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Performance of combined daylighting strategies in varied sky conditions: post occupancy evaluation of lecture rooms in a tropical climate

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ABSTRACT

Due to the inadequate attention given to daylighting in lecture rooms in tropical wet and dry climate, this study, using field measurement, evaluates combined daylighting strategies in three lecture rooms labelled LLH, BMS and ANB with distinct bilateral glass louvre windows, window floor ratio, orientation and shading strategies. It determines the difference in illuminance in varied sky conditions, and the relationship between the strategies. Results revealed that under the clear sky condition, combined strategies in LLH and BMS rooms were effective in illuminance performance except during evening hours while the one in ANB was ineffective. Both rooms recorded poor daylight uniformity. Similar performance was obtained under overcast sky but they produced effective daylight uniformity. An effective daylighting was obtained throughout the process in the intermediate sky condition, however, the strategy in ANB room was ineffective in the evening hours. Only ANB room had an effective daylight uniformity in the intermediate sky. The strategy in LLH room had a strong positive relationship with BMS's. The strategy in LLH had a weak positive correlation with ANB's, but ANB's strategy had strong positive correlation with BMS's. Overall, the study contributes to the performance of combined daylighting strategies in tropical wet and dry climate.

1. Introduction

Students spend a great part of their life in school [1] and a greater part of their academic life in the lecture room. As such, the lecture room being one of the most important learning spaces in the school should be given appropriate attention, especially, its indoor environmental quality. Daylighting is one of the parameters of indoor environmental quality, its importance and association with the effectiveness of the lecture room has been acknowledged by authors [1–4]. They linked daylight to students' health, attention, absenteeism, visual comfort, pleasant environment, circadian physiology, behaviour, academic performance, and productivity. It is also one of the solutions put forward by the scientific community to mitigate the effect of global warming.

Daylight is in very high supply in the tropics unlike the temperate region. It has been reported that the tropical climate can record daylight supply of about 10 hours a day with a stationery supply of 120 klux [6]. This could be as a result of its proximity to the equator. But upon the superfluous supply of solar radiation in the tropics, daylight has not been fully exploited [7]. This indicates that there is a great need to tap the outdoor supply of daylight for indoor use, as it can replace the use of electricity for illumination in the lecture room especially in the daytime. Already the use of electricity for lighting of indoor learning spaces is a great burden to a third world country like Nigeria as a result of its attendant high cost of operation, insufficient supply, noise pollution and environmental degradation.

This inadequate exploitation of the outdoor daylight for indoor use in the tropics may be linked to the complexity nature of daylight [8–10] and the design that can fit its purpose. In this regard, several conscious design decisions have been explored by designers to exploit the available outdoor daylight in the tropics. These design decisions which are called daylighting strategies, include building geometry, façade orientation, shading systems, window configuration, window proportion, window floor ratio (WFR), window wall ratio, window to total room volume, glazing type and indoor reflectance as applicable to the need of the building. The effectiveness of these design strategies which is affected by the climate, sky condition, surrounding building, and outside obstruction plays a vital role on the visual comfort of the building users [11].

Visual discomfort issues, as a result of over- or under-daylighting, could potentially be avoided if design decisions were informed by evidence from post occupancy evaluation (POE) of existing day lit buildings [12–14]. Most of the daylighting studies gave little attention to school buildings [15], the few ones were more interested in unilateral daylighting strategies [16], [17] than combined strategies of WFR, orientation and shading parameters in varied sky conditions.

In the tropical climate of Nigeria, POE is viewed as a recent research venture and has not been given adequate attention [18], and as such, daylighting research in this aspect is limited [19]. Most of the studies in Nigeria focused on office, secondary school classrooms, workshop and libraries [20–30], unlike university lecture rooms. Daylighting findings in one climate may not be applicable to another due to its dynamic nature. Daylight has already been reported to be time-varying as a result of difference in geographical latitude, seasons in a year, time of day, monthly variations, local weather, sky conditions, and building geometry [31]. This poses a question, whether the daylight design strategies in university lecture rooms in the tropical wet and dry climate of Nigeria have been able to meet the desired daylighting quantity and quality intent of the design. This is crucial since there is a reported poor daylighting consideration during the architectural design stage [32].

The present study is vital as it ascertains the aptness of certain daylight design strategies as they are replicated in many lecture rooms in the study area. In addition, the peculiarity nature of daylight in the tropical climate makes a case for the field study of its design strategies. The focus of this experimental study is on three distinct strategies in lecture rooms in a university setting anchoring on WFR, orientation and shading systems. They are combined strategies of bilateral, (a) glass louvre windows (covered with mesh net) complemented with terrace shading on both walls, WFR of 19% in E-W orientation, (b) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and blank wall on the opposite end, WFR of 11% in N-S orientation, and (c) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and egg-crate on the opposite end, WFR of 14%, in E-W orientation. In the description of the strategies, (a), (b), and (c) are found in three lecture rooms labelled LLH, ANB, and BMS, respectively. Using illuminance as static performance metric, this POE determines the difference in effectiveness of the strategies in three different sky conditions and the correlation between them.

1.1 Objective

The present study evaluates the effectiveness performance of three daylighting strategies of university lecture rooms in a tropical wet and dry climate. The daylighting strategies are combined strategies of bilateral, (a) glass louvre windows (covered with mesh net) complemented with terrace shading on both walls, WFR of 19% in E-W orientation, (b) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and blank wall on the opposite end, WFR of 11% in N-S orientation, and (c) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and egg-crate on the opposite end, WFR of 14%, in E-W orientation.

This part includes validation of the measuring instrument (HS 1010 light meter), continuous measurement of illuminance in the morning, afternoon and evening in clear, overcast and intermediate sky conditions. Determination of statistical difference in terms of sky conditions and finding the relationship between them. The next section explores daylighting strategies with peculiar attention to side lighting, external shading strategies, WFR, orientation, POE and review of related studies. This is followed by method, results, discussion. The study concludes with key implications for research and practice.

1.2 Daylight Strategies

Daylighting strategies are design options used in a building for the exploitation of outdoor daylight for indoor use. The availability of natural light, which is determined by the latitude of the building site and the conditions immediately surrounding the building, (example, the presence of obstructions) affect the functioning of daylight strategies. Daylighting strategies are also affected by climate [2]. Studying both sky conditions and daylight availability at a building site is key to understanding the operating conditions of the building's facade.

1.2.1 Side-lighting strategy

Side-lighting is the placement of windows on the perimeter walls of a building for harvesting of outdoor daylight. Side-lighting is very common, as windows provide views to the exterior, one of the most important psychological benefits of daylight [33]. Moreover, it is the main way to provide daylight to all floors of multi-story buildings. Side-lighting usually produces horizontal daylight illuminance levels that are highest near the window and decrease rapidly deeper into the space [34], lacking uniformity [35]. Daylight openings and external controls should vary by compass direction since each façade of a building, based on orientation, receives differing amounts of daylight throughout the day and across seasons.

1.2.2 Common side lighting strategies

Unilateral side lighting is the practice of one-sided placement of windows in a building for harvesting of daylight. Example of studies about unilateral side lighting exist, see [36-37]. It is a difficult issue to create a comfortable visual indoor environment with one-side lighting and zone close to the window is always 'hotspot' for users [38]. Bilateral lighting occurs when light enters rooms from two side directions, thus improving uniformity of distribution depending on the width of a room, height, and location of glass, see examples [39-40]. Due to the harsh condition of the tropical climate, bilateral side lighting is also used for cross ventilation of indoor spaces. Combined daylighting strategy is a concept of daylight exploitation for indoor use that applies more than one particular strategy. It could combine bilateral, shading and WFR to have a controlled daylight admission into a learning space, similar to what is obtained mostly, in the study area.

