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Factors influencing the state of blinds and lights in primary schools: Behavioural models and opportunities to improve children's visual environment

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ABSTRACT

The state of blinds and lights affects children's visual environment and comfort, however, there is a significant gap in research on the factors leading to the operation of blinds and lights in primary school classrooms. This study identifies and categorises the main drivers of operations on blinds and lights and investigates optimal light levels for children in primary schools. The study collected measurements of environmental variables, observations of operations on blinds and lights using forms and time-lapse cameras and visual sensation questionnaires in 31 naturally ventilated classrooms in the UK for one year. Results suggest that operations on blinds and lights are influenced by a range of contextual, occupant-related and building-related factors. Behavioural models of blind and light operation in primary schools are developed using the data collected. With regards to children's visual comfort, in the current study, at 730 lux, 80% of the children were satisfied with the light level in their classroom. The findings and models presented in this study could be used by designers of schools to achieve more visually comfortable classrooms. For example, the results suggest that vertical blinds rather than roller blinds may be a better design choice for classrooms as their slats can be adjusted to control direct sunlight but also allow ventilation. The research concludes with a range of strategies for managing the visual environment through operations on blinds to both reduce lighting energy consumption, as well as increase the quality of the visual environment thereby improving school children's health and productivity.

Acronyms

T_{op}	Operative Temperature ($^{\circ}C$)
R_s	Solar Radiation (W/m^2)
A_s	Solar Altitude
T_{out}	Outdoor temperature ($^{\circ}C$)
VSV	Visual Sensation Votes
IEQ	Indoor Environmental Quality

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1. Introduction

Children spend long periods in schools and carry out activities that involve concentration and mental effort as part of their learning process [1]. Fry [2] states that it is essential to provide all comfort aspects in classrooms because the learning process happens through various senses (i.e. listening, speaking and visualising). Several other studies have highlighted the role of the visual environment and lighting conditions on students' writing progress [3], concentration [4], learning [5], performance, productivity and health [6–8].

A study by Slegers et al. [4] evaluated the effect of lighting conditions on the concentration of elementary school children, with the results showing the influence of the lighting system on pupils' concentration. The study by Hviid et al. [6] conducted a field lab study on 92 children, aged 10–12, to determine how ventilation and lighting impact children's academic abilities. The results showed that math skills, concentration and processing speed improved the most in a combined scenario with dynamic cool lighting and high ventilation rates [6]. A study by Küller and Lindsten [8] assessed the effects of light on students' body growth, academic performance, sick leave and the production of stress hormones in four classrooms with different levels of natural and artificial fluorescent light, with the results suggesting an impact on all the variables.

Furthermore, using daylight as the main source of lighting in classrooms can provide a pleasant visual environment, impact students' academic performance [9] and reduce energy consumption [10]. Hescong and Wright [9] showed that students had better test scores in daylit rather than artificially lit classrooms.

The classroom visual environment needs to provide visual comfort, a condition in which students can see the classroom board and their own desk without any difficulty (such as direct sunlight or lack of light). Visual comfort is defined as the ability to detect, identify and analyse anything in the line of vision, taking into account the speed, quality and accuracy of perception [11]. Therefore, the visual environment as one of the aspects of Indoor Environmental Quality (IEQ) and visual comfort as one of the aspects of comfort [12–14] needs to be further investigated in classrooms.

Visual environment and comfort are significantly impacted by building occupants' use of blinds and lights, which in turn affect lighting energy consumption. Operations on shades can quickly and easily change visual and thermal environments [15], by changing the level of solar radiation [16]. When curtains are closed, children were more likely to switch on or request artificial lighting [17]. The review of studies carried out in schools shows that studies have investigated students' visual perception or preference [1,17–19] and their operations on blinds [20–22] and lights [20,23,24], Table 1.

The study by Giuli et al. [18] compared illuminance measurements over the desks with the students' visual satisfaction through surveys during mid-season and summertime in Italian primary schools. The results showed that students' visual perception was different for similar illuminance levels and they were the same for significantly different illuminance levels, which suggests the subjective nature of visual comfort [18]. The study by Noda et al. [1] analysed the perception of 9–11 years old children about the lighting quality in three public elementary schools in Brazil. With the median light level of 324, most students perceived the classrooms as being light [1]. The study by Vásquez et al. [17] investigated children's preferences for luminous environments and window views in six preschool classrooms in Brazil. The results suggested that visual contact with the outside view was important to the children, with a higher preference for natural views [17]. Furthermore, the study by Theodorson [19] carried out a post-occupancy field study of daylit classrooms in three elementary schools in Washington, with the results showing that daylight strategies need to be considered within the context of orientation and end-user interactions [19].

The study by Hunt [23] used time-lapse photography to collect the light use data from schools and offices. The study showed that

Table 1
A review of studies on visual environment conducted in primary or elementary schools.

Study	Location	Building Type	Period	Subjects	Studied Metrics with regards to blinds, lights and light level			
					Visual perception/preference	Blinds/shade operation & related factors	Lights' operation and related factors	Blinds or lights' Behavioural Models
[18]	Italy	Primary schools	Midseason and summertime	62 students (10–11 years)	✓			
[1]	Brazil	Elementary schools	Winter season	97 students (9–11 years)	✓			
[17]	Brazil	Pre-school	March–November	84 children	✓			
[19]	Washington	Elementary schools	April	Teachers	✓	✓		
[23]	UK	-	June–July	-			✓	✓ (Lights' operation)
[20]	Netherlands	Primary schools	Spring	1145 students (9–12 years)		✓	✓	
[21]	Taif city in Saudi Arabia	Primary schools	Winter	121 students, 44 teachers		✓		
[24]	United Arab Emirates	Elementary schools	April–February	-			✓	
[22]	Spokane, Washington	Elementary schools	April	-		✓		

Table 2

An overview of the architectural features of the classrooms and their controls (windows, blinds and external shades).

