parameters: ventilation rate and lighting conditions. These parameters are known from previous studies to affect work performance individually, but this study will contribute to the very limited knowledge base on what happens when they work together to create the overall indoor environment. The motivation was to be able to separate the work performance effect of two essential measures in order to provide a better planning tool for indoor environmental quality in classrooms.

Consequently, the hypothesis of this study was: there is a significant positive effect in the pupils' performance when undertaking tasks mimicking the cognitive processes involved in learning as well as satisfaction with the indoor environment, when their classroom indoor environment is changed from having low ventilation rates and constant warm lighting, to higher ventilation rates and dynamic cool lighting. In addition, we hypothesized that the combined effect of lighting and ventilation does not add up nor boost each other. Rather we hypothesized that a certain cancellation effect would occur in the combined test scenarios.

2 Experimental design

The aim of the experiment was to detect the individual and combined effect that changing ventilation and lighting have on the performance of the pupils. The experiment was designed in such a way that the effect of the variables could be gauged individually, but also as a combined effect of both variables.

Table 1 lists the scenarios that were tested and the naming convention. The tested ventilation rates reflect indoor climate category I (10 l/s person) & III (4 l/s person) [21]. The lighting conditions are determined by the physical properties and proprietary dynamic algorithms of the lighting system. The time plan and execution order of the scenarios is detailed in .

Table 1

The five contrasting scenarios with naming convention. The test conditions are explained in detail in Section 3.

Scenario	Test condition A	Test condition B	Description
1	3.9l/s_ 2900K	3.9l/s_ 4900K	Effect of changing to dynamic cool lighting at low ventilation rates
2	10.6l/s_ 2900K	10.6l/s_ 4900K	Effect of changing to dynamic lighting at high ventilation rates
3	3.9l/s_ 2900K	10.6l/s_ 2900K	Effect of changing to high ventilation rate when lighting is constant and warm
4	3.9l/s_ 4900K	10.6l/s_ 4900K	Effect of changing to high ventilation rate when lighting is cool and dynamic
5	3.9l/s_ 2900K	10.6l/s_ 4900K	Effect of both dynamic cool lighting and high ventilation rate

2.1 Cross-over design

The experimental design was inspired by Petersen et al. [4] who conducted a double-blind 2x2 crossover experiment with high and low ventilation rates in four classrooms. That study took 2 weeks to execute plus one rehearsal week and one baseline week. A comparable crossover experiment with two ventilation rates and two lighting settings creates $(n!/(n-r)!) = 12$ permutations requiring 12+2 weeks to execute. The temporal dimension of this experimental design poses an extra risk because it is difficult to

execute repetitive tasks to the same level of quality. Fatigue and apathy among pupils and teachers would influence the results leading to unusable or missing data and possibly overall failure of the entire experiment. Consequently, we established a compromise where the lighting level is tested in two genuine 2x2 crossover periods: one period is with high ventilation rate in all rooms, the other with low ventilation rate in all rooms. Thus, by design, the experiment counter-acted the risk of air mixing between zones and suppressed the false positives from allowing the pupils to move to well-ventilated rooms during teamwork sessions.

This leads to an experimental design with a time span of 4 weeks plus 2 rehearsal weeks. Fig. 1 illustrates the intervention plan.

Fig. 1. Intervention plan with 2x cross-over periods, test conditions and timing of tests. The tests are described in more detail in Section 4.1- 4.4. The classes are described in Section 3.

The effect of the external factors, like solar radiation and outdoor temperature, positive learning curve, fatigue, pupil-teacher relation and personal life of subjects, was minimized by taking special precautions:

- The performance tests were executed in October and November when overcast skies and stable outdoor temperature of approx. 8-12 °C are prevalent in a Danish climate. This also provided the best test conditions for the lighting system.
- The learning curve is positive because the performance of the pupils will increase over time caused by an increased familiarity with the performance tests [8]. The learning curve is theoretically S-shaped, meaning that the learning progression starts slowly, then accelerates and reaches a maximum over time. To ensure that pupils were completely familiarized with the tests, a rehearsal period was added prior to the actual experiment. Each test was rehearsed at least 8 times before the actual experiment began.
- Fatigue was fought by dividing the experiment into three periods, separated by two breaks, one of them coinciding with the autumn holiday week. The first period was the rehearsal weeks and subsequent periods the 2x2 crossover weeks. Also, to keep motivation high, a prize in the form of two pieces of candy were handed out to each pupil after the final test of the day. The motivation was also gauged every test week by adding motivational questions in the questionnaire, see Section 4.4.
- The effect of the pupil's personal life on the results was disclosed by adding two questions in the questionnaire (Section 4.4) regarding the overall well-being when in school and when outside school. Thus, it was then possible to filter for pupils that showed signs of distress due to personal issues.

3 Field lab

The school *Byens Skole* is from 1971 and located in the city of Valby close to Copenhagen, Denmark. The school comprises several buildings and educates children from preschool to 9th grade, in total 10 grades. It is a private school which, in this context, means that approx. two-thirds of the tuition fee is subsidized

by the local government. It means that the pupils are from homes with financial resources above average, but also that some pupils have moved to the school because they were struggling in the public school sector. The school has approx. 455 pupils and a staff of 50 people. The field lab are four side-by-side classrooms on the ground floor denoted Classroom A, B, C & D. on Fig. 2. The classrooms were occupied by two classes of 4th graders (class A & B) and two classes of 5th graders (class C & D), in total 92 children, 44 girls and 48 boys aged 10-12 years. To compensate for the age difference between 4th and 5th graders each test condition was concurrently applied in one class of 4th graders and one class of 5th graders. In this way the classes were grouped A+C and B+D and tested as detailed in Fig. 1, i.e. every pupil was tested under every test condition. To ensure sample sizes as big as possible, each test condition sample was constructed by merging the datasets from class A+C with B+D.

The four side-by-side classrooms were particularly suited for an intervention study since they had the same dimensions and same window sizes with identical orientation towards South-East. The window dimensions and format are depicted on Fig. 2 and Fig. 3. The light transmittance of the 2-pane low-E glazing was estimated to be 82% and internal screens were manually operable. The users were strictly forbidden to open the windows during the tests and signs were placed over the window handles. Several spot visits ensured that the occupants complied with the signs and it was only necessary to enforce the ban during the rehearsal weeks.