1.2.3 Shading strategies

One of the main objectives of shading is the reduction of direct solar radiation at required periods; purposeful control of diffuse and reflected radiation; prevention of glare impact from external and internal sources without compromising daylighting and ventilation. A study reported that façade shadings, including vertical louver, horizontal louver, egg crate louver, overhang, vertical louver slat, horizontal louver slat, and light shelf can be affected differently depending on the change in orientation and design [41]. In the tropical climate, the high supply of daylight entails that appropriate shading at some point of the day or month or season is crucial to reduce the glare effect in the building.

For classrooms whose orientation lies towards the equator, the use of overhangs is typical to reduce or completely block direct sunlight during the summer season [42]. This element can be modified to have dropped edges or can be sloped for less projection on the facade. The use of a horizontal overhang for shading a rising low east or setting low west sun is difficult. They are mostly applicable in the south elevation [43]. Simulation review of shading devices [44] reported that most of the studies done were rated theoretically 54%; experimentally 20% and both theoretically and experimentally 26%. Moreover, most of the studies concentrated in USA and Italy with office building as the major building type. Venetian blinds were the most-studied shading devices among others.

1.2.4 Window floor ratio (WFR)

WFR is the percentage of window area to the floor area of a space. Several studies came up with different WFRs for buildings. It is also called fenestration factor. However, the illumination requirement for a lecture room is different from that of a residential building because of the difference in use in these buildings.

Different countries have different WFRs depending on the climatic condition of the place. The building standards as seen in National Building Code for Nigeria recommended a 10% minimum WFR [45]. This does not define the upper limit so the tendency of glare admission is high especially when the solar radiation is high in any area of the country. For example, negative impact on thermal conditions for buildings located in clear sky conditions of Uyo, Akwa Ibom State could be recorded.

The following were cited in a study [46]; 20% can provide effective daylight up to 1.5 times the height of room in non-domestic buildings, 15- 20% gave effective daylighting in small classrooms with north window façades in Malaysia. 10-12.5% was stipulated by Neufert [47] while 20% was stipulated by Wu and Ng [48]. A study [49] questioned the validity of the current standard WFR as stipulated by Iran's National Building Daylight Regulation. Using daylight factor, uniformity ratio, 24 window design alternatives based on shape, size and dimensions were explored and the result of the study indicated that 12% WFR was ineffective based on LEED, BREEAM and Green Star standards but 15-24% WFR was the optimal range proposed. However, the study used only south facing building but it is vital to the present study since WFR is a parameter of concern.

1.2.5 Orientation strategy

Orientation of buildings is a major factor in the exploitation of outdoor daylight for indoor illumination. To a great extent, daylight admission is affected by the orientation of windows on building facades [50-51]. A study [8] reported that certain metrics, such as daylight factor, are not affected by orientation change. The metric gives a common performance report in all orientations and shading controls. This is one of the demerits of daylight factor.

Using simulation and field measurement, a study [52] was conducted in CIE over cast sky and clear sky conditions of tropical climate of Malaysia. The study revealed that orientation change had no effect on daylighting under overcast sky but windows on eastern and western orientations were exposed to excessive daylighting during early hours of the day and afternoon demanding shading strategies while the north and south windows had adequate daylight. A study reported that during clear and partly cloudy conditions, significant differences between north, south, east and west light sources in terms of quality, quantity, colour and directionality are observed in buildings [11].

1.3 Post occupancy evaluation

Post occupancy evaluation (POE) is the assessment of the building when it has been occupied. Different methods of data collection are used for POE, such as questionnaires, interviews, and environmental monitoring / physical measurement [18]. It is useful to building performance as it tells the extent which a building has been able to meet its expectation with regards to the design intent [18]. In the tropical climate of Nigeria, several daylighting strategies have been used and they are replicated in many lecture rooms without recourse to whether they are performing effectively or not with regards to the designer's intent. Several POE studies [53–56] have been done but inadequate attention has been given to daylighting in lecture rooms. A POE study [57] using physical measurement investigated the daylight levels in the IBB library in Modibbo Adama University of Technology, Yola, Nigeria.

1.4 Illuminance and Uniformity Ratio

Different metrics are broadly divided into static and dynamic performance metrics [58-59]. For the purpose of this study, illuminance will be used as a static metric for measurement. Illuminance is the measure of the amount of light received on a surface. It is typically expressed in lux. Illuminance levels can be measured with a light meter, or predicted using computer simulations with recognised and validated software (example, diva for rhino). It is the measure of light currently used by most performance indicators to determine daylight availability in the interior. However, it is time-dependent, and it must be assessed for many durations in order to get a clear picture of how daylight is exploited in an interior space. Illuminance is the basis for the development of other metrics such daylight factor, useful daylight illuminance, daylight autonomy and it has been used by several studies as a metric to measure daylight strategies in buildings [60-61]. According to several standards, the average maintained illuminance in a lecture room should be kept above 300 lux [35]. However, to check the exposure of occupants to glare, an upper limit is vital, as such, 2000 lux has been reported as an upper limit acceptable in this regard [62-63]. This study bases its measurement on 300 lux – 2000 lux as the range of illuminance acceptable as effective for the lecture room.

For the sake of daylight spread in lecture rooms, the consideration of uniformity ratio (U_o) as a daylight metric is crucial [64]. U_o is the ratio, in a given moment, between the minimum value of the illuminance on the plane (E_{min}) and the average illuminance on that plane (E_{av}) [43, 65]. With regards threshold values, some recommended uniformity ratios are listed in [65] and for this study, 0.7-0.8 was adopted as good uniformity ratio.

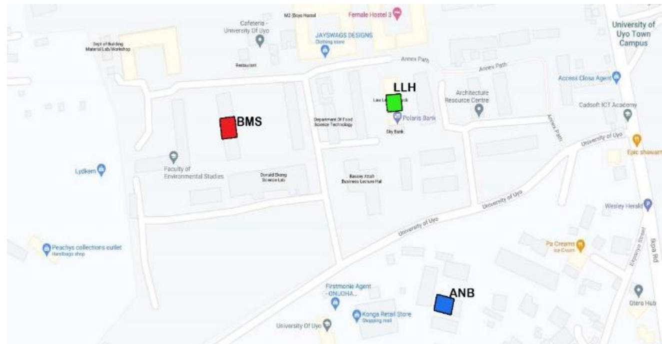
1.5 Sky Conditions in the Tropical Wet and Dry Climate

The set of fifteen skies as adopted by the International Commission on Illumination (CIE) are grouped under 3 major classes which consist of clear, intermediate, and overcast sky conditions [66]. The clear sky has less than 30% cloud cover and is brighter along the horizon and less intense at the zenith [67]. Clear skies and the corresponding sun act both as a diffuse and point source of light, which can cause overheating, glare, excessive lighting and poor distribution when improperly used. In the tropical wet and dry climate of Uyo (the study area), in typical year, the clear sky is obtained from January to April and the month of April is chosen to represent this sky condition in this study. Overcast skies have about 70-100% cloud cover with no visible sun. These skies produce diffuse light and are brightest at their zeniths and decrease at the horizon to approximately one-third of their maximum brightness. May to July represents the overcast sky in the tropical wet and dry climate. The month of July was chosen to represent the overcast sky condition. Intermediate skies have hazy clouds that can be very bright, usually brighter than the overcast sky. They have more than 30% and less than 70% cloud cover [66] and is constantly changing between direct sunlight and hazy daylight, fluctuating in intensity, distribution and colour temperature. Intermediate sky covers from October to December in the study area. The month of October was chosen to represent the intermediate sky in this study.