Seasons	Date	No.	Floor	Orientation	Class Area (m ²)	Area of Window (m ²) ¹	Area of Glazing (m ²) ²	No. of Windows	Window Operation	Window Opening	Depth to Height Ratio	Glazing to classroom Ratio	Blind Type	BA ³	External Shade
Non-heating	July/Sep 2017	1.1	First	NE	60	8	8	8	Manually	Top-hung outward openings at two levels	7/3.2 = 2.2	8/60 = 13%	Roller blinds	H	No
		1.2	First	SW	60	8	8	8	Manually				H	No	
		1.3	First	SW	60	8	8	8	Manually				H	No	
		1.4	First	SW	60	8	8	8	Manually				H	No	
		1.5	First	NE	60	8	8	8	Manually	Top-hung outward openings at two levels	7/3.2 = 2.2	8/60 = 13%	Roller blinds	H	No
		2.6	First	NW	60	8	8	8	Manually				H	No	
		2.7	First	SE	60	8	8	8	Manually				H	No	
		2.8	First	SE	60	8	8	8	Manually				H	No	
Heating	Oct/Nov 2017	3.10	Ground	S & W	65	2	14	5	Manually	Top-hung outward	10/3.5 = 2.9	14/65 = 22%	Roller blinds	L	Yes
		3.11	Ground	S & W	70	2.2	9	6	Manually	Top-hung outward openings at two levels	11/3.5 = 3.1	9/70 = 13%	Vertical blinds	L	Yes
		3.12	First	NW	60	2.5	6.5	5	With a handle		6.5/3.2 = 2	6.5/60 = 11%	Vertical blinds	L	No
		4.13	Ground	W	50	0.5	2.3	2	Manually		9/2.6 = 3.5	2.3/50 = 5%	Vertical blinds	L	No
	4.14	Ground	W	60	0.5	2.3	2	Manually	9/2.6 = 3.5		2.3/60 = 4%	Vertical blinds	L	No	
	Jan/Feb 2018	5.15	First	SW, SE	55	5.7	14.1	8	Manually	Top-hung outward openings at two levels	7/2.5 = 2.8	14.1/55 = 26%	Vertical blinds	H	No
		5.16	First	SW	55	5.7	10.1	8	Manually				10.1/55 = 18%	Vertical blinds	H
		5.17	First	SW & NW	55	5.7	14.5	8	Manually	Top-hung outward opening	8.5/2.8 = 3	9.5/60 = 16%	14.5/55 = 26%	H	No
		5.18	Ground	SW	55	5.7	12.5	8	Manually				12.5/55 = 23%	H	Yes
		5.19	Ground	SW & NW	55	5.7	16.1	8	Manually				16.1/55 = 29%	H	Yes
		6.20	First	SE	60	1.8	9.5	4	With a remote control				Roller blinds	L	Yes
		6.21	First	SE	60	1.8	9.5	4	With a remote control				Roller blinds	L	Yes
		6.22	First	SE	60	1.8	9.5	4	With a remote control				Roller blinds	L	Yes
		6.23	First	SE	60	1.8	9.5	4	With a remote control				Roller blinds	L	Yes
6.24		First	SE	60	1.8	9.5	4	With a remote control	Roller blinds				L	Yes	
Non-heating	April/May 2018	7.25	Ground	SE & SW	70	3.9	20.9	6	With a handle	Top-hung outward opening	12/3.6 = 3.3	20.9/70 = 30%	Vertical blinds	L	No
		7.26	Ground	SE & SW	55	3.3	16.6	3	Manually	Top-hung outward opening	6/2.5 = 2.4	16.6/55 = 30%	Vertical blinds	H	No
	7.27	First	NE & NW	55	5.4	16.2	6	Manually	Top-hung outward opening	6/2.5 = 2.4	16.2/55 = 29%	Vertical blinds	L	No	
	8.28	Ground	NE	60	2.2	6.2	4	Manually	Top-hung outward opening	10/2.5 = 4	6.2/60 = 10%	Roller blinds	L	Yes	
	8.29	Ground	NE	60	2.2	6.2	4	Manually	Top-hung outward opening	10/2.5 = 4	6.2/60 = 10%	Roller blinds	L	Yes	
	8.30	Ground	NW	55	2.2	6.2	4	Manually	Top-hung outward opening	9/2.5 = 3.6	6.2/55 = 11%	Roller blinds	L	Yes	
	8.31	Ground	NW	55	2.2	6.2	4	Manually	Top-hung outward opening	9/2.5 = 3.6	6.2/55 = 11%	Roller blinds	L	Yes	

1. The total area of operable windows.

2. The total area of operable and non-operable windows.

3. Accessibility for blinds operations: High (H) and Low (L).

occupants switched lights on and off throughout the day in the classrooms and the probability of switching on was closely related to the time of day and daylight level [23]. The study by Zhang and Bluysen [20] investigated the actions of school teachers in 21 primary schools in the Netherlands. Results showed that teachers' actions did not have a significant impact on children's perception of comfort and teachers could not fulfil the needs of all children. The study by Alwetaishi et al. [21] on primary schools in Saudi Arabia has focused on the ultimate type of shading devices in relation to day-lighting. The results of the study showed that vertical shading systems can block solar radiation and sunlight significantly [21].

The study by Fadeyi et al. [24] examined IEQ in sixteen elementary schools in the United Arab Emirates (UAE) between April to February. Results showed that most classrooms relied on lights even though there was abundant daylight, which was mainly due to the poor integration between interior arrangement and glazing such as cupboards and papers covering windows [24]. The study by Theodorson [22] conducted a field study in three elementary schools over spring in Washington. The results showed that south classrooms were subject to dynamic sunlight patterns with large fluctuations of daylight distribution. The study suggested that shades need to be designed based on orientation as there were significant differences between the visual environment of north and south-facing classrooms according to diagrams, false colour photo renderings, and descriptive statistics [22]. Table 1 provides a summary of the reviewed studies on visual environment carried out in primary and elementary schools.

The review suggests that previous studies have not investigated a comprehensive assessment of the factors affecting the visual environment including operations on blinds and lights integrated, especially in the UK. More importantly, Table 1 indicates that there is a significant gap in behavioural models with regard to blinds and lights operations. Also, studies were not conducted throughout the whole year which can show a significant difference in the visual environment. Furthermore, the optimum light level for children still requires further investigation. International standards such as ASHRAE-55 [25] and Illuminating Engineering Society (IES) [26] do not provide varying standards or values for different age groups and there is a significant gap in research regarding visual comfort standards for children. This study aims to examine the factors related to the visual environment, specifically, operations on blinds and lights, and children's optimal light levels in primary schools. More specifically, the objectives of this study are:

- (i) Identifying and categorizing the main drivers of operations on blinds and factors affecting the state of blinds and lights;
- (ii) Developing behavioural models based on the state of blinds and lights in relation to drivers;
- (iii) Evaluating students' preference against illuminance measurements on the desks.

2. Methodology

2.1. Classrooms

The study was carried out in Coventry, West Midlands, UK, from mid-July 2017 until the end of May 2018 to represent climatic conditions throughout an annual period. In total, 31 naturally ventilated classrooms in eight primary schools were selected and studied on 31 distinct days throughout one year, during non-heating and heating seasons. Table 2 shows an overview of the schools, date of observation, the classrooms orientation and architectural features of windows and blinds. Classrooms are numbered by the school number (1–8) followed by the classroom number (1–31), Table 2, column 3. In addition to light controls, light levels could be controlled in all the classrooms by the use of blinds; 19 classrooms had roller blinds and 12 classrooms had vertical blinds. Furthermore, 13 classrooms also had external shades. Classrooms with blinds that were accessible at lower heights for children, easy to operate and throughout the length of the classroom (alongside students' seats) are classified in Table 2 as classrooms that provide high accessibility for blinds operations. Classrooms with blinds that were at higher heights for children or difficult to operate (with handle), or were located at the end of the classroom (behind the teacher's desk), are classified as classrooms that provided low accessibility for blinds operation.

Fig. 1 shows typical classrooms in each of the eight schools studied (from school 1 represented in Fig. 1.a to school 8 displayed in Fig. 1.h), illustrating different window and blind designs.

2.2. Data acquisition

2.2.1. Visual observations

An observation form was used to collect information passively on occupancy, students' location in the classroom, state of blinds (percentage open or closed), state of lights (on and off), the number of blind operations, the reasons for blinds operations and the person responsible for the blinds operations at 10-min intervals, Table 3.

State of blinds (%) shows the percentage of blinds that is open or closed and closed blinds (%) shows the proportion of closed blinds area (m^2) to the classroom's total blinds area (m^2). For example, when the total blind area in a classroom was $8 m^2$ with $6 m^2$ of them being closed, closed blind (%) is 75%. When vertical blinds covering windows were adjusted at a certain angle to let daylight in, they were considered open blinds. The reasons for blind operations were divided into blind opening (arrival, window opening, daylight and view) and blind closing (departure, direct sunlight on screen and desk). The reasons for blinds operations and the person responsible for operations were clear to observe, therefore, the flow of the classroom and the occupants' operations were not disrupted. Each classroom was divided into three areas to see how light levels and visual sensation are different in different locations in relation to the distance to windows: the area near to windows (0–2 m), the area in the middle of the classroom (2–4 m) and the area away from windows (>4 m).

Visual observations were conducted to investigate how students behave when there is visual discomfort and to identify explanatory predictors influencing operations on blinds to build more valid behavioural models. However, visual observations alone fail to describe the level of environmental variables, therefore, it was also necessary to measure indoor environmental variables in the classrooms and



Fig. 1. Type of internal blinds in classrooms in 8 primary schools.

obtain outdoor environmental variables.

To reduce the bias of observations as suggested by Briggs et al. [27], first, the observation was accompanied by subjective and objective measurements and time-lapse cameras. Second, the observation procedure underwent piloting to check its validity. Third, the observer remained silent in the back of the classroom without interrupting classroom activities or the operation of controls. Furthermore, to make children feel at ease, the procedure of observation was not explained, however, it was explained that time-lapse cameras were recording the state of controls and not children.

