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WHERE DO I SIT? A VISUAL COMFORT ANALYSIS OF GHANAIAN PUBLIC BASIC SCHOOLS BASED ON WINDOW-WALL RATIOS

Joyce Twumwaa Akubah[1], Barbara Simons[2]*, Samuel Amos-Abanyie[3], Michael Nii Addy[2]

[1]Department of Building Technology, Tamale Technical University, Tamale, Ghana
[2]Department of Construction Technology and Management, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[3]Department of Architecture, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

***Corresponding author: nanaakuaayebea@yahoo.co.uk**

ABSTRACT

This study analyses the visual comfort of classroom spaces of Public Basic Schools (PBSs) in Ghana based on window-to-wall ratios through a simulation approach. Three fenestration types were identified as being the most predominantly used openings in PBSs and therefore formed a focal part of the study. Eight scenarios based on the features of the classrooms were used in the simulations. It was found that an 8% WWR for a classroom was inadequate and would require supplementary lighting to be provided, irrespective of the fenestration type. This WWR would afford pupils sitting only at the edge of windows to be visually comfortable. In a scenario where a classroom has casement fenestration with 15% WWR and has verandahs on both side-lit walls with a North-South orientation, adequate daylight illuminance (≥ 200lux to<750lux) could be achieved for 63.4% to 65.1% of classroom space. Supplementary lighting would be required for the "middle front", and "middle back" of the classroom in both climatic zones. Comparatively, if the verandahs are East-West oriented, a much higher percentage of classroom area would receive adequate daylighting (66.4% to 73.4%) and would require supplementary lighting for occupants only in the "middle" and "middle back" areas of the classroom. This study opens up a new area that has been largely overlooked in Ghana.

Keywords: Public Basic Schools, Visual Comfort, Window-to-Wall Ratio, Simulation, Fenestrations

INTRODUCTION

Education plays a crucial role in the development and well-being of individuals and societies. The physical environment of classrooms, including seating arrangements, significantly impacts students' learning experiences (Gabryś-Barker, 2016). Winterbottom, and Wilkins (2009) have asserted that one of the most important aspects of classroom design is visual comfort, which is characterized as an individual's level of visual satisfaction and ease. Light (2011) defines visual comfort as ''a subjective visual well-being condition induced by the visual environment" which indicates the psychological dimension of comfort. Visual comfort is important in school buildings because students spend as much as 30% of their time studying at school (De Giuli *et al.*, 2012) hence encouraging visual comfort in the classroom is essential to student engagement, focus, and overall academic success (Beeland Jr, 2002).

Daylight primarily enters classrooms through windows (Izmir Tunahan *et al.*, 2021) and depending on the physical arrangement of desks and chairs, visual comfort can be significantly affected (Winterbottom and Wilkins, 2009). The orientation, layout and spacing may contribute to this (Kong *et al.*, 2018). As Al-Sallal (2010) alludes, direct sunlight due to inappropriate solar orientation (e.g., west or east), one-sided lit spaces and windows facing the students' eyes or the rear of a student's desk create serious problems of high brightness contrast and acute glare that result in deteriorating visual comfort and in some cases, causing health problems such as eyestrains in various forms, muscular aches and pain and general reactions such as fatigue, irritability and headaches.

According to a report by the Ministry of Education (2018), only 43% of Public Basic Schools in Ghana have access to electricity leaving well over 50% to solely rely on daylight for teaching and learning purposes. Whiles this is laudable, parameters such as the fenestration type and its position, window-to-wall ratio, orientation etc. has hindered visual comfort in most schools. A typical Public Basic School (PBS) block is composed of sandcrete blocks or in rare cases, mud and bricks. Depending on circumstances like the school's location, classrooms can range in size from $35m^2$ to $50m^2$ and can hold 35 to 60 pupils. The form of the structure is rectangular with verandah lying either on all four sides, two sides, a side or standing alone. Corrugated roofing sheets are used to cover the buildings, and the classrooms either have no ceiling material or little to none. Typically, interior walls are painted or are just plastered, while interior floors are screeded with mortar. The building is made up of separate, connected classrooms with an outdoor walkway on either one or both sides. The classrooms have access to natural light and ventilation through the doors and windows that extend out into the hallways. Fenestration variations include louvre blades, casement windows made of wood or metal, and design blocks placed in patterns with holes. To a large extent, daylight remain the only source of light for classroom activities in most schools. The Window-Wall Ratio (WWR) in most of these classrooms are very low thus not allowing much lighting into the interior spaces. Not until 2018, there was no standard of what WWR would be appropriate to allow enough daylight into these classrooms. The Ghana Building Code GS 1207-1:2018 (2018) was standardized and became a public document in 2018 to serve as a working document for the Ghanaian built environment. Clause 13.11.2 of the code on Public Basic Schools however recommends a minimum WWR of not less than 8% of the total floor area (which typically is 7mx8m) of the occupied room for natural illumination. The current study therefore analyses the classroom space to determine where one can sit to feel visually comfortable based on probed WWRs.

