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Lighting affects students' concentration positively: Findings from three Dutch studies

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The importance of lighting for performance in human adults is well established. However, evidence on the extent to which lighting affects the school performance of young children is sparse. This paper evaluates the effect of lighting conditions (with vertical illuminances between 350 lux and 1000 lux and correlated colour temperatures between 3000 and 12 000 K) on the concentration of elementary school children in three experiments. In the first two experiments, a flexible and dynamic lighting system is used in quasi-experimental field studies using data from 89 pupils from two schools (Study 1) and 37 pupils from two classrooms (Study 2). The third experiment evaluated two lighting settings within a school-simulating, windowless laboratory setting ($n = 55$). The results indicate a positive influence of the lighting system on pupils' concentration. The findings underline the importance of lighting for learning. Several suggestions are made for further research.

1. Introduction

Research has indicated that both natural and artificial lighting affect people's health, mood, well-being and alertness.[1–3] Studies suggest that the intensity and colour temperature of artificial lighting affect various physiological processes in the human body, such as blood pressure, heart rate variability, EEG, core temperature and melatonin.[4–8] Moreover, exposure to lighting with different illuminances and correlated colour temperature (CCT) can affect the quality of sleep, the mood, alertness and perceived self-efficacy of the subjects studied.[6,9–19] One of the beneficial biological effects of lighting is the inhibition and suppression of cortisol and melatonin in human subjects exposed to different lighting systems.[20] In addition to physiological and psychological effects of different types of illumination, research has indicated that specific lighting conditions may also increase human performance.[3] For instance, studies suggest that artificial lighting can have positive effects on working speed, accuracy and task performance.[12,21–23]

Empirical studies supporting the effects of lighting have been conducted in various settings, such as retail environments,[24] offices[13,18] and schools.[25–27] The findings of these studies indicate that the effect of lighting is in part dependent on the situation, the task at hand and the specific environment.[9,28–30] Although these studies did find some effects, they do not unequivocally verify

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or falsify the effects of lighting in different settings as expected in the literature.[31] In this study, we add to the literature base by exploring the extent to which classroom lighting conditions in elementary schools affect children's concentration. While educational research has provided valuable insights as to the importance of various aspects of learning environments, such as learning tasks and materials, time on task, feedback, and teachers' instructional behavior, systematic empirical research into the influence of physical aspects of students' learning environment, such as lighting, is limited.[32] In a recent study, positive effects were found for brighter lighting (500 lux) compared to standard lighting (300 lux), on the reading, writing and mathematics of elementary school children.[33] Besides the effects of illuminance, studies also indicate positive effects of lighting of different CCTs (4000 K and 17000 K) on various physical, psychological and performance outcomes of children, such as dental health, physical growth and development, attendance, alertness and academic achievement.[34,35]

In addition to these studies into 'static' forms of lighting, researchers have started to examine the potential effects of dynamic lighting in school settings. Dynamic lighting refers to lighting that provides different lighting settings, in specific combinations of illuminance and CCT, that can be applied over time to support both mental alertness and relaxation. The findings indicate that dynamic lighting systems may have positive effects on students' visual performance, arousal and well-being.[36–38] Furthermore, dynamic lighting has been found to improve both pupils' performance as assessed by increased reading speed and pupils' behavior in terms of restlessness and aggressive behavior.[25,26] While some studies support the effects of dynamic lighting on performance on elementary school children and university students.[26] other evidence disputes these effects.[39]

Although the literature suggests that lighting in school settings can affect pupils' achievement and behaviour, empirical evidence on these suggested effects is still very limited. Moreover, the studies vary greatly with regard to the research designs (field studies and experiments), types of lighting systems (static and dynamic, differences between illuminance and spectrum), target groups (young children, adolescents, or adults) and outcome measures (e.g., subjective measurements, objective tests, physical measures). In addition, research suggests that the timing and duration of the lighting available plays an important role.[34,35] In some studies, students were followed for a longer period of time, other studies were conducted in different seasons, and in some studies students were exposed to different preset lighting conditions for a short period of time. More research is needed to understand the influence of artificial lighting in schools and classrooms and to establish consistent and unequivocal support for these effects. Given the lack of empirical evidence, studies into the influence of dynamic lighting systems on children's alertness are indicated. This paper makes a contribution to the existing body of knowledge by examining the extent to which dynamic lighting in elementary schools affects children's concentration. Our inquiry examined the following question: To what extent does a dynamic lighting system affect the concentration of Dutch elementary school children?

In this paper, we will present the results of three different and complimentary studies, namely two quasi-experimental field studies and one randomized laboratory experiment, into the effects of dynamic lighting on the concentration of elementary school children. The studies were conducted in different seasons: Winter and spring. We used instruments that have been used by other researchers to measure pupils' concentration. By doing so, this paper aims to validate earlier findings and make a unique contribution to increased insights on the effects of lighting conditions on children's concentration in elementary schools.

