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Research Article

Window Area Effects on Air Movement in Naturally Ventilated Living Rooms in Enugu State Housing Development Corporation High-Density Estates, Nigeria

Aloysius O. Onochie[1*], Oluchi C. Ifebi[2], Charles C. Munonye[2], Kelechi E, Ezeji and Chukwunonso O. Umeora[2]

[1] Department of Architecture, Nnamdi Azikiwe University, Awka, Nigeria

[2] Department of Architecture, Chukwuemeka Odumegwu Ojukwu University, Anambra State, Nigeria

*Corresponding Author: Aloysius O. Onochie, E-mail: ossyonochie1@gmail.com

Abstract

The performance of natural ventilation in a building relates to the design parameters of window areas as control mechanisms to regulate air movement and thermal comfort levels. This study assessed the relationship between window area and air movement levels in 433 units of naturally ventilated living rooms in Enugu State Housing Development Corporation (ESHDC) high-density estates in Enugu Capital Territory, Nigeria. The study was conducted in the evenings during the peak of the rainy season in the warm and humid tropical climate of southern Nigeria. The findings showed that the recorded air movement values were below the acceptable threshold recommended by ASHRAE standard 55 and ISO 7730 standards. The results showed that 53.7% of the occupants voted 'acceptable' for LAMA (Level of Air Movement Acceptability), indicating that the recorded air movement levels were less than the 80% minimum benchmark of ASHRAE's definition of thermal acceptability. The Pearson product-moment correlation tool was used to test the significant relationship. The result indicated a significant relationship between window area and air movement sensation levels in naturally ventilated living rooms in warm and humid tropical climates. Therefore, this study aligns and recommends that a window area >30% <50% WWR of the wall surface allows more airflow and enhances air movement levels than a window area of >10% <30% WWR of the wall surface.

Keywords: Air movement levels, Living room, Natural ventilation, Thermal acceptability, Window area, Warm-humid tropical climate.

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1. Introduction

Achieving comfortable thermal environments in enclosed spaces, such as living rooms, in warm and humid tropical regions without using mechanical means has become a major design challenge given the high cost of electricity. According to Charles (2022) and Pathirana *et al.* (2019), proper choice of design parameters of window area can improve the effectivity of natural ventilation in buildings by enhancing indoor air movement levels and reducing building energy required for thermal satisfaction of building occupants in the warm and humid tropical climate of southern Nigeria. Sensible air movement can alleviate high temperatures and humidity in a building, thereby modifying its indoor thermal comfort conditions. Related studies have argued that paying special attention to the design parameters of the window area, such as the size, placement, and orientation of the window, can mitigate challenges restraining air penetration. This will improve sensible air perception and thermal comfort in naturally ventilated living rooms (Nicol *et al.*, 2014; Rizk and Henze, 2014; Nguyen *et al.*, 2012; Yang and Clements-Croome, 2012).

A window is an access point or an opening in a building envelope through which air enters and leaves the building (Ko *et al.*, 2020; Karanen, 2016; Kleiven, 2012). The window area connotes the win-

dow size and is usually used in computing the wall-to-window ratio (WWR). Understanding how windows influence natural ventilation in buildings is crucial because of its impact on indoor thermal conditions and the well-being of the occupants (Charles, 2022; Ko *et al.*, 2020). Previous research has shown a significant connection between natural ventilation and thermal comfort. Natural ventilation in buildings enhances evaporative cooling of the body and facilitates detectable air movement, thereby influencing the thermal comfort of building occupants (Munonye and Ji, 2018; Adunola and Ajibola, 2016; Idowu *et al.*, 2018; Shetapbivash, 2015; Rizk and Henze, 2014; Nguyen *et al.*, 2012; Nicol *et al.*, 2014; Yang and Clements-Croome, 2012).

Observations show that many residents of the ESHDC high-density estates prefer to spend more time on their balconies and terraces than in living rooms in the evenings, where they were supposed to congregate for an extended period to interact, relax, and socialise. Preliminary observations link this habit with the failure of the living room to provide adequate ventilation for achieving an acceptable thermal condition, as most living room windows appear identical in size and area. Adunola (2015) posits that the intensity of a residential space's usage depends on its comfort conditions. Furthermore, related studies have revealed that thermal discomfort can result from designers' oversight of the influence of window area on space use/function, environmental conditions, and local climate at the initial design stage (Haruna *et al.*, 2018; Akadiri, 2016; Alwetaishi, 2016). In a residential building, a living room serves as an essential space for entertainment, relaxation, and socialisation (Hou, 2016; Marshall, 2012). Nowadays, most homes regard the living room as the activity hub, where family members congregate to interact, watch television, and listen to the news, building bonds and enculturation (Ogunola, 2018). Given this essential role, Rechavi (2008) advocates living rooms that are spacious, aesthetically pleasing, and thermally comfortable for occupants.