2.2.2. Environmental measurements

Environmental variables were recorded at 5-min intervals by multi-functional SWEMA equipment, temperature and humidity data loggers with USB, TGE-0011 CO₂ meter and CEM DT-1300 light meters. SWEMA equipment, designed to comply with ISO Standard 7726 (2001) and ISO Standard 7730 (2005) standards, collects data from three sensors: air velocity and temperature, air humidity and temperature and radiant temperature. The CEM DT-1300 light meter can measure within an accuracy of $\pm 5\% \pm 10d$ for $<10000\text{Lux}$ and $\pm 10\% \pm 10d$ for $>10000\text{Lux}$, with $\pm 10d$ meaning \pm ten times the value of the least significant digit. Furthermore, indoor temperature was also recorded by data loggers that could measure a range between -35 and $+80$ °C, with a resolution of 0.1 °C and accuracy of ± 0.3 °C. Details of the equipment including their range, resolution and accuracy are provided in Table 4.

To evaluate students' visual sensation of variations in actual light levels, the illuminance values on students' desks for spot surveys

Table 3

Observation form for occupancy patterns and operations on blinds and lights in the classroom.

Observation form for occupancy and adaptive behaviours			
Occupancy and position			
Occupancy pattern in the classroom? <input type="checkbox"/> Occupied, <input type="checkbox"/> Not occupied, <input type="checkbox"/> Left for break, <input type="checkbox"/> Left for PE, <input type="checkbox"/> Left for lunch, <input type="checkbox"/> Left for assembly, <input type="checkbox"/> Left for home			
Each student's desk location in the classroom? <input type="checkbox"/> The area near to windows (0–2 m), <input type="checkbox"/> The area in the middle of the classroom (2–4 m) <input type="checkbox"/> The area away from windows (>4 m)			
Environmental Adaptive Behaviours			
State of controls	Operations		Who did adjustment
Blinds	Percentage of closed blinds?	Total No. of Blind Operations? <input type="checkbox"/> Arrival, <input type="checkbox"/> Departure, <input type="checkbox"/> Window opening (temperature), <input type="checkbox"/> Daylight, <input type="checkbox"/> View, <input type="checkbox"/> Direct sunlight on screen, <input type="checkbox"/> Direct sunlight on desk	<input type="checkbox"/> Teacher <input type="checkbox"/> Teacher assistant <input type="checkbox"/> Caretaker
Lights	On or off?	-	<input type="checkbox"/> Student on his/her will <input type="checkbox"/> Student on teacher's request <input type="checkbox"/> Teacher on student's request

were recorded during the monitoring period. Calibrated light meters measured the illuminance level on students' working desks while students were filling out the questionnaire to capture the differences in the light levels on different desks. Time-lapse cameras were installed inside the classrooms to record the state of windows, blinds and doors at 10-min intervals. Outdoor temperature was taken from local weather stations that were maximum 3 miles away from each study site [28].

To assess the state of blinds and lights against solar altitude and radiation, solar altitudes were taken from Sustainable By Design [29] and solar radiations were taken from the National Renewable Energy Laboratory, which were calculated based on solar parameters data and a given specific location [30]. The solar altitude (or solar elevation or solar height) is the sun's angular height above the observer's celestial horizon [31]. The solar radiation received from the sun is the sum of the direct and diffuse radiations on a horizontal surface at the level of the ground [32].

2.2.3. Students' light sensation

For this study, children in their late middle childhood (9–11 years old) were selected because they have a better understanding of their environment compared to their peers in early middle childhood (6–9 years old). Students' sensation of light level was assessed with the statement 'The light in my classroom is ... a) Much (1) b) Enough (2) c) OK (average) (3) d) Not enough (4) e) Little (5)'. Students' visual preference vote was assessed with 'Right now I would like the light in my classroom to be ... a) more b) as it is c) less'. An earlier study by the author [33] checked the validity and reliability of the questions. The study cross-checked sensation and preference questions and found 97 inconsistent votes, which were removed from the analysis. Inconsistent votes were for children who found the light in the classroom 'little' and preferred the light to be 'less' (84 votes), and children who found the light in the classroom 'much' and preferred the light to be 'more' (13 votes). Questionnaires were filled out at the end of morning sessions (approximately 12:20 p.m.) and afternoon sessions (approximately 3:30 p.m.) to not disturb teaching activities.

2.3. Statistical analyses

The statistical analyses undertaken in this study can be categorized into three main groups.

Correlational analysis was applied to show the strength and direction of the relationship [34] between the state of blinds (m^2) and predictors.

Predictive analysis was used to describe how the state of blinds and lights change by changes in environmental variables such as solar radiation and solar altitude and building-related factors such as the area of glazing in each classroom. The set of classical statistical models used in the field of occupant behaviour modelling includes general and generalized linear models, mixed effects models, linear time 50 series models, (hidden) Markov chains, and Bayesian networks [35]. In this study, linear regression models were used to

Table 4

Equipment specifications.

Probe/Brand	Variables	Meas. Range	Resolution	Accuracy
SWEMA 3000 Universal Instrument	Humidity and air temperature	0 to 100 %RH, –40 to +60 °C	0.1% RH 0.1 °C	±0.8 %RH at 23 °C ±0.3 °C at 23 °C
	Air velocity and Air temperature	0.05–3.0 m/s at 15–30 °C, +10 to +40 °C	1.1 m/s 0.1 °C	±0.04 m/s at 0.05–1.00 m/s, ±4% read value at 1.0–3.0 m/s
	Radiant temperature (Ø globe: approx. 150 mm)	0 to +50 °C	0.1 °C	±0.1 °C
Data Logger (EL-USB-2-LCD+)	Temperature	–35 to +80 °C	0.1 °C	±0.3 °C
CO2 meter (TGE-0011)	Humidity	0 to 100 %RH	0.5% RH	±0.2 %RH
	CO ₂	0–5000ppm	1 ppm	50 ppm
Light Meter (CEM DT-1300)	Light level	0 to 50000 Lux/Fc	0.1 Lux/Fc	±5%±10d (<10000Lux) ±10%±10d (>10000Lux)

describe the state of blinds mainly because both dependent variable (closed blinds (0–100%)) and independent variables (environmental variables) are continuous variables. Linear regression can produce a line of best fit by minimising the Residual Sum of Squares (RSS) which is the difference between an observed y and that predicted by the model [1]. Furthermore, linear models can explain the observed data well in a simple way which according to Annex 66 can help the selection process of a good model [35]. The R^2 value in linear regression models indicates how well the behavioural model implied by the regression equation fits the data [34]. Due to the binary state of lights (on and off), binary logistic regression was used to assess the probability of switching lights on. Logistic regression investigates the relationships between a categorical outcome variable and one continuous predictor variable and it leads to a model for predicting the probability of the event happening [36].

Group differences analysis (cause and effect) was used to determine whether two or several groups of categorical data were the same or not. Kruskal-Wallis for a not-normally distributed interval-scale variable is used to compare the medians of two or more samples to determine if the samples have come from different population scores or not [34,37]. In this study, data on the state of closed blinds (%) was not normally distributed, therefore, Kruskal-Wallis was used to compare their medians between different seasons. Furthermore, One Way Analysis of Variance (ANOVA) for approximately normally distributed interval-scale variable is used to compare the means of more than two independent groups [37,38].

The data were analysed using the Statistical Package for Social Sciences (SPSS) 25 software [39].