2. Method

2.1. The dynamic lighting system: Settings and conditions

A system for dynamic lighting of classrooms was designed to support the rhythm of activity in the classroom with four different lighting settings. The teacher is able to select the most appropriate setting via a five-button, wall-mounted control panel located in the classroom. The system has four preset lighting settings:

- Energy setting. This setting is intended to be used to activate the pupils at the start of the day or after lunch. The average horizontal illuminance measured at desk level is 650 lx, and the CCT is 12 000 K (a 'cold', blue-rich white light.)
- Focus setting. This setting aids concentration during challenging tasks, such as exams and tests. The average horizontal illuminance measured at desk level is 1000 lx with a CCT of 6500 K (a bright white light).
- Calm setting. This setting brings a relaxing ambience to support independent and collaborative learning. The average horizontal illuminance measured at desk level is 300 lx with a CCT of 2900 K (white light with a warm, red colour tone).
- Standard setting. This lighting setting is used for regular classroom activities. The average horizontal illuminance measured at desk level is 300 lx, and the CCT is 3000–4000 K (standard white light as commonly used in indoor workplaces).

The settings were created by colour-mixing the light output from a surface-mounted Philips Savio luminaire fitted with a diffuser (TCS770 3xTL5-49W/452/827/452 25/90/25 Electronic PC MLO). The light output was pre-programmed in the ballasts for each setting.

2.2. Research design and sample

2.2.1. Study 1

The first study was designed as a pre-test-post-test nonequivalent control group study. Two schools in the south of the Netherlands were appointed to the control and experimental condition. A timeline for the administration of the pre- and post-tests is presented in Table 1. As can be seen from Table 1, data from two post-tests were gathered 1 month after the installation of the dynamic system in November and December.

The illuminances produced in both schools have been measured on a horizontal plane at the pupil's desk level, without outdoor lighting, using a Konica Minolta CL - 200A.

The original lighting condition of the classroom in the experimental school (pre-test) was nine recessed conventional luminaires with a louvre creating about 300 lx at desk level and with a CCT of 4000 K (Figure 1). Table 2 summarizes the cumulative use of the different settings of the dynamic lighting system in the experimental school in the period November 2009 to March 2010. The ventilation of the class rooms was uncontrolled. All tests in the experimental school were administered using the Focus setting of the dynamic lighting system (Figure 2). Figure 3 shows the pattern

Table 1 Time points for the assessment of concentration (Study 1)

Time point	Date	Illumination
1	23 October 2009	Pre-test (no dynamic lighting)
2	24 November 2009	First post-test (dynamic lighting)
3	2 December 2009	Second post-test (dynamic lighting)

Figure 1 Conventional lighting system in the control school/classroom and the experimental school/classroom (pretest)

Table 2 Cumulative percentage use of the different settings of the dynamic lighting system in the experimental school during November 2009 to March 2010 (Study 1)

Lighting setting	Grade 4		Grade 6	
	Mean (%)	Standard deviation (%)	Mean (%)	Standard deviation (%)
Standard	51.0	21.4	74.2	20.6
Energy	3.3	3.7	4.0	4.2
Focus	14.2	10.8	6.6	11.3
Calm	31.4	20.9	15.2	15.3

of use of the dynamic lighting system during a test day

The control school was equipped with conventional recessed luminaires fitted with louvres (Figure 1). The average illuminance was about 600 lx at desk level with a CCT of 4000 K for both classes. The ventilation of the classrooms was uncontrolled.

Concentration tests were administered on the same days in both the experimental and control school. The exact starting time was agreed upon and managed by both schools for each of the time points, and took place between 9 and 10 a.m. The outdoor conditions during the test days were classified as cloudy and overcast by the Dutch weather station KNMI.

A total of 98 pupils participated in the study; 52 pupils from the control school (27 pupils in grade 4 and 25 pupils in grade 6) and