Windows are positioned to allow light to enter the classroom, especially for desk work but in most cases are woefully inadequate thus according to Brakopowers (2023), aside from the challenge with the learning space, classrooms in Ghanaian public schools are poorly lit, and this makes it difficult for learners to concentrate on classroom activities. This is reiterated by Yeboah (2016), Ackah-Jnr and Danso (2019) and Opoku-Nkoom and Ackah-Jnr (2023). One would therefore ask where do I sit to effectively perform my classroom duties? hence the study.

Stone (2022) asserted that the seat selection process is a result of the individual's prior experiences in that space or deliberate choices among alternatives while entering the space, regardless of whether deciding consciously or unconsciously (Kahneman, 2011). This assumption has also been supported, indicating that seating decisions could be different for individuals familiar and unfamiliar with the physical settings in the space because human response to the physical environment is strongly subject to prior experiences (Keskin, 2019). In that case, students can choose to sit or not to sit at a position in class based on how comfortable they were the last time they sat at that particular location. The degree of freedom of choice could also influence the seating decision because individuals can choose only available seats or space. For instance, the first set of students who come to class early would sit where they prefer to sit as compared to the student who comes in late and will have no option but to sit at the only seat available. However, understanding occupant behaviour and their interaction with the indoor environment could help improve the occupants' satisfaction (Paone and Bacher, 2018).

Previous studies have shown that daylight is the most dominant reason when selecting desks, followed by privacy, outdoor view, and quietness. Although the reasons for seat selection varied, the majority of the participants agreed that a satisfactory daylighting level, facing the least number of people, and a greenery outdoor view were particular reasons for seat selection (Izmir Tunahan *et al.*, 2021). The authors further mentioned that people avoid selecting places with insufficient daylight and unacceptable levels of daylight which usually result in visual discomfort.

Some studies reported that enhancing visual comfort could indirectly improve occupants' perception of thermal satisfaction (Garretón *et al.*, 2016). The study of Al-Sallal (2010) affirms this by highlighting that proper lighting designs can improve visual comfort which is crucial for students' concentration and learning efficiency. An indoor environment with good indoor environmental quality (IEQ), which includes lighting improves the occupant's mood, which affects the comfort perception of the occupant (Kapoor *et al.*, 2021). However, poor seating arrangements, inadequate lighting, and inappropriate visual stimuli can lead to distractions, reduced attention spans, and visual fatigue (Meng, 2023). In addition, Al-Sallal (2010) mentioned space size and depth-to-height ratio, window orientation, lighting direction and desk position as some design issues that impact visual quality.

MATERIALS AND METHODS

Study area and Physical Characteristics of Public Basic Schools in Ghana

The study considered basic schools located within the Savannah and Wet Equatorial climatic Regions of Ghana. PBS buildings are made up of separate, connected classrooms with an outside walkway on either one or both sides. The doors and windows that open into the corridors provide natural light and ventilation into the classrooms. Fenestration variations include casement windows made of wood or metal, design blocks placed in patterns with holes and louvre blades (Uduku, 2015). This was confirmed through a pilot study. Windows are positioned to allow light to enter the classroom, especially for desk work. However, in some cases, this may not be practical because preschoolers may use shorter furniture, which could put them below the level of daylight entry. The 3 fenestration types above were therefore used in the current study. Figures 1-3 show images of the fenestration types while Figure 4 indicates a typical classroom sitting layout.

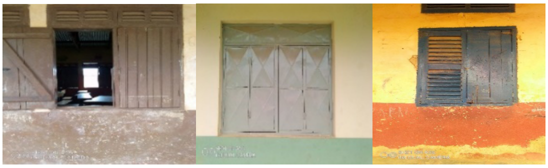

Figure1: Variations of Casement fenestrations used in Public Basic Schools

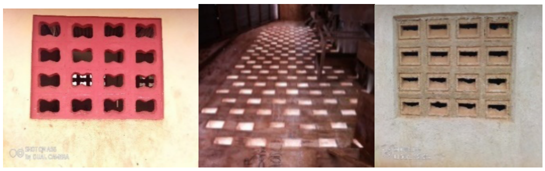

Figure 2: Variations of Design blocks used in Public Basic Schools

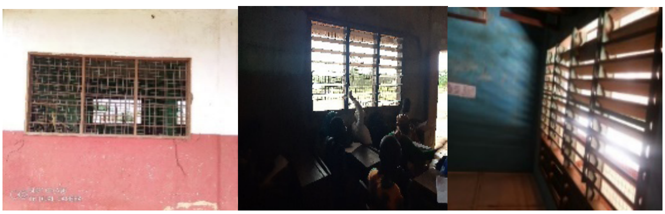

Figure 3: Variations of Louvre blade fenestration used in Public Basic Schools

Figure 4: A typical seating arrangement in a block of classrooms

Simulation and WWR Options

The simulation parameters were used to model the various classroom blocks in Autodesk Revit 2019 (Table I) based on the proposed typologies which aided in the development of the daylight design after which the UDI and sDA were assessed. Figure 5 for instance shows the model of a typical louvre blade classroom with a single verandah. Double verandah and no verandah typologies. The models were subsequently exported into Rhino and then into Grasshopper, a graphical algorithm editor serving as a parametric modelling link for Rhino. Ladybug and Honeybee software which are plug-ins for Rhino were also used in the performance of environmental analysis in terms of the computation of the various metrics of daylight illuminance adopted for the study. In addition, the software Cove. tool, an automated design platform which employs ASHRAE 2019 as a guideline for intelligent building performance was used for simulating parametric cost versus daylight optimization. This simulation software also allowed for a Revit plugin which allowed easy import of the modelled blocks onto the Cove. tool platform and presentation of 3D visualizations for daylight and glare for this study.