The school went through an extensive refurbishment prior to the performance experiments. The refurbishment introduced a 3-in-1 concept *aereNmore*¹ specifically designed for classrooms and hallways. The concept is intended to simplify the process of refurbishing schools with mechanical balanced ventilation, LED-lighting panels as well as acoustic ceilings and wall absorbers.

Fig. 2. School façade with location of the four classrooms in the field study

Fig. 3. Cross section of classroom

3.1 Diffuse ventilation

The ventilation air is provided by an air handling unit capable of supplying 6000 m³/h in total to 6 classrooms and hallways. Each classroom is designed with a maximum supply ventilation rate of 900 m³/h. With approx. 23 pupils and one teacher in each classroom, this is enough to keep the CO₂-level below 950 ppm. The inlet flow damper is controlled by a CO₂-sensor in the extract and the extract damper operates as slave. The system balances the ventilation supply between classrooms and hallways to adjust for the whereabouts of the pupils. The ventilation is supplied in the void between the concrete slab and the suspended ceiling, in effect exploiting the void as a pressure chamber which distributes the ventilation air to the occupied zone through the perforations at very low velocity. This concept is often referred to in the literature as diffuse ventilation [22–25]. The ventilation supply temperature was set to

21 °C during test weeks with high ventilation rate and 19°C during weeks with low ventilation rate to compensate for reduced cooling effect.

Fig. 4. Ventilation plan

3.2 Dynamic lighting

The lighting system in each classroom is made from 11 LED luminaires recessed in the ceiling suspension system, see Fig. 5. Through a control panel on the wall the users can choose between constant lighting

scenario with a yellowish hue and dynamic lighting scenario with a bluish hue. The corresponding correlated colour temperatures and illuminances were measured with an ELMA 1336 chromameter to be 2900 ± 89 K and 4900 ± 149 K. The resulting illuminances at the table height for constant and dynamic lighting mode are depicted on Fig. 6. The average values at full power are 447 ± 15 lux and 748 ± 24 lux, respectively. In the dynamic lighting scenario, the luminaires adjust both colour temperature and luminance based on a preset schedule depicted on Fig. 7. However, in the hours prior to the testing time slot immediately before lunch, the colour temperature and illuminance level was constant. For both lighting scenarios the maintained illuminance E_m of minimum 300 lux at work plane height is met [26]. The users are normally able to override the automatic settings, but this feature was disabled during the test weeks.

Fig. 5. Diffuse ventilation ceiling with luminaires

Fig. 6. Contour map of the illuminance of the constant warm white (a), and the dynamic cool white light (b), corresponding to what was present during the tests between 11:10 and 11:30. There is approx. 67% higher illuminance in the classrooms with dynamic lighting compared to constant lighting.

Fig. 7. Dynamic lighting mode in relation to constant lighting mode

3.3 Acoustics

The acoustic ceiling and wall absorbers installed in each classroom create together the acoustic environment. The wall absorbers were mounted on the walls opposite the blackboard. The reverberation time T_{20} was measured according to ISO 3382-2 [27] without pupils but with furniture. The rounded result is 0.5 seconds in all classrooms A,B,C,D hence fulfilling the Danish Building Code for classrooms which requires $T_{20} < 0.6$ s. The acoustic performance was not changed during the performance experiments. Ambient noise levels were negligible.

3.4 Equipment

The indoor environment was closely monitored throughout the experiment weeks. The main parameters, CO₂-concentration (± 30 ppm), air temperature ($\pm 0.3^\circ\text{C}$), relative humidity ($\pm 2\%$) and noise levels (n/a) were measured with wireless IC-Meters [28]. Data was logged with 5 min interval and through a GSM connection the data was accessible and online. The IC-Meter unit was placed in each classroom in the corner furthest away from the door and the façade approx. 1 m from the wall. It was placed at a height of 1.20 m from the floor representing head height for a seated person. To capture uneven temperature distribution Hobo loggers model U12-012 from Onset were placed on the pillar between the windows and on the opposite wall at the height of 1.6 m. The advertised accuracy of the air temperature measurements is $\pm 0.35^\circ\text{C}$ from 0 - 50°C . The IC-Meter and HOBO logger locations are depicted on Fig. 3.

4 Measurements of performance

Three tests were used to evaluate different cognitive processes imperative for the learning capability of school children. The tests were designed to assess cognitive performance in terms of attention, concentration, logical reasoning and math skills. During the rehearsal weeks the maximum number of

assignments was adjusted to ensure that none of the children would be able to complete them all within the given time.

4.1 d2-test

The d2-test is a cancellation task, where the subjects are asked to mark targets and avoid so-called distractors. It evaluates the visual scanning speed of an individual and measures how well focus can be kept on a task [29]. It has been used previously in research into the processing speed of school children [30], attention of university students [31] as well as the effect of lighting on the concentration of pupils [18]. The test consists of 14 lines each containing 57 symbols. Each symbol is either a letter d or a p with either one or two dots (‘ or ’) above or below the letter as depicted on Fig. 8. The respondents were given 20 seconds per line to mark only the symbol d with two dots (targets) while avoiding the other symbols (distractors). From the d2-test we deduct two metrics: TOT CORR is calculated as the amount of letters processed minus the amount of errors, i.e. the total sum of distractors incorrectly marked and number of d2-targets that have not been marked. CONC is the total number of correctly marked d2-targets minus the total number of incorrectly marked distractors. TOT CORR and CONC are complimentary metrics of processing speed and concentration. The timing is very important in this test, as the subjects scan each of the 14 test lines for a fixed duration of time. In order to facilitate correct execution, short video clips with instructions and count-down timer were played-back during the test. The total duration of the test was approx. 5 minutes.

Fig. 8. Example of d2-test with 57 symbols in each line

4.2 Baddeley test

In terms of logical reasoning, the Baddeley test is a short test that involves the understanding of sentences of various levels of syntactic complexity [32]. It gives a quick feedback on each individual's ability to think logically and sensible and has been used before to evaluate student performance before [4,8]. The test used in this study is a refinement of the original and is depicted on Fig. 9. It combines a statement with a geometric figure and requires the pupils to categorize the statement as True or False. Thus, the reasoning test combines both reading, comprehension and geometric aptitude. Two metrics were generated from the test: number of correctly marked and number of incorrectly marked answers. The test was eight min long.