2.4. Overview of the recorded data

Table 5 shows descriptive statistics of the indoor and outdoor environmental variables during the studied period. Mean operative temperature (T_{op}), outdoor temperature (T_{out}), solar radiation (R_s) and solar altitude (A_s) were 23.8 °C, 17.5 °C and 297 W/m² and 42° during the non-heating season and 21.8 °C, 7.1 °C and 109 W/m² and 17.5° during the heating season. The operative temperature was calculated using the below equation:

$$\text{Operative temperature} = \frac{(t_r + (t_a \times \sqrt{10v}))}{(1 + \sqrt{10v})} \quad (1)$$

Where

t_a = air temperature

t_r = mean radiant temperature

v = air speed (m/s)

In total, around 1090 data points (at 10-min intervals) of environmental variables, as well as the state of blinds and lights were analysed.

3. Results

3.1. Operations on blinds and state of blinds

3.1.1. Drivers for blinds operations

Visual observations showed that blinds were closed when leaving the classroom (on departure), or due to direct sunlight on screens or desks. Blinds were opened to not obstruct fresh air when trying to open the windows to cool the classroom. Blinds were also opened for daylight, upon arrival into the classroom in the morning and to obtain an outside view (for example, when it was snowing).

3.1.2. Control Logic Diagram for blinds operations

Fig. 2 shows a Control Logic Diagram for school occupants' operations on blinds based on the visual observations. On some occasions, windows and blinds were opened by caretakers before teachers and students' arrival. When blinds were not opened by caretakers, they were sometimes opened by teachers or teacher assistants upon their arrival if the classroom was perceived dark. Blinds can also be opened during teaching sessions, mostly to get more daylight, or when windows are opened or to have an outside view. Once the blinds were open, they would be kept open unless disturbing factors such as direct sunlight on a desk or screen resulted in blinds closing. Although not all blind operations followed this control logic, it can closely represent the scenario in most of the studied classrooms.

Table 5
Descriptive statistics of indoor and outdoor environmental variables.

Seasons	Descriptive Statistics	Indoor variables		Outdoor variables	
		T_{op} (°C)	T_{out} (°C)	R_s (W/m ²)	A_s (°)
Non-heating season	Minimum	17.9	9.6	85	9.7
	Maximum	28.1	25.1	434	58.7
	Mean	23.8	17.5	297	42
	Std. Deviation	1.8	3.6	92	11
Heating season	Minimum	16.2	0.7	11	5.2
	Maximum	27.4	14.6	194	25.3
	Mean	21.8	7.1	109	17.5
	Std. Deviation	1.8	3.1	41	4

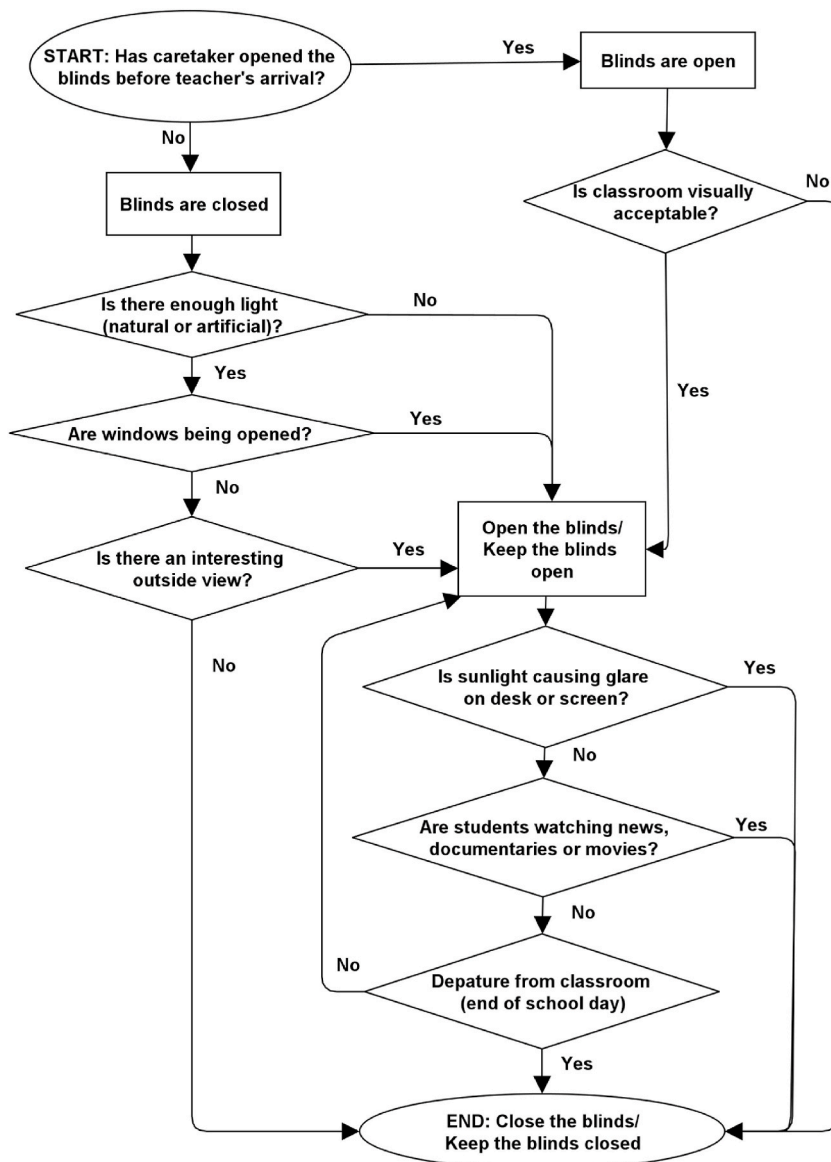


Fig. 2. A Control Logic Diagram for school occupants' blinds operations based on visual observations.

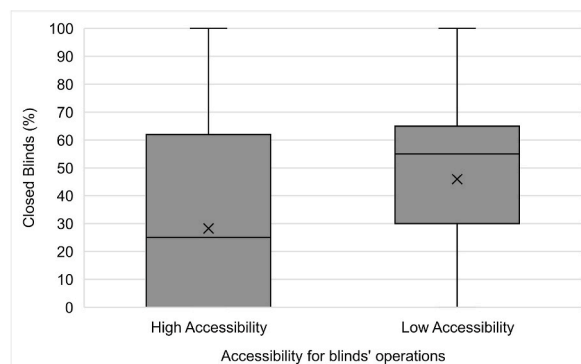


Fig. 3. The distribution of closed blinds (%) in classrooms with high and low accessibility for blinds operations.

3.1.3. State of blinds in different categories

Fig. 3 shows the distribution of closed blinds (%) in two categories: classrooms with high and low accessibility for blinds operations. Kruskal-Wallis H test shows that there is a statistically significant difference in the median of closed blinds (%) between different categories ($\chi^2(1) = 65.75, p = 0.000$). The median closed blinds (%) was higher in classrooms with low accessibility for blinds operations (55%) than in classrooms with high accessibility for blinds operations (25%).

Fig. 4 shows the distribution of closed blinds in categories with internal blinds and external shades. Results of Kruskal-Wallis H test show that there is a statistically significant difference in median closed blinds between different categories ($\chi^2(1) = 12.04, p = 0.000$). The median closed blinds (%) was higher in classrooms with no external shades (32%) than in classrooms with external shades (24%).

The distribution of closed blinds in different categories of orientation was also compared. Results of Kruskal-Wallis H test show that there is a statistically significant difference in median closed blinds between different categories ($\chi^2(4) = 79.48, p = 0.000$). The median closed blinds (%) was higher in south-west orientation (65%), followed by north-west (62%) and south-east (50%).

3.1.4. Linear regression models for the state of blinds

Visual observations showed that blinds were operated due to direct sunlight, which can be related to solar radiation and solar altitude, and windows operations, which can be related to operative and outdoor temperature. Therefore, environmental variables including solar radiation (R_s), solar altitude (A_s), operative temperature (T_{op}) and outdoor temperature (T_{out}) were tested against percentage of closed blinds. Table 6 shows the results of the Spearman correlation between closed blinds (%) and environmental variables. Results of the Spearman correlation in Table 6 show that solar altitude (Spearman correlation = $-0.387, P < 0.001$) and operative temperature (Spearman correlation coefficients = $-0.353, P < 0.001$) during the non-heating season and solar altitude (Spearman correlation = $0.327, P < 0.001$) and solar radiation (Spearman correlation = $0.214, P < 0.001$) during the heating season have the strongest relationship with closed blinds (%).