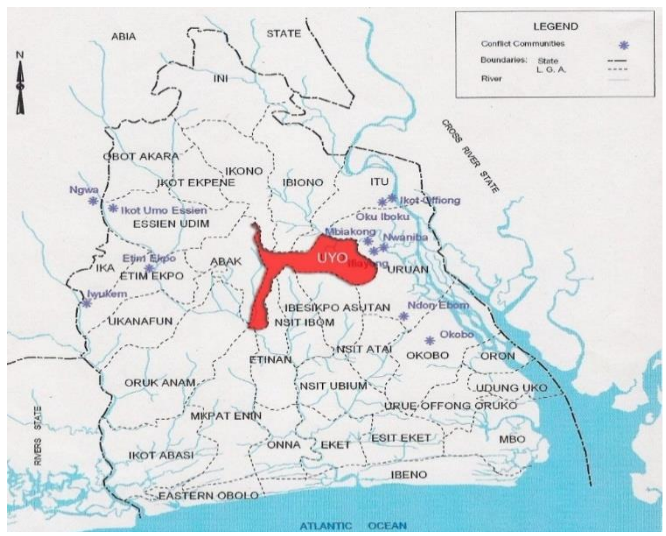
2. Method

2.1 Stage one: Identification of daylighting strategies in the lecture rooms

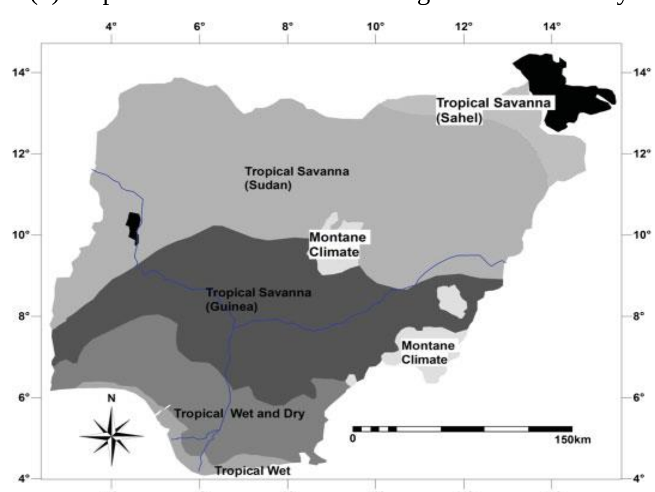
The first stage of this section was the identification of specific strategies in the lecture rooms with their characteristics. Three lecture rooms (labelled LLH, BMS and ANB as shown in a portion of the campus layout in Fig. 1(a) with distinct daylighting strategies in University of Uyo, Uyo, Akwa Ibom state, Nigeria located in the tropical wet and dry climate were chosen for this study. Uyo is the capital of Akwa Ibom State (see Fig. 1(b)), located between latitude 5.03º N and 5.09º N of the equator and longitude 7.93º E and 8.10º E of Greenwich Meridian. Uyo has a land mass of approximately 28.48 km^2 and is situated about 55km inland from the Atlantic coast. The tropical wet and dry climate, also called the tropical rainforest climate, designated by the Koppen climate-classification as 'Af', is found in the southern part of Nigeria where Uyo, Akwa Ibom State is located including other towns like Ikeja, Calabar, Benin (see Fig. 1(c)). A 14-year weather analysis of Uyo gotten from Nigerian Meteorological Station, Department of Geography and Regional Planning of University of Uyo indicates that the highest and lowest total monthly solar radiation of 12.73607 MJ/m^2 and 10.51037 MJ/m^2 are obtained in the months of April and July, respectively [68].



(a) Layout showing the lecture rooms of LLH, ANB and BMS in University of Uyo



(b) Map of Akwa Ibom state showing the location of Uyo.

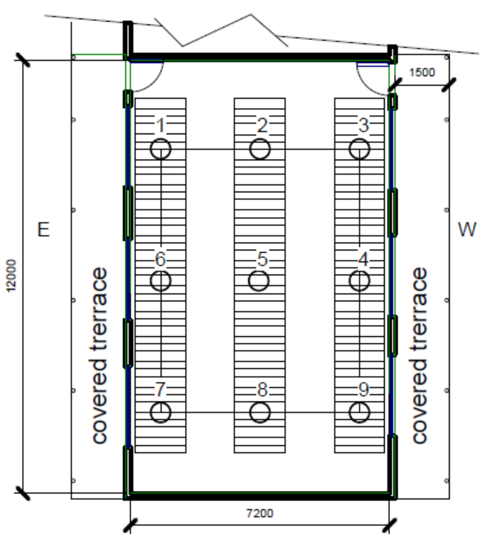


(c) Map of Nigerian climate

Fig. 1. Study area description

The POE approach adopted was physical measurement with reference to illuminance standard for lecture rooms (see section 1.4). Similar past studies have used the same method [36, 50, 57]. Physical measurements were done with the use of measuring tape, pen, and notebook. For the elevations, pictorial views were taken using Gionee M7 Power phone camera. As-built drawings of the samples were done using Revit software. WFR, orientation strategy, and bilateral shading strategy determined the choice of lecture rooms for study. However, for ease of grouping, samples' stratification was based on WFR. Groupings 0-11%, 12-15 %, and 16-20% WFRs were used for the stratified sampling technique. For WFR 0-11%, lecture room called ANB was selected, WFR 12-15 %, lecture room called BMS was selected, and lecture room called LLH was selected for WFR 16-20% randomly.

Sample 1 is LLH, a lecture room (as shown in Fig. 2) with a combined strategy of bilateral glass louvre windows (covered with mesh net) complemented with terrace shading on both walls, WFR of 19% in E-W orientation. It has a headroom of 3.6 m.

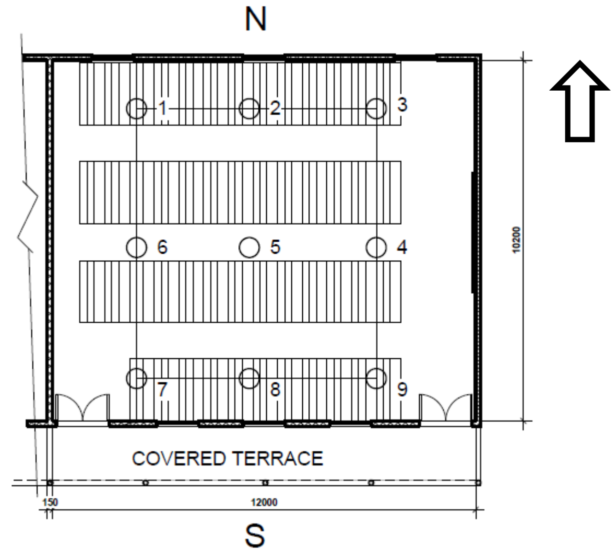


(a) Plan and placement of sensors 1-9 for field measurement

(b) Pictorial view

Fig. 2. Strategy in lecture room LLH

Sample 2 is ANB, a lecture room (as shown in Fig. 3) with a combined strategy of glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and blank wall on the opposite end, WFR of 11% in N-S orientation. It has a headroom of 3.6 m.