Most people love to spend approximately 90% of their time indoors; research efforts to reduce energy consumption while maintaining thermal comfort are increasing (Hu *et al.*, 2023; Haliu *et al.*, 2021; Idowu *et al.*, 2018; Sanctamouris, 2016). Similar studies conducted in other countries affirm that window areas influence air penetration, air volume, ventilation rate, and indoor thermal conditions (Oropeza-Perez, 2018; Rizk and Henze, 2014; Kleiven, 2012). However, studies on the effect of window area on air movement levels in naturally ventilated living rooms in high-density housing within Nigeria's warm, humid tropical climate are limited. To fill this research gap, this study examines the relationship between window area and air movement levels among occupants in naturally ventilated living rooms in warm and humid ESHDC high-density estates. This investigation was part of a broader research initiative examining the effect of natural ventilation on the thermal conditions of living rooms in Enugu State Housing Development Corporation (ESHDC) high-density estates in Enugu Capital Territory, Nigeria. The specific objectives are to determine the design parameters of window areas and their effects on air movement in naturally ventilated living rooms in high-density ESHDC estates.

2. Literature Review

2.1. Natural Ventilation

Ventilation is the process of air change between a building indoors and outdoors by natural or mechanical means for the building occupants' comfort (Haruna *et al.*, 2018). Natural ventilation relies on natural forces to operate in buildings without the help of mechanical ventilation (Chen *et al.*, 2017;

Anunobi *et al.*, 2015). Natural ventilation serves the function of cooling the occupants and the building structures.



Figure 1. Cross ventilation is driven by wind effect alone
Adopted from: Yang and Clements-Croome (2012)



Figure 2. Map of Lagos State showing Murtala Mohammed International Airport
Adopted from: Yang and Clements-Croome (2012)

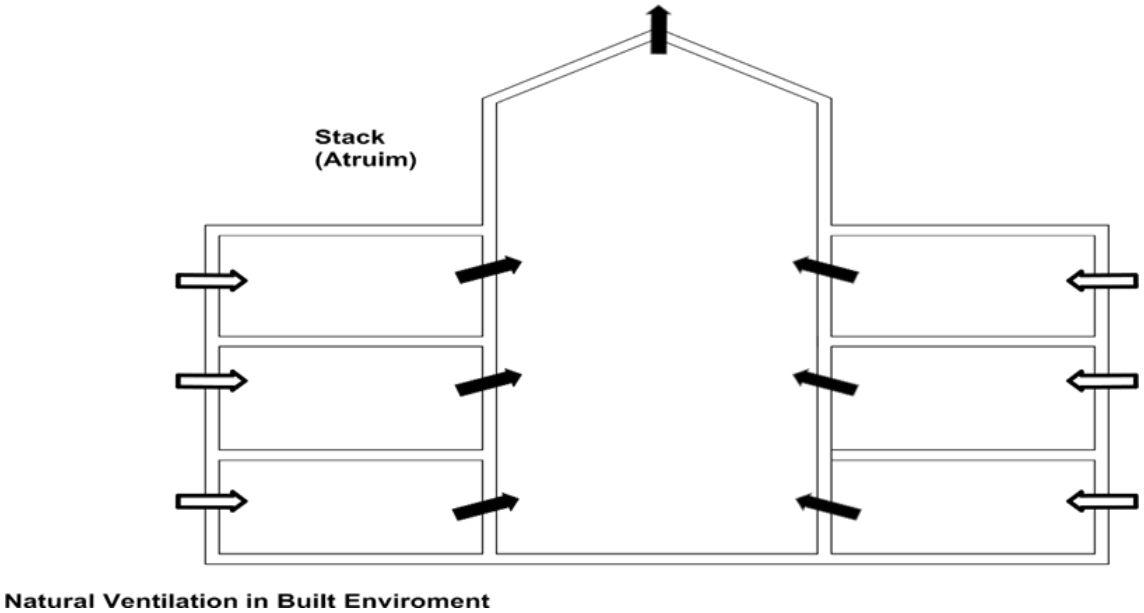


Figure 3. Stack effect ventilation from high-level openings/atria/chimneys
Adopted from: Yang and Clements-Croome (2012)

Atolegba (2014) and Rizk and Henze (2014) assert that the performance of natural ventilation in a building is related to its capacity to achieve thermal comfort through various levels of indoor air movement. Cross ventilation, also known as wind-driven ventilation, is the horizontal process that depends on wind forces to operate in a building with openings in the opposite walls, as shown in Figure 1. It is particularly effective in sparse and less dense settlements. Single-sided ventilation is a buoyance-driven process characterised by vertical air displacement through openings on one side of the building. Thus, it is less effective for comfort cooling, as illustrated in Figure 2. However, the efficiency of both systems is partially dependent on window areas and spatial sizes of rooms. Stack effect ventilation, as shown in Figure 3, is a vertical process that depends on the difference in temperatures within and outside the building (thermal buoyance) to operate. It is effective in dense urban settlements, facilitating the removal of air contaminants, and structural cooling of building elements (Rizk and Henze, 2014). However, horizontal and vertical processes of natural ventilation can operate separately or concurrently in a building (Awbi, 2010).