Fig. 9. Short example of Baddeley test

4.3 Math

In the math test the pupils were asked to solve equations of multiplication and subtraction. The multiplication calculations were made as numbers between 2 and 5 multiplied by numbers between 10 and 50. The subtraction problems were made as numbers between 10 and 40 subtracted from numbers between 50 and 80. Two metrics, number of correct answers and number of erroneous answers were deducted. Plenty of equations were given to ensure that none of the children would be able to finish the test within the given eight minutes.

4.4 Questionnaires

A questionnaire was handed out after the Baddeley-test in every test week to determine the pupils' perception of the indoor environment. The questions were grouped into three overall parts. The first

part was about the individual's overall well-being when in school and when outside school. This part was included to be able to identify and filter pupils with significant personal distress. The second part had eight questions about the perceived indoor environment in the classroom. These questions were about: Temperature, sensation of draught, air quality, noise and whether there was too much light or it was too dark in the room. The third part asked pupils to rate their motivation regarding headache, concentration difficulties, tiredness, work effort and well-being. A 5 point scale, illustrated as smileys, was used as assessment. It was only allowed to mark one smiley and if the mark was unclear or placed between two smileys it was not taken into account.

All tests and questionnaires were anonymized and given a unique ID-number before being further analyzed. The d2-test and math test were executed on Thursdays, and the Baddeley test and questionnaire on Fridays. Both days immediately before lunch and under the administration of the head teacher of the class. In test week 2, the tests on Thursday were moved to Wednesday due to an excursion.

4.5 Statistical analysis

With the given experimental design with four test conditions, it is obvious to apply a 2x2 ANOVA analysis on the datasets to disclose the separate significance of ventilation and lighting on the pupil's performance plus interactions. However, during the experimental design we realized that sample size and data quality in a less-controlled field study environment were big risk factors. Consequently, we took a more solid approach and compared the indoor climate condition with low ventilation rate and constant lighting, which represents the "before refurbishment" situation or reference situation, to the condition with high ventilation rate and dynamic lighting, which represents the "after refurbishment" situation (scenario 5 in Table 1). Then, four other contrasting scenarios were constructed to uncover the effect of increasing the ventilation first, then followed by dynamic lighting and vice versa. These

scenarios, we believe, aligns well with the decision process prior to a holistic refurbishment project where the order and funding of refurbishment measures is planned and prioritized.

The overall acceptable significance level is $P < 0.05$ (two-tailed), but when conducting several hypothesis tests, the family-wise error rate is increased. With a significance level of 0.05, we may falsely reject the null hypothesis by chance 5 in 100, i.e., it will happen, but rarely. However, when we conduct multiple hypothesis tests with the same data, the risk of a rare event increases, and therefore the likelihood of incorrectly rejecting the null hypothesis. With five tests the chance of erroneously rejecting the null hypothesis at least once among the family of analyses (the family-wise error rate) amounts to $\alpha_{FW} = 1 - (1 - 0.05)^5 = 22.6\%$. Consequently, we apply the Bonferroni correction to the overall significance level. With 5 hypothesis tests, this leads to a new acceptable significance level across all comparisons of $0.05/5 = 0.01$.

When two test conditions are compared, the Shapiro-Wilk's test was run on each dataset to test for normality. When both datasets were normally distributed, the paired Student's t-test was applied, otherwise the Wilcoxon matched-pair signed-rank test was used. We used the open-source software tool RStudio (2019).

4.6 Filtration of responses

Before each hypothesis testing the datasets were filtered for responses that did not exist in both datasets, i.e. only complete within-subject responses are included. The major cause of this was pupils being absent due to sickness or leave. The questionnaire did not disclose any reasons why some pupils should be excluded due to personal distress or bad relations.

In the final test week, Class D made the Baddeley test and the questionnaire without their usual head teacher and instead with a temporary teacher. The pupils expressed afterwards that the class had been with many distractions. In addition, the analysis showed highly divergent results from the previous

weeks. Consequently, the Baddeley test data from class D in week 4 was discarded all together. The questionnaire data was not discarded.

5 Results

The results are presented in the following paragraphs. The physical conditions, temperature and CO₂-concentration during the experiment is presented first. Then follows the results of the statistical hypothesis testing of ventilation and lighting interventions separately, and lastly the combined effects of both interventions.

5.1 Indoor environment conditions

Table 2 summarizes the indoor environment conditions during the test experiments. The physical values are measured with IC-Meters, except the façade temperature and the outdoor temperature which were logged by HOBO loggers, see Fig. 3. The summary includes weekly values averaged over the occupied hours, and the indoor conditions specific to the performance testing periods. The ventilation flow rate was controlled by VAV dampers from CO₂-sensors. Assuming perfect mixing, the low and high mean ventilation flow rate was found through CO₂-decay method to be approx. 3.9 and 10.6 l/s per person, respectively. These values align with the ventilation system design values of 180-900 m³/h per classroom and 22 persons present on a daily basis (2.3 and 11.4 l/s per person).

It was important during the four performance testing weeks to keep the other indoor physical conditions constant. As summarized in Table 2, the mean weekly CO₂-concentration in low ventilation conditions was 1148 ppm, peaking at 1860 during tests and 753 ppm in high ventilation conditions, peaking at 966 ppm. The outdoor temperature was approx. 13 °C, dropping to 7 °C and the indoor temperature was within comfort with a weekly mean of 23 °C, dropping as low as 21.3°C and peaking as high as 25.6°C during some tests. On average the temperature during tests was approx. 24 °C in low ventilation weeks and 23 °C in high ventilation weeks.

The temperature at the façade was slightly colder, but not significantly. Weekly mean relative humidity was also well within comfort range at 30-46%. In this moderate environment, the effect of relative humidity on operative temperature is very modest and on par with the accuracy of the temperature measuring equipment and therefore deemed negligible.