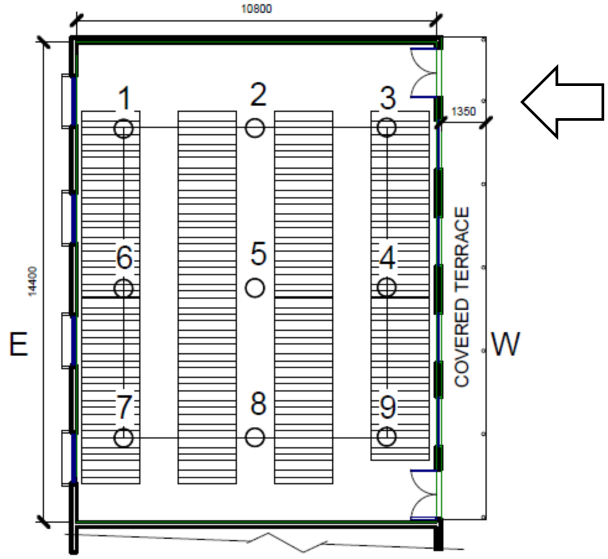
(a) Plan and placement of sensors 1-9 for field measurement

(b) Pictorial view 1

(c) Pictorial view 2

Fig. 3. Strategy in lecture room ANB

Sample 3 is BMS, a lecture room (as described in Fig. 4) with a combined strategy of glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and egg-crate on the opposite end, WFR of 14%, in E-W orientation. It has a headroom of 3.6m.



(a) Plan and placement of sensors 1-9 for field measurement

(b) Pictorial view 1

(c) Pictorial view 2

Fig. 4. Strategy in lecture room BMS

2.2 Stage Two: Calibration of Measuring Instrument

The second stage in this section covered the choice of the measuring instrument and its calibration. HS 1010 light meter was deployed for field measurement (see Fig. 4). This instrument has been previously used in a similar study but in a different context [69]. The light meter has a test range of 1-200 klux, calibrated to standard incandescent lamp at colour temperature of 28562 K. It has an accuracy of ± 4% ± 10 digits (<10000 lux) and ± 5% ± 10 digits (>10000 lux) and repeatability of ± 2%.

The light was calibrated against a known already calibrated sensor. With the help of Lutron LX-102 electronic light meter (see Fig. 5), the HS 1010 was tested. The reference device annotated with 'R' was the device of known accuracy while the one under test was referred to as Sensor 100 annotated with 'S'.

The Lutron LX-102 electronic light meter was calibrated by environmental experts at the Victoria University of Wellington, New Zealand. The meter's measuring range is 0-50 klux with accuracy of ± (5% + 2 d).

(a) Lux HS1010 meter

b) Lutron LX-102 electronic light meter

Fig. 5. Light Meters

Both the test and the reference devices were placed together for series of spot measurements to find a tolerance level.

2.3 Stage Three: Field Measurement

The third stage was field measurements and documentation of indoor illuminance. With the help of voluntarily-chosen research assistants who were fourth-year students from the Department of Architecture of University of Uyo, the process of sensor placement, measurements and recordings were done simultaneously in all the three rooms with the doors shut and the electrical switches turned off. Previously, the research assistants were trained on how to handle the sensors to check occurrence of errors. Sensors labelled 1- 9 were placed in 9 zones (see the arrangements in Figures 1- 4) at a desk height of 900mm. Recordings were done at every 15minutes and an average was computed for morning (7:00-10:00), afternoon (10:00-13:00) and evening (13:00-16:00) of a typical school day in the middle of April, July, and October of 2019. The choice of the 3 months was done to take care of the climatic differences based on seasons, sky conditions in a typical year in the tropical wet and dry climate of Nigeria (see further detail in section 1.4). The results and statistical analyses are reported in the next section.

3. Results

3.1 Validation of Instrument

The instrument - HS 1010 light meter was validated with the use of Lutron LX-102 electronic light meter and the results indicated that the test device accuracy level was ±2% as shown in Table 1. This defined the internal validity for the use of the light meter for the field measurement.

Table 1

Calibration readings

Date	Time	Sensor Code	Light (lux)	Light (lux)	Light - Factor (%)
05/03/2019	9:00	100	250	245	2
05/03/2019	16.30	100	450	440	2
06/03/2019	12:34	100	633	620	2
06/03/2019	13:44	100	402	394	2
06/03/2019	15:18	100	710	698	2
06/03/2019	16:45	100	540	531	2
07/03/2019	9:00	100	285	280	2
07/03/2019	11:45	100	690	679	2

Note: Calibration Variation (R- S)/R x 100, where R is Reference Instrument and S is Test Sensor

3.2 Difference in Illuminance in Terms of Sky Conditions (Months) per Strategy

The results of illuminance and illuminance uniformity measurements are presented in Table 2. The time of the day, date, sky condition (period of the year), and the strategies are also reported.

Table 2

Average illuminance distribution in 2019

(a) LLH in April 2019 (15/04/19, 1st period of the year)

Sensor	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
points	Max	Min	Max	Min	Max	Min
C1	1388	1200	1280	980	3980	3566
C2	1091	931	1030	620	3400	2800
C3	988	809	900	535	3100	2400
C4	991	788	880	533	3109	2389
C5	1070	1000	1040	700	3454	2700
C6	1401	1199	1299	990	3989	3570
C7	1400	1209	1290	990	3999	3499
C8	1080	999	1020	680	3404	2800
C9	999	780	921	500	3111	2300

(b) LLH in July 2019 (14/07/19, 2nd period of the year)

Sensor	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
points	Max	Min	Max	Min	Max	Min
C1	1350	1134	990	788	4980	4706
C2	970	850	730	620	4700	3990
C3	1350	1134	990	788	4980	4706
C4	1345	1190	996	790	4989	4770
C5	997	860	740	700	4754	3900
C6	1345	1190	996	790	4989	4770
C7	1300	1200	1000	890	5001	4790
C8	1000	877	720	689	4704	4000
C9	1300	1200	1000	890	5001	4790

(c) LLH in October 2019 (16/10/19, 3rd period of the year)

Sensor	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
points	Max	Min	Max	Min	Max	Min
C1	1280	990	1160	910	1799	1590
C2	1030	880	880	929	1409	1208
C3	1280	990	1160	910	1799	1590
C4	1290	1090	1109	906	1801	1503
C5	1010	890	885	719	1390	1400
C6	1290	1090	1109	906	1801	1503
C7	1300	1060	1100	900	1790	1600
C8	1000	901	890	700	1450	1300
C9	1300	1060	1100	900	1790	1600

(d) ANB in April 2019 (15/04/19, 1st period of the year)

Sensor	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
points	Max	Min	Max	Min	Max	Min
C1	658	329	620	335	650	330
C2	671	339	630	320	660	340
C3	668	330	608	325	680	350
C4	501	300	459	270	489	307
C5	510	310	470	280	503	309
C6	511	299	480	279	509	300
C7	409	200	381	190	411	198
C8	410	209	390	208	404	200
C9	400	230	394	210	399	221

(e) ANB in July 2019 (14/07/19, 2nd period of the year)

Sensor	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
points	Max	Min	Max	Min	Max	Min
C1	800	680	907	788	1380	1106
C2	809	660	900	777	1300	990
C3	820	650	904	780	1290	1006
C4	750	600	796	590	1009	998
C5	780	655	740	600	1054	990
C6	760	650	770	650	1089	970
C7	600	490	650	490	901	790
C8	600	477	620	501	904	800
C9	602	479	670	499	901	890

(f) ANB in October 2019 (16/10/19, 3rd period of the year)

Sensor points	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
	Max	Min	Max	Min	Max	Min
C1	500	409	690	550	279	179
C2	490	380	680	529	270	168
C3	489	399	660	510	274	159
C4	460	390	599	476	185	153
C5	468	391	585	480	190	140
C6	470	390	590	470	180	150
C7	330	231	410	299	130	100
C8	329	211	420	300	150	90
C9	313	222	410	298	133	101