The slope in linear regression models shows the sensitivity of closed blinds (%) in response to environmental variables, and R^2 in models shows the percentage (%) of changes in closed blinds (%) that could be explained by environmental variables.

Fig. 6 shows the behavioural models of the relationship between closed blinds (%) and solar radiation (W/m^2) and Fig. 7 shows the behavioural models of the relationship between closed blinds (%) and solar altitude ($^\circ$) during non-heating and heating seasons. According to Figs. 5 and 6, 14% and 22% of changes in closed blinds can be explained by solar radiation ($R^2 = 0.14$) and solar altitude ($R^2 = 0.22$) during the non-heating season, while 5% and 8% of changes could be explained by solar radiation ($R^2 = 0.05$) and solar altitude ($R^2 = 0.08$) during the heating season.

Figs. 6 and 7 show that increases in solar radiation and solar altitude during the non-heating season, result in occupants opening a higher percentage of blinds. Conversely, an increase in solar radiation and solar altitude during the heating season, increases the percentage of closed blinds. For the same solar radiation of $150 W/m^2$, the proportion of closed blinds (%) is 65% during the non-heating season but 23% during the heating season. At the same solar altitude of 20° , the percentage of closed blinds is 73% during the non-heating season whereas it is only 20% during the heating season.

It should be noted that solar radiation and solar altitude have a significantly strong correlation (Spearman correlation coefficients = $0.885, P < 0.001$), which can explain the similar relationship between closed blinds (%) with these two variables. Solar radiation and altitude are both higher during the non-heating season than the heating season.

The percentage of closed blinds is not correlated with operative temperature and outdoor temperature during the heating season, however, the behavioural models show their relationship during the non-heating season. Fig. 8 shows that 13% and 12% of changes in closed blinds can be explained by operative temperature ($R^2 = 0.13$) and outdoor temperature ($R^2 = 0.12$) during the non-heating season. According to Fig. 8, an increase in operative and outdoor temperature, results in the percentage of closed blinds decreasing during the non-heating season. This can be related to more window openings to reduce the operative temperature, which consequently results in more blinds opening, as explained below. The results of the Spearman correlation shows that closed blinds and the percentage of open windows are significantly and negatively correlated during the non-heating season (Spearman correlation coefficients = $-0.20, P < 0.001$). This suggests that opening windows during the non-heating season results in more blinds opening, so that blinds do not obstruct the flow of fresh air. Around 81% of blinds studied during the non-heating season are roller blinds, therefore, the impact of blinds design (roller and vertical blinds) on window operations and state of blinds is investigated below.

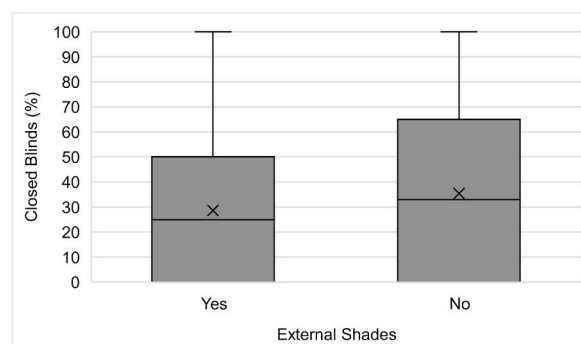


Fig. 4. The distribution of closed blinds in categories with internal blinds and external shades

Table 6
Descriptive statistics of indoor and outdoor environmental variables.

Seasons	Correlation/Regression of Closed Blinds (%) with ...	R_s	A_s	T_{op}	T_{out}
Non-heating	Correlation Coefficient	-.284**	-.387**	-.353**	-.201**
	Regression	0.14	0.22	0.14	0.12
Heating	Correlation Coefficient	.214**	.327**	-0.086	0.034
	Regression	0.05	0.08	-	-

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

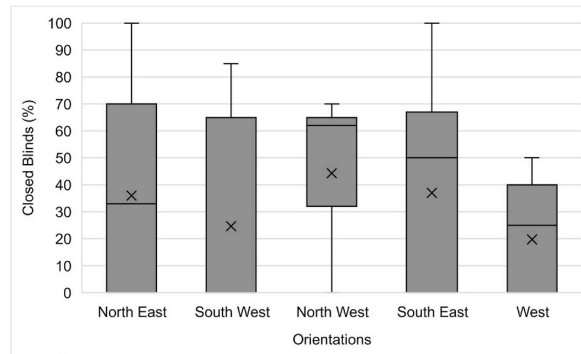


Fig. 5. The distribution of closed blinds in different categories of orientation.

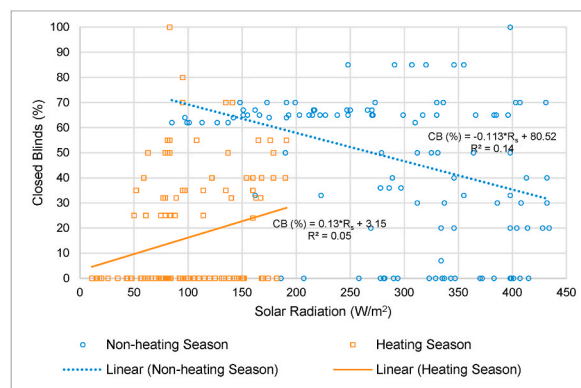


Fig. 6. Linear models showing the relationship between closed blinds and solar radiation (W/m^2) during non-heating and heating seasons.

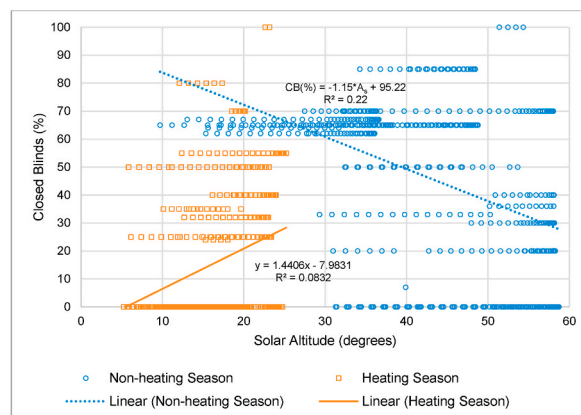


Fig. 7. Linear models showing the relationship between closed blinds (%) and solar altitude during non-heating and heating seasons.

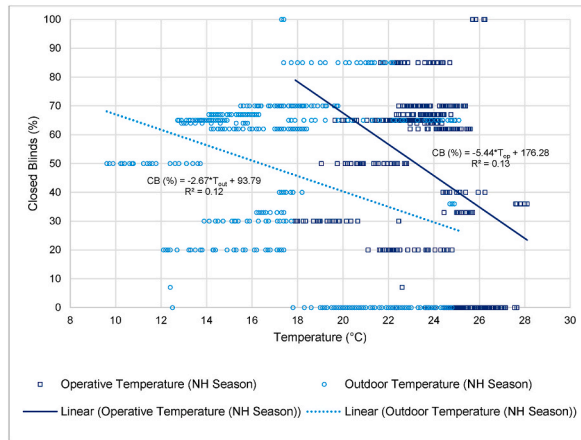


Fig. 8. Linear models showing the relationship between closed blinds (%) and operative and outdoor temperature during the non-heating season.

The impact of blinds design (roller and vertical blinds) on window operations and state of blinds is investigated. Fig. 9 shows the behavioural model on the relationship between closed blinds (%) and open windows (%) for roller and vertical blinds. Fig. 9 suggests that in classrooms with roller blinds, when open windows (%) increased, a higher percentage of blinds were opened to let fresh air in ($R^2 = 21$), however, in classrooms with vertical blinds, when open windows (%) increased, a higher percentage of blinds were closed ($R^2 = 0.09$).