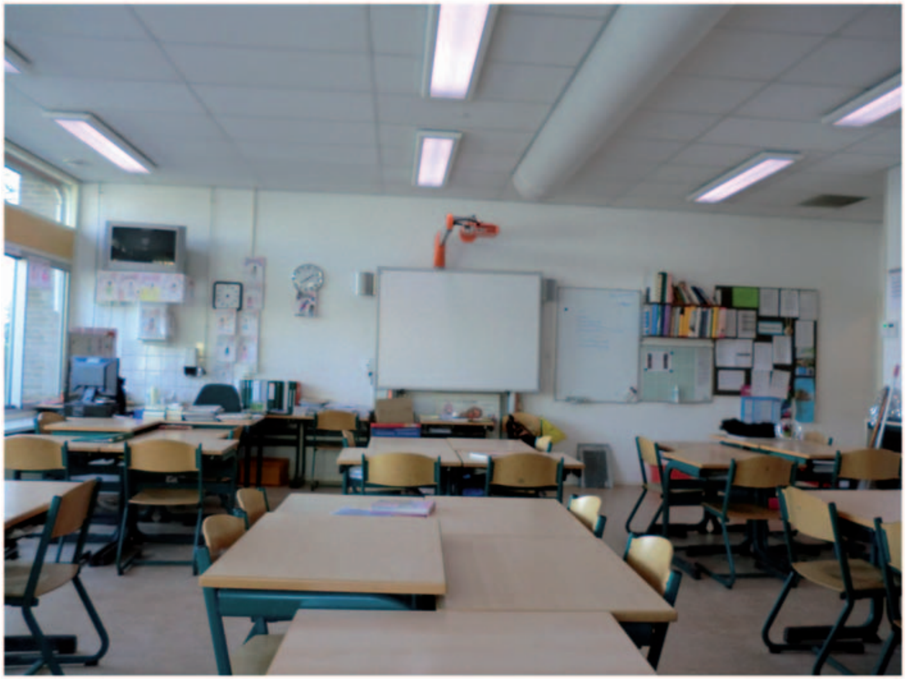

Figure 2 The dynamic lighting system in the focus setting (post-tests)

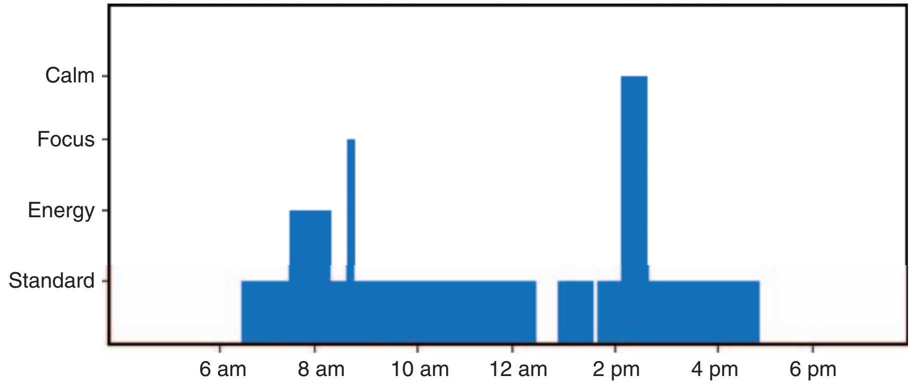

Figure 3 The use of the dynamic lighting system during a test day in Study 1

46 pupils from the experimental school (21 pupils in grade 4 and 25 pupils in grade 6). In all, 39 pupils (40%) were boys, and 59 pupils (60%) were girls. The average age was 10 years. Pupils with learning disabilities (e.g. dyslexia, behavioral disorder) were excluded from the sample.

2.2.2. Study 2

The second study was also designed as a pre-test-post-test nonequivalent control group study. In contrast to the first study, in study 2 two classrooms within the same school in the west of the Netherlands were appointed to the control and experimental condition. A timeline for the administration of the pre- and post-tests is presented in Table 3. As can be seen from Table 3, data from two post-tests were gathered 2 weeks after the installation of the dynamic system scene in February.

During the pretest (baseline), the intervention group was equipped with conventional lighting where the light distribution is created by a Philips SmartForm luminaire fitted with a diffuser (TBS471 3xTL5 54 W 830 Electronic PC MLO). The average illuminance at desk level was about 350 lx with a CCT of 3000 K.

The lighting of the experimental classroom (post-tests) was six luminaires with constant Focus setting of the dynamic lighting in the period 21 January 2011 to 18 February 2011. After the baseline measurements, the average illuminance at desk level was about 750 lx with a CCT of 3000 K.

Table 3 Time points for the assessment of concentration (Study 2)

Time point	Date	Illumination
1	20 January 2011	Pre-test (no dynamic lighting)
2	03 February 2011	First post-test (dynamic lighting)
3	17 February 2011	Second post-test (dynamic lighting)

The control group was equipped with conventional lighting where the light distribution is created by a Sylvania Sylpack luminaire fitted with a louvre (SYLPACK2 2 x F36W/830). The average illuminance at desk level was about 380 lx with a CCT of 3000 K.

The ventilation and the temperature in the experimental and control classrooms were controlled at CO_2 level 1000 ppm and 21°C, respectively. The temperature and ambient acoustics were recorded during the test period. Table 4 shows the average values of these environmental variables in the control and experimental classrooms.

As mentioned above, all post-tests in the experimental classroom were administered using the Focus setting of the dynamic lighting system (Figure 2). The concentration tests were administered on the same days in both the experimental and the control classroom. The exact starting time was agreed upon and managed by both classrooms at 10 a.m. The outdoor conditions during the test days were classified as cloudy and overcast by the Dutch weather station KNMI.

A total of 44 pupils participated in the study (23 boys; 21 girls; average age = 10 years); 22 pupils from the control classroom and 22 pupils from the experimental classroom. Pupils with learning disabilities (e.g. dyslexia, behavioral disorder) were excluded from the sample.