(g) BMS in April 2019 (15/04/19, 1st period of the year)

Sensor points	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
	Max	Min	Max	Min	Max	Min
C1	1758	1520	1629	1305	3500	3330
C2	1402	1210	1130	920	2960	2340
C3	1008	930	898	790	2480	2250
C4	1001	939	839	770	2419	2209
C5	1410	1200	1170	981	2953	2312
C6	1700	1509	1680	1279	3519	3219
C7	1709	1500	1638	1290	3491	3198
C8	1410	1209	1190	1008	2940	2200
C9	1020	930	894	818	2399	2202

(h) BMS in July 2019 (14/07/19, 2nd period of the year)

Sensor points	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
	Max	Min	Max	Min	Max	Min
C1	1500	1281	1007	880	5280	4306
C2	1350	1261	908	779	4100	3790
C3	1082	965	800	744	3390	2706
C4	1175	1000	799	760	3359	2798
C5	1378	1265	940	690	4054	3770
C6	1668	1306	1070	850	4489	3971
C7	1608	1310	1050	890	4401	3890
C8	1360	1270	962	700	4064	3801
C9	1162	1079	770	752	3390	2890

(i) BMS in October 2019 (16/10/19, 3rd period of the year)

Sensor points	(7:00-10:00)		(10:00-13:00)		(13:00-16:00)	
	Max	Min	Max	Min	Max	Min
C1	1200	1009	1390	1150	977	770
C2	900	860	1080	929	717	660
C3	759	590	840	610	604	447
C4	760	579	849	596	585	453
C5	898	791	1085	980	790	645
C6	1270	1090	1370	1090	980	750
C7	1239	1036	1420	979	960	700
C8	829	761	1020	1000	750	660
C9	753	572	910	598	583	461

In addition to illuminance, illuminance uniformity was also computed and the results are presented in Table 3.

Table 3

Illuminance uniformity distribution in all the strategies

Period	Strategies	(7:00-10:00)	$U_{O\,Av}$	(10:00-13:00)	$U_{O\,Av}$	(13:00-16:00)	$U_{O\,Av}$
15/04/19	CBN EW	8000	0.8	3445	0.7	9000	0.8
1st period	LLH EW	1074	0.7	899	0.6	3198	0.7
of the	ANB NS	405	0.5	381	0.5	403	0.5
year	BMS EW	1298	0.7	1124	0.7	2773	0.8
14/07/19	CBN EW	4751	0.8	3174	0.7	10265	0.9
2nd period	LLH EW	1144	0.7	839	0.7	4696	0.8
of the	ANB NS	659	0.7	702	0.7	1020	0.8
year	BMS EW	1279	0.8	853	0.8	3803	0.7
16/10/19	CBN EW	6138	0.9	3130	0.8	4081	0.9
3rd period	LLH EW	1096	0.8	954	0.7	1574	0.8
of the	ANB NS	382	0.6	498	0.6	168	0.5
year	BMS EW	883	0.6	994	0.6	694	0.6

To determine the statistical difference among the samples, two well-known tests for normality of data, namely Kolmogorov-Smirnov and the Shapiro-Wilk Tests were used for this purpose. To ascertain the skewness and kurtosis tendency of a set of data, these tests are widely used [70]. From the test, illuminance data of the strategies were not normally distributed since the significant values were all less than 0.05 (see Table 4). It is noted that when significant value of the Kolmogorov-Smirnov and the Shapiro-Wilk Tests are more than 0.05, the data are normally distributed [71].

Table 4

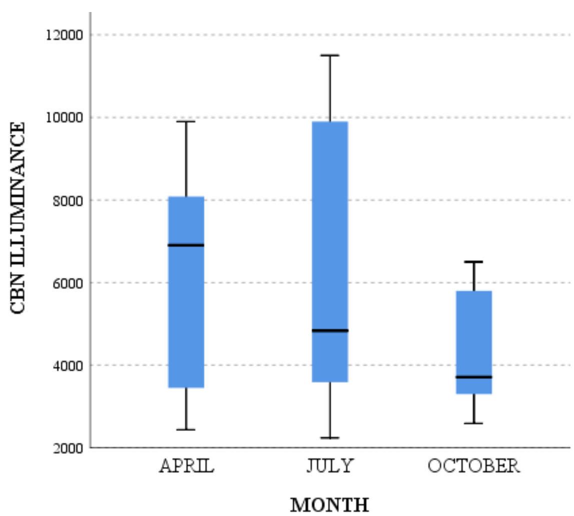
Normality test results

Illuminance	Kolmogorov-Smirnov strategy [a]			Shapiro-Wilk strategy		
	Statistic	df	Significance	Statistic	df	Significance
LLH	.293	162	.000	.717	162	.000
ANB	.102	162	.000	.955	162	.000
BMS	.243	162	.000	.778	162	.000

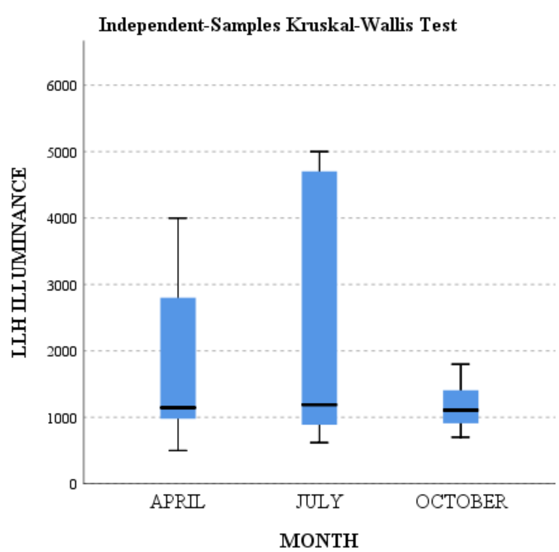
[a] Lilliefors significance correction

As such, the data could only be analysed with non-parametric statistics for validity of result. In this regard, Kruskal-Wallis test was used to determine the statistical difference among the strategies. The Kruskal-Wallis H test is sometimes called the "one-way ANOVA on ranks", it is a non-parametric tool used to determine the statistical difference between groups of independent variables and a continuous or ordinal dependent variables. In addition, Spearman Rank Correlation was used for relationship analysis.

Kruskal-Wallis H test was conducted using IBM SPSS v26. The independent variables being the three daylighting strategies at default orientations (LLH, ANB, and BMS), the dependent variables were illuminance values obtained per month of April, July and October. It was done with significant level of 0.05 and confidence interval of 95%. One of the core assumptions of Kruskal-Wallis H test is the choice between the use of median or mean rank (distribution) to check for difference. For this study, mean ranks were chosen as the distribution of illuminance among the strategies being the independent variable were dissimilar as seen in Fig. 6. The result showed that the distributions of the illuminance were dissimilar for all strategies, as assessed by visual inspection of the boxplot. Following the result, investigation of distribution difference ensued.