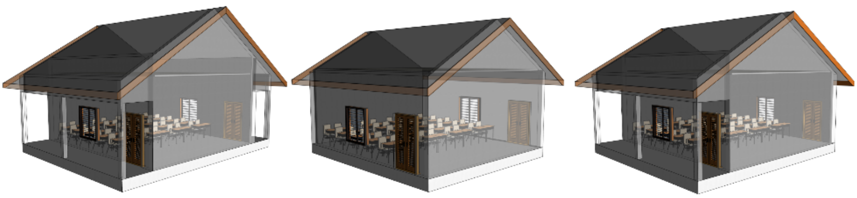

Figure 5: Modelled louvre blade classroom with verandah placement variations

The study proposed to investigate the minimum Wall-To-Window ratio recommended by Ghana Building Code GS 1207-1:2018 (2018) and build on that to determine if daylight illuminance levels would improve with a bigger WWR while at the same time, taking note of glare issues. The WWR investigated by the study were 8%, 15%, 23% and 31%. The simulation parameters based on the Ghana Building Code specifications and literature are shown in Table I below with the proposed typologies indicated in Table II. The WWR in relation to the windows probed in the study therefore are as follows:

- WWR-8% (Two 2-bay windows, one on each side-lit wall and 2 doors),
- WWR-15% (Four 2-bay windows, two on each side-lit wall and 2 doors),
- WWR-23% (Six 2-bay windows, three on each side-lit wall and 2 doors), and
- WWR-31% (Eight 2-bay windows, four on each side-lit wall and 2 doors).

Figure 6 indicates the plan view of the single verandah typology for all fenestration types based on the above WWRs.

Daylight Metrics Used

With reference to literature, (Madaljevic et.al., 2009:2012; IESNA 2012) 2 climate-based daylight assessment metrics were used for this study, thus Useful Daylight Illuminance (UDI) and Spatial Daylight Autonomy (sDA). The use of UDI provided the opportunity of annually forecasting daylight over a given portion of space for a specific percentage of time during the day where the required visual task uses only daylight (Reinhart *et al.,* 2006) whiles the sDA gauged the percentage of the occupied hours that exceeded the set minimum illuminance threshold by the study which is the percentage of the floor area within the classroom space which exceeded a threshold illuminance of 300lux for a specific number of hours within the year (at least 50% of the total hours of occupation for 55% of the floor area as acceptable or 75% as preferred).

Table 1: Simulation parameters (based on the Ghana Building Code)

Class measurement (metres)	Ceiling	Orientation	Verandah/ Size (metres)	Doors	Window type/ description/ Measurement (metres)	Classroom Wall colour
Length (7) Width (8) Height (3.6)	White	Varies	1.5	One door on each side of external wall; (Width -1.2; Height - 2.1)	Louvre blade/ Casement/ Design Blocks/2-bay windows in variations of 1,2,3 and 4 sets along each opposite walls (Width 1.4; Height -1.5)	Off-White

Table 2: Characteristics of proposed typologies

Typologies	Description	Orientation	WWR	Verandah/Overhang
Case One	Single Verandah on North facing windows, South in direct contact with sun	North-South	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at north side; o.6m overhang at south side
Case Two	Single Verandah on South facing windows, North in direct contact with sun	North-South	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at south side; o.6m overhang at north side
Case Three	Single Verandah on East facing windows, West in direct contact with sun	East-West	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at east side; o.6m overhang at west side
Case Four	Single Verandah on west facing windows, East in direct contact with sun	East-West	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at west side; o.6m overhang at east side
Case Five	Verandah on both North and South facing windows	North-South	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at both north and south sides
Case Six	Verandah on both East and West facing windows	East-West	8%, 15%, 23%, 31%	1.5m verandah with o.6m overhang at both east and west sides
Case Seven	No verandah, NS oriented windows	North-South	8%, 15%, 23%, 31%	No verandah; o.6m roof overhang at both north and south sides
Case Eight	No verandah, EW oriented windows	East-West	8%, 15%, 23%, 31%	No verandah; o.6m roof overhang at both east and west sides

a b c d

Figure 6: Plans for Single Verandah Typology for all fenestrations (Rotate as North, South, East or West) for a. 8% WWR, b. 15%WWR c. 23%WWR, d. 31% WWR

