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Directional Access to the Sky as a Criterion of Residential Environmental Quality in Sustainable Urban Design

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Abstract

Access to the sky is a key element of residential environmental quality. In densely built-up urban areas, exposure to the sky is often limited not only quantitatively but, above all, directionally. Traditional illuminance metrics, such as the Sky View Factor (SVF) or Daylight Factor (DF), describe the proportion of visible sky or the amount of light in an averaged manner, without considering its relationship to the functional organisation of the human field of view.This article introduces the Relative Retinal Image (RRI) metric, which evaluates directional access to the sky through geometric analysis of viewing directions in relation to functional zones of the visual field, without reconstructing perceived images or simulating physiological processes. Within this geometric framework, human vision is interpreted as operating simultaneously in two visual cones: a narrow central cone responsible for acute, conscious vision (RRI-A), and a wider peripheral cone enabling the reception of low-resolution but spatially stable stimuli (RRI-B). For clarity, three concentric central ranges are distinguished: foveal (0–2.5°), sharp central (0–5°), and extended interpretative central vision (up to 10°). The proposed approach provides a geometry-based analytical tool that complements existing daylight metrics in the assessment of sustainable residential environments, without formulating normative or biological design prescriptions. Based on geometric and graphical analyses and a case study of the Józefowiec housing estate in Katowice, the results indicate that the directional structure of the sky view may be lost despite compliance with conventional planning criteria.

Keywords: sky access; directional daylight; residential environment; visual perception; retinocentric analysis; spatial legibility; daylight assessment; urban density; housing quality; sustainable urban design; human-centred sustainability; environmental performance

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1. Introduction

The view of the sky is one of the fundamental, though often unrecognised, elements of experiencing space. In everyday use, it rarely becomes the subject of conscious analysis, but it serves as a constant point of reference for orientation and assessment of the surroundings (Figure 1). In contrast to local light contrasts, which are perceived point by point, the view of the sky engages a wide field of vision and acts as a background that organises the entire spatial scene.

In an urban environment, access to the sky is gradually limited by buildings, superstructures and tall greenery. A key limitation of classic assessment indicators, such as the

Sky View Factor, is that they describe access to the sky in an averaged way, without taking into account its directional structure. Two places with a similar proportion of the visible sky hemisphere can generate fundamentally different spatial experiences: in one case, the user has contact with a wide sector of the sky with a clear height structure, in another, only with a narrow, difficult to locate slit of light appearing just above the line of obstruction. From the point of view of perception, these are fundamentally different situations, even though in geometric analysis they can be classified as comparable areas.

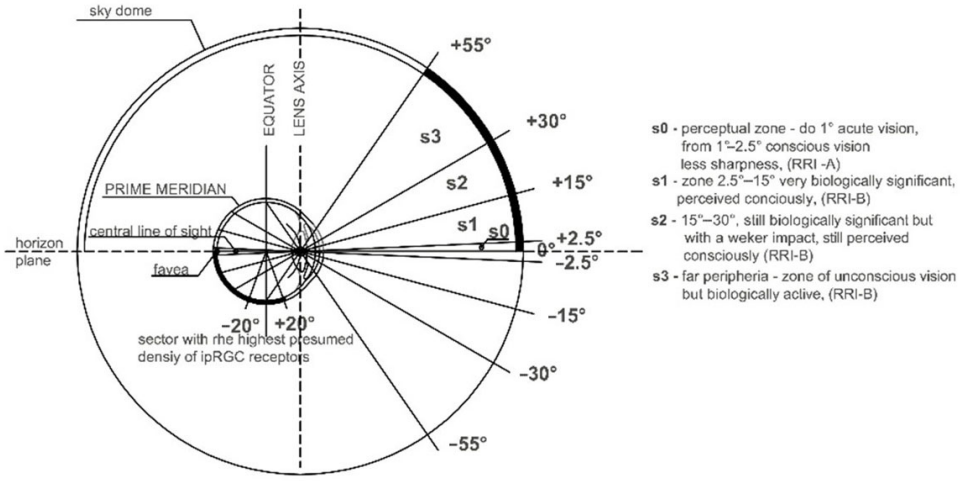


Figure 1. The analysis was carried out with the eye looking straight ahead, and the observer's head in a natural, upright position. The central line of vision lies in the horizontal plane. A vertical cross-section through the zero meridian of the eyeball showing the analysis of sky perception in terms of angular image representations in the sectors of the retina. Source: authors ZP, MP.

A similar limitation applies to current standards for assessing access to daylight, such as EN 17037 [1], which focus on quantitative and geometric criteria for sky visibility and interior lighting, without referring to the directional structure of the sky view or how it is perceived in the user's field of vision. As a result, normative assessment may indicate that the required parameters are met, even though experiential contact with the sky remains limited or fragmentary. From a perceptual perspective, human vision may be interpreted as operating simultaneously within a narrow central field and a wider peripheral field of view.

The narrow central cone, with a vertex angle of approximately 5°, is responsible for sharp and conscious vision, while the much wider peripheral cone of vision enables the reception of low-resolution but highly spatially stable stimuli. This may apply in particular to light coming from large areas of the sky, including the short-wave component of daylight resulting from atmospheric scattering. In this work, this aspect is treated as an environmental and perceptual context, justifying the analysis of directional access to the sky, without formulating direct physiological conclusions.

Given the interdisciplinary nature of the present study, the cited literature may be broadly understood within several thematic domains.

For clarity, the referenced knowledge may be grouped thematically as follows:

(i) Architectural approaches to sky-access assessment and angular sightline analysis, providing conceptual and methodological background for the repeatable geometric protocol (Appendix A) [2,3];
(ii) Retinal organisation and visual-field eccentricity [4,5];
(iii) Non-image-forming photoreception and melanopsin-related mechanisms, treated here as contextual background rather than physiological inference [6–12];
(iv) Behavioural and environmental psychology related to visual contact with outdoor space [13–16];

(v) Environmental daylight and sky assessment methods, including hemispheric subdivision, luminance modelling, and computational spatial analysis [17–21].
This grouping is intended solely as an orientation aid for the reader and does not affect the formal citation order adopted in the manuscript, which follows the standard sequence of appearance in the text. In all figures where sight-limiting rays are shown, the colour of the lines carries no analytical meaning and serves solely to visually indicate the extent of the available field of view.

(vi) The European Committee for Standardisation (CEN) standard EN 17037: 2018 "Daylight in buildings" [1] is referred to as an example of a normative approach, but it does not constitute the methodological basis of the proposed framework.

This paper proposes an approach combining geometric analysis with knowledge of the functional organisation of the field of view, enabling the assessment of access to the sky in a manner consistent with perceptual mechanisms.