Similar to the impact of window opening on blinds opening, it was observed that blinds of non-operable windows were usually not operated unless they were very close to or in the middle of operable windows.

3.2. State of lights

By visual observations and time-lapse cameras, it was possible to record the state of lights and classroom occupancy. Fig. 10 shows the state of lights during different classroom occupancy patterns. Results suggest that when classrooms were not occupied, lights were on for 70% of the time.

Considering the binary state of lights (on and off), binary logistic regression in Table 7 was used to show the probability of lights on in relation to solar radiation and closed blinds (%). The state of lights has a significant negative relationship with solar radiation and solar altitude and has a significant positive relationship with closed blinds (%).

Fig. 11 shows that the probability of being lights on decreases from 90% to 50% as solar radiation increases from 0 up to 500 W/m², suggesting that when there was more solar radiation, occupants were more likely to turn off the lights.

Fig. 12 shows that the probability of lights being on increases from 40% to 90% as closed blinds increases from 0 to 100%,

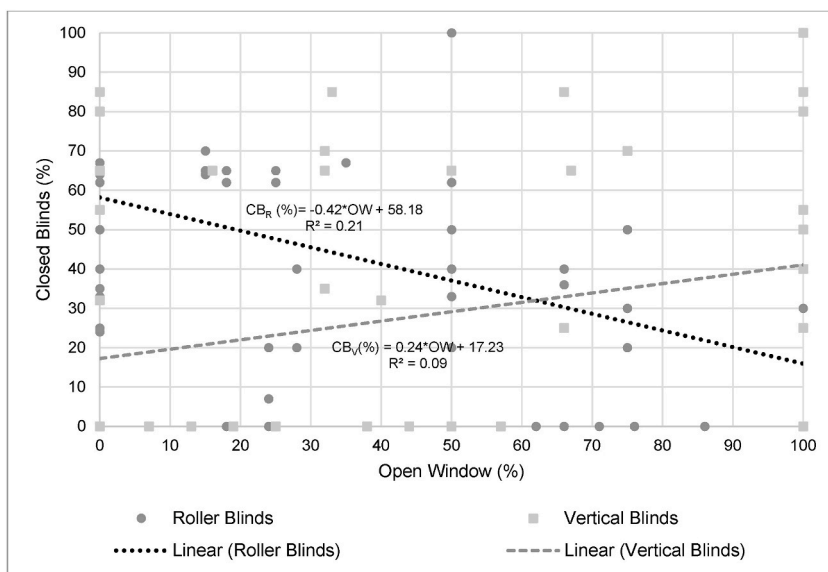


Fig. 9. Linear models showing the relationship between closed blinds (%) and the percentage of open windows (%) for roller and vertical blinds.

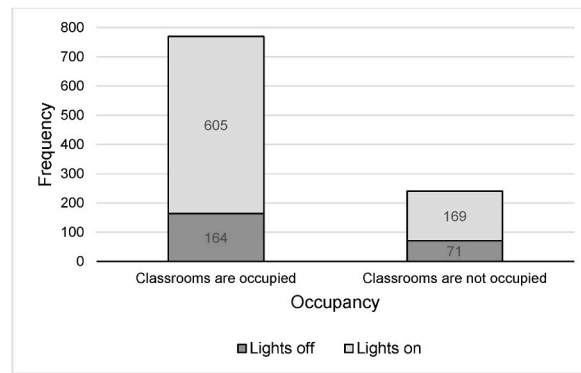


Fig. 10. The state of lights during different classroom occupancy patterns.

Table 7

Binary logistic regression showing the relationship between the probability of lights on and independents.

Binary Logistic Regression (Probability of lights on by ...)				
Independents	Solar Radiation		Closed Blinds (%)	
B/Sig.	B	Sig.	B	Sig.
Slope	-0.004	0.000	0.023	0.000
Constant	2.059	0.000	-0.520	0.002

suggesting that when occupants closed more blinds, they were more likely to turn on the lights. This can also be interpreted as when lights were already on, occupants did not feel the need to open the blinds.

As closed blinds account for 40–90% of the probability of lights being on, the frequency of the state of lights in each category of blinds can help to understand how lights operation can be improved in relation to blinds operations. Fig. 13 shows that when blinds are 100% open, the lights are on 72% of the time. When more than 60% of the blinds are open, the lights are on 76% of the time. Furthermore, when blinds are 60–100% closed, the lights are on 72% of the time. Generally, when blinds are partially closed or the majority of them are closed, the lights are on for 79% of the time.

3.3. The sensation of light level

To study the relationship between students' preference of the visual environment and light level (lx), the proportion of students with 'much' (i.e. Visual Sensation Votes (VSV) = 1) and 'little' (i.e. VSV = 4 or 5) votes was calculated for each survey and categorized as 'unsatisfied'. Similarly, the proportion of students with 'enough' (i.e. VSV = 2 or 3) votes was calculated and labelled as 'satisfied', Fig. 14. The light level corresponding to an 80% satisfaction level is approximately 730 lx which can be considered the optimal value.

Fig. 15 shows the distribution of measured light levels on students' desks in different locations within the classroom in relation to the distance to the windows. Mean light levels varied from 750 lx near the windows (0–2 m), 500 lx for the middle of the classroom (2–4 m) and 350 lx for the area away from windows (>4 m).

Fig. 16 shows the distribution of Visual Sensation Votes (VSVs) (much (1) to little (5)) in different locations of the students' desks within the classroom. Results of the ANOVA test showed that $[F(2, 1354) = 43.176, p = 0.000]$ mean values were significantly different at different locations. Mean VSVs) varied from 2.7 near the windows, 3 for the middle of the classroom and 3.2 for the area

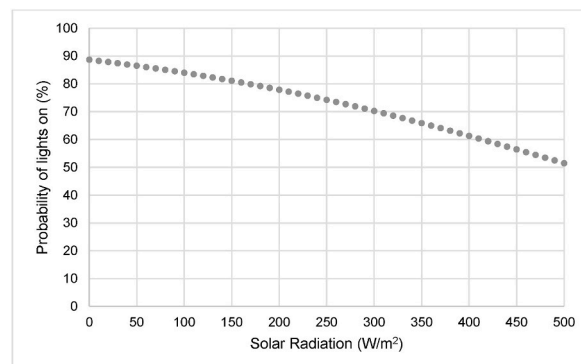


Fig. 11. The probability of lights on in relation with solar radiation.

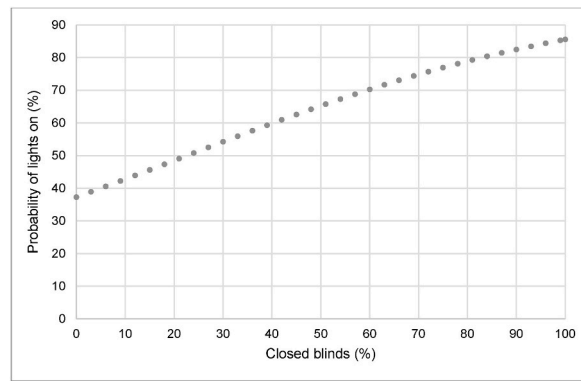


Fig. 12. The probability of lights on in relation with closed blinds (%).