Simulated data depicting daylight conditions within the classrooms and data from the proposed typologies were analysed using the standard compliance levels for the adopted metrics to determine when illuminance ranges were in compliance. According to clause 28.5.1.3 of the Ghana Building Code GS 1207-1:2018 (2018), recommended illuminance levels for educational spaces include a range of 200-300-500 lux for teaching spaces, lecture theatres, library, music and sports rooms and workshops and a range of 300-500-750 lux is set for demonstration benches, seminar rooms, art rooms, needlework rooms and laboratories. However, classrooms in PBS in Ghana mostly utilize the classroom space for other activities which include art works, needlework, demonstrations and other fine works. Therefore, the minimum illuminance of 200 lux and a maximum illuminance of 3000lux was adopted to conform to UDI-a in compliance with UDI benchmarks by Nabil and Mardaljevic (2006); Zomorodian and Tahsildoost (2019); Shafavi *et al.* (2020).

A modified version of the methodology adopted by Moreno and Labarca (2015) was adapted for defining the ranges of compliance for UDI in this study. Moreno and Labarca (2015) used the categories "too low" at 200 lux; "low" at 200 lux to 300 lux; "in range" from 300 lux to 2000 lux; and "high" at 2000 lux to 3000 lux to predetermined ranges of illumination attained. This study however, adopted the main ranges including "low" for when illuminances are not suitable/ "fell-short" (below 200 lux adopted from Ghana Building Code GS 1207-1:2018 (2018) and supplementary lighting will be needed. Also, illuminance "in range" was ≥ 200 lux to <750 lux for when illuminances suitable for visual tasks were in compliance with the Ghana Building Code (GS 1207-1:2018, 2018). The high limits were also defined with the aim of recognizing when lux levels exceed the recommended levels in the Ghana Building Code (GS 1207-1:2018, 2018) and also recognizing the area of space and time at which the classrooms are at risk of glare. Therefore the "high" range (≥750 lux to ≥ 2000 lux) was set for when illuminances were above the recommended illuminance of 750lux but still within 2000lux and "too high" (≥ 2000 lux to ≥ 3000 lux) for when illuminances exceeded 3000 lux (UDI-e).

RESULTS AND DISCUSSION

This section presents the Tabulated data relating to daylight distributions throughout the classrooms based on the WWRs as well as the fenestration types. Table 3 presents details of each fenestration type for the various typologies under study for 8% WWR. Here, single verandahs on either the North or the South facing side-lit windows would likely require supplementary lighting within the whole classroom. This is corroborated by the fact that sDA was not "acceptable", meaning the classroom would not be able to maintain an illuminance of 300lux for at least 55% of the classroom area for 50% of the occupation time of 7am to 3pm.

Though about 60% of the classroom area with louvre blade fenestration with no verandahs would likely receive daylight illuminance between 200 lux to 750 lux, supplementary lighting would still be needed within the "edge with no window", "middle front", "middle" and "middle back" of the classroom space (refer to Fig. 4). In this case however, issues of glare are likely to occur within 3.3% to 5.1% and 2.5% to 3.1% of classroom space in the savannah and wet equatorial climate respectively for a North-South oriented block with no verandahs. Meanwhile for an East-West oriented block with no verandahs for this case, about 6.2% to 8.1% and 4.2% to 5.1% of classroom space respectively would likely experience glare issues.

The likely daylight performance of a classroom with a 15% WWR with either louvre, design block or casement fenestrations is illustrated in Table IV. A classroom with casement window at 15% WWR would need no supplementary lighting if there are no verandahs and orientation is either North-South or East- West. Supplementary lighting would be required for the whole space of a classroom with louvre blade fenestration and a single verandah on the South and verandah on both North/South facing windows. However, for a single verandah on the North only the "middle", "middle front" and "middle back" areas will require supplementary lighting. In the case of a single verandah on the East or West facing side-lit wall, occupants seated in the "middle" only would require supplementary lighting. Supplementary lighting would be required for the whole space of a classroom with design block fenestration with a 15% WWR and a single verandah on the North or South. However, for a single verandah on the East and West only the "edge with no window", "middle" and "middle back" areas will require supplementary lighting. Meanwhile, the likelihood of experiencing glare will occur if the classrom has a single verandah on west facing windows with the East in direct contact with the sun. In the case where the classroom has verandahs on both side-lit walls with a North-South orientation, adequate daylight illuminance (≥ 200lux to<750lux) could be achieved for 36.4% to 40.5% and 37.6% to 40.7% of classroom space. Supplementary lighting would be required for the "middle front", "middle" and "middle back" of the classroom. Comparatively, if the verandahs are East-West oriented, a much higher percentage of classroom area would receive adequate daylighting (68.8% to 72.9%) and would require supplementary lighting for occupants only in the "middle" and "middle back" areas of the classroom.

In a scenario where a classroom has casement fenestration with 15% WWR and has verandahs on both side-lit walls with a North-South orientation, adequate daylight illuminance (≥ 200lux to<750lux) could be achieved for 63.4% to 65.1% of classroom space. Supplementary lighting would be required for the "middle front", and "middle back" of the classroom in both climatic zones. Comparatively, if the verandahs are East-West oriented, a much higher percentage of classroom area would receive adequate daylighting (66.4% to 73.4%) and would require supplementary lighting for occupants only in the "middle" and "middle back" areas of the classroom.