To this end, hemispheric analysis and two metrics—RRI-A and RRI-B—have been introduced to distinguish situations in which the sky is only formally visible from those in which it performs a real function (Figure 2).

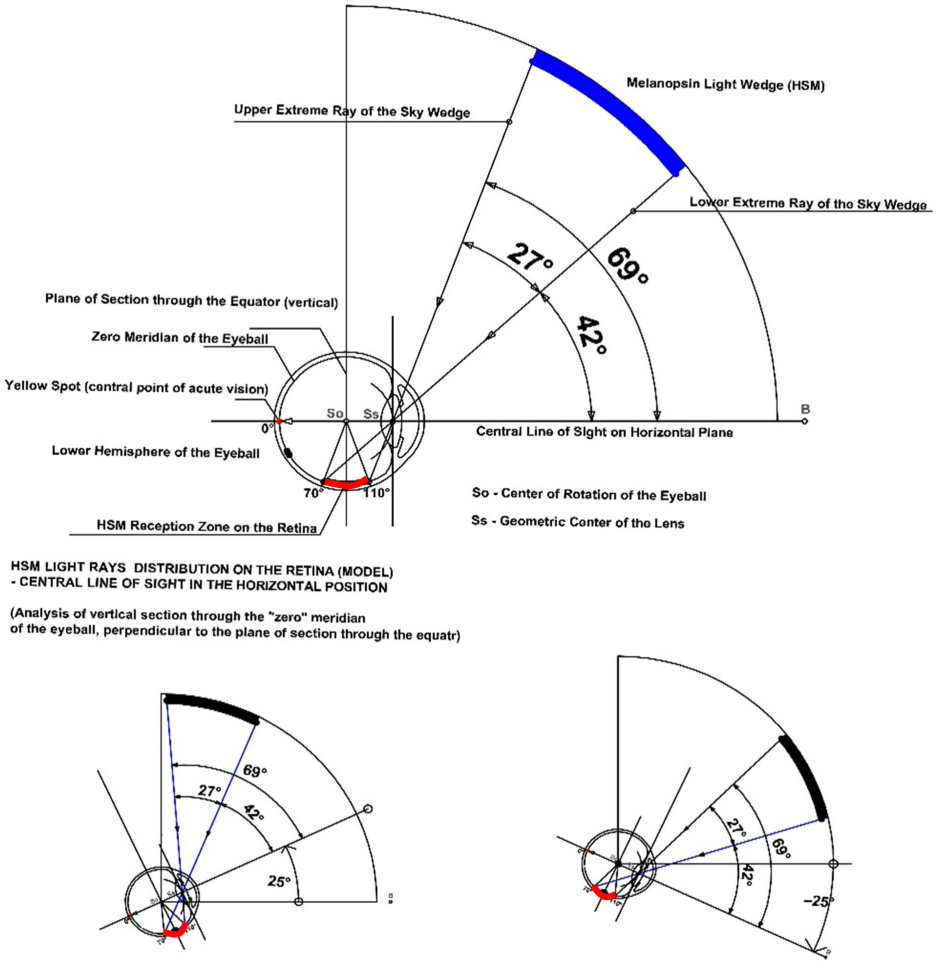


Figure 2. The apexes of the cones of vision coincide with the geometric centre of the eye's optical system, reduced to a point corresponding to the centre of the lens, with the axes of the cones lying on the axis of vision. The figure illustrates the principle of relative retinal image (RRI) formation in a cross-section of the eye. The exposure of the equatorial retina (+/−20°) to blue light is analysed. From above: the eye looks horizontally. From below: the eye is positioned at an angle of +25° or −25°. The light from the sky can then be read through a 27° wedge, even with head rotation. The red sector indicates the equatorial retinal exposure, while the black and blue segment represents the analysed directional sky wedge. Source: authors ZP, MP.

At selected stages of manuscript preparation, an artificial intelligence (AI) tool was used as editorial support to improve language consistency and clarify scientific terminology. All conceptual, methodological, and interpretative aspects remain the responsibility of the authors.

2. Interdisciplinary Background and Related Work

Research on access to the sky intersects several strands of literature that are rarely discussed together in the assessment of residential environments.

In particular, these strands are often addressed separately within physiology, visual perception, environmental psychology, and urban daylight analysis, despite their relevance to the quality and sustainability of residential environments.

The first strand concerns the neurophysiology of light beyond classical image formation.

Studies documenting the discovery, anatomy and circadian functions of intrinsically photosensitive retinal ganglion cells (ipRGC) are well established [6–8].

Subsequent physiological and modelling studies expanded the understanding of melanopsin-mediated pathways [9–12,22–24].

Further work addressed spectral and computational frameworks related to daylight and non-visual responses [25,26]. Additional work suggests that melanopsin-mediated pathways may also contribute to visual adaptation within early visual processing [27].

These studies indicate that daylight, and particularly large-scale sky-related light patterns, play a role in non-image-forming visual pathways, including circadian regulation and adaptive visual responses.

A second strand addresses the functional organisation of the visual field and the relationship between eccentricity and visual processing, including the notion that large-scale spatial perception relies substantially on non-foveal and peripheral mechanisms. This body of work suggests that spatial orientation and the perception of extended environmental structures depend largely on peripheral and non-foveal vision, which motivates analysing sky visibility in a directional and eccentricity-sensitive manner rather than as a single averaged quantity [4,28–31] for functional vision and [5] for peripheral organisation.

Figures 1 and 2 schematically illustrate this differentiation by distinguishing between central, near-peripheral, and peripheral visual zones and by relating these zones to corresponding angular sectors of the sky that may contribute to spatial orientation and environmental legibility.

An essential basis for urban and environmental analyses is provided by studies on daylight, sky models, and geometric indicators of access to the sky hemisphere, including the Sky View Factor and hemispheric analyses [17–19]. While these approaches are widely used in sustainability-oriented urban studies, they primarily operate on averaged or global measures and do not explicitly address how sky visibility is structured directionally from the user's habitual viewing position.

These issues are complemented by research in environmental psychology and architectural perception, which points to the regenerative and orientational significance of visual contact with natural elements and open spatial structures [13–16]. In this context, visual contact with the sky functions not only as a source of daylight but also as a stable environmental reference supporting orientation, perceived openness, and psychological comfort in dense residential settings.

In this context, Cajochen's work is also essential, documenting the impact of light—particularly its spectral composition and diurnal variability—on alertness, mood, and circadian rhythm regulation, especially under limited exposure to natural daylight [23].

Although these findings are primarily physiological, they underline the broader relevance of daylight quality and temporal exposure patterns for residential environments where access to natural light may be constrained.