2.2. Air Movement

Air movement is one of the six variables affecting human thermal comfort (Humphreys et al., 2016; Olanipekun, 2014; Nicol *et al.*, 2014). The other five include three physical variables: air temperature, mean radiant temperature, and relative humidity, together with two personal variables, namely metabolic rate and clothing insulation. Air movement may provide desirable cooling effects in warm conditions (Nguyen et al., 2012; Kleiven, 2012), but it may also increase the risk of an unacceptably cool draft (Nicol et al., 2014). Detectable air movement may be perceived by occupants as enhancing the freshness and pleasantness of the breathing air, yet it may also be perceived as annoying. The thermoregulatory mechanism in humans maintains the body's heat balance at a core set point of 98º F (37ºC) within the constraints of the six variables. These physical variables control the release of metabolic heat by regulating skin temperature, primarily by varying skin blood supply and sweating at the skin surface (Ifebi, 2020; Brown *et al.*, 2012).

The performance of air movement is affected by opening configurations that control air permeability and determine thermal acceptability (Charles, 2022; Annuobi *et al.*, 2015). Nicol *et al.* (2014) assert that increased air movement enhances evaporative and convective processes, changes the skin and clothing surface heat transfer, and produces a physiological cooling effect. In addition, Oropeze-Perez (2018) submits that the volumetric airflows inside a building are also determined by the window area. The implication, therefore, is that a window with a large opening area admits more air than one with a small opening area, thereby influencing the levels of air movement within a room. Previous studies have confirmed a close relationship between thermal sensation ratings and skin temperature in comfortable conditions (Humphrey *et al.*, 2016). In warm and humid conditions, skin moisture significantly affects thermal sensation. Convective heat transfer at the skin varies with surface temperature and local air movement across the skin. The local air movement is an important factor in thermal comfort standards given the interdependence of heat loss, skin temperature, skin witness and thermal sensation (Nicol et al., 2014).

2.3. Windows and Window Area

Windows serve as access points in the building envelope, through which air enters and exits the building. The performance of indoor air movement is affected by opening configurations (Charles, 2022; Annuobi *et al.*, 2015; Gao and Lee, 2011). Windows functions as the primary means for accessing outdoor and nature views. According to Ko *et al.* (2020), windows can impact the thermal comfort, emotion-

al responses, and cognitive performance of the building's occupants. The operable windows enable occupants to regulate air movement and thus help to achieve sensible air movements, and preferable or acceptable levels of indoor air movement at any time of day (Nicol *et al.*, 2014). In addition, the percentage window area of WWR >50% can positively influence indoor air movement levels, improve evaporative cooling of the skin, reduce the indoor air temperature and humidity, and have a positive impact on the well-being and thermal satisfaction of building occupants (Charles, 2022; Ko *et al.*, 2020;).

The window area simply connotes the size of the window, and it is usually used in determining the wall-to-window ratio (WWR) for effective passive ventilation in the building. Understanding the correlation between window area and natural ventilation is crucial because of its impact on indoor air movement, thermal comfort, and well-being of the building occupants (Charles, 2022; Ko *et al.*, 2020). Additionally, Oropeza-Perez (2018) calls for more emphasis on natural ventilation performance parameters at the initial design stage helps to improve indoor air movement in a room. The parameters of window area such as size/position/orientation and room size help to determine the quantity of air entering the room and the ventilation rate. For example, cross ventilation is more effective when the room width is equal to or less than five times its height as shown in Figure 4. Conversely, single-side ventilation is effective when the room's width is less than twice its height, as shown in Figure 5. This indicates the impact of window area and room size wind-driven ventilation (Charted Institute of Building Service Engineers, CIBSE, 2010).

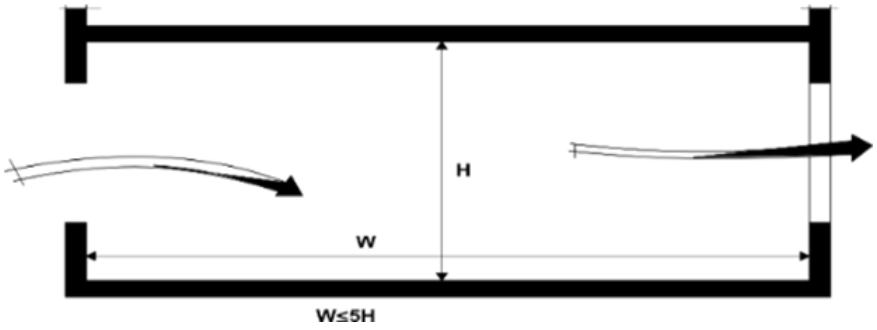


Figure 4. Cross ventilation
Source: Chartered Institute Building Service Engineers, CIBSE, (2010)