Table 4 Measured environmental conditions in the experimental classroom (Study 2)

Experimental classroom	20 January 2011	3 February 2011	17 February 2011
CO_2 level (ppm)	1208	1072	1024
Temperature (°C)	20.5	20.6	20.3
Noise level dB(A)	Not measured	40	40
Control classroom	**20 January 2011**	**03 February 2011**	**17 February 2011**
CO_2 level (ppm)	1118	1156	1112
Temperature (°C)	20.4	20.9	20.7
Noise level in dB(A)	Not measured	40	40

2.2.3. Study 3

The third study was designed as an experimental post-test-only control group design. For this study, the dynamic lighting system was installed in a windowless lecture room designed for 28 students at the University of Twente in the Netherlands. As the data were gathered during springtime (in May/June 2010), exposure to natural light may affect the effects of artificial lighting more than during the winter season.[35] Therefore, we asked the students to visit the University early in the morning. The pupils were welcomed and instructed by two researchers of the university. A third researcher was responsible for manipulating the setting of the dynamic lighting system so that during the test, both pupils and researchers did not know which lighting setting was used. Several tests were administered to the pupils to assess their concentration, mood and performance. The concentration test was administered half way through the session.

In total, 55 pupils from 6 schools (grades 4, 5 and 6) near the university participated in the study that ran for a total of 6 weeks. The pupils were randomly assigned to one of the two lighting settings (Focus or Standard) and experienced the same, constant lighting conditions (illuminance and CCT) rather than different settings and conditions for different activities as in the field studies. A total of 25 boys (45%) and 30 girls participated in the study. The average age was 10 years. Pupils with learning disabilities (e.g. dyslexia, behavioral disorder) were excluded from the sample.

2.3. Measurement of concentration

To assess the concentration of the pupils, we used the d2-test as developed by Brickenkamp and colleagues.[40] This test has been used in previous research into the effect of lighting on the concentration of pupils.[25,26] The d2-test consists of 14 lines, each containing 47 symbols. A symbol is either a letter p or a letter d with one or two lines (either ' or ") above and/or below the letter (see Figure 4). The assignment is to mark each letter d that has a total of two lines above and below the letter. In order to do the test perfectly, respondents should not mark any other symbol than a d2, and all d2 symbols should be marked. The d2-test is timed, and respondents are given 20 seconds to complete each line. After these 20 seconds, respondents have to continue on the next line. As such, the test assesses concentration in terms of both accuracy and speed.

Several measures can be derived from the d2-test. In this study, we focus on two measures; concentration performance (CP) and the total number of errors made by the pupils (E). CP is assessed as the number of correctly marked d2-symbols minus the number of incorrectly marked symbols (symbols that are not d2-symbols). This measure is the most reliable measurement of concentration as it captures both accuracy and speed in the assessment of concentration and it is not very sensitive to extreme scores due to incidental coincidences (so-called outliers).[41] The total number of errors is assessed as the number of errors made by failing to identify a correct d2-symbol plus the number of errors made by incorrectly marking symbols that are not d2-symbols.[41] This measure was also used in previous studies to assess the impact of lighting on concentration,[25,26] and therefore an examination of this measure will facilitate the comparison of this study with previous work. We also included gender as a variable, because research into the effects of lighting on problem solving has shown that men, compared to women, perform better in bright light.[21,22,42]

2.4. Analysis strategy

To analyze the differences between the experimental and control conditions on the repeated measures variables (Study 1 and 2), we conducted mixed ANOVAs. A repeated

Figure 4 Example of part of the d2-test for measuring concentration

measures design is a sensitive design that reduces sampling error. By comparing pupils' scores on the concentration test at least twice over time and across schools and classrooms, it can be assumed that the variation in individuals' scores will be due to the experimental manipulation of lighting and that any variation that cannot be explained by these manipulations must be due to random factors outside our control.[43]

By doing so, we could check for so-called 'learning effects', meaning children may just perform better on the concentration test because they have learned how to perform well on the test.[44] Specific contrasts were formulated to identify treatment effects (focused effects). Effect sizes (*r*) were calculated for these contrasts using the effects size estimate calculated as the square root of the F-ratio divided by the sum of the F-ratio and the residual degrees of freedom.[43] Following Cohen,[45] we interpret an effect size of 0.10 as a small effect, while effect sizes of 0.30 and 0.50 point to a medium and large effect, respectively.

To validate the findings of the quasi-experimental field studies and offer additional support for the effect of lighting on the concentration of young children, we contrasted two different lighting settings (Focus setting vs. Normal setting) of the dynamic lighting system as used in the experiment (Study 3). The differences between the performances on the concentration test by the

Table 5 Average scores and standard deviations for concentration performance for three measurement times (Study 1)

School/grade	*N*	Pre-test	Post-test (1)	Post-test (2)
		Mean (SD)	Mean (SD)	Mean (SD)
Experimental	38	114.70 (20.88)	141.11 (33.32)	161.18 (38.40)
Grade 4	17	106.24 (15.46)	125.59 (21.28)	143.71 (18.79)
Grade 6	21	121.56 (22.48)	153.67 (36.35)	175.33 (44.44)
Control	51	140.00 (28.44)	154.18 (33.39)	165.35 (45.89)
Grade 4	27	140.86 (31.00)	134.81 (27.21)	140.95 (34.98)
Grade 6	24	139.03 (25.90)	175.97 (35.59)	192.79 (41.34)

pupils in these two experimental groups were tested with a *t*-test.