Biological Background (Context Only)

Melanopsin is a photopigment expressed in a specialised group of intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells are particularly sensitive to the short-wave component of daylight and are involved in non-image-forming visual pathways, including circadian regulation and adaptive responses to ambient illumination [6].

Signals mediated by ipRGCs are discussed in the literature in relation to circadian processes; however, these relationships depend on multiple parameters such as spectral composition, intensity, exposure duration, and geometry of light incidence. In this article, references to melanopsin and ipRGCs serve exclusively as contextual background and do not form the basis for physiological conclusions.

An important anatomical aspect is that the distribution of ipRGCs varies with retinal eccentricity, with distinct patterns across central and more peripheral regions [27]. Consequently, sky-related light may reach functionally differentiated retinal areas depending on viewing direction, even when attention is directed elsewhere.

The biological information presented here provides interpretative context for distinguishing between conscious central viewing and directionally structured peripheral exposure. The present study remains strictly within a geometric and perceptual framework.

Table 1 summarises selected milestones in the recognition of non-image-forming photoreception. The table is explanatory in nature and does not imply that physiological outcomes are analysed in this study.

Table 1. Chronological milestones in the recognition of non-image-forming photoreception in humans (contextual background).

Year	Contribution	References
2001	Spectral sensitivity of melatonin suppression	Brainard [7]; Thapan [8]
2002	Discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs)	Berson [9]; Hattar [10]

Subsequent studies (ca. 2010–2015) showed that melanopsin-expressing retinal ganglion cells do not constitute a uniform population but comprise several functional subtypes (commonly referred to as M1–M6) [27] that differ in sensitivity, central projections, and functional roles.

This refinement does not alter the basic chronology of discoveries summarized above and is cited here solely to provide additional context.

3. Materials and Methods: Retinocentric and Geometry-Based Assessment of Sky Access

The basis of the adopted method is to link the analysis of access to the sky with the functional organisation of the human field of vision. For clarity, three concentric eccentricity ranges are distinguished in this study: the foveal zone (0–2.5°), associated with highest-acuity vision; the central sharp-vision zone (0–5°); and an extended central interpretative zone (up to approximately 10°), beyond which predominantly peripheral mechanisms dominate spatial integration.

The proposed method of analysing directional access to the sky was developed primarily to assess the perceptual conditions in ground-floor flats, which in dense developments are most vulnerable to losing visual contact with the sky.

3.1. Observation Point and Geometric Assumptions

The observation point is defined as the position of a person located approximately 1.0 m from the window plane, with the axis of vision located at a height of approximately 1.6 m above floor level. The adopted distance is a reference assumption rather than a rigid physical parameter; its purpose is to standardise the comparative conditions and ensure a clear geometric scale of the analysed projections. From the point of view of the method, the angular relationships between the directions of vision and the obstructions are of key importance, rather than the absolute distance of the observer from the window plane.

The range of eye movement in the vertical plane, used here as a geometric design reference, is approximately 7.5° above the horizon and approximately 30° below the horizon. This means that slight upward deviations of the visual axis, within the range of up to 7.5°, can be achieved without head movements and without changing body posture. The criterion of this vertical upward viewing angle (7.5°) is the basis for adopting the observer's reference distance from the window plane, treated in the analysis as the projection plane.

Assuming that the axis of vision is 1.6 m above the floor and the upper edge of the window opening is approximately 0.75 m above the horizon, the geometric fulfilment of the 7.5° angle condition corresponds to an observer distance of approximately 1.0 m. This distance is a result and a reference, not arbitrary, and follows directly from the adopted angular criterion.

3.2. Definition of the Vertical Section of the Sky

Two boundary lines of sight define the analysed angular range: the upper line is drawn tangentially from the point of the eye to the upper edge of the window opening (lintel) or another element limiting the view upwards, while the lower line is drawn tangentially to the highest point obscuring the sky on the opposite side. The angle between these lines is a measure of the available vertical sky segment in a given spatial configuration (Figure 3).

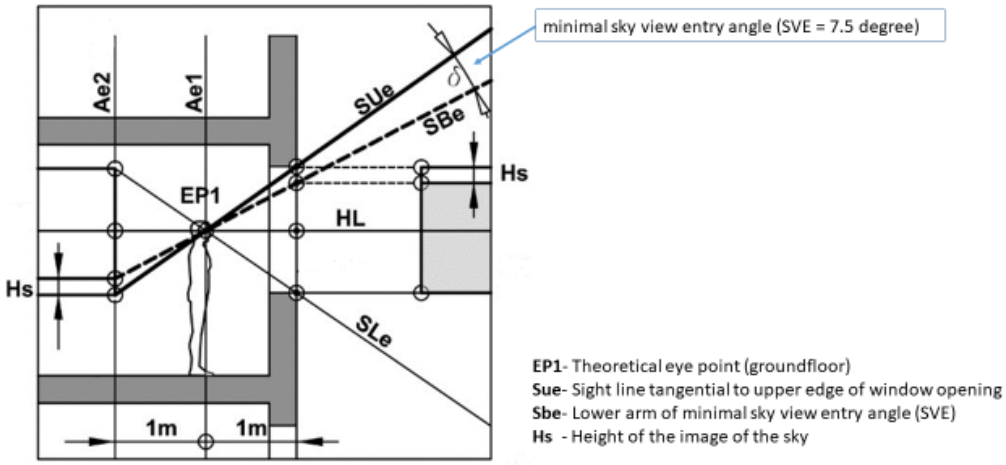


Figure 3. Method for determining the adopted minimum sky opening angle (7.5° geometric criterion).

3.3. Geometric Projection and Relative Retinal Image (RRI)

The window plane is treated as the front projection plane. The analysis applies classical geometric-optical relationships of the eye in order to link viewing directions to angular sectors corresponding to retinal eccentricities. For clarity and comparability of configurations, a symmetrical auxiliary projection plane is introduced 1.0 m behind the observer's eye.

This rear projection plane functions exclusively as a geometric reference surface. It enables angular relationships between directions of view and functional zones of the

visual field to be mapped as proportional surface sectors. The projection does not reconstruct a perceived image and does not simulate perceptual or neurophysiological processes. Its purpose is analytical: to preserve angular proportions and to allow directional exposure patterns to be compared across spatial configurations. This construction is referred to as the Relative Retinal Image (RRI).

Access to the sky can be analysed either by direct reference to the retinal surface or by means of this auxiliary plane. Direct retinal mapping operates on a curved and functionally heterogeneous surface, whereas the rear projection plane provides a geometrically simplified and operationally transparent representation of the same angular relationships. The auxiliary plane therefore serves as a comparative geometric abstraction rather than a substitute for anatomical modelling.