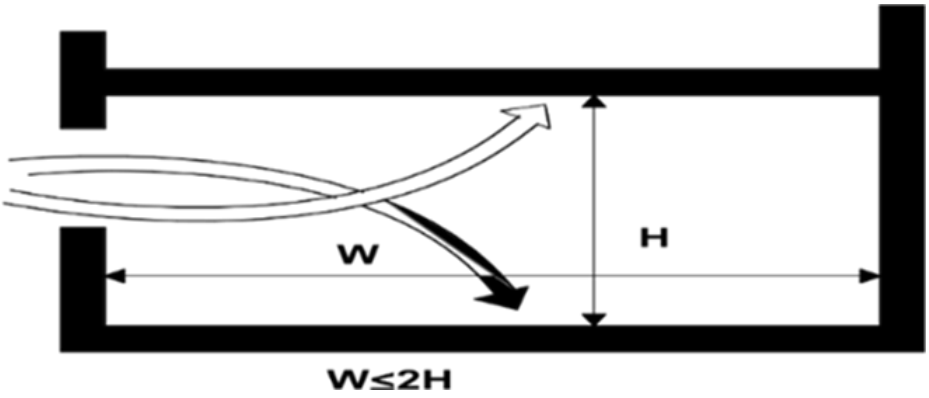


Figure 5. Single-sided ventilation (less effective)
Source: Chartered Institute Building Service Engineers, CIBSE, (2010)

2.3. Thermal Acceptability

The issue of human adaptation to the built environment is the basic behavior that underlies how building occupants react to discomfort. This is crucial for thermal comfort studies related to occupant's thermal perception. The human response aligns with the basic assumption of the adaptation principle, which states that an undesirable change can cause a shift in thermal balance, consequently influencing the thermal acceptability of the indoor environment. Thermal acceptability defined by ASHRAE 55 standard (2017), is the environment that is thermally acceptable to at least 80% of the occupants. The construct 'thermal acceptability' has since become one of the methods for assessing occupant's satisfaction with the thermal environment. Additionally, thermal comfort is a person's mental state that expresses satisfaction or dissatisfaction with the thermal environment and is assessed by subjective evaluation. This definition implies that the level of satisfaction with the thermal environment is subjective, as thermal comfort is also determined by the psychological condition that interprets comfort based on what is deemed acceptable or unacceptable by most building occupants.

3. Research Methodology

3.1. Study Area

The study was conducted in the Capital Territory of Enugu State, located in the south-eastern part of Nigeria. It is located approximately between latitudes 060 21" and 060 30" N of the equator and longitudes 070 26' E and 070 37" E of the Greenwich Meridian.

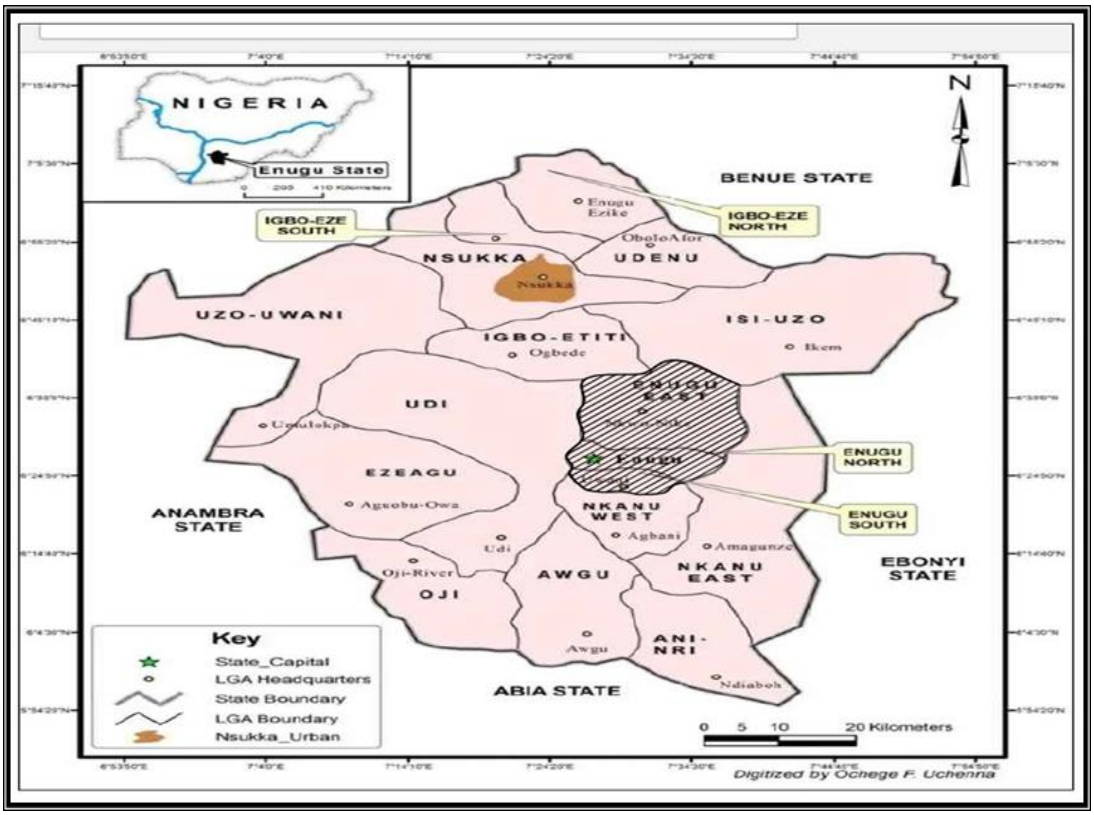


Figure 6. Average Monthly Temperature and Rainfall in Nigeria, 1991 – 2021
Adopted from: Enugu State Government Diary (2013)