Table 3: 8% WWR (Two 2-Bay Windows) in a Casement, Design Blocks and Louvre blade classrooms

Design typology/ Orientation	Casement				Design Blocks				Louvre Blade			
	Area with adequate daylight (≥ 200lux to<750lux)	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**	**Area with adequate daylight (≥ 200lux to<750lux)**	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**	**Area with adequate daylight (≥ 200lux to<750lux)**	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**
Single Verandah on North facing windows, South in direct contact with sun	50.2%-55.8%	ENW, M, MF, MB	0.8%-1.3%	Not acceptable	28.7%-37.9%	Whole	0% -0%	Not acceptable	39.5%-49.5%	Whole	0%-1.1%	Not acceptable
Single Verandah on South facing windows, North in direct contact with sun	55.2%-58.7%	ENW, M, MF, MB	0.8%-1.4%	Not acceptable	32.9%-39.8%	Whole	0%-0%	Not acceptable	42.4%-52.4%	Whole	0%-1.3%	Not acceptable

Single Verandah on East facing windows, West in direct contact with sun	58.4%-62.1%	ENW, M, MF, MB	1.1%-1.6.1%	Not acceptable	37.9%-41.3%	Whole	0%-0%	Not acceptable	49.4%-59.6%	Whole	0.2%-2.7%	Acceptable
Single Verandah on west facing windows, East in direct contact with sun	61.2%-64.7%	M, MF, MB	1.3%-1.8%	Not acceptable	48.7%-49.3%	Whole	0%-0.2%	Not acceptable	53.6%-64.5%	MF, M, MB	1.2%-3.2%	Acceptable
Verandah on both North and South facing windows	46.7%-51.1%	ENW, M, MF, MB	2.2%-4.1%	Not acceptable	14.1%-15.1%	Whole	0%-0%	Not acceptable	20.3%-30.1%	Whole	0.4%-0.7%	Not acceptable
Verandah on both East and West facing windows	53.3%-59.7%	MF, M, MB	3.3%-5.4%	Not acceptable	26.8%-30.5%	Whole	0%-0.2%	Not acceptable	44.9%-45.4%	MF, M, MB	0.4%-1.3%	Not acceptable
No verandah, NS oriented windows	54.3%-57.8%	MF	5.1%-6.7%	Acceptable	58.5%-63.8%	MF, M, MB	0.7%-1.3%	Acceptable	50.1%-60.5%	MF, M, MB	3.3%-5.1%	Acceptable
No verandah, EW oriented windows	65.5%-68.9%	None	6.1%-7.7%	Acceptable	58.9%-62.9%	ENW, MF, M, MB	2.5%-3.1%	Acceptable	44.1%-55.3%	MF, M, MB	6.2%-8.1%.	Acceptable

***M-Middle *MB-Middle Back *MF-Middle Front *ENW -Edge with no window *EBW – Edge by window**

Table 4: 15% WWR (Four 2-Bay Windows) in a Casement, Design Blocks and Louvre blade classrooms

Design typology/ Orientation	Casement				Design Blocks				Louvre Blade			
	Area with adequate daylight (≥ 200lux to<750lux)	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**	**Area with adequate daylight (≥ 200lux to<750lux)**	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**	**Area with adequate daylight (≥ 200lux to<750lux)**	**Section requiring supplementary lighting (<200lux)**	**Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)**	**sDA for 50% of occupation time (7am-3pm)**
Single Verandah on North facing windows, South in direct contact with sun	62.3%-67.3%	MF, MB	1.8%-3.2%	Not acceptable	41.7%-47.9%	Whole	0%-0%	Not acceptable	58.7%-69.4%	MF, M, MB	1.2%-2.2%	Not acceptable
Single Verandah on South facing windows, North in direct contact with sun	64.4%-68.7%	MF, MB	2.1%-4.9%	Not acceptable	44.3%-48.9%	Whole	0%-0%	Not acceptable	55.1%-65.2%	Whole	2.2%-7.1%	Not acceptable

Single Verandah on East facing windows, West in direct contact with sun	64.3%-68.8%	MF, MB	3.2%-4.9%	Acceptable	49.3%-51.1%	ENW, M, MB	0%-0%	Not acceptable	58.9/5-69.6%	M	2.2%-5.5%	Acceptable
Single Verandah on west facing windows, East in direct contact with sun	67.1%-69.7%	MF, MB	5.2%-5.9%	Acceptable	58.7%-60.3%	Whole	0%-1.2%	Acceptable	63.2%-74.4%	M	5.2%-9.7%	Acceptable
Verandah on both North and South facing windows	63.4%-65.1%	MF, MB	3.1%-3.9%	Not acceptable	15.4%-20%	Whole	0%-0.1%	Not acceptable	33.9%-35.9%	Whole	1.4%-2.8%	Not acceptable
Verandah on both East and West facing windows	66.4%-73.4%	MF, MB	3.4%-4.0%	Not acceptable	36.4%-40.5%	MF, M, MB	0%-0.2%	Not acceptable	44.7%-53.3%	M, MB	1.5%-2.3%	Not acceptable