Within this framework, calculating the proportion of sky projected onto the reference plane does not represent physical illuminance or actual light exposure. It constitutes a relative geometric descriptor of directional sky availability. This allows spatial situations that may appear equivalent under averaged indicators (e.g., hemispheric ratios) to be distinguished on the basis of their directional structure.

The angular mapping between retinal eccentricity and visual direction is treated here as a geometric abstraction based on simplified optical models of the eye. The method remains strictly within a geometry-based framework and does not infer the biological effectiveness of light stimuli.

This approach enables directional access to the sky to be analysed in a manner geometrically referenced to the organisation of the visual field, while maintaining methodological independence from physiological modelling. Future extensions may incorporate physical optical simulations; however, such developments lie beyond the scope of the present study.

3.4. Justification of the 7.5° Criterion

The value of 7.5° is introduced as a geometrically derived ergonomic reference used for comparative analysis. It reflects the range of slight upward eye movement achievable in a natural posture without head rotation and serves as a design-oriented angular benchmark.

An additional justification for this criterion is provided by earlier urban studies conducted by the authors on the modernist planning principle according to which the distance between multi-family residential buildings should equal at least twice the height of the taller building (2H rule). These analyses demonstrated that such a spatial configuration yields a minimum sky opening angle of approximately 7.5° for ground-floor dwellings. This correspondence provides historical and geometric context for adopting the same value in the present study.

Notably, the 7.5° value lies within the extended central interpretative zone (up to approx. 10°), bridging the range of sharp central vision and the onset of peripheral spatial integration. The 7.5° value therefore operates as a conservative central reference within the broader angular framework used later for peripheral wedge assessment.

3.5. Methodological Considerations and Alternative Approaches

An alternative research approach, beyond the scope of this study, could be to use a physical or electronic eye simulator, in which the image of the surroundings would be recorded by an optical system with specified parameters and then projected onto a light-sensitive surface with specific angular characteristics. Such a system could provide quantitative data, such as the percentage of the illuminated surface in individual angular ranges, but would require additional optical and physical assumptions.

The method of projecting viewing directions onto an auxiliary vertical reference plane used in this study has previously been used in design practice, including during the analysis of the geometry of the Silesian Stadium auditorium, carried out as part of the

design process for the facility. The Silesian Stadium was developed concurrently with the construction of Silesian Park. It was opened in 1956 and served unchanged for nearly 40 years, until 1993. The design was created by Warsaw architect Julian Brzuchowski. His spatial and functional assumptions gave the facility the character of a landscape stadium, harmoniously fitting into the park's wooded structure. Natural wear and tear after four decades of use necessitated its reconstruction. The modernization of the Silesian Stadium was carried out in stages as part of two separate design processes. The first phase involved the design and implementation of a new seating geometry, developed by a Polish design studio. The architect (Z.P.) served as the lead designer of this project from 1993 to 2007. The second phase, carried out by a German design studio, involved the design and construction of the stadium roof. The main design challenge of the first stage was to ensure optimal visibility of the pitch in a stadium that originally featured earthen stands and an arena connecting the football field and athletics track. This configuration resulted in large distances, requiring precise control of the required arena visibility in various seating areas. As part of this process, a geometric model, conceptually analogous to the relative retinal image method presented in this article, was used to determine appropriate stand visibility profiles. The geometry of the eastern stand, designed at this stage, remained unchanged during subsequent design.

It serves only to indicate that the geometric-analytical approach used has precedents in design practice, where the analysis of angular relationships in the field of view was an important criterion in shaping the geometry of the object.

Table 2 summarises the key assumptions and components of the proposed retinocentric approach. The table is intended as a structured overview of the adopted geometric framework, linking assumptions concerning the organisation of the visual field with the applied projection method, the definition of RRI-based metrics, and the minimum angular threshold used in the analysis.

Table 2. Summary of assumptions, projections and metrics used in the retinocentric assessment of sky view structure.

Approach	Description of the Method and Objective
Assumptions of the retinocentric approach	It is assumed that central vision (up to approx. 2–2.5°) is responsible for analysing and recognising details, while with increasing eccentricity of the field of vision, spatial resolution decreases and the importance of information about brightness and direction increases. This differentiation is the starting point for analysing the structure of the sky view in geometric terms.
Hemispheric projection	A hemispherical projection was used to analyse the structure of the sky view, which preserves the directional nature of the field of view and allows the distribution of visible sectors to be described in the azimuth-elevation system. This method is commonly used in daylight analyses and reveals differences that are not apparent in approaches based on average measurements.
RRI-A and RRI-B metrics	The RRI-A (Relative Retinal Image–Aperture) metric describes the geometric size and shape of the aperture of the view of the sky in angular terms, corresponding to the situation of consciously directing one's gaze towards a fragment of the sky. The RRI-B metric extends this analysis by referring to functional zones of the field of vision and eccentricity thresholds, allowing an assessment of whether the available view of the sky covers areas responsible for the perception of large-scale structures present in the field of vision, even outside the area of sharp vision.
Minimum angle of 7.5°	The minimum opening angle of 7.5° refers to the ergonomic range of eye movement in a natural body posture and is a design reference for comfortable sky viewing in a residential environment. This value is not a physiological threshold, but a conservative minimum perception resulting from the geometric relationship between the window, the observer's position and the range of eye movement.
Eye models	The analyses were based on classical optical models of the eye, including the Gullstrand and reduced models, which link the angular geometry to the mapping of stimuli on the retina.

It does not introduce new methodological steps, but synthetically organizes the elements described in detail in the surrounding text.

The reference to the Silesian Stadium in this section exclusively concerns the geometric method of sightline optimisation and should be understood as a methodological precedent. Broader spatial and landscape aspects are discussed separately in Section 6.2.

3.6. Graphical-Geometric Method of Analysing Directional Access to the Sky

This chapter organises the graphical and geometric means used to analyse directional access to the sky and explains their auxiliary role in describing the RRI-A and RRI-B indicators.

The drawings presented here serve as analytical tools for following the successive steps of geometric reasoning, linking the geometry of the view with the organisation of the observer's field of view.

The graphic material has been selected to enable a clear understanding of the relationship between the observer's position, viewing directions and the structure of sky visibility. The drawings are limited to geometric relationships applicable in architectural and urban analysis and do not constitute perceptual or neurophysiological models.

Some of the schematic diagrams presented in this section originate from earlier methodological studies of angular sightline geometry [3]. In the present article, they serve exclusively as graphical support for the geometric reasoning and do not introduce additional analytical variables beyond those explicitly defined in the text and Appendix A.