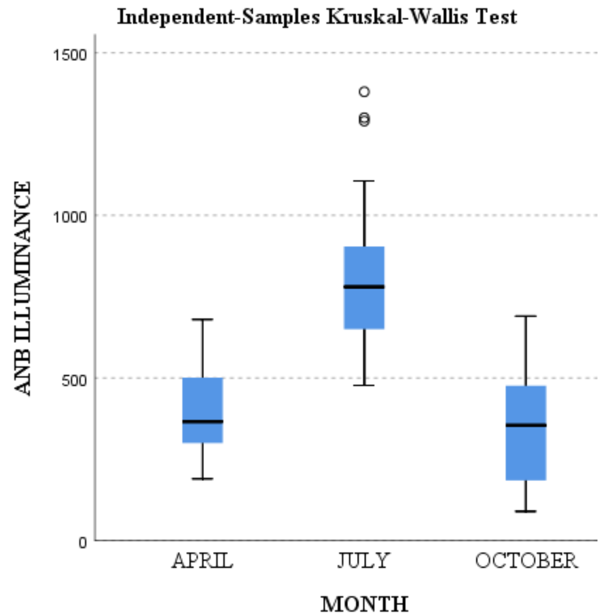


(a) Strategy in CBN

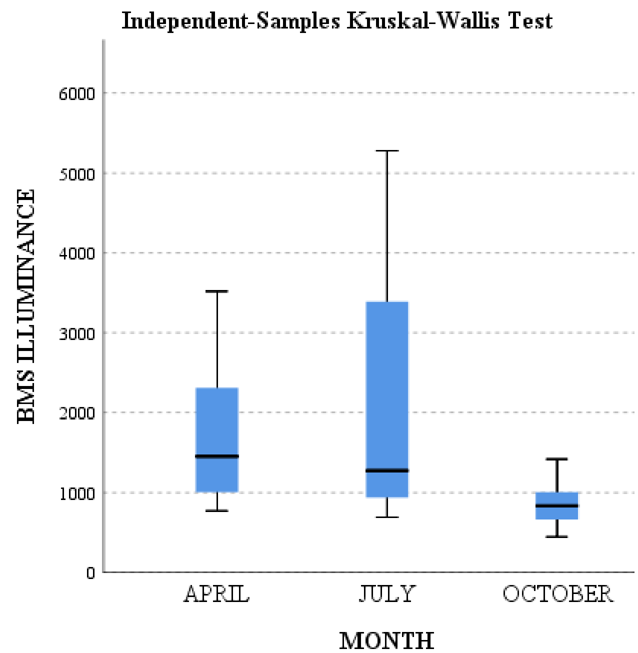


(b) Strategy in LLH.

Fig. 6. Box plots showing dissimilarity of the distribution of the monthly illuminance in strategies



(c) Strategy in ANB



(d) Strategy in BMS

Fig. 6. Box plots showing dissimilarity of the distribution of the monthly illuminance in strategies

In this study, it was hypothesised that the distribution of daylight illuminance in all the strategies is the same across the different months of the year. The results indicated that the distribution of illuminance in lecture rooms ANB and BMS were not the same across the categories of months sampled as the significant values were <.05. However, it was the same for lecture room LLH as the significant value was >.05 (see Table 5).

In Table 6, the test statistic is summarized. It is crucial to note that p-values (level of statistical significance) agree with the p-values in the Significance

(Sig.) column in the Hypothesis Test Summary table in Appendix C, it is the same as in the "Asymptotic Sig. (2-sided test)" row in the test statistic table. "Asymptotic" means that the p-value approaches the real value as sample size increases. This means that for smaller sample sizes the p-value computed from this approach gives only an approximation to the true p-value, with the approximation improving with increasing sample size. The reference to "(2-sided test)" is more commonly known as a 2-tailed test.

Table 5

Hypothesis test summary of difference in illuminance per month of each strategy (Asymptotic significances are displayed and the significance level is .050)

S. No.	Null Hypothesis	Test	Sig.	Decision
1	The distribution of LLH illuminance is the same across categories of months	Independent-Samples Kruskal-Wallis Test	.631	Retain the null hypothesis
2	The distribution of ANB illuminance is the same across categories of months	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis
3	The distribution of BMS illuminance is the same across categories of months	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis

The non-parametric examination indicated that the result was statistically significant, so the null hypothesis was rejected and alternative hypothesis was accepted for strategies in lecture rooms ANB and BMS.

Inclusion of the value of Kruskal-Wallis H statistic (the 'Test Statistic' row) and the degrees of freedom (the 'Degrees of Freedom' row) is crucial. The 'Test Statistics' row in Table 6 provided the value of the H-statistic, which are .919, 88.349 and 50.573. In approximation, using Kruskal & Wallis approach [72], the statistic followed a $\chi 2$-distribution with k – 1 degrees of freedom, where k is the number of months of the independent variable, group (i.e., 3 – 1 = 2 degrees of freedom, as reported in the 'Degrees of Freedom' row).

Table 6

Test statistic summary of difference in illuminance based on months of each strategy.

Independent-Samples Kruskal-Wallis Test	LLH	ANB	BMS
Total N	162	162	162
Test Statistic [a]	.919	88.349	50.573
Degree of Freedom	2	2	2
Asymptotic Sig. (2-sided test)	.631	.000	.000

[a] The test statistic is adjusted for ties

From the analysis, the Kruskal-Wallis H test reported statistically significant value indicating that the mean rank of strategies was not equal, as such, the need to run a post hoc test was crucial for ANB and BMS strategies. A pairwise comparisons (see Table 7) was run and interpreted using Dunn's (1964) procedure with a Bonferroni adjustment, similar approach exist in a previous study [73].

The post hoc analysis revealed statistically significant differences in mean rank illuminance ($p = .0005$) between months of October (44.59) and July (96.99), and July and April (102.92) for strategy in lecture room BMS. For lecture room ANB, the difference was found in months of October (51.88) and July (130.10), and October and April (62.52). There was no other difference in any other combination.

The pairwise comparisons were calculated as described by Dunn (1964) and the complete data set were used when making a specific pairwise comparison. This contrasts with running separate Mann-Whitney U tests which only the data involved in each specific pairwise comparison would have been used. The significance levels were adjusted by SPSS Statistics using a Bonferroni correction and the result was reported in the 'Adjust (Adj.) Sig.' column to check Type 1 error.

3.3 Difference in Illuminance Distribution for the 3 Daylighting Strategies

A Kruskal-Wallis H test was run to determine if there were differences in illuminance across LLH, ANB and BMS daylighting strategies in UNIUYO classroom at default orientation as presented in Appendix D. Mean rank of illuminance (see Table 8) was significantly different between groups (p = .0005).

Table 7

Pairwise Comparisons of illuminance based on Months for each strategy.

ANB Strategy					
Months	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
October-April	10.639	9.027	1.179	.239	.716
October-July	78.222	9.027	8.665	.000	.000
April-July	-67.583	9.027	-7.487	.000	.000
BMS Strategy					
Months	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
October-July	52.398	9.028	5.804	.000	.000
October-April	58.324	9.028	6.461	.000	.000
July-April	5.926	9.028	.656	.512	1.000

Note: Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is .05. And, the significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 8

Mean ranking of illuminance distribution per month of each strategy

Illuminance	Month	N	Mean Rank
LLH	April	54	81.19
	July	54	85.97
	October	54	77.33
	Total	**162**	
ANB	April	54	62.52
	July	54	130.10
	October	54	51.88
	Total	**162**	
BMS	April	54	102.92
	July	54	96.99
	October	54	44.59
	Total	**162**	

Subsequently, pairwise comparisons were performed for LLH, ANB and BMS using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons as presented in Table 9. Adjusted p-values are presented. This post hoc analysis revealed statistically significant differences in mean rank illuminance between ANB (104.04) and BMS (310.49) (p = .0005), ANB and LLH (335.55) (p = .0005). There was no other difference in any other combination.