No verandah, NS oriented windows	74.2%-76.9%	None	12.9%-15.5%	Acceptable	68.8%-72.9%	M	5.0%-5.2%	Acceptable	61.5%-70.3%	None	8.3%-13.3%	Acceptable
No verandah, EW oriented windows	74.7%-78.5%	None	15.9%-18.5%	Acceptable	77.7%-82.1%	M	6.0%-10.2%	Acceptable	63.4%-73.4%	None	10%-2.3%	Acceptable

***M-Middle *MB-Middle Back *MF-Middle Front *ENW -Edge with no window *EBW – Edge by window**

The daylight occurrence in classrooms with 23% WWR is shown in Table V below. Classrooms with louvre blade fenestration and a verandah on either a North or South facing side-lit would be able to maintain an illuminance of 300lux for at least 55% of the classroom area of classroom area for 50% of the occupation time of 7am to 3pm as sDA levels are "acceptable". In the case where the verandahs are either on the East or West facing side-lit wall a "preferred" sDA is likely to be achieved for at least 75% of the classroom area of classroom area for 50% of the occupation time of 7am to 3pm. Supplementary lighting would be required for occupants in the "middle front" and "middle back" for a verandah on the North, "middle front", "middle" and "middle back" for a verandah on the south and "middle" for a verandah on the East side-lit wall. In the case of the verandah being on the West side-lit wall, occupants will likely not require supplementary lighting.

When a classroom block has a design block fenestration but has no verndahs on any side-lit wall, adequate daylight would be achieved for as much as 75.3% to 80.4% of classroom space when the block is North-South oriented. In the case where it is East-West oriented, 85.2% to 89.0% would receive daylight illuminance reaching between 200 lux to 750 lux. Supplementary lighting would not be required in this case. Also, glare would not be a source of discomfort for occupants. In addition, the classrooms would be able to maintain an illuminance of 300lux for at least 75% of the classroom area for 50% of the occupation time of 7am to 3pm as sDA levels are "preferred". That notwithstanding, the issue of thermal discomfort which could be felt by the occupants because of the East-West orientation needs to be looked at.

In the case of a classroom with casement fenestration with a verandah on both side-lit walls facing North-South, the percentage of classroom area receiving adequate daylighting would likely reduce to between 62.1% to 66.3%. For an East-West orientation, areas receiving adequate daylighting would further reduce to between 58.7%-65.9%. Supplementary lighting would still be required for both North-South ("middle front" and "middle back") and East-West oriented blocks ("middle"). In all the cases of classrooms with casement fenestration with single verandahs, supplementary lighting would be required for the occupants seated at "middle", for North or South facing side-lit walls and only in the "middle front" for East or West facing side-lit walls irrespective of the two climatic zones. sDA levels would be "acceptable" for all cases with single verandahs in this typology.

Table 5: 23% WWR (Six 2-Bay Windows) in a Casement, Design Blocks and Louvre blade classrooms

Design typology/ Orientation	Casement				Design Blocks				Louvre Blade			
	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)
Single Verandah on North facing windows, South in direct contact with sun	69.1%-75.2%	M	12.2%-13.7%	Acceptable	64.1%-67.9%	MF, M, MB	4.2%-5.7%	Acceptable	63.8%-74.6%	MF, MB	6.6%-7.6%	Acceptable

Single Verandah on South facing windows, North in direct contact with sun	**69.1%-75.2%**	**MF**	**12.2%-13.7%**	**Acceptable**	**67.8%-71.9%**	**MF, M, MB**	**4.3%-6.1%**	**Acceptable**	**65.2%-70.6%**	**MF, M, MB**	**7.8%-8.4%**	**Acceptable**
Single Verandah on East facing windows, West in direct contact with sun	66.2%-71.1%	None	12.1%-14.1%	Acceptable	69.4%-73.9%	MF, MB	5.0%-5.5%	Acceptable	70.7%-74.9%	M	8.7%-10.5%	Preferred
Single Verandah on west facing windows, East in direct contact with sun	**65.9%-70.9%**	**None**	**11.7%-14.2%**	**Acceptable**	**69.9%-74.6%**	**MF, MB**	**5.6%-6.2%**	**Acceptable**	**74.2%-79.2%**	**None**	**10.3%-17.7%**	**Preferred**

Verandah on both North and South facing windows	62.1%-66.3%	MF, MB	11.0%-12.2%	Not acceptable	57.9%-65.2%	MF, M, MB	4.0%-5.0%	Not acceptable	54.5%-56.0%	MF, M, MB	6.5%-6.7%	Acceptable
Verandah on both East and West facing windows	58.7%-65.9%	MF	10.3%-13.3%	Not acceptable	58.2%-69.6%	MF, MB	4.3%-5.3%	Not acceptable	53.9%-56.2%	MF, MB	6.2%-7.9%	Acceptable
No verandah, NS oriented windows	59.2%-65.5%	None	20.8%-22.1%	Acceptable	75.3%-80.4%	None	7.0%-7.5%	Preferred	57.4%-62.9%	None	23.5%-27.2%	Preferred
No verandah, EW oriented windows	58.7%-64.1%	None	20.8%-29.8%	Preferred	85.2%-89.0%	None	7.6%-8.2%	Preferred	46.5%-57.1%	None	26.9%-31.5%	Preferred

***M-Middle *MB-Middle Back *MF-Middle Front *ENW -Edge with no window *EBW – Edge by window**

The likely daylight performance of classrooms with 31% WWR with either louvre, design block or casement fenestrations are highlighted in Table 4.