Figures 1–3. Simplified optical diagrams of the eye are presented, used solely to determine the geometric relationship between viewing directions and corresponding areas of the field of view. These diagrams serve to explain the principles of mapping viewing directions onto the retinal image in a geometric sense and do not refer to perceptual or neurophysiological processes.

Figures 4 and 5. The figures illustrate the angular organisation of the field of view and the geometric and ergonomic reasons for adopting a minimum reference angle for access to the sky. The designs presented refer to the observable ranges of eye and head movement in a natural body posture and have been introduced as design geometric references rather than experimentally confirmed limits.

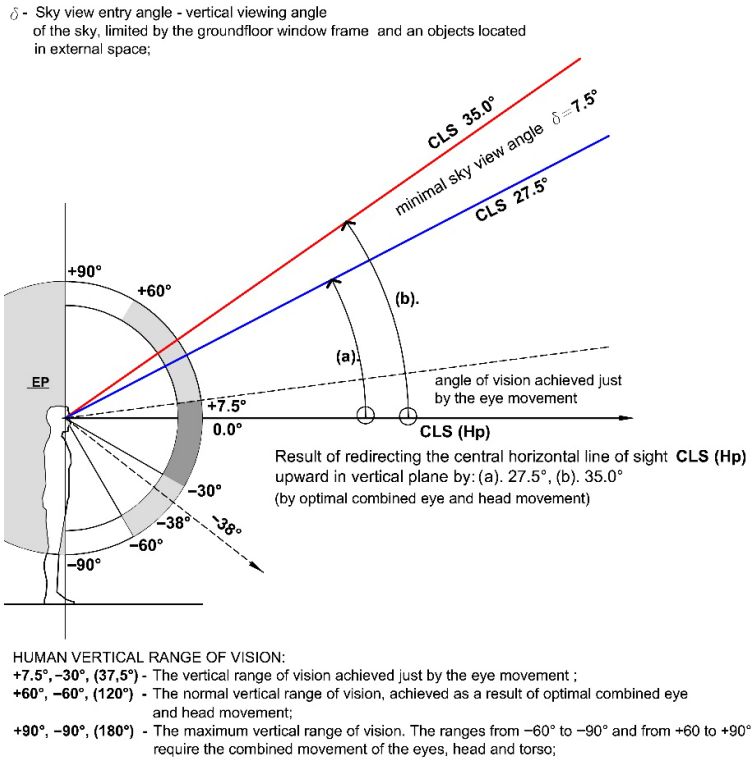
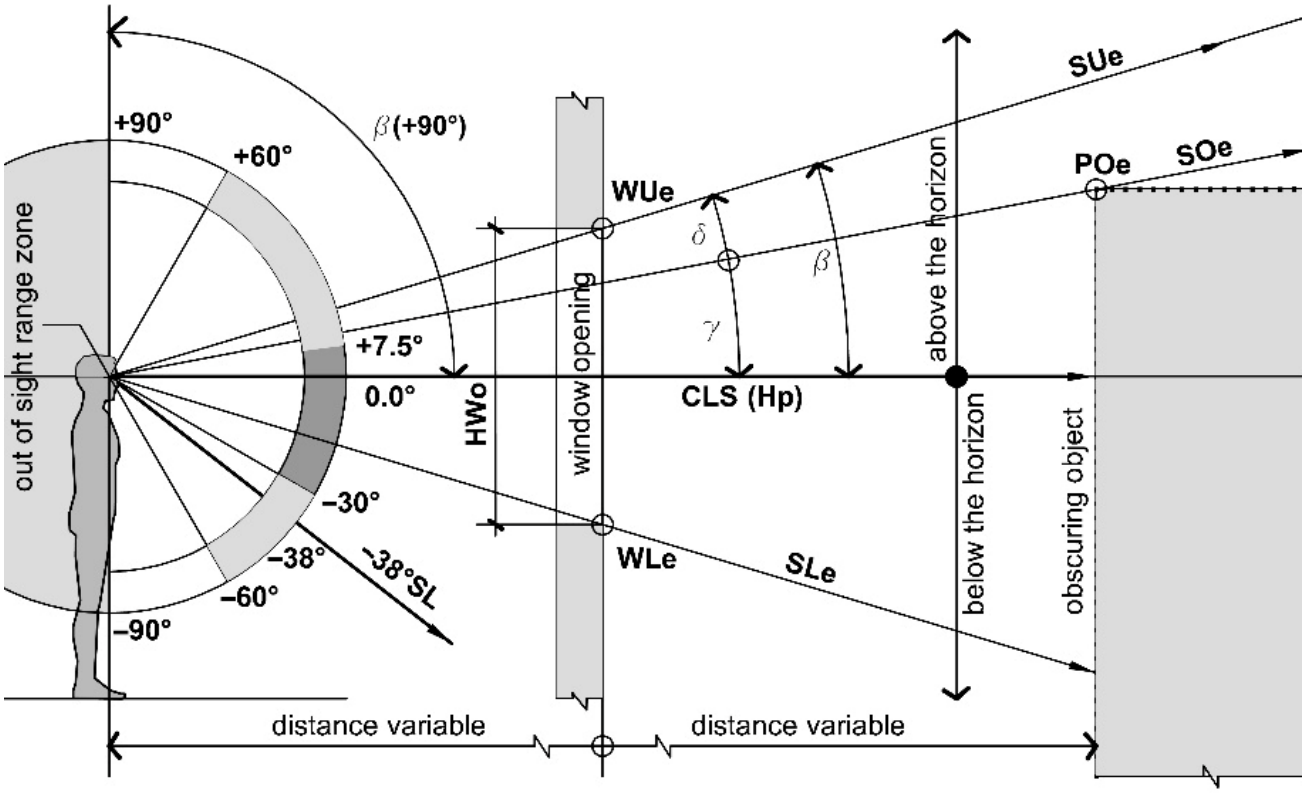


Figure 4. The diagram is presented against the background of the total vertical range of human vision, illustrating the ergonomic basis for the adopted 7.5° geometric threshold. Source: authors ZP, MP.



The above diagram should be considered as a projection onto a central vertical plane CVp (xz plane).

LEGEND:

EP - The theoretical eye point (*Cyclops eye*), lacated in the middle of the segment of the horizontal line joining geometric centers of lenses of the pair of eyes; **CLS (Hp) -** The central line of sight - a horizontal sight line perpendicular to the horizon line and going out from the theoretical eye point (EP); **WUe -** Window opening upper edge; **WLe -** Window opening lower edge; **SUe -** Sight line tangential to the upper edge of the window opening; **SLe -**Sight line tangential to lower edge of window opening; **POe -** The point of obscuring object upper edge; β **(+90°) -** Maxiumum angle of vertical vision range of the sky in the open space; β - vertical vie - wing angle of the sky image in the window frame when obscuring objects do not exeed the horizon line; δ - Sky view entry angle - vertical viewing angle of the sky limited by the window frame and an objects located in external space; γ - Vertical viewing angle of the part of obscuring building exceeding the horizon line; **HWo -** The height of the window opening; **SOe -** Sight line of POe point.