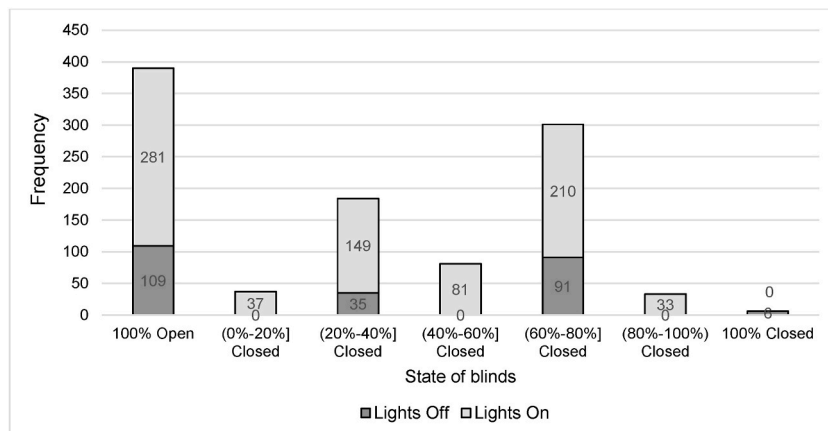


Fig. 13. The frequency of the state of lights for each category of blinds closed (%).

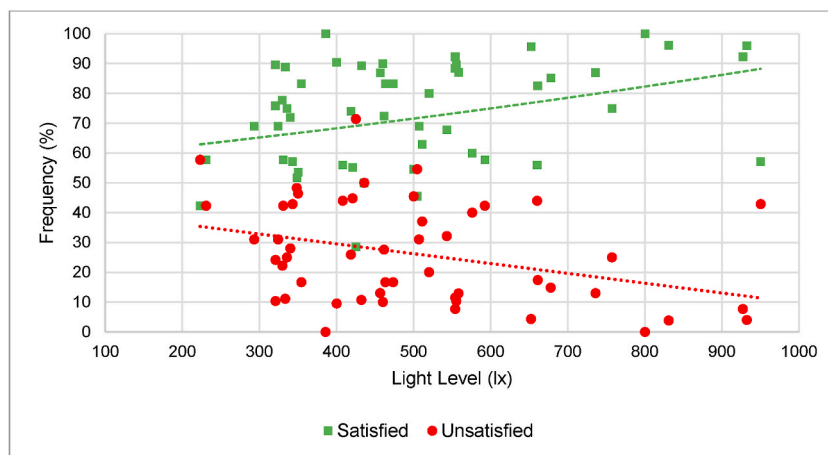


Fig. 14. The proportions of satisfied and unsatisfied VSVs by light levels.

away from windows. The standard deviation (SD) of VSVs away from windows (1.01) is higher than SD of VSVs in the middle of the classroom (0.88) and near the windows (0.98). The results suggest that students have a more scattered sensation of light level when they are away from windows.



Fig. 15. Distribution of measured light level on students' desks in relation to the distance to windows.

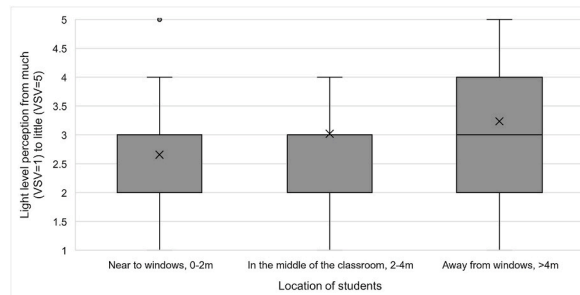


Fig. 16. Distribution of VSVs by the location of students' desks in relation to the distance to windows.

4. Discussion

4.1. State of blinds and operations on blinds

Factors impacting the state of blinds and drivers for blinds operations can be categorized into three groups of contextual (direct sunlight, daylight, outside view, solar radiation, solar altitude, operative and outdoor temperature), occupant-related (upon arrival or departure) and building-related factors (window operations, type and design of blinds and external shades). These factors are explained further below.

4.1.1. Contextual factors

Direct Sunlight: Visual observations suggested that students would react quickly to sunlight on desks and screens by asking teachers to close the blinds, therefore, sunlight resulted in immediate adaptive action. In this study, blinds were also closed while watching news or documentaries. Several other studies have suggested that reasons for closing shades include sunlight [11,19,20,24,40–42] and presentations on the screen [19]. For example, one study showed that 61% of the teachers were asked to adjust shades once a day because children complained of sunlight and sun reflection [20]. Another study showed that glare was the most important problem in the classrooms due to the wrong window design and orientation, and teachers preferred to exclude natural light by drawing curtains and using artificial lighting [11].

Outside view: In this study, blinds were opened to get an outside view when it was snowing. It has previously been shown that visual contact with a view from the classroom window is important to children, with a higher preference for natural views [17]. Pleasant outside views can encourage occupants to operate blinds [43]. However, it is also shown that blinds were closed due to outside distractions [40,41].

Solar Radiation and Altitude: The results of this study showed that solar radiation and altitude account for a higher percentage of changes in closed blinds (%) during the non-heating season than the heating season. Furthermore, an increase in solar radiation and solar altitude (high sun angle) during the non-heating season, resulted in occupants opening a higher percentage of blinds. Conversely, an increase in solar radiation and solar altitude during the heating season, triggered occupants to close a higher percentage of blinds.

Solar altitude had the strongest correlation with closed blinds (%) during both non-heating (-0.387) and heating seasons (0.327). In other words, the location of the sun at lower altitudes, which can cause direct sunlight, increased closed blinds during the non-heating season. Contrary, the low sun angles during the colder months, which can allow direct sunlight deep into the building and raise the temperature, resulted in more open blinds. No previous study was found on the relationship between solar altitude and radiation and blinds occlusion in primary schools.

Operative and Outdoor Temperature: This study showed that an increase in operative and outdoor temperature resulted in a lower percentage of closed blinds during the non-heating season. This can be related to higher operative temperatures triggering more window openings, which resulted in more blinds openings. This study suggested that when operative temperatures were high, opening windows was given priority over keeping blinds closed to reduce solar radiation during the non-heating season. It needs to be highlighted that 81% of blinds studied during the non-heating season were roller blinds, which were shown to be rolled up when

windows were open. However, other studies have supported that excessive solar heat gain and overheating [40,41] are among the reasons for closing blinds. It should be noted that blinds can also impact indoor temperature by affecting solar radiation and radiant temperature and also by covering windows and obstructing air flows.

4.1.2. Building-related factors

Orientation: The results showed that the median closed blinds (%) was the highest in southwest orientation (65%), which can be explained by a more vibrant daylight pattern of south orientation. Other studies have supported that south classrooms were more subject to daylight fluctuations and dynamic sunlight patterns [19,22]. In the studied classrooms, blinds were not designed based on the orientation of the buildings, however, future studies are recommended to take into account the impact of orientation on blind design including its thickness, solar transmittance, solar reflectance, visible transmittance and visible reflectance.

Blinds Design: Results of this study suggest that blinds were more closed (median = 55%) in classrooms with low accessibility for blinds operations than in classrooms with high accessibility for blinds operations (median = 25%). Therefore, it is important to design easy to access (designed alongside the classroom rather than the end of the classroom) and easy to use (accessible for children with shorter heights) blinds as their operation can provide natural light and save lighting energy, as suggested previously [43]. Previous studies have highlighted the design of shading systems including being damaged, broken or inoperable [44–46], malfunctioning [47], hard to reach [46] and difficulty in use [45,46] were among the common reasons for not operating them. A literature review by Korsavi et al. [43] suggests that the most recurring factors affecting the visual environment in schools are the type of controls, access to controls, and their ease of use [43]. Another study suggests that interior blinds should be orientated appropriately, easy to operate, and should allow a variety of options for the light interception, room darkening and view preservation [19]. To provide these qualities for blinds, their type and location need to be carefully considered by the design team and their regular maintenance needs to be carried out by the maintenance team. Similarly, another study suggests that blinds need to be regularly maintained, and enable maximum versatility for school occupants to regulate lighting levels [47]. It is shown that seasonal adjustment of interior shades can result in improved daylight management [19].