In all cases of classrooms with louvre blade fenestration and single verandahs, supplementary lighting would be required for the occupants seated at "middle" and "middle front" for North or South facing side-lit walls and only in the "middle" for East facing side-lit walls irrespective of the two climatic zones. In the case where the single verandah is on the west facing windows with the East in direct contact with sun, no supplementary lighting would be required, though glare would cause discomfort for up to 10.2%-11.3%. sDA levels would be "acceptable" for all cases with single verandahs on North or South facing side-lit walls and would be "preferred" on East or West facing side-lit walls.

A North or South oriented design block fenestration classroom with a single verandah facing the side-lit wall would have up to 74.1% of its classroom space receiving between 200 lux to 750 lux of daylight. East and West facing side-lit walls with verandahs however, would have up to 79.8% receiving adeqaute daylight illuminance. In the case of a classroom with a verandah on both side-lit walls facing North-South, the percentage of classroom area receiving adequate daylighting would likely reduce to between 60.2% to 66.2%.

A North, South, East or West facing single verandah by a side-lit wall casement classroom would have up to 70% - 80% of classroom area receiving adequate daylight (between 200 lux and 750 lux) in both savannah and wet equatorial climatic areas. None of the side-lit windows with verandahs on any orientation would likely require supplementary lighting. sDA would be "acceptable" in North or South and "preferred" on East or West oriented verandahs on side-lit walls.

The recommended WWR of 8% of the total floor area of occupied space in Clause 13.11.2 of the Ghana Building Code GS 1207-1:2018 (2018), was found to be ineffective and not able to provide adequate daylight for the studied classrooms. The study revealed that even at 15%WWR, classrooms struggled to attain adequate daylighting levels. This was more prominent with classrooms with either louvre or design block fenestartions. The suggestions for an optmial WWR have been linked to location and climate (Alwetaishi, 2019; Sayadi *et al.*, 2021). Studies such as Shaeri *et al.* (2019) who researched into the optimum window-to-wall ratio of office buildings in hot–humid, hot–dry, and cold climates in Iran, suggested optimal WWR ranges of between at least 10% to 30% for all the investigated climates. Irrespective of where one will sit in an 8% WWR classroom, daylighting alone would not be adequate to achieve visual comfort as indicated in Table III. As the window-to-wall ratio is increased, one can deliberately choose a seat that would aid in visual comfort across the fenestration types. For no verandah north-south and east-west oriented windows, casement and louvre blade will provide the entire space with visual comfort such that no supplementary lighting would be needed when WWR is 15%. Though with the same WWR, the condition cannot hold for design blocks classrooms whose middle portions would need to be artificially lit. A study by Fallah (2019) also suggested optimal WWR should be 30% for the southern façades in hot-dry climates when they are equipped with double-glazed windows but 15% while using single-glazed windows. Palarino and Piderit (2020) have also suggested a 20% to 40% WWR for side-lit working spaces whiles Alwetaishi (2019) suggests that WWR of 25% is preferable in hot climates in order to control the excessive heat gain in summer.

Table 6: 31% WWR (Eight 2-Bay Windows) in a Casement, Design Blocks and Louvre blade classrooms

Design typology/ Orientation	Casement				Design Blocks				Louvre Blade			
	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)	Area with adequate daylight (≥ 200lux to<750lux)	Section requiring supplementary lighting (<200lux)	Area with likelihood of glare (≥ 750 lux to ≥ 3000 lux)	sDA for 50% of occupation time (7am-3pm)
Single Verandah on North facing windows, South in direct contact with sun	66.6%-70.2%	None	6.9%-14.7%	Acceptable	65.5%-73.7%	MB	3.2%-5.2%	Acceptable	65.2%-75.3%	MF, M	8.2%-9.6%	Acceptable
Single Verandah on South facing windows, North in direct contact with sun	64.7%-72.1%	None	6.4%-12.8%	Acceptable	68.9%-74.1%	MB	4.5%-7.1%	Acceptable	67.7%-76.4%	MF, M	8.2%-9.3%	Acceptable