HUMAN VERTICAL RANGE OF VISION:

+7.5°, −30°, (37.5°) - The vertical range of vision achieved just by the eye movement ;

+60°, −60°, (120°) - The normal vertical range of vision, achieved as a result of optimal combined eye and head movement;

+90°, −90°, (180°) - The maximum vertical range of vision. The ranges from −60° to −90° and from +60 to +90° require the combined movement of the eyes, head and torso;

−38° SL - The sight line of vertical angle −38° ensuring optimal, the most natural, positioning of the eyes and head (requiring the least effort).

Figure 5. Access to the view of the sky—a diagram illustrating the general theoretical basis for the analysis of directional eye contact with the sky in a residential environment when the observer looks through a window. Source: author ZP.

Figures 6–10. The figures show the application of the geometric design described above to selected urban layouts and residential configurations. These examples illustrate how buildings and tall greenery modify the directional structure of sky visibility from a typical observer's position.

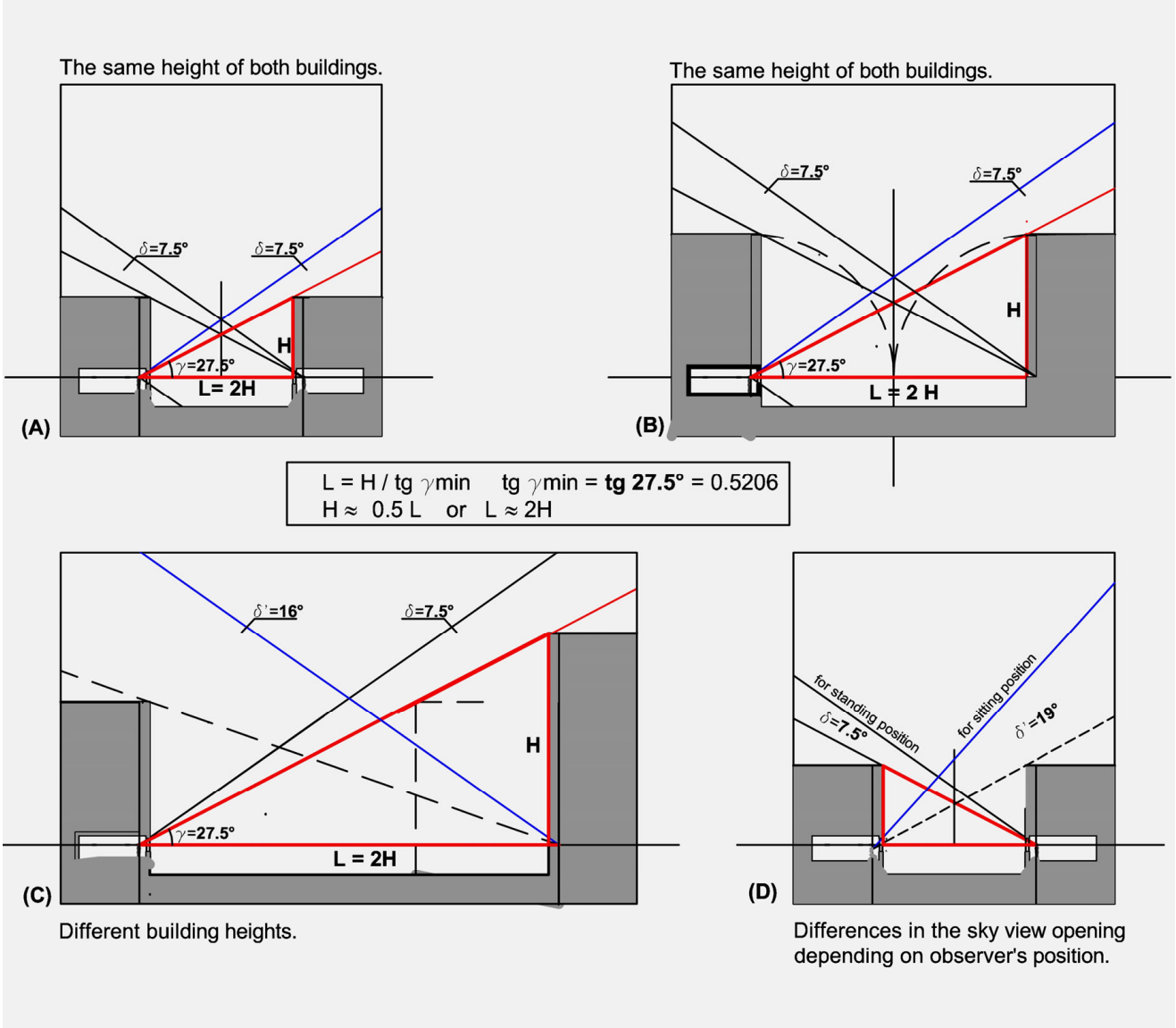
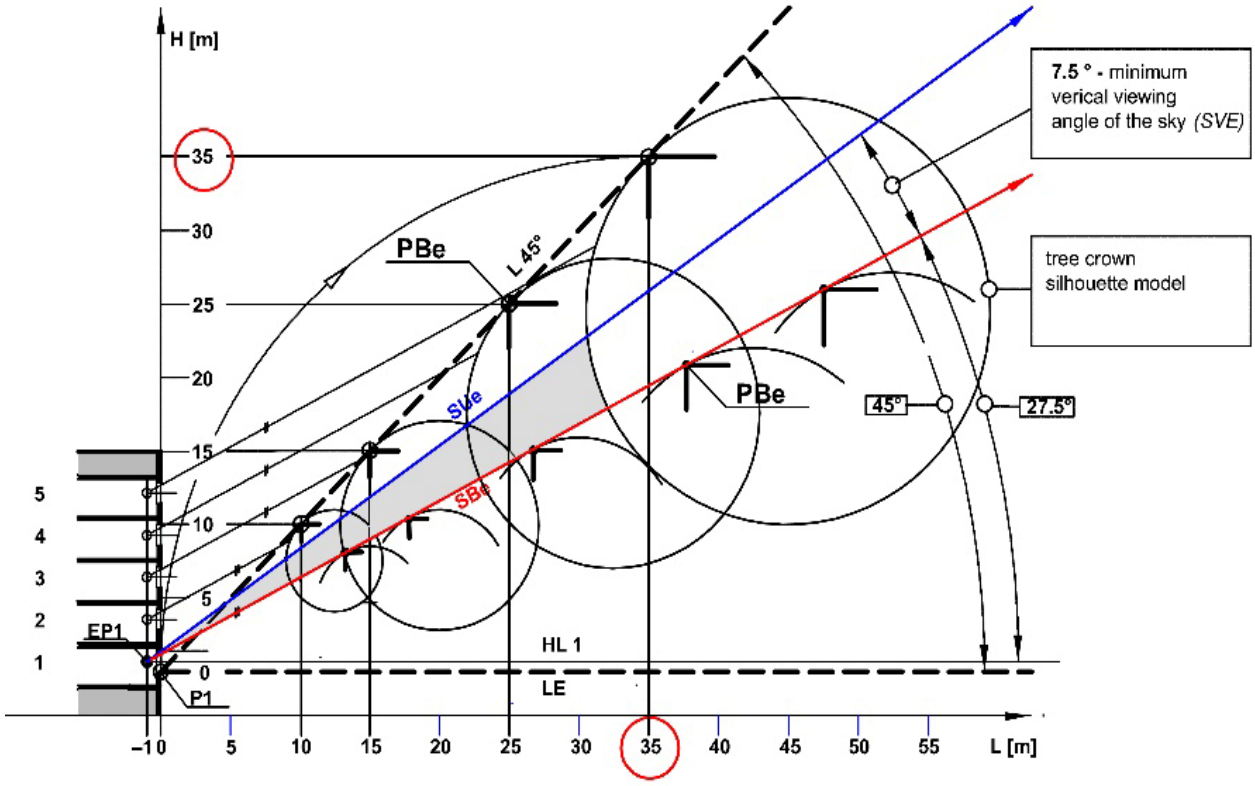