Figure 6 shows the map of Enugu State, with the hatched portion designating the Capital Territory. It is bounded in the north by Igbo-Etiti and Isi-Uzo Local Government Areas, in the west by the Udi Local Government Area, in the south by the Nkanu West Local Government Area, and in the east by the Nkanu East Local Government Area.

3.2. Climatic/Topographic Characteristics of the Study Area

The Capital Territory sits on undulating hilly topography. Six rivers are situated in the Capital Territory: Aria, Asata, Ekulu, Idaw, Nyaba, and Ogbete rivers, helping to modify the region's microclimate. According to Koppen's global climate classification, Enugu State belongs to the Tropical Moist Climate, TMC. The vegetation is of the tropical rainforest with a derived savannah character. The Capital Territory is 304.7m above sea level and experiences a naturally warm and humid climate. The average maximum temperature is 34.90 C, the minimum is about 22.30 C, and the annual mean temperature is about 26.70 C. Enugu State has only two seasonal periods, the rainy and dry seasons, with more than 8 months of rainy season and peaking annually from June to August (Iloege, 2001). Figure 7 presents a graphic chart of the Average Monthly Temperature and Rainfall in Nigeria, from 1991 – 2021. Southern Nigeria experiences heavy rainfall events during the rainy season from March to October. The peak period of the rainy season occurs from June to August, with the annual average amounting between 200cm – 400cm, and the yearly mean temperature is about 25.0^0 C – 27.0^0 C in the same period (World Bank Group, WBG, 2021).

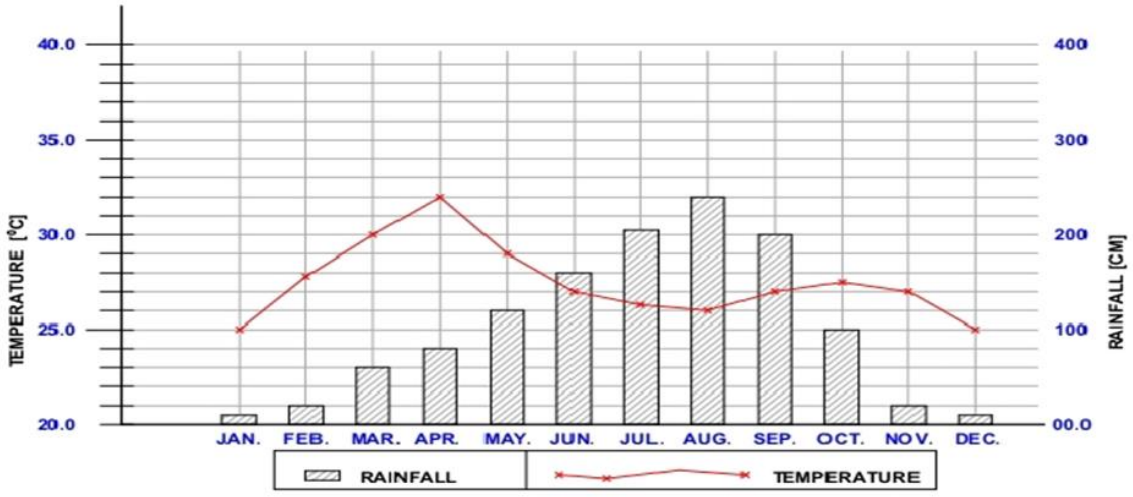


Figure 7. Map of Enugu State (showing the Capital Territory in the hatched spot)
Source: World Bank Group, WBG, (2021); Climate Risk Profile, Nigeria

3.3. Research Design

The research adopted a cross-sectional survey design to elicit subjective and objective data. The field survey used the mixed methods approach, done in the evenings from 4 pm to 7 pm during the peak period of the rainy season, from June to August 2024. The study involved concurrent measurements of

the physical variables of air temperature, mean radiant temperature, relative humidity, and air movement. Alongside, it administered questionnaires to occupants in the 130 sampled living rooms to evaluate their opinions on air movement sensation, air movement preference, and air movement acceptability. The following procedures were employed for eliciting objective and subjective data:

1. The researcher and assistant researchers collected objective data utilising various weather reading instruments, including Testo 174H mini-data loggers for measuring and recording air temperature and relative humidity; digital anemometers for measuring air movement and air temperature inside and outside buildings; digital magnetic compasses or smart mobile phones were used for indicating geographical locations of buildings or orientation of buildings; measuring tapes were used to gather data on the dimensions of rooms, windows, window areas, window sills and ceiling heights.
2. Subjective and objective data were collected simultaneously, asking occupants to evaluate air movement sensation, preference, and acceptability in their living rooms during the evenings.