5.2 Performance tests

The results of the statistical hypothesis testing are reported in Table 3, Table 4, Table 5, Table 6 and Table 7. The five tables report the statistics from the scenario comparisons that were listed in Table 1 in order to disclose the effect of individual measures as well as the combined effects. Significant effects after application of the Bonferroni correction are highlighted in bold. An overview of the most noteworthy combined effects is conveyed by the illustrations in Fig. 10, Fig. 11 and Fig. 12.

Most of the performance metrics show improvement when changing to higher ventilation rate and/or changing to dynamic cool lighting. In some instances, the error metrics show decreased performance but these numbers are calculated from very small sample sizes: the total number of errors was quite small compared to the number of correctly executed tests and in most instances the mean value shifts just 1 or 2 to either positive or negative side. Consequently, we put less emphasis on the error metrics, positive or negative.

367 **Table 2** Indoor climate in the classrooms during the test weeks and during the performance tests.

Class room	Week 1				Week 2				Week 3				Week 4			
	3.9l/s_4900K		3.9l/s_2900K		3.9l/s_2900K		3.9l/s_4900K		10.6l/s_4900K		10.6l/s_2900K		10.6l/s_2900K		10.6l/s_4900K	
	A	C	B	D	A	C	B	D	A	C	B	D	A	C	B	D
Weekly occupied conditions																
CO ₂ -concentration,	1175	1212	1119	1166	1094	1136	1123	1159	784	777	762	707	797	725	730	739
mean ± SD [ppm]	± 292	± 357	± 323	± 298	± 319	± 358	± 325	± 296	± 136	± 179	± 114	± 174	± 155	± 125	± 102	± 68
Air temperature,	24.3	24.3	24.0	23.0	23.5	23.7	23.0	21.2	23.2	23.1	23.1	22.5	22.4	22.6	22.3	22.0
mean ± SD [°C]	± 0.8	± 0.9	± 0.8	± 0.5	± 1.3	± 1.7	± 1.0	± 0.8	± 0.9	± 0.9	± 0.7	± 0.7	± 0.7	± 1.0	± 0.7	± 0.6
Air temp. at façade†,	22.1	21.9	21.9	21.7	20.8	20.7	20.3	19.8	20.7	20.5	20.7	21.5	19.9	19.5	19.7	21.0
mean ± SD [°C]	± 1.3	± 1.4	± 1.5	± 1.5	± 1.4	± 1.4	± 1.5	± 1.5	± 1.4	± 1.4	± 1.5	± 1.5	± 1.3	± 1.4	± 1.5	± 1.5
Relative humidity,	40	40	39	42	41	41	42	46	42	43	42	43	30	30	30	32
mean ± SD [%]	± 4	± 5	± 5	± 4	± 4	± 5	± 5	± 4	± 4	± 4	± 4	± 4	± 2	± 2	± 2	± 2
Outdoor temperature,	13.4	14.0	13.3	12.5	12.5	12.9	12.4	11.8	12.2	12.3	12.1	12.0	7.9	7.2	7.2	6.9
mean ± SD [°C]	± 5.3	± 6.2	± 6.3	± 5.3	± 5.0	± 5.6	± 5.3	± 4.3	± 3.5	± 3.4	± 3.4	± 3.8	± 4.1	± 3.0	± 3.0	± 2.9
Conditions during d2 & math																
CO ₂ -concentration,	1525	1639	1598	1648	1173	1619	1513	1443	840	911	845	720	795	905	830	808
min-max [ppm]	1630	1860	1704	1781	1608	1821	1623	1537	893	966	928	777	930	941	901	900
Air temperature,	25.1	25.1	24.6	23.7	23.8	24.1	23.6	21.3	23.5	23.9	23.8	23.0	22.3	23.0	22.5	21.8
min-max [°C]	25.6	25.2	24.9	24.0	24.5	24.7	23.9	21.5	23.9	24.1	23.8	23.0	22.7	23.1	22.7	21.9
Number of persons	22	24	23	21	22	23	22	22	23	22	24	20	23	22	23	21
Vent. rate* [l/s/pers]	4.0	3.5	3.7	3.6	4.7	3.5	4.0	4.3	10.1	8.6	9.5	13.5	10.6	8.9	10.1	10.4
Conditions during Baddeley & questionnaires																
CO ₂ -concentration,	1508	1582	1499	1394	1564	1469	1556	1404	779	847	768	718	846	827	751	734
min-max [ppm]	1753	1807	1653	1660	1724	1685	1735	1666	918	923	856	836	926	878	833	815
Air temperature,	24.9	24.0	24.1	22.6	24.6	24.1	23.9	21.9	24.0	23.9	24.0	23.1	22.0	22.1	21.8	21.5
min-max [°C]	25.1	24.6	24.2	23.2	25.1	24.5	24.3	22.0	24.7	24.3	24.1	23.2	22.4	22.4	21.9	21.7
Number of persons	22	23	23	22	23	20	22	22	22	22	23	21	24	20	20	21
Vent. rate* [l/s/pers]	3.8	3.6	4.1	4.1	3.8	4.0	3.7	4.2	10.7	9.7	11.4	12.3	9.5	10.3	12.2	12.3

368 † Temperature measured by HOBO logger mounted on façade pillar separating the window sections at the height of 1.6 m.

369 *Estimated flow rate based in CO₂-decay method assuming metabolic CO₂-production of 14.4 l/h per pupil and 20.4 l/h from the teacher. Outdoor CO₂-level of 400 ppm.

5.2.1 Lighting

The true crossover design included changing the lighting conditions at first low and then at high ventilation rate. This is reported in Table 3 and Table 4. At low ventilation rate, the math test improved significantly (12.1%, $P=0.009$) with smaller non-significant improvements in the d2-test when dynamic cool lighting was provided (Table 3). Then, when dynamic lighting was combined with high ventilation rate, the d2-test improved significantly with TOT CORR 5.4% ($P=0.003$) and CONC 6.1% ($P=0.002$) (Table 4). Math also improved (5.7%) but without significance. The results indicate that the cognitive processes involved in the d2-test is boosted by the combination of high ventilation rate and dynamic cool lighting conditions, whereas math skills benefit from changing to dynamic lighting (12.1%, $P=0.009$) at low ventilation rates and less for higher ventilation rates (5.7%, $P=0.147$), which suggests that initial improvements from a reference situation have the biggest impact and subsequent changes a smaller impact on math skills. The significant impact of dynamic lighting on the “before” situation concurs with the claims of the producer of the LED-panels, who names the dynamic cool lighting condition “math” light. These results supplement Mott et al. [7] who found that 3rd graders oral reading fluency improved 36% when given 1000 lux at 6500K instead of 500 lux at 3500K but found no influence on motivation or concentration.