3. Results

3.1. Study 1

3.1.1. Concentration performance

The results showed a significant main effect of CP ($F_{(1.35, 117.05)} = 79.28$; $p < 0.001$, $\eta_p^2 = 0.477$). On average, pupils in the control school performed better on CP than their peers in the experimental school and, overall, pupils' performance increased at the consecutive time points, indicating a potential learning effect (see Table 5). More importantly, a significant interaction effect was found between school and time for pupils' performance ($F_{(1.35, 117.05)} = 6.88$, $p < 0.01$, $\eta_p^2 = 0.073$). This indicates that although the performance of pupils in both sample schools increases, this increase is more pronounced for pupils of the experimental school. To get a better understanding of this interaction, contrasts were performed comparing the second post-test with both the pre-test and the first post-test across the experimental and control schools. The findings indicated significant interactions when comparing CP scores of pupils across schools on the second post-test with the pre-test ($F_{(1, 87)} = 8.57$, $p < 0.01$, $r = 0.30$) and with the first post-test ($F_{(1, 87)} = 6.29$, $p < 0.05$, $r = 0.26$). As such, the results suggest that in addition to an overall learning effect for pupils in both schools, the Focus light setting had a positive effect on pupils' concentration in the experimental school.

3.1.2. Errors made

These results showed that, in general, pupils performed better on the d2-test over time indicating a learning effect ($F_{(1.35, 117.24)} = 78.83$, $p < 0.001$, $\eta_p^2 = 0.475$). On average, pupils in the experimental condition made more errors than their peers in the control condition at the three different time points (Table 6). Furthermore, there was a significant interaction effect between school and time on errors made ($F_{(1.35, 117.24)} = 6.93$, $p < 0.01$, $\eta_p^2 = 0.074$). Although the number of errors made in the experimental and control school decreases, this decrease is more pronounced for pupils in the experimental school. Contrasts yielded significant interactions when comparing errors of pupils across the schools for the second post-test versus pre-test ($F_{(1, 87)} = 8.63$, $p < 0.01$, $r = 0.30$) and second post-test versus first post-test ($F_{(1, 87)} = 6.57$, $p < 0.05$, $r = 0.26$). These findings also suggest that the Focus light setting had a positive effect on pupils' concentration.

3.1.3. Differences between grades

As grade 6 pupils of both schools achieved higher scores on CP and made fewer errors over the three time points than pupils from grade 4 (Tables 5 and 6), we also performed a mixed analysis of variance for the two grades separately.

Table 6 Average scores and standard deviations of number of errors made for three measurement times (Study 1)

School/grade	*N*	Pre-test	Post-test (1)	Post-test (2)
		Mean (SD)	Mean (SD)	Mean (SD)
Experimental	38	183.90 (20.73)	157.56 (33.32)	137.30 (38.69)
Grade 4	17	192.43 (15.35)	173.08 (21.28)	154.96 (18.79)
Grade 6	21	177.00 (22.25)	145.00 (36.35)	123.00 (44.80)
Control	51	158.62 (28.38)	144.39 (37.42)	133.32 (45.89)
Grade 4	27	157.80 (31.00)	163.77 (27.29)	157.72 (34.98)
Grade 6	24	159.54 (25.76)	122.60 (35.57)	105.87 (41.34)

For pupils in grade 4, we found a significant main effect of time on CP ($F_{(1.48, 62.21)} = 22.20$, $p < 0.001$, $\eta_p^2 = 0.346$). In addition, a significant interaction effect was found between school and time for pupils' CP ($F_{(1.48, 62.21)} = 22.31$, $p < 0.001$, $\eta_p^2 = 0.347$), indicating that the increase in CP of pupils in grade 4 of the experimental schools is more pronounced over time than the increase of CP of their peers in the control school. Contrasts revealed significant interactions when comparing the second post-test versus the pre-test ($F_{(1, 42)} = 27.25$, $p < 0.001$, $r = 0.63$) and the second post-test versus the first post-test ($F_{(1, 42)} = 7.62$, $p < 0.01$; $r = 0.39$).

The results also showed a significant main effect of time on CP in grade 6 ($F_{(1.58, 67.82)} = 110.92$, $p < 0.001$, $\eta_p^2 = 0.721$). In contrast to the findings for grade 4, no significant interaction effect between school and CP was found ($F_{(1.58, 67.82)} = 0.29$, n.s.). As such, lighting appears to positively affect the concentration of pupils in grade 4 but not in grade 6.