The sampling technique used was the stratification method based on residential density. The ESHDC high-density residential buildings, consisting of multifamily apartment buildings, were selected for the study. The study's sample frame comprises high-density, 3-story multifamily buildings containing 2-3 bedroom housing units, constituting 433 housing units, as illustrated in Table 1.

Table 1. Sampling Frame: ESHDC High-density Estates in Enugu Capital Territory.

S/N	Name of Estate	Number of Housing Units
1	African Real Estate	109
2	Maryland Estate	324
	Total	433

Source: Physical Planning Unit, ESDHC, (2023)

To have a feasible sampling size, sampling by ratio and percentage proportional allocation techniques were applied. St. Olaf College (2023) posited that a minimum ratio of 30% in sampling by ratio can ensure equitable representations of the sample. Kothari (2014) posited that the percentage proportional allocation technique can also reduce the sampling frame to a feasible sampling size for an effective study. The sample size for each estate was further kept proportional to the size by the application of the 30% random selection of housing units in each of the selected estates, resulting in a total of 130 housing units for the survey study. Table 2 illustrates the sample size for both the dwelling units and occupants/respondents.

Table 2. Sampling Size: ESHDC high-density estates in Enugu Capital Territory (Achieved by 30% proportional method for both housing units and adult respondents).

S/N	Name of Estate	Number of Housing Units	Number of Occupants/Respondents
1	African Real Estate	33	33
2	Maryland Estate	97	97
	Total	130	130

Source: Physical Planning Unit, ESDHC, (2023)

4. Discussion of Findings

4.1. Aggregated Analysis for Window Area of Living Room (WALR)

The data presented in Figure 8 indicate various window areas from randomly selected living rooms in both housing estates. The findings reveal that most living rooms have window areas of above 3.0 sq.m, representing a frequency of 97 units and a valid percent of 78.9%. Conversely, window areas ranging from 1.6–2.0 sq.m; 2.1–2.5 sq.m; and 2.6–3.0 sq.m, collectively represent a valid percentage of 22.1% and a total frequency of 26 units. This finding further indicates that most of the windows in the two sampled estates are identical in size and area, implying a failure to recognise the unique functions of the living room and environmental conditions at the initial design stage (Akubue, 2019; Akadiri, 2016; Haruna et al., 2018).

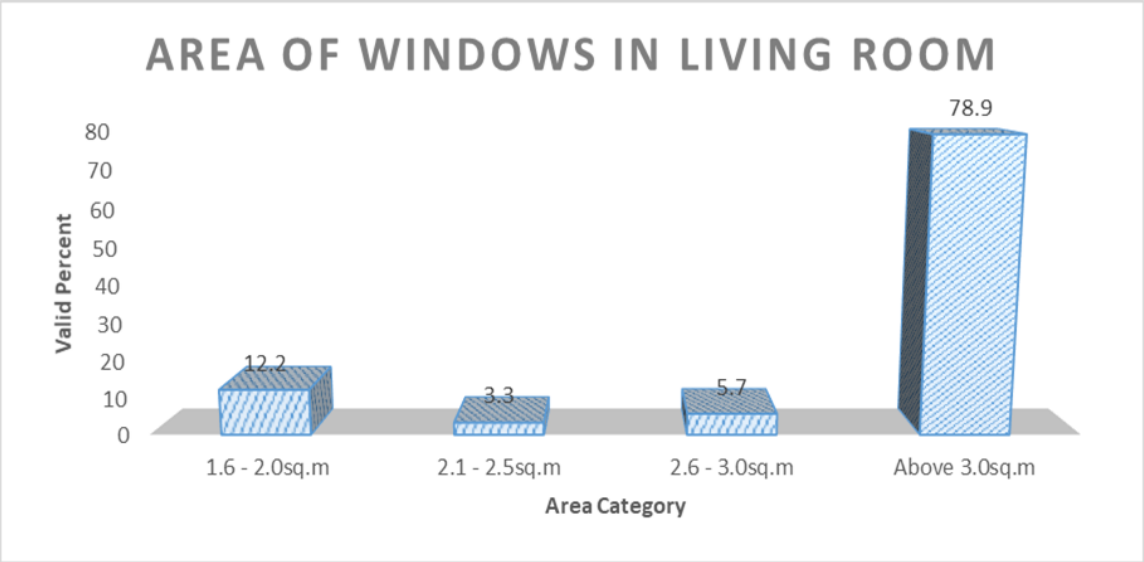


Figure 8. Analysis of aggregated data of Window Area
Source: Researchers' Fieldwork (2024)