Figure 6. Analysis of cases of minimum distance between buildings derived from the minimum viewing angle equal to 7.5° from ground floor flats, in terms of building height. The presented results demonstrate the geometric correspondence between the minimum viewing angle of 7.5° and the historical "2H" rule. In the conducted analysis, a simple method was used, employing a universal template in the form of a triangular geometric construction shown here in red. Source: authors ZP, MP.

Figures 11–14. Photographic documentation illustrating long-term spatial changes, such as building densification and the growth of tall greenery, is presented. These materials serve to place the geometric analyses in a real spatial context and do not constitute an independent basis for conclusions.

Figure 15. The figure shows an example of landscape integration on a larger scale, where access to the open sky has been preserved through appropriate spatial organisation. This example illustrates how planning decisions can promote the preservation or restoration of directional access to the sky.

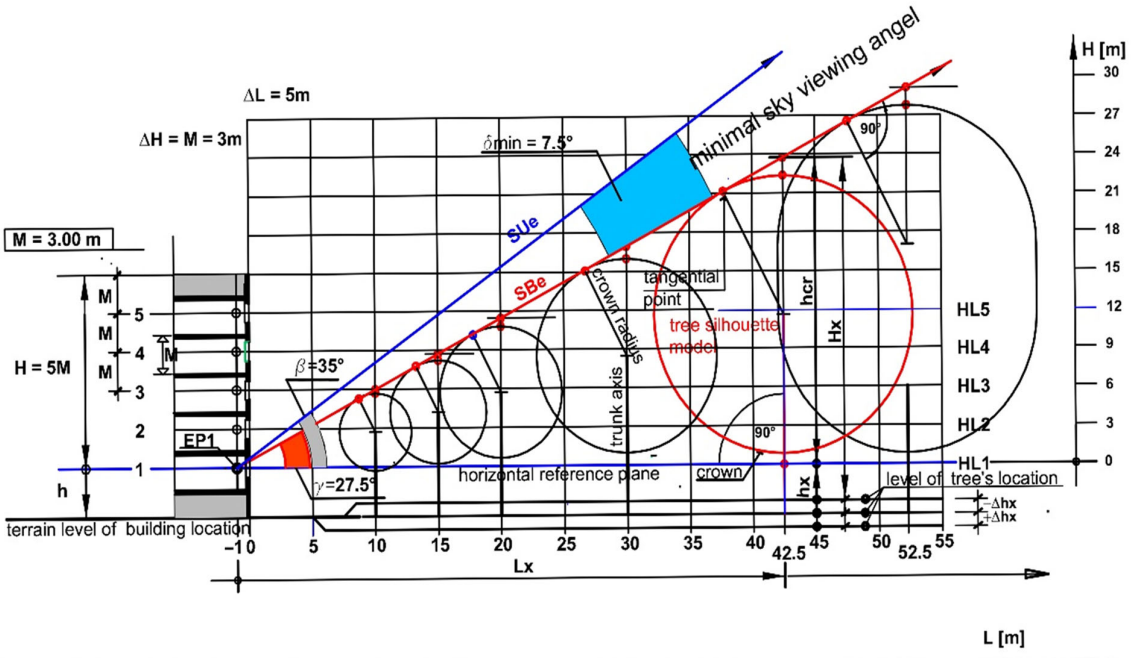


LEGEND:

EP1 - The theoretical eye point on the groundfloor of 5 storey building , the vertical axis of which is 1m away from the building face; **SUe** - Sight line tangential to the upper edge of the window opening, inclination $\beta = 35$ beeing the upper arm of *minimal sky view entry angel* (*SVE*), assumpted as δmin=7.5°; **SBe** - Sight line beeing the lower arm of ***SVE*** angle with inclination $\gamma = 27.5°$; **P1'** - Point of external edge of windowsill of the first floor as reference point for **LE** horizontal line, constituting the basis for determining the height of the shading object; **L45°** - Line establishing relation: L = H, derived from poinnt P1 (in the height range up to H=35m **PBe** - Points of tangency of the upper edge of the screening building or points of tangency of the tree crowns with the L45° line or the SBe line.

Figure 7. Comparison of the requirement for access to the sky view with the Polish building regulations in force regarding the natural lighting of flats. According to the law currently in force in Poland, lighting in residential buildings is considered to meet the required standards if the angle of incidence of light from the dome of the sky is at least 45°. The above analysis shows that a ground-floor flat can meet the standard lighting conditions without meeting the minimum angle requirement for access to the sky. Source: authors ZP, MP.