5.2.2 Ventilation

The effect of higher ventilation rate at different lighting conditions is reported in Table 5 and Table 6. The ventilation rate was increased from 3.9 l/s to 10.6 l/s per person on average, illustrated by a CO₂-concentration reduction from approx. 1600 ppm to 900 ppm (Table 2). While showing overall positive performance changes in all tests with negligible effect on the error rates, only the d2 metrics show significant improvement but only when given both high ventilation rate *and* dynamic lighting ($\Delta > +5.0\%$, $P<0.003$). Indeed, providing higher ventilation rate to the pupils seems to have had a smaller effect on

their performance than anticipated based on results in the literature. Wargocki and Wyon [33] found that doubling the outdoor air supply rate increased the execution speed of school-work related tasks by 8% overall, and 14% in the most significantly affected tasks. Similarly in 2016, Petersen et al. [4] found statistically significant performance increases for different schoolwork tasks of 3.2% to 7.4% when increasing the ventilation rate from 1.7 to 6.6 l/s per person. The results reported in Table 5 and Table 6 support that the d2-metrics are boosted by combining indoor environment improvements. The math results – though non-significant - benefit more from higher ventilation rates at warm constant lighting conditions (6.1%, $P=0.108$) than at dynamic cool lighting conditions (2.7%, $P=0.539$), which suggests some canceling effect between improvements.

In Table 7 the combined effect of providing higher ventilation rate *and* dynamic lighting conditions is reported. Both d2-tests and math tests were significantly impacted from the combination. The metrics TOT CORR and CONC showed improvements of 6.6% and 8.3% ($P<0.001$) and the math test showed 11.8% ($P=0.006$).

The Baddeley performance metrics (Correct answers and Errors) did not show any significance in any of the scenarios and the scores point in both positive, neutral, and negative direction. Thus, we disregard the Baddeley test results all together.

Table 3

Scenario 1: performance by children when lighting changes from constant warm to dynamic cool at low ventilation rate

Performance test	Sample size n (n _A +n _B +n _C +n _D)	Performance metric	3.9l/s_2900K mean ± SD (median)	3.9l/s_4900K mean ± SD (median)	Performance change [†] , %	Statistical test	P-value
d2	82 (19+21+22+20)	TOT CORR	366 ± 79 (375)	372 ± 69 (380)	1.6	t-test	0.185
		CONC	143 ± 42 (144)	146 ± 33 (152)	2.1	Wilcoxon	0.251
Baddeley	79 (20+21+18+20)	Correct answers	37 ± 15 (36)	35 ± 16 (35)	-5.4	Wilcoxon	0.265
		Errors	5 ± 7 (2)	6 ± 10 (2)	-20.0	Wilcoxon	0.93
Math	80 (19+21+21+19)	Correct answers	33 ± 18 (32)	37 ± 19 (38)	12.1	Wilcoxon	0.009**
		Errors	3 ± 3 (3)	4 ± 4 (2)	-33.3	Wilcoxon	0.484

Note: Asterisks emphasize the significance: P-value ≤ 0.05 (*), ≤ 0.01 (**) and P-value ≤ 0.001 (***).

[†]The term “change” refers to the relative change in the mean values between the scenarios. Positive values denote a performance increase, negative a decrease.**Table 4**

Scenario 2: performance by children when lighting changes from constant warm to dynamic cool at high ventilation rate

Performance test	Sample size n (n _A +n _B +n _C +n _D)	Performance metric	10.6l/s_2900K mean ± SD (median)	10.6l/s_4900K mean ± SD (median)	Performance change [†] , %	Statistical test	P-value
d2	80 (21+22+19+18)	TOT CORR	371 ± 91 (382)	391 ± 86 (391)	5.4	t-test	0.003**
		CONC	148 ± 42 (146)	157 ± 40 (156)	6.1	t-test	0.002**
Baddeley [#]	57 (21+19+17+0)	Correct answers	39 ± 15 (40)	39 ± 15 (39)	0.0	t-test	0.822
		Errors	9 ± 13 (2)	7 ± 10 (2)	22.2	Wilcoxon	0.079
Math	79 (21+22+19+17)	Correct answers	35 ± 21 (33)	37 ± 20 (38)	5.7	Wilcoxon	0.147
		Errors	3 ± 6 (2)	4 ± 5 (3)	-33.3	Wilcoxon	0.168

Note: Asterisks emphasize the significance: P-value ≤ 0.05 (*), ≤ 0.01 (**) and P-value ≤ 0.001 (***).

[#]The results from class D in test week 4 are not included due to badly executed Baddeley test by temporary teacher.[†]The term “change” refers to the relative change in the mean values between the scenarios. Positive values denote a performance increase, negative a decrease.

Table 5

Scenario 3: performance by children when ventilation rate changes from low to high in constant warm lighting conditions

Performance test	Sample size n (n _A +n _B +n _C +n _D)	Performance metric	3.9l/s_2900K mean ± SD (median)	10.6l/s_2900K mean ± SD (median)	Performance change†, %	Statistical test	P-value
d2	82 (20+22+21+19)	TOT CORR	366 ± 80 (375)	371 ± 91 (382)	1.4	t-test	0.391
		CONC	142 ± 43 (144)	146 ± 43 (146)	2.8	Wilcoxon	0.053
Baddeley	79 (22+21+16+20)	Correct answers	37 ± 16 (38)	39 ± 16 (39)	5.4	t-test	0.398
		Errors	5 ± 7 (2)	8 ± 12 (2)	-60.0	Wilcoxon	0.375
Math	79 (20+22+20+17)	Correct answers	33 ± 19 (32)	35 ± 21 (33)	6.1	Wilcoxon	0.108
		Errors	4 ± 3 (3)	3 ± 6 (2)	25.0	Wilcoxon	0.022*

Note: Asterisks emphasize the significance: P-value ≤ 0.05 (*), ≤ 0.01 (**) and P-value ≤ 0.001 (***).