4.2. Aggregated data for Indoor Air Movement Levels (IMAL)

Figure 9 shows the various measurements of indoor air movement in the selected living rooms, recorded in the evenings from 4 pm to 7 pm for three months (i.e., from June to August) in both estates under consideration. Figure 8 presents data illustrating the three levels of air movement within the surveyed living rooms in the sampled housing estates. Of all housing units surveyed, a valid percentage of 37.4%, representing 46 units, exhibited an air movement level of 0.00–0.1 m/s, and another valid percentage of 34.1% (42 units) fell within the air movement level of 0.1–0.2 m/s. The next valid percentage of 28.5% fell within 0.2-0.3 m/s, representing the frequency of 35 units. The findings showed that the living rooms in the surveyed estates had air flow rates between 0.1–0.2 m/s and 0.2–0.3 m/s. These levels complied with ASHRAE standard 55, which recommends indoor air movement of 0.18 m/s and 0.25 m/s as the ideal levels for optimal air movement perception and acceptability for the Standard Effective Temperature (SET).

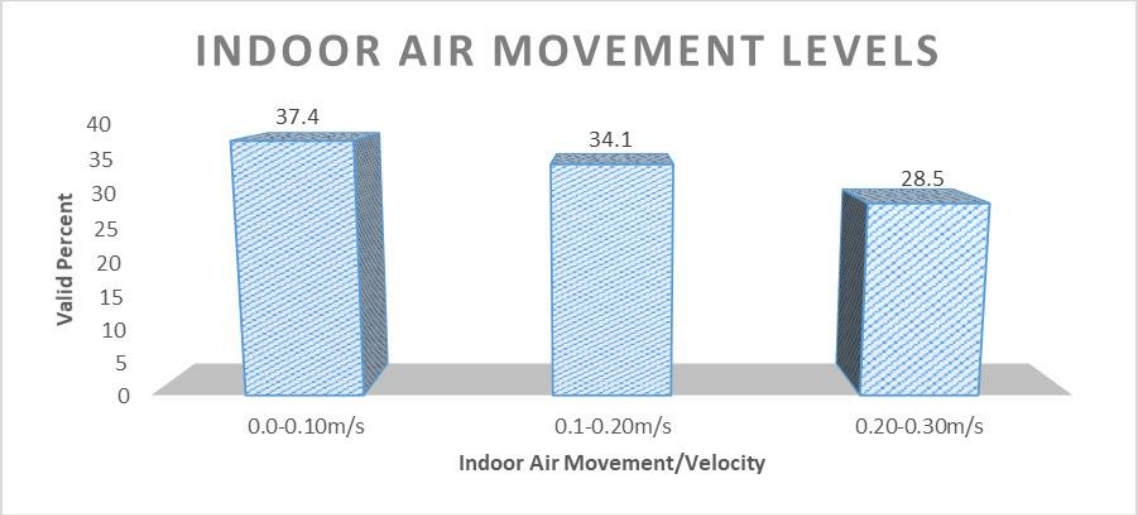


Figure 9. Analysis of aggregated data on Indoor Air Movement Levels
Source: Researchers' Fieldwork (2024)

4.3. Aggregated data for Level of Air Movement Sensation (LAMS)

The analysed data depicted in Figure 10 presents the frequency and the valid percentage of occupants surveyed for air movement sensation levels across the selected ESHDC high-density estates. The results revealed that 55.3% of respondents answered 'Just ok' to the question 'How do you feel about air movement now in this living room?' 41.5% of the sampled occupants voted 'Low,' and 3.3% indicated 'Very high.'

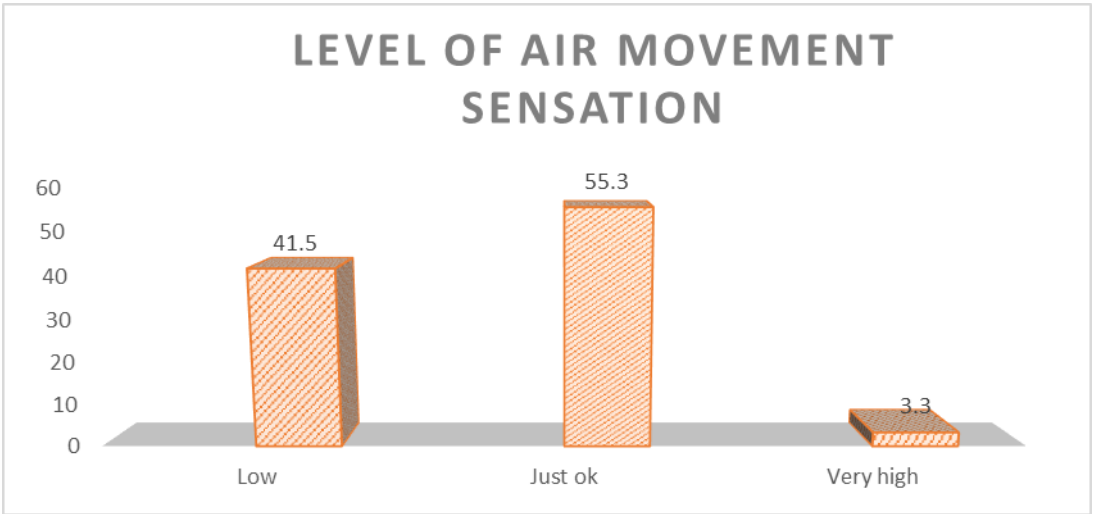


Figure 10. Analysis of aggregated data on the level of Air Movement Sensation
Source: Researchers' Fieldwork (2024)