Table 9

Pairwise Comparison summary of difference in illuminance of the different strategies.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
ANB NS-BMS EW	-206.444	20.800	-9.925	.000	.000
ANB NS-LLH EW	231.503	20.800	11.130	.000	.000
BMS EW-LLH EW	25.059	20.800	1.205	.228	1.000

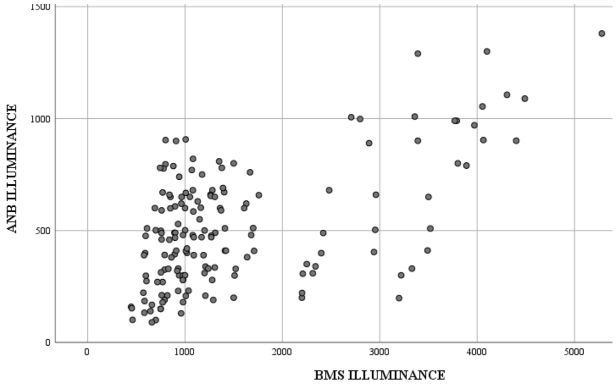
Note: Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is .05. And, the significance values have been adjusted by the Bonferroni correction for multiple tests.

3.4 Relationship Analysis Between the Strategies

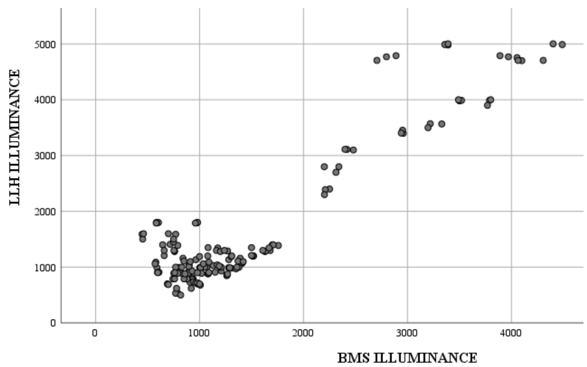
A Spearman's rank-order correlation was conducted to examine the relationship in illuminance between the three daylighting strategies (LLH, ANB and BMS). This is presented in Fig. 7 and Table 10.

4. Discussion

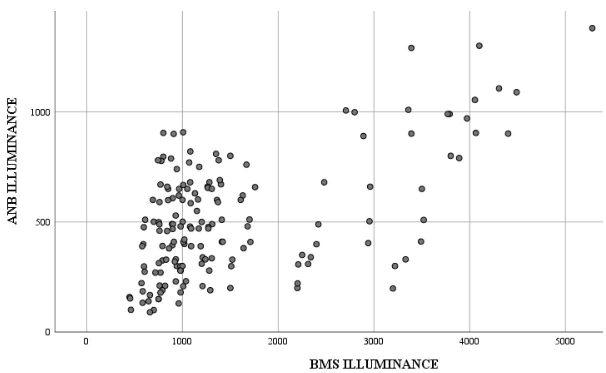
This study first identified three different combined daylighting strategies that have not been given adequate attention in terms of research in the tropical wet and dry climate of Nigeria. They are embedded in lecture rooms LLH, BMS and ANB (as described in section 2.1). Interestingly, these strategies have been used in many lecture rooms in the study area without recourse to whether they are performing to the design intent or not. This lack of attention to their performance is likely associated with the complexity of the design strategies with regards to the outdoor daylight [8-9] and the process of measurement in tropical wet and dry climate of Nigeria. In addition, the zeal for POE of buildings has already been detected to be low in the developing countries as reported in a previous study [18].



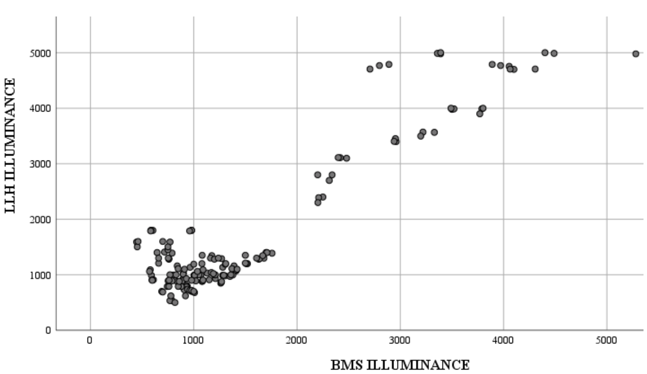
(a) BMS and ANB



(b) BMS and LLH



(c) BMS and ANB



(d) BMS and LLH

Fig. 7. Scatter plot showing illuminance distribution relationship between strategies

Table 10

Correlation analysis between the different strategies (Spearman's rho)

		LLH	ANB	BMS
LLH	Correlation Coefficient	1.000	.124	.568**
	Sig. (2-tailed)	-	.117	.000
	N	162	162	162
ANB	Correlation Coefficient	.124	1.000	.454**
	Sig. (2-tailed)	.117	-	.000
	N	162	162	162
BMS	Correlation Coefficient	.568**	.454**	1.000
	Sig. (2-tailed)	.000	.000	-
	N	162	162	162

Regrettably, the building manual [74] in the study area is silent about daylight design strategies or any specification with regards to daylight. The closest building regulation literature to the study area is the National Building Code [45] which specifies daylight factor of not less than 2% to cover the entire country (Nigeria) comprising the three distinct tropical climates (tropical dry, tropical wet and dry, and tropical wet climates) irrespective of WFR, orientation or shading strategy or building type. These three climates exhibit different environmental conditions with different supply of global illuminance, and as such, the recommendation of a specific daylight standard would not effectively favour all the climates at the same time. Worse still, the differences in hourly, monthly and seasonally supply of global illuminance raise doubt on the effectiveness of the use of daylight factor as a standard metric across board in the different climate as described in previous studies [62-63]. Daylight factor is best in overcast sky condition. For this study, illuminance and uniformity ratio were the metrics adopted for the daylight measurement since they are not specific to any sky condition.

For the experimental method used in this study, the light meter (HS 1010) was validated with an already calibrated meter. HS 1010 light meter has previously been deployed for similar evaluation of classrooms but in another context [69]. In that study, the instrument was not validated with an already calibrated instrument and issues such as shading strategy and multiple sky conditions were not considered for the study. In the present study, the use of the instrument was extended to other sky conditions (such as overcast and intermediate) and for the sake internal validity, the instrument was validated with an already calibrated daylight instrument. This validation is in alignment with previous studies [75-76]. The procedure of measurement in the morning, afternoon and evening of the different months in a year was followed due to the variability nature of daylight. Studies have already explained the dynamic nature of daylight that warrants continuous measurements in a day to have a realistic result [9, 31].

The results show that the month of April had the highest illuminance in the different lecture rooms. This was expected since April has the highest supply of global illuminance in the study area [66]. In the month of April with its clear sky characteristics, the strategy in lecture room LLH with E-W orientation gave an illuminance distribution that was within acceptable 300-2000 lux for morning and afternoon hours but in the evening, it was exposed to glare as the readings were above 2000 lux. The strategy in ANB lecture room produced an effective illuminance distribution as the readings were between 381- 405 lux all day. Strategy in BMS lecture room oriented E-W produced a similar distribution like LLH lecture room. These results suggest that during sunset, the strategies in LLH and BMS were not effective. However, these results were expected since sun sets in the west direction in addition to the great supply associated with clear sky condition [36]. This calls for the need to give attention to the west end of the lecture rooms. An option of changing the shading strategy to include horizontal members on the strategies could reduce the level of exposure to glare. An introduction of internal shading strategy such as venetian blinds could help to reduce the impact of glare from the west direction.

For the month of July representing the overcast sky condition, the strategies produced almost a similar reading to that of April in terms of the acceptable lower and upper limits. But in the evening, the readings were higher than that of April. A great difference was recorded for the month of October representing the intermediate sky condition. The strategies produced a distribution that was within acceptable limits. However, ANB room with N-S orientation had 168 lux in the evening which was lower than the acceptable 300 lux. This indicates that the daylight during sunset was too low in the lecture room, thereby calling for an optimisation. This optimisation can be through artificial lighting during evening periods in the intermediate sky condition. Expansion of the window width or height can also be considered but the cost involvement will be a good concern.