†The term “change” refers to the relative change in the mean values between the scenarios. Positive values denote a performance increase, negative a decrease.

Table 6

Scenario 4: performance by children when ventilation rate changes from low to high in dynamic cool lighting conditions

Performance test	Sample size n (n _A +n _B +n _C +n _D)	Performance metric	Scenario 3.9l/s_4900K mean ± SD (median)	Scenario 10.6l/s_4900K mean ± SD (median)	Performance change†, %	Statistical test	P-value
d2	81 (20+21+21+19)	TOT CORR	374 ± 66 (380)	393 ± 83 (396)	5.1	t-test	0.003**
		CONC	149 ± 32 (152)	158 ± 39 (158)	6.0	t-test	<0.001***
Baddeley [#]	57 (19+19+19+0)	Correct answers	38 ± 16 (40)	39 ± 15 (39)	2.6	t-test	0.76
		Errors	7 ± 11 (2)	6 ± 10 (2)	14.3	Wilcoxon	0.474
Math	81 (20+21+21+19)	Correct answers	37 ± 19 (39)	38 ± 20 (39)	2.7	Wilcoxon	0.539
		Errors	4 ± 4 (2)	4 ± 5 (3)	0.0	Wilcoxon	0.342

Note: Asterisks emphasize the significance: P-value ≤ 0.05 (*), ≤ 0.01 (**) and P-value ≤ 0.001 (***).

[#]The results from class D in test week 4 are not included due to badly executed Baddeley test by temporary teacher.

†The term “change” refers to the relative change in the mean values between the scenarios. Positive values denote a performance increase, negative a decrease.

Table 7Scenario 5: performance by children when ventilation rate changes from low to high *and* lighting conditions changes from constant warm to dynamic cool

Performance test	Sample size n (n _A +n _B +n _C +n _D)	Performance metric	Scenario 3.9l/s_2900K mean ± SD (median)	Scenario 10.6l/s_4900K mean ± SD (median)	Performance change†, %	Statistical test	P-value
d2	81 (20+22+20+19)	TOT CORR	366 ± 77 (375)	390 ± 86 (396)	6.6	t-test	<0.001***
		CONC	145 ± 39 (145)	157 ± 40 (158)	8.3	Wilcoxon	<0.001***
Baddeley [#]	56 (20+19+17+0)	Correct answers	37 ± 16 (38)	39 ± 15 (39)	5.4	t-test	0.49
		Errors	5 ± 8 (2)	6 ± 10 (2)	-20.0	Wilcoxon	0.932
Math	80 (20+22+20+18)	Correct answers	34 ± 19 (32)	38 ± 20 (39)	11.8	Wilcoxon	0.006**
		Errors	4 ± 3 (3)	4 ± 5 (3)	0.0	Wilcoxon	0.984

Note: Asterisks emphasize the significance: P-value ≤ 0.05 (*), ≤ 0.01 (**) and P-value ≤ 0.001 (***).

[#]The results from class D in test week 4 are not included due to badly executed Baddeley test by temporary teacher.

†The term “change” refers to the relative change in the mean values between the scenarios. Positive values denote a performance increase, negative a decrease.

5.2.3 Combined effect of ventilation and lighting

The most noteworthy performance changes from Table 3-Table 7 are put into the graphs in Fig. 10 (TOT CORR), Fig. 11 (CONC) and Fig. 12 (Math). The graphs show the combined effect of higher ventilation rate and dynamic lighting with high statistical significance (dashed horizontal line). For the metrics TOT CORR (Fig. 10) and CONC (Fig. 11) the total performance increase coincides very closely to the added effect of introducing first one improvement, then another. The P-values are included to indicate the trustworthiness of each individual measure.

The graphs show that the cognitive processes involved in the d2-test is boosted by the combination of high ventilation rate and dynamic cool lighting conditions irrespective of the initial measure. The math results (Fig. 12) show 50-50 attribution when ventilation is applied first whereas dynamic lighting as a first measure seems to have a big stand-alone effect making any subsequent improvements from ventilation very uncertain. The graphs underpin the importance of refurbishing holistically as the major impact comes from a combination of improvements and not from any stand-alone measures with the sole exception of dynamic lighting from a reference situation on math skills.

Fig. 10. TOT CORR as a metric for processing speed. Expected performance increase based on higher ventilation rate or changing to dynamic lighting or doing both. Significance level 0.01 (two-tailed).

Fig. 11. CONC as a metric for concentration. Expected performance increase based on higher ventilation rate or changing to dynamic lighting or doing both. Significance level 0.01 (two-tailed).

Fig. 12. Subtraction and multiplication tests as a metric for math abilities. Expected performance increase based on higher ventilation rate or changing to dynamic lighting or doing both. Significance level 0.01 (two-tailed).

5.3 Questionnaires

At the end of each test week, the pupils gave feedback on the perceived indoor climate. Table 8 summarizes the results for each test condition. In general, the feedback shows little impact from the four test conditions, which renders the results largely inconclusive. The classrooms were assessed to be too warm, which corresponds well with the verbal feedback from the teachers and the measured air temperatures, which started at +24°C and trending towards 22°C in the final week. The pupils seem to be indifferent to the change in ventilation flow rate, which is positive in terms of both draught and noise and may be due to the diffuse ceiling ventilation concept. The noise score is towards the negative side, but this is probably due to the pedagogic approach with a large share of work in teams and therefore a lot of human background noise. In terms of perceived air quality, lighting conditions and motivation there were no changes to be detected.