As for the number of errors made, there was a significant main effect of time on the total number of errors made by all pupils in grade 4 ($F_{(1.48, 62.44)} = 22.06$, $p < 0.001$, $\eta_p^2 = 0.344$). Furthermore, there was a significant interaction effect between school and time for the total number of errors made ($F_{(1.48, 62.44)} = 22.17$, $p < 0.001$, $\eta_p^2 = 0.345$) indicating that the decrease in pupils' errors was different for both schools over the three time points. Contrasts revealed significant interactions when comparing the second post-test to the pre-test ($F_{(1, 42)} = 27.18$, $p < 0.001$, $r = 0.63$) and to first post-test ($F_{(1, 42)} = 7.66$, $p < 0.001$; $r = 0.39$). These results indicate that although the total number of errors made by the pupils from grade 4 in both schools decreases, this decrease is more pronounced for the pupils in the experimental school.

The errors made by the pupils in grade 6 showed a significant main effect of time ($F_{(1.58, 67.71)} = 109.17$, $p < 0.001$, $\eta_p^2 = 0.717$). We did not find significant interaction effects of school and time on number of errors made ($F_{(1.58, 67.71)} = 0.32$, n.s.). As such, these findings reflect the CP results meaning that lighting appears to positively affect the concentration of pupils in grade 4 but not in grade 6.

3.1.4. Gender

As statistically significant effects were found for the influence of lighting on children's concentration, we performed additional analyses to examine whether this effect may be stronger for boys than girls, as suggested by the literature.[21,22,42] Results indicated a main effect of gender on concentration, indicating that on average, girls perform better on CP than boys ($F_{(1, 85)} = 7.92$, $p < 0.01$, $\eta_p^2 = 0.085$) and

Table 7 Average scores and standard deviations of concentration performance for three measurement times (Study 2)

Classroom	*N*	Pre-test	Post-test (1)	Post-test (2)
		Mean (SD)	Mean (SD)	Mean (SD)
Experimental	18	158.56 (21.99)	192.00 (26.31)	206.89 (29.97)
Control	19	158.79 (26.56)	166.26 (27.82)	178.32 (30.81)

make fewer errors ($F_{(1,85)} = 8.02$, $p < 0.01$, $\eta_p{}^2 = 0.086$).We did not find statistically significant interaction effects involving gender on both CP ($F_{(1.35, 114.49)} = 1.54$, n.s.) and number of errors ($F_{(1.35, 114.72)} = 1.55$, n.s.). When we examined whether the increase in concentration for boys and girls differed between both sample schools, we found that this three-way interaction effect was not significant for both CP ($F_{(1.35, 114.49)} = 1.00$, n.s.) and number of errors ($F_{(1.35, 114.72)} = 1.00$, n.s.). Moreover, three-way interaction analyses for both grades separately indicated that gender did not play a role in the effect of light on CP for grade 4 ($F_{(1.46, 58.33)} = 0.11$, n.s.) nor grade 6 ($F_{(1.67, 68.30)} = 0.14$, n.s.). As such, these results suggest that there are no significant differences between boys and girls regarding the effect of lighting on CP.

3.2. Study 2

3.2.1. Concentration performance

The results showed a significant main effect of time on CP ($F_{(2, 70)} = 89.16$; $p < 0.001$, $\eta_p{}^2 = 0.718$). The finding showed that on average, pupils in the experimental classroom performed better on CP than their peers in the control classroom, and that overall, pupils' performance increased at the consecutive time points, indicating a potential learning effect (see Table 7). More importantly, a significant interaction effect was found between classroom and time on pupils' CP ($F_{(2,70)} = 19.25$, $p < 0.001$, $\eta_p{}^2 = 0.355$). This indicates that although the performance of pupils in both sample classrooms increases, this increase is more pronounced for pupils of the experimental condition. Contrast revealed significant interactions when comparing CP of pupils across classrooms on the second post-test with the pre-test ($F_{(1,35)} = 24.07$, $p < 0.001$, $r = 0.64$), but not on the first post-test ($F_{(1,35)} = 0.41$, n.s.). These findings suggest that above an overall learning effect for pupils in both classrooms, the Focus light setting had a positive effect on pupils' concentration in the experimental classroom.

3.2.2. Errors made

We found a significant main effect of time on the total number of errors made by all pupils in both the experimental and control condition ($F_{(2,70)} = 89.24$, $p < 0.001$, $\eta_p{}^2 = 0.718$). On average, pupils in the experimental condition made fewer errors than their peers in the control condition at the three different time points (Table 8). Furthermore, there was a significant interaction effect between classroom and time and errors made ($F_{(2,70)} = 19.22$, $p < 0.001$, $\eta_p{}^2 = 0.354$). Although the number of errors made in the experimental and control classrooms decreases, this decrease is more pronounced for pupils in the experimental classroom. Contrasts yielded significant interactions when comparing errors of pupils across the classrooms for the second post-test versus pre-test ($F_{(1,35)} = 24.03$, $p < 0.001$, $r = 0.64$) but not on the first post-test ($F_{(1,35)} = 0.41$, n.s.). These findings suggest that the Focus light setting had a positive effect on pupils' concentration.