Blinds Type: The results of this study suggest that in classrooms with vertical blinds, opening windows does not impact the state of blinds, as individual slats of vertical blinds can be adjusted differently to let fresh air in while obstructing glare and sunlight. However, in classrooms with roller blinds, blinds need to be rolled up to some extent to not obstruct fresh air. Another study confirmed that internal blinds can conflict with airflow from open windows [48]. Results of this study suggest that vertical blinds can be a better design option for classrooms to control sunlight and let fresh air in, as the operation of windows works separately from the operations of blinds. It is shown that venetian blinds that can be tilted can have a significant effect on blocking direct sunlight and thermal environment [49].

External Shades: Furthermore, the results of this study show that blinds were more closed (median = 32%) in classrooms with no external shades than classrooms with external shades (median = 24%). This suggests that external shades (orientated appropriately) help to keep the internal blinds open more often as they can help with sunlight and provide more uniform daylight. Furthermore, it is shown that adding external shades can improve different aspects of IEQ, especially visual and thermal conditions, by addressing direct sunlight or overheating [50,51]. Another study showed that vertical shading devices resulted in a massive reduction in sunlight, especially in the early morning and late afternoon in hot climates [21]. External shades in this study were all horizontal, therefore, future studies need to investigate the most optimum external shading for classrooms in the UK.

4.2. State of lights

Factors impacting the state of lights can be categorized into contextual (solar radiation) and building-related factors (blinds occlusion). However, the state of lights was not different in different categories of occupancy (occupied, partially occupied and not-occupied).

Occupancy: This study shows that when classrooms were not occupied, lights were on for 70% of the time, suggesting that school occupants mostly did not turn the lights off after leaving the classroom. Another study by Serghides et al. [52] in educational buildings suggested that 40% of energy could be saved if lights, air-conditioning and general building equipment were used only during operating hours.

Solar Radiation and Daylight Availability: Results of this study suggest that the probability of turning lights off was higher when there was more solar radiation. The study by Hunt [23] suggested that in intermittent spaces such as schools, light switching behaviour declined as daylight availability increased. On the other hand, studies have also shown that many classrooms relied on artificial light even when there was abundant daylight available outside [12,24]. Another study in schools shows that 64% of pupils answered that even if it is a sunny day the artificial lighting was still on [11].

Blinds Occlusion: Results of this study suggest that the probability of turning lights off was higher when a higher percentage of blinds was open. The study by Katafygiotou and Serghides [11] highlighted that the use of artificial lighting increased when blinds were closed to avoid glare. However, this study suggests that when more than 60% of blinds were open, the lights were still on 76% of the time. The scenarios under which the majority of blinds (more than 60%) were open and lights were on suggest that either the design of windows and blinds did not provide enough daylight for the classroom or occupants did not turn off lights even though enough daylight could be provided. Both scenarios increase electricity consumption. Furthermore, when blinds were partially closed or the majority of them were closed in this study, the lights were on for 79% of the time. The number of hours with lights on could simply be avoided by opening more blinds. It can be assumed that the operations on lights were easier and more accessible than on blinds for school occupants (16 classrooms provided low accessibility for blinds operations), therefore, there were still many observations under which lights were on regardless of state of blinds.

Lighting Energy Consumption: This study suggests many scenarios under which lighting energy consumption could be reduced, such as turning off lighting when leaving the classrooms, turning off lights when blinds were open providing enough daylight and opening blinds when conditions would permit instead of turning on lights. Reducing lighting energy consumption can be significant as previous studies have shown that artificial lighting is one of the major electricity consuming items in school buildings [11,12,16,24,50]. Despite the contribution of daylighting to energy conservation [16,53,54], better IEQ, creating a positive environment for students and their productivity and performance [16,53], it can be blocked by occupants' operation on shading systems. Therefore, appropriate management of lighting conditions (a combination of natural and artificial lighting) is required to reduce lighting energy consumption [11]. A range of lighting management strategies can be discussed:

- Providing classrooms with more accessible and user-friendly blinds for school occupants (teachers and students) that can encourage blinds operations.
- Considering the optimum orientation (depending on the context and site) for classrooms to reduce direct sunlight and provide enough daylight.
- Considering the installation of external shades (design depending on orientation) to reduce direct sunlight, increase operations on blinds and provide more uniform light.
- Installing vertical blinds rather than roller blinds as their slats can control direct sunlight and let fresh air in.
- Designing non-operable windows close to operable windows so that their blinds are operated frequently as well.
- Informing school occupants about the importance of their operations on lights and blinds on saving electrical energy.

4.3. Students' perception of light level

In this study, mean Visual Sensation Votes varied from 2.7 near the windows (mean light level = 750 lx), 3 for the middle of the classroom (mean light level = 500 lx) and 3.2 (mean light level = 350 lx) for the area away from windows, suggesting that young students can differentiate between light levels in different locations in the classroom. The study by Giraldo et al. [17] on visual preferences of young children in classrooms indicated that young children can differentiate lighting needs according to the activity performed. However, the study by Giuli et al. [18] that investigated students' perception in different positions in the classrooms (near the windows, central and on the far side of the classroom) showed no relationship between students' perception and their positions in the Italian classrooms [18].

The optimum level of lighting is still an active research area [55], especially for young children. BS EN 12464-1:2011 [56] and The Society of Light and Lighting, CIBSE [57] recommend minimum light level of 300 lx in classrooms and tutorial rooms and 500 lx in art classrooms. The results of this study suggest the light level of 730 lx as the students' optimum light level which corresponds to an 80% satisfaction level.

5. Conclusion

Visual environment and visual sensation are important for students' academic performance, improving indoor environmental quality and reducing lighting energy consumption, however, a comprehensive analysis of the factors related to the controls of the visual environment (such as blinds and lights) in primary schools and their related behavioural models is missing, especially in the UK. This study provides a comprehensive analysis of the predictors that affect operations on blinds and variables related to the state of blinds and lights in 31 naturally ventilated classrooms in the UK and surveys 805 primary school students on their sensation of light levels.

Visual observations showed that blinds were closed when leaving the classroom (on departure) and due to direct sunlight on screen or desk. Blinds were opened for daylight, upon arrival into the classroom in the morning and for an outside view (for example, when it was snowing). Blinds were also opened when trying to open the windows to cool the classroom so that blinds do not obstruct fresh air.

Visual observation and time-lapse cameras showed different blinds occlusion (%) in classrooms with low and high accessibility for blinds operations and in classrooms with or without external shades, with median closed blinds (%) being higher in classrooms with low accessibility for blinds operations and in classrooms with no external shades. Designing external shades (design depending on orientation) can help to minimize too much light, visual discomfort, direct sunlight and excessive contrast.

Environmental measurements and behavioural models also show that the state of blinds was impacted by solar altitude and solar radiation (which can provide daylight and cause direct sunlight) and indoor and outdoor temperature (which impact windows operations). The location of the sun at lower altitudes increased closed blinds (%) during the non-heating season and the low sun angles during the colder months resulted in more open blinds. Furthermore, an increase in operative and outdoor temperature resulted in a decrease in the percentage of closed blinds during the non-heating season which was related to the effect of higher temperatures on more window openings and consequently more blinds opening. The results suggest that vertical blinds, rather than roller blinds, can be a better design option for classrooms as their slats can be adjusted to control direct sunlight and let fresh air in.

The study showed that occupants were more likely to turn off the lights when there was more solar radiation and when a higher percentage of blinds were open. However, many scenarios were observed in which lighting energy consumption could be reduced, therefore, a range of lighting management strategies was proposed to reduce lighting energy consumption and facilitate blinds operations.

This study assessed Visual Sensation Votes with regard to light availabilities, with results suggesting the light level of 730 lx as the students' optimum light level. However, visual comfort is a subjective measure that can be affected by several other factors such as glare, light distribution and contrast, which are suggested to be further studied by future studies to provide more suggestions on the

most optimum light level for primary school children.

CRedit authorship contribution statement

Sepideh S. Korsavi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Rory V. Jones:** Conceptualization, Investigation, Supervision, Visualization, Writing – review & editing. **Alba Fuertes:** Conceptualization, Investigation, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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