Table 8

Questionnaire feedback from pupils from each test week merged into four test conditions

	Week 1	Week 2	Week 3	Week 4
	3.9l/s_2900K	3.9l/s_4900K	10.6l/s_2900K	10.6l/s_4900K
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Wellbeing in school: bad(1) - great(5)	3.8 ± 0.7	3.8 ± 0.7	3.7 ± 0.8	3.9 ± 0.9
Wellbeing outside school: bad(1) - great(5)	4.3 ± 0.7	4.2 ± 0.8	4.1 ± 0.9	4.2 ± 0.8
Classroom was: bad(1) - great(5)	3.4 ± 0.9	3.2 ± 0.9	3.3 ± 0.9	3.4 ± 0.8
Too warm(1) - Not too warm(5)	2.7 ± 1.2	2.5 ± 1.2	2.9 ± 1.3	3.1 ± 1.4
Too cold(1) - Not too cold(5)	4.3 ± 0.8	4.4 ± 0.8	4.3 ± 0.9	4.2 ± 0.9

Draught(1) - No draught(5)	4.3 ± 1.0	4.3 ± 1.0	4.2 ± 1.0	4.3 ± 0.9
Air was stuffy(1) - Air was fresh(5)	3.0 ± 1.2	2.8 ± 1.3	2.8 ± 1.2	2.9 ± 1.2
Too noisy(1) - Quiet(5)	2.6 ± 1.1	2.7 ± 1.1	2.8 ± 1.0	2.8 ± 1.1
Too bright(1) - Not too bright(5)	3.8 ± 1.2	3.6 ± 1.2	3.9 ± 1.0	3.7 ± 1.1
Too dark(1) - Not too dark(5)	4.4 ± 0.9	4.3 ± 0.8	4.1 ± 0.9	4.2 ± 1.0
Headache(1) - No headache(5)	3.5 ± 1.5	3.3 ± 1.4	3.3 ± 1.3	3.3 ± 1.3
Concentration was: difficult(1) - easy(5)	3.6 ± 1.0	3.3 ± 1.0	3.2 ± 1.0	3.4 ± 1.1
Sleepy(1) - Awake(5)	3.7 ± 1.1	3.6 ± 1.2	3.6 ± 1.3	3.7 ± 1.2
Feeling like: not working(1) - working(5)	3.8 ± 1.1	3.8 ± 1.1	3.8 ± 1.0	3.9 ± 1.1
Feeling not well(1) - Feeling well(5)	4.1 ± 0.9	3.8 ± 1.0	4.0 ± 1.0	4.0 ± 1.0

487

488 6 Discussion

489 6.1 Main findings

490 The aim of the study was to examine the effect in the pupils' cognitive performance and satisfaction
 491 with the indoor environment by changing their classrooms from having low ventilation rates and
 492 constant warm lighting to higher ventilation rates and dynamic cool lighting.

493 Out of the five contrasting scenarios, the move to higher ventilation rates *and* dynamic cool lighting was
 494 especially interesting, as both d2-test (TOT ERR and CONC) and math test improved significantly
 495 ($P < 0.001$, $P < 0.006$), even considering the Bonferroni correction. The results of the individual measures,
 496 higher ventilation rates *or* dynamic lighting, point in the same positive direction, but was not statistically
 497 significant in all cases. Application of the Bonferroni correction changed significance of only one
 498 performance metric in one scenario, as denoted by the single asterisk (*) in Table 5, and we did not put
 499 emphasis on this metric anyway due to the extremely small sample size.

500 The individual effect of higher ventilation rate was overall lower than expected and not always
 501 significant. For each 1 l/s per person ventilation increase the effect amounted to an overall average of
 502 0.6%. In comparison, others have published significant performance increases of 0.5% (math scores,
 503 range 0.9-7.1 l/s per person) [34], 1.1% (math and language tasks, range 1.7-6.6 l/s per person) [4] and

about 2% (math and language tasks, range 3-9.5 l/s per person) [33]. The low effect is probably due to the relatively satisfactory ventilation rate in the reference condition (3.9 l/s person, approx. cat III [21]). The effect of dynamic lighting is low and insignificant for low ventilation rate, but increases to 6.1% (CONC) during higher ventilation rates and CO₂-levels of approx. 800-900 ppm. This result concurs with a published study, where schoolchildren's concentration performance also increased significantly when given 1000 lx at 6500 K rather than 300 lux at 3000 K [18].

The Baddeley-test did not show any significant difference throughout the experiment. This is consistent with Wargocki & Wyon [8], who used the same type of test in a similar study concerning ventilation flow rate and temperature. One reason could be that the test was too difficult for the age group or the eight minute period was too short. Petersen et al. [4] did find a significant ($P=0.04$) improvement by the use of a Baddeley-test when pupils were given higher ventilation flow rate. But we noticed a major difference in the average score of 'Correct answers', being 62 in the study by Petersen and only 37 in this study. The higher score might be caused by age difference because in Petersen's study the population only consisted of 5th graders. Furthermore, two more minutes were given compared to this experiment. Thus, no conclusions can be drawn from the Baddeley test results.

Prior to the study, we hypothesized that the combined effect of lighting and ventilation would not add up or boost the final results. Rather we hypothesized that a certain cancellation effect would occur, making it hard to find statistically significant results when lighting was combined with ventilation or vice versa. In Fig. 10, Fig. 11 and Fig. 12 the incremental positive performance changes due to either higher ventilation rate or dynamic cool lighting or combinations hereof are depicted. The figures illustrate that the total positive performance change from *combined* measures matches the summed up effect of *individual* measures. The exact contribution of the individual measures is uncertain due to the statistical significance level, but the d2-test results in Fig. 10 and Fig. 11 show that higher ventilation rate or dynamic lighting *individually* cause approx. the same effect on the pupil's cognitive performance, but in

combination they boost one-another. In the math test results in Fig. 12 the measures seems to add up or even have some canceling effect, but the statistical significance here is low. Thus, the hypothesis is partly contradicted and partly supported by the results.

The results indicate that neither higher ventilation rate nor dynamic lighting as *individual* measures provide the full potential performance increase. Rather the results support the notion that the indoor climate parameters support one-another, and to gain the full potential of a refurbishment, it is imperative to consider the indoor climate from a holistic perspective.

6.2 Limitations

The data was pooled to create sample sizes as big as possible. Considering the physical adjacency, orientation and resemblance of the classrooms, we consider this statistically acceptable, but the effect of the teacher-pupil relation was obscured. Very light filtration of the test responses was implemented and only for obvious reasons: pupils showing signs of being deeply un-motivated with only very few responses or with tests badly doodled or with expressions of strong dislike of the whole situation. Thus, only 1-3 pupils in each dataset was discarded. Another filter was applied to the first and last line in every d2-test because many tests showed signs of premature start or delayed finish.