Furthermore, lecture rooms LLH and BMS representing 16-20% WFR and 12-15% respectively were only effective in intermediate sky but needs some control in other sky conditions especially during sunset. This seems to align with the provisions of previous studies [46, 48-49] where WFR 15-24% was recommended. In a similar vein, as earlier discussed, the result is consistent with the recommendation of the National Building Code [45] of WFR that is not less than 10%. Lecture room ANB that represented 0-11% WFR was effective in clear and overcast sky conditions but needs an upgrade in intermediate sky condition. This result is not congruent with the report that global supply of daylight in the intermediate sky condition is higher than that of the overcast sky [66]. However, the findings demonstrated that in some circumstances, the intermediate sky could be supplied with lesser global illuminance than the overcast sky. This further lends credence to the variability nature of daylight supply as reported in prior studies [8-9]. From another view, this result seems to suggest that bilateral shading strategy in combination with the WFR in the N-S orientation produces to a good extent, a favourable daylighting in the study area for lecture rooms. The difference in daylighting condition in the east and west ends of the room corroborates the findings of prior studies [11, 50-51] that daylighting is affected by orientation.

In terms of uniformity ratio, the combined strategy in LLH room was effective throughout the measurement periods except in the afternoon of April when it was less than 0.7. This suggests that the illuminance spread during that time was not sufficient to reach the target. This is in alignment with the illuminance value of that period which had the lowest reading. This also indicates that the learning condition in this lecture room is exposed to under-daylighting during clear sky condition. In ANB room, the U_o was only effective during the overcast sky condition. In clear and intermediate sky conditions, the U_o was also below acceptable levels. In BMS room, the only time the U_o was not effective was during the intermediate sky condition. The U_o was below acceptable levels in the month of October. For the poor spread of daylight in the rooms, optimisation with artificial lighting could up the illuminance level to achieve a balanced uniformity.

For the test of hypothesis, the null hypothesis of similarity of illuminance effectiveness across the different months for the strategy in LLH room was retained since the $p > .05$. This suggests that there was no satisfactory evidence to reject nullity. And as such, the illuminance could be said to be insignificantly different across the year with the strategy in LLH lecture room. For other strategies in ANB and BMS lecture rooms, there was enough evidence to reject nullity and the alternative hypotheses were accepted since there were significantly different in their illuminance performance thought out the year. It was based on $p<.05$ that post hoc analysis interpreted by Dunn's procedure was conducted. For ANB room, the pairwise comparison was significant for the months of October-July and April-July. For BMS room, significant difference was found in the months of October-July and October-April. These results infer that in the different sky conditions, different strategies perform differently and this calls for some interventions to address the insufficiency of illumination in lecture rooms in the study area. These interventions can be the augmentation of the illumination using electricity, the use of light shelves [77] that can reflect illuminance into the middle area of the lecture rooms.

The null hypothesis of similarity of illuminance effectiveness among the strategies was rejected as they were dissimilar in performance. This is seen in difference between ANB and BMS rooms, ANB and LLH rooms as indicated in the post hoc analysis. The alternative hypothesis was accepted. These findings suggest that every strategy of daylighting is peculiar and the need to study a particular strategy before adoption in any architectural design as this will enable an appropriate discernment to be made before its use.

For the correlation between the strategies, based on their performances, preliminary analysis showed the relationship to be monotonic, as assessed by visual inspection of a scatterplot in Fig. 6. The monotonic state elucidates that, it is either when one variable increases, the other increases or when one variable increases, the other decreases. Statistically significant correlation in illuminance distribution in LLH's strategy with strong positive association with BMS's indicates that they can possibly predict each other. Strategy in LLH has a weak positive correlation with ANB's but it is insignificant. This tends to show that there is a slim chance of prediction between strategies in LLH and ANB. This calls for further study to give adequate position to this prediction. The significant correlation of ANB's strategy with strong positive association with BMS's indicates that they can predict each other.

5. Conclusions

The inadequate research attention in tropical wet and dry climate to the performance of combined daylighting strategies of bilateral (a) glass louvre windows (covered with mesh net) complemented with terrace shading on both walls, WFR of 19% in E-W orientation, (b) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and blank wall on the opposite end, WFR of 11% in N-S orientation, and (c) glass louvre windows (with view and clerestory members) complemented with terrace shading on one wall and egg-crate on the opposite end, WFR of 14%, in E-W orientation was the interest for the present study. The strategies in a), b) and c) are used in lecture rooms LLH, ANB and BMS in the University of Uyo, Akwa Ibom State, Nigeria. The measuring instrument (HS 1010 light meter) was first validated, followed by the evaluation of the three strategies by finding the (a) difference in illuminance in terms of variations in sky conditions per strategy, (b) difference in illuminance distribution for the 3 strategies, and (c) relationship between the strategies. The following maybe concluded from the study.

1. In the month of April (clear sky condition), the strategy in lecture room LLH gave an effective illuminance performance for morning and afternoon hours, but in the evening, it was poor. A similar level of result was found for the strategy in lecture room BMS. The strategy in ANB lecture room produced an effective illuminance performance throughout the day.

2. In the month of July (overcast sky condition), a similar level of effectiveness like that of April was found even though in the evening, the results were slightly higher than that of April.

3. In the month of October (intermediate sky condition), all the strategies produced an effective illuminance performance. However, the strategy in ANB room was less than effective in the evening hours.

4. In terms of U_o, the strategy in LLH room was effective throughout the measurement periods except in the afternoon of April when it was less than effective. In ANB room, the U_o was only effective during the overcast sky condition. In clear and intermediate sky conditions, the U_o was not effective. In BMS room, the only time the U_o was not effective was during the intermediate sky condition.

5. The different combined strategies perform differently in the different sky conditions with slight similarities.

6. The strategy in LLH lecture room has a strong positive relationship with that of BMS and it was statistically significant. Possibly, the tendency of one predicting the other was high. The strategy in LLH has a weak positive correlation with ANB's and it is insignificant. This indicates a slim chance of prediction between strategies in LLH and ANB. Significantly strong positive correlation of ANB's strategy BMS's was found, indicating possibly, that they can predict each other.

The findings can help architects in making appropriate decisions on the choice of the daylight strategies during the design stage of building procurement (lecture rooms) in the tropical wet and dry climate. One of such decisions is the increase of WFR beyond 19%, however, care must be applied so that the lecture rooms will not be exposed to glare. The policy makers can better understand the performance of the combined strategies and necessary actions to take in this regard. The study has also contributed to the debate on daylighting strategies in the tropics.

5.1 Limitations and Directions for Future Research

The aforementioned results and their implications should be considered with several limitations. First, this study used illuminance as a static performance metric to evaluate the combined daylighting strategies. Thus, it will be useful if various dynamic performance metrics such as daylight autonomy, useful daylight illuminance are used to evaluate the strategies in the same setting.

Second, this study was conducted using a single day in each sky condition. This approach is prone to reporting none comprehensive daylight situation in the lecture rooms since daylight is dynamic with hourly and daily variations [8-9]. A different result may be reported if all the days in the different sky conditions were considered. Further studies should contemplate on measuring the total number of days in the sky conditions to avoid such potential problem.

In closing, other strategies in different buildings in the university setting should be studied to advance the debate of effectiveness performance of combined daylighting strategies in the tropical wet and dry climate. Optimisation study of the strategies should also be considered as this would shed further light on our understanding of the daylighting in the tropics.

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