Table 8 Average scores and standard deviations of number of errors made for three measurement times (Study 2)

Classroom	*N*	Pre-test	Post-test (1)	Post-test (2)
		Mean (SD)	Mean (SD)	Mean (SD)
Experimental	18	140.39 (21.87)	107.00 (26.31)	92.11 (29.97)
Control	19	140.21 (26.56)	132.74 (27.82)	120.68 (30.81)

As the first study showed, we found differences in the effect of lighting across grades. Therefore, we also performed additional analyses to examine whether the effects of lighting maybe stronger for younger than for older pupils. There were main effects of age, indicating that, on average, older pupils showed better CP than younger pupils at all three measurements points ($F_{(3, 29)} = 3.87$; $p < 0.05$, $\eta_p^2 = 0.286$) and made fewer errors ($F_{(3, 29)} = 3.87$; $p < 0.05$, $\eta_p^2 = 0.286$). No significant interaction effects of age on both CP ($F_{(6, 58)} = 1.45$, n.s.) and number of errors were found ($F_{(6, 58)} = 1.45$, n.s.). Three-way interaction analysis indicated that age does not play a role in the effect of lighting on CP ($F_{(6, 58)} = 0.78$; n.s.) and number of errors made ($F_{(6, 58)} = 0.77$; n.s.).

3.2.3. Gender

As in the first study, we also found a statistically significant main effect of gender on CP ($F_{(1, 33)} = 15.02$; $p < 0.001$, $\eta_p^2 = 0.313$) and number of errors made ($F_{(1, 33)} = 15.00$; $p < 0.001$, $\eta_p^2 = 0.313$). This indicates that, on average, girls do perform better than boys on the concentration test. There were no significant interaction effects of gender on both CP ($F_{(2, 66)} = 2.54$, n.s.) and number of errors ($F_{(2, 66)} = 2.58$, n.s.). Moreover, no significant three-way interaction effects were found for both CP ($F_{(2, 66)} = 0.07$, n.s.) and number of errors ($F_{(2, 66)} = 0.08$, n.s.), indicating that gender does not play a role in the effect of lighting on concentration.

3.3. Study 3

3.3.1. Concentration performance

The results showed that pupils in the Focus lighting setting performed better on the CP ($M = 159.57$; $SD = 27.78$) than pupils in the Normal lighting setting ($M = 157.69$; $SD = 31.21$). A similar pattern was found for the total number of errors made: Pupils in the Focus lighting setting made fewer errors ($M = 139.10$; $SD = 27.78$) than their peers in the Normal lighting setting ($M = 140.97$; $SD = 31.21$). Although pupils in the Focus setting performed better on the concentration test than pupils in the Normal lighting, these differences were not statistically significant for both CP ($T_{(53)} = 0.24$, n.s.) and total number of errors made ($T_{(53)} = -0.24$, n.s.). These findings indicate that the Focus setting does not have a larger impact on the concentration of pupils than the Normal lighting setting. Although we did not find the expected positive effect of Focus lighting, the results do support the direction of the expected effect on the concentration of pupils. As we did not find statistically significant effects of lighting on pupils' concentration in the third study, additional analyses including background variables were considered redundant.

4. Discussion

The following research question guided our investigations: To what extent does a dynamic lighting system affect the concentration of Dutch elementary school children? In order to find answers to this question, we conducted two field studies and an experiment to examine the effect of dynamic lighting on the concentration of pupils in elementary schools. Following previous research, we focused on pupils' CP[25,26] and evaluated the impact of different lighting conditions and settings on pupil's concentration. In addition, we examined the differential effects of classroom lighting conditions on concentration for gender. We evaluated the effects of lighting, conducting analyses of variance, using three samples of data from 181 elementary school children. In this section, we discuss our most important findings.

First, the results of our field studies offer support for the positive influence of classroom lighting conditions on concentration. Although all pupils performed better at the concentration test at the consecutive measurement points, it appeared that the performance of the pupils in the experimental groups improved more than the performance of their peers in the control groups. Furthermore, the findings of the first field study show differences between grades: we find effects of lighting on concentration for pupils from grade 4 but not for pupils from grade 6. These findings suggest that older pupils' concentration might be less affected by the lighting conditions used than younger pupils. One plausible explanation is that older pupils are more trained to concentrate while performing tests than younger pupils. Because pupils in Dutch elementary schools are tested on a regular basis to assess their development in basic skills such as reading and mathematics, pupils become more skilled in testing during their school career. Moreover, pupils in grade 6 are in their final year of elementary education and will participate at the end of the school year in the nation-wide standardized Final Primary Education Test. Based on the performance of this test – together with noncognitive factors such as attitudes, motivation and interests, and the teacher's judgements with regard to the child's home situation – an educational recommendation will be provided for the transition from primary to secondary school at the end of elementary school. Given the importance of this test for the future school career of their pupils and to prepare them for this test as well as possible, grade 6 teachers might be paying more attention to testing the basic skills of the pupils (teaching to the test) than their colleagues from other grades. This may explain the possible differences between grades as found in the field study. Although the findings of the second field study show that, on average, older children perform better on concentration tests than their younger peers, no additional support was found for the role of age in the effect of lighting on concentration. This may be related to the small number of different age groups within both classrooms.