Single Verandah on East facing windows, West in direct contact with sun	61.9%-68.3%	None	12.2%-13.2%	Preferred	75.2%-78.9%	None	5.8%-7.5%	Preferred	65.2%-75.5%	M	9.9%-10.3%	Preferred
Single Verandah on west facing windows, East in direct contact with sun	60.7%-66.3%	None	15.9%-16.0%	Preferred	77.7%-79.8%	None	4.8%-8.3%	Preferred	63.7%-77.2%	None	10.2%-11.3%	Preferred
Verandah on both North and South facing windows	66.2%-72.3%	None	12.3%-15.3%	Acceptable	60.2%-66.2%	MF, MB	5.2%-6.3%	Acceptable	61.6%-71.6%	M, MB	7.5%-8.6%	Acceptable
Verandah on both East and West facing windows	63.3%-68.9%	None	11.2%-12.7%	Acceptable	65.4%-69.6%	MF, MB	7.3%-9.8%	Acceptable	55.9%-66.8%	None	7.6%-8.5%	Acceptable

No verandah, NS oriented windows	55.5%-60.9%	None	15.4%-21.9%	Preferred	65.9%-74.6%	None	7.3%-11.6%	Preferred	58.4%-63%	None	15.2%-16.1%	Preferred
No verandah, EW oriented windows	38.4%-44.1%	None	25.4%-29.9%	Preferred	69.4%-73.2%	None	9.3%-14.1%	Preferred	48.4%-58.4%	None	16.0%-17.9%	Preferred

***M-Middle *MB-Middle Back *MF-Middle Front *ENW -Edge with no window *EBW – Edge by window**

These suggestions appear to be true for the current study based on the results. That is, whiles the smaller WWR (8%) have led to almost the whole space needing supplementary lighting, 15% to 31% have provided certain spaces with visual comfort with 31% WWR providing full visual comfort with no supplementary lighting if the fenestration type is casement. This therefore could afford the pupils the freedom of choosing these areas to sit. The study has also showed that if the design of the classroom block was to include a verandah on one side, the WWR should be at least 23% to 31% of the total classroom space. In the case where the design would include a verandah by both side-lit walls, the block would perform better if it was East-West oriented with at least 23% to 31% WWR. If the classroom design would not include a verandah, the least WWR considered should be 15% and if oriented in the North-South orientation, will suffer less glare than if oriented in the East-West orientation. Alozie and Alozie (2016) have made similar recommendations with regards to the use of verandahs as a way of shading side-lighted windows. Meanwhile, Alwetaishi (2019) suggests that, it is preferable to maximise the elongation in east and west axis in hot climates whiles Kim *et al.* (2016) has also described the west orientation as providing the highest influence on energy load but will be proper for optimizing daylight in a working space. This study further revealed that the use of verandahs on both side-lit walls for all the fenestrations and single verandahs for North-South facing side-lit walls would require supplementary lighting in the middle portions of classrooms and for 8% to 15% WWR, supplementary lighting would be required for the whole classroom. This is because daylight penetration is lower with the use of a single or double verandah and can be more problematic in spaces like classrooms with a large depth. Therefore with 8% to 15% WWR, penetration to the innermost portions of the classrooms especially in the case of a double verandah would be difficult and would require some form of supplementary lighting in order to enhance visual comfort. Sepúlveda *et al. (*2020) who studied room depth and the effect on choice of shading found that the North East, North West and West oriented office rooms studied with depths of at least 3.5 m did not fulfill sDA of 55% when shading was used. The results of the study further showed that if the casement fenestration was selected as a fenestration option, designs to combat glare should be considered for all design typologies with WWR of 8% to 31%. If the design block was selected, patterned glare arising from the shapes of the design blocks falling on horizontal and vertical spaces should be considered in the design decision process. Issues with glare would be minimal in a louvre blade fenestrated classroom as the occupants would be able to regulate the fenestration to protect themselves. The higher the WWR of casement fenestration, the lesser the areas "in-range" and the higher the areas with "high" and "too high" illuminances of over 2000lux. In some cases, especially at WWR of 31%, some design block typologies which consistently performed least in daylight quantity, recorded more percentage of classroom space with 200lux to 750lux than the casement fenestration. This signifies that larger opening bring both good daylight for visual comfort and glare which produces visual discomfort.

CONCLUSION

Daylighting as we well know it has enormous benefits for the human system. The right amount of it at the right time in classroom spaces for instance continue to benefit not only the human body but also a drastic reduction on the use of supplementary light which has a heavy toll on energy. With well over 50% of Public Basic Schools in Ghana solely relying on daylighting, it is imperative that it's design should be well thought through for pupils to achieve comfort. In the investigated scenarios and fenestration types, the design block as a fenestration type was found to perform poorly across all the scenarios causing the need for supplementary lighting within the classroom spaces. This was followed by the louvre blades which had problems providing good visual comfort for those who sat in the middle front, middle and middle back and sometimes the entire classroom space if the WWR was 8% for instance. It can therefore be concluded that the use of design blocks as fenestrations should be re-looked at. Classroom blocks should look at a design with bigger and wider voids to bring in a lot more light. This study recommends future research on subjective evaluation of daylight in classrooms. Another direction could be a typical case analysis of daylighting of a Public Basic School in Ghana.

Declaration of Conflict Of Interest

The authors declare that there is no conflict of interest in this study.

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