Great care was taken to avoid positive learning effects by rehearsing each test at least eight times before the real performance tests began. The cross-over periods were designed to eliminate the effect but we cannot completely disregard that some of the effect, especially in scenario 5 with data from early and late test weeks, is due to a positive learning curve. But we argue that the initial comprehensive and repetitive rehearsals should have made the students reach their maximum proficiency prior to the real tests and minimized the effect..On the opposite, fatigue caused by repetition was a bigger concern. Fatigue would be partly evident by the last four questions in the questionnaire relating to motivation but no trend of decreasing motivation could be observed. Thus, we did not find evidence of fatigue.

The pupils knew they were being tested – in some respects the rigorous test regime collided with the pedagogic teaching methods that the pupils were used to – so it was impossible to hide the fact from them. Neither pupils, nor teachers knew which test condition they had a given week, but the colour temperature of the lighting fixtures and to some extent the perceived air quality was impossible to disguise. The 2x cross-over experimental design, however, helped in obscuring any patterns to the test subjects and by running each test condition for at least three full school days prior to the first performance test the pupils acclimatized and minimized any carry-over effect. The questionnaire did not reveal either that the pupils noticed any changes to the air quality or lighting conditions. We sacrificed the double-blind test regime even though it would have carried more power, because we deemed the risk of jeopardizing the entire experimental operation too high if we as researchers did not keep a close record of everything. The questionnaire did not seem to capture the real feeling of the pupils. This is, however, in alignment with literature [4,8,35] where very little evidence was found that the pupil's self-evaluation reflects the actual indoor climate conditions. One important source of error was the daylight entering from the windows. The dynamic cool lighting was designed to mimic daylight and was therefore not as affected by additional daylight as the constant warm lighting was. We tried to minimize the effect by conducting the experiment in October and November where it is quite dark and overcast in Denmark, but the reported findings with the two lighting conditions might have been even more clear if the warm lighting conditions had not been 'contaminated' by daylight. Using the shading was not a viable option because it would substantially aggravate the learning environment. We do not have reliable daylight data to compensate for the effect, but in real schools the lighting system is also "contaminated" with daylight. Consequently, we regard the test results to be conservative and to be reflecting the effect that will be observable in real schools.

The temperature was not constant during all the tests in all classes and this may have influenced the result as temperature is a key factor for work performance. But by the process of aggregating tests from different classes from different days into scenarios, the temperature differences are leveled out. Thus, in the scenarios where ventilation rate was increased (scenario 3-5) the temperature dropped by approx. 1°C.

According to the thermal comfort model by Seppanen et al. [36], this amounts to a relative performance increase of 0.6% which concurs closely to Haverinen-Shaughnessy's study [34] who found 0.5% per 1 °C decrement. 2% was found by Wargocki & Wyon [33]. Thus, a minor part of the performance increment found in the scenarios with higher ventilation rate is probably due to increased thermal comfort. In temperate climates, this inter-dependency is most often positive, but in warmer climates care should be taken to avoid that higher ventilation rates negatively affect thermal summer comfort and cannibalizes the performance improvement from higher ventilation rates.

6.3 Future research

This study focuses only on the inter-relations of two indoor environmental quality parameters: ventilation and lighting and only at specific levels. Future research should aim at determining the critical levels of these IEQ parameters where further improvement does not reflect in the student's performance; also because improved ventilation and lighting consumes more energy. Acoustics might also be included as an important IEQ aspect that is often considered when refurbishments are planned. Also further evidence for the conclusions should be gained by increasing the sample size and extent the investigation to include other academic skills, such as creative thinking and project work.

7 Conclusion

This article reports on a field study where 92 pupils between the age of 10 and 12 years have been tested in processing speed, concentration, logical reasoning and math skills while they were subjected to different ventilation rates and lighting conditions. The tests were selected to measure the performance of various cognitive processes in the pupils. The experiment was designed as two 2x2 crossovers where the lighting was changed from constant warm light with a correlated colour temperature of 2900 K and illuminance 450 lux to a dynamic cool light with a maintained average of CCT 4900 K and 750 lux. Each 2x2 crossover was tested at both low (3.9 l/s per person) and high ventilation rate (10.6 l/s per person). Five statistical scenarios were constructed to contrast the different indoor climate test conditions. The scenarios showed that processing speed (6.6%, $P < 0.001$), concentration (8.3%, $P < 0.001$) and math skills (11.8%, $P < 0.006$), improved the most in the combined scenario with high ventilation rate and dynamic cool lighting. The logical reasoning test did not show significant changes in any of the scenarios. The scenarios also indicated that the processing speed and concentration metrics were boosted when both ventilation and lighting was improved. The math test indicated a more equal balance between the effect of lighting and ventilation, perhaps even some canceling effect. The weekly questionnaires showed a general satisfaction with the environmental conditions, but dissatisfaction concerning overheating, air quality and noise was persistent irrespective of the actual indoor conditions. However, this is most likely due to the formulation of the questions and the pupils having difficulty reflecting on their indoor environment.

Declaration of interest

In accordance with Elsevier policy and our ethical obligations as researchers, we report that the main author is partly employed by the Saint-Gobain Group, but has conducted this research independently by virtue of his affiliation with the University. We declare that neither the school, nor the refurbishing

companies have had any influence, nor attempted to gain influence on the experimental design, results and/or conclusions of this study in any way or at any time.

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Note

1. Concept developed by Saint-Gobain aereNmore, Nordic countries and Brainlit AB, Sweden. Research conducted independently.

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- Schoolchildren's performance is affected by ventilation rate and lighting conditions
- The effect of individual measures was small compared to combined effect
- Neither improved ventilation rate, nor lighting conditions should be individual measures
- Combine improved ventilation rate and lighting conditions to boost performance
- The results support a holistic view on indoor environmental refurbishment

Declaration of interest

In accordance with Elsevier policy and our ethical obligations as researchers, we report that the main author is partly employed by the Saint-Gobain Group, but has conducted this research independently by virtue of his affiliation with the University. We declare that neither the school, nor the refurbishing companies have had any influence, nor attempted to gain influence on the experimental design, results and/or conclusions of this study in any way or at any time.