Our results partly concur with findings from two recent studies into the effects of dynamic lighting on concentration conducted in Germany.[25,26] In one of their studies, the researchers found differences in errors made when comparing elementary school pupils in the experimental setting with the control setting. By substantiating these earlier findings, results from our study offer additional support for the effect of dynamic lighting on concentration for young children. More research is needed to test the effects of different lighting conditions and settings on the school performance of different age groups. Future studies should use reliable and repeated measurements of concentration in order to reduce bias, increase the validity of the design used and evaluate the possible long-term effects of lighting on school performance of young children in natural school environments.

Second, the results of the third study showed no statistically significant effect of lighting on concentration and do not substantiate the findings of the two field studies in a controlled environment. One possible explanation for not finding a significant effect in the third study might be related to the differences in the designs used. The randomized experimental design features of the third study promise full control over extraneous sources of variances. If correctly done, the random assignment experiment ensures that any outcome differences between groups are likely to be due to the treatment, not to differences between groups that already existed at the start of the study.[46] Although we have tried to get a more valid estimate of the treatment effect by using a sensitive design (repeated measures) that reduces sampling error, the quasi-experimental design features of the two field studies create less compelling support for counterfactual interferences than the randomized experimental design used in the third study. This suggests that the statistically significant differences found in the field studies might be caused by uncontrolled extraneous influences that might limit or bias observation. In order to validate the findings of the third study, more randomized experiments are needed. Results from multiple randomized experiments on the effect of dynamic lighting on pupils' achievement can yield more accurate estimates than any one individual study.

It might also be that differences between the findings are related to differences in the way the children were exposed to the lighting conditions and settings in the different environments. In the field studies, the pupils in the experimental conditions were subjected to different lighting settings and conditions during one day for a longer period of time (Study 1) or were constantly exposed to the Focus setting for one month (Study 2), while the pupils in the controlled environment were subjected to the same lighting conditions during one morning (Study 3). Although we did not evaluate the dynamic nature of the light system used, our findings seem to suggest that an environment in which different lighting settings and conditions are used to support the specific activities and tasks at hand during a longer period of time may be more effective for pupils' learning than an environment in which pupils are exposed to the same lighting condition for a relatively short period of time. The effect of lighting might be situation-, task- and time (duration)-dependent as previous studies also have indicated.[28–30,34] Future research should, therefore, focus on the interaction between light conditions and settings, specific activities and tasks and duration (in terms of exposure). This may increase our understanding of the variability of the effect of lighting among classroom environments, school activities, tasks and student performance and the potential effects of dynamic lighting in school settings.

The differences between the findings of the field studies and the third study for the relationship between lighting and concentration may also have to do with seasonal effects. As described above, the field studies were conducted between October and February (autumn and winter) while the third study was conducted during a six-week period from May to June (spring). Although in all three studies the tests were administrated in the morning, the pupils who participated in the third study were more exposed to daylight than pupils in the field studies before they visited the lecture room at the university and were tested. The pupils in the two field studies were less exposed to normal daylight before the administration of the post-tests; due to seasonal conditions, it was still relatively dark outside when school started and the test were made. Seasonal effects were also found in a more recent study into the effects of dynamic lighting on student alertness in a lecture room environment.[35] The results of that study showed that in spring no change in alertness could be detected, while in the autumn study the decrease of alertness during lectures was significant. These findings shed light on the effects of exposure to lighting conditions during different seasons and the effect of the dynamic nature of light (both artificial and daylight). As such, attention should be paid to the added value of artificial lighting in combination with exposure to daylight for the improvement of the performance of students in educational settings. We therefore agree with Rautkyla and her colleagues[35] that more systematic research is needed on the relation of daytime and artificial light, concentration and seasonal effects, using objective measures to analyze performance in real-life settings and with prolonged exposure.

Third, the results of our field studies showed no evidence of differential effects of gender in the relationship between lighting and concentration. Although earlier studies did find effects of lighting on performance and mood differ between men and women, our findings do not indicate gender-related effects of lighting on pupils in elementary education. This may be related to the difference between children and adults in effects of lighting, for instance in regard to the development of psychological and affective preferences for the environment in general, and lighting specifically.

The positive effects of lighting conditions on pupils' concentration as found in our study were based on data from samples of 'normal' children. As mentioned above, in all three studies, pupils with learning disabilities were excluded from the sample. We therefore encourage researchers who are interested in examining the role of lighting in learning environments to also evaluate the impact of lighting on the performance of children with learning disabilities (both cognitive and behavioral). For example, studies into the effect of lighting on concentration, reading speed and accuracy of children with dyslexia compared to 'normal' readers could validate our findings and provide valuable insights in the differential effects of dynamic lighting. By doing this, the findings of these studies may help to increase our understanding of person/environment interaction and its impact on the performance and learning of elementary school children.

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Conflict of interest

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