4.4. Aggregated data for Level Air Movement Acceptability (LAMA)

Figure 11 shows the frequency and valid percentage of responses to the level of air movement acceptability in their living rooms in the selected ESHDC high-density estates. The findings indicated that 53.7%, representing 66 out of surveyed living rooms, voted 'Acceptable' to the question 'Do you accept the level of air movement in this living room now?' While 46.3%, representing a frequency of 57 units,

voted 'Unacceptable.' Therefore, the results validate that 'the environment is thermally acceptable if at least 80% of the occupants voted acceptable' (HSE, 2021; ASHRAE -55 standard, 2017; Nicol et al., 2014).

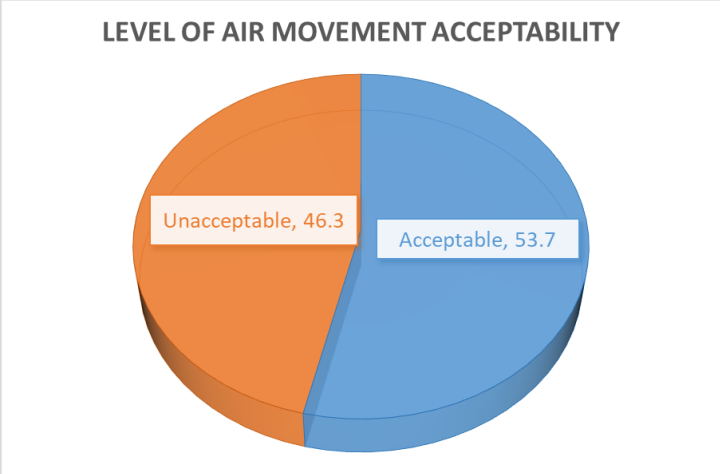


Figure 11. Analysis of aggregated data on the Level of Air Movement Acceptability
Source: Researchers' Fieldwork (2024)

4.5. Hypothesis Test

Investigating the significant relationship between the Window Area in Living Rooms (WALR) and the Indoor Air Movement Levels (IAML) in living rooms of the ESHDC high-density estates. Given that the two variables considered were measured on interval scales, Pearson's product-moment correlation analysis tool was used to test the significance of their relationship, as all variables examined were interval variables. The analytical outcome in Table 3 showed a Pearson Correlation Coefficient of 0.410** with a p-value of 0.000. This implies that a positive, moderate relationship exists between the variables. A probability value of 0.000 signifies that the relationship is statistically significant. The null hypothesis is rejected, while the alternate hypothesis is accepted, *indicating a significant relationship between the window area in living rooms and indoor air movement levels.*

Table 3. Pearson's Product Moment Correlation analysis results in the relationship between WALR and IAML.

		V2- Indoor Air Movement Level
V1- Window Area of Living Room	Pearson Correlation coefficient value	0.410**
	Sig. (2-tailed)	0.000
	N	123

Source: Researchers' Fieldwork (2024)

4. Conclusion and Recommendation

The following conclusions have emerged from the assessment of the relationship between window area and indoor air movement levels in the naturally ventilated living rooms of ESHDC high-density estates in Enugu Capital Territory, Nigeria:

1. This study posits that the window area significantly affects indoor air movement levels in naturally ventilated living rooms, thus, influencing air movement sensation and acceptability, which determines thermal perception.
2. This study suggests the need to consider design parameters of window areas, including size, placement, and orientation, at the initial design stage to improve indoor air movement levels in naturally ventilated living rooms.
3. The study emphasizes the importance of window areas for effective climate-responsive designs.

Recommendations were drawn from the study's findings and pertinent literature. The Window Area in Living Rooms (WALR) helps regulate energy consumption in a naturally ventilated building. To improve operable window performance, the initial design stage should properly consider window area, size, position/arrangement, and orientation relative to the wind direction.

1. Adjustable shading devices and blinds can mitigate the adverse effects of solar radiation and daylight entering the building through windows along with the air.
2. Window areas >30% <50% WWR provide greater airflow than those >10% <30% WWR.
3. Operable windows with larger access areas, such as louvre and casement windows, let in more air than sliding and top-hung windows.
4. Window placement in external walls influences air penetration and indoor air movement levels. The symmetrical arrangement works better for cross-ventilation, and the asymmetrical type benefits oblique winds. Vertical air displacement from high-level vents helps buoyance-driven ventilation known as the air stack effect.
5. Windowsill heights in living rooms >300mm< 600mm ensure even distribution of indoor air at the sitting level than the windowsill heights >900mm <1200mm due to indoor airflow above occupants' heads at sitting posture, which can cause hot and cool drafts in living rooms.

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