Collectively, the graphic material in this section constitutes a structured analytical framework combining geometric construction, directional visibility assessment, and spatial context. This framework enables transparent replication of the method and provides a foundation for future computational implementation and quantitative extensions. Together, these elements form a coherent geometry-based framework for analysing directional sky exposure in relation to functional viewing zones.



$$Hx = hcr + hx \qquad tg\gamma = \frac{hcr}{Lx} \qquad Lx = hcr / tg\gamma \qquad hcr = Lx \times 0.5206$$

$$Lx = hcr / Lx \qquad Lx = tg\gamma \times 0.5206 \qquad hcr = Lx \times 0.5206 \qquad hcr = Lx \times 0.5206$$

$$tg\gamma = tg\ 27.5° = 0.5206$$

LEGEND:

EP1 – The theoretical eye point on the groundfloor of 5 storey building, the vertical axis of which is 1m away from the building face;

SuE – Sight line tangential to the upper edge of the window opening, inclination β = 35°, being the upper arm of minimal sky view entry angel (SVE), assumed as α_{min} =7.5°;

SBe – Sight line being the lower arm of SVE angle with inclination γ = 27.5°;

HL 1-5 – Horizontal sight lines of points of eye situated on floors 1–5;

M – Vertical, modular distance between the central horizontal sight lines, specific to the eyepoints on particular storeys, also the modular height of the storey; **h** – Elevation of HL1 horiz-

hcr – Height of the model crown; **hx** - Elevation of HL1 line above the ground level of tree location;

Δhx – The difference between the value of ***h*** and ***hx***:

- if $hx = h$, then $\Delta hx = 0$;
- if $hx < h$, then $hx = h - \Delta hx$;
- if $hx > h$, then $hx = h + \Delta hx$;

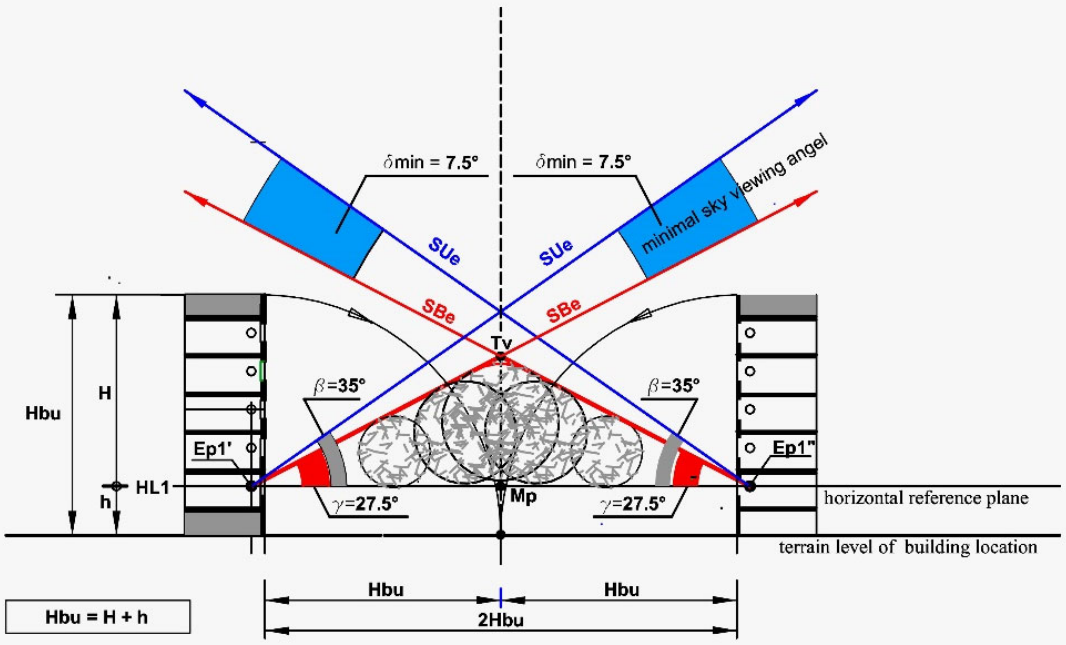
Hx - Height of the tree model with the crown tangent to the **SBe** line;

Lx - Required distance to the trunk axis of the analyzed model tree silhouette that meets the conditions of tangency with the SBe line.

Hx - Height of the tree model with the crown tangent to the **SBe** line;

Lx - Required distance to the trunk axis of the analyzed model tree silhouette that meets the conditions of tangency with the SBe line.

Figure 8. Analysis of the impact of the criterion of access to the view of the sky on the size of tree crowns and their minimum distance from the windows of residential buildings. Source: authors ZP, MP.



Note: Figure 9 should be read in conjunction with Figure 8, the legend of which contains remaining markings.

LEGEND:

Hbu - Total height of the building; **H -** Building height above the HL1 line; **h -** Elevation of the horizontal reference plane (HL1) above terrain level; **Mp -** Midpoint of the EP1' EP1" triangle base; **Tv -** Triangle vertex point;

Figure 9. The criterion of access to the sky view as a determinant of tree stand formation in spaces between residential buildings. An illustrative presentation of the design principles. The condition that the eye points Ep1′ and Ep1″ have a minimum angle of access to view of the sky requires that the treetop silhouettes do not exceed the "SBe" lines.Source: authors ZP, MP.



Figure 10. Józefowiec housing estate in Katowice—aerial view showing the current state of spatial relations between residential buildings and groups and masses of trees. It illustrates the mutual interaction of buildings and tall greenery on access to the sky on the scale of the housing estate. Source: author ZP.



Figure 11. An example of the relationship between a tree and a residential building, showing the reduction in the visibility of the sky for flats located in its immediate vicinity. Source: author ZP.

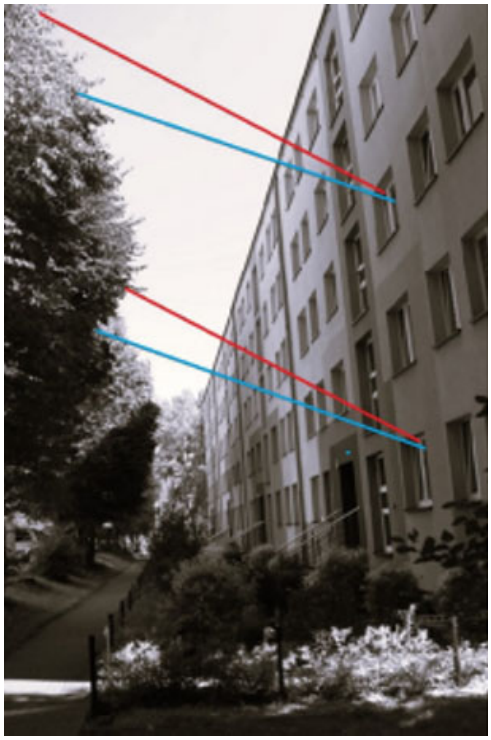


Figure 12. The relationship between tall greenery and the reduction of sky visibility in the immediate vicinity of the observer. Red lines indicate the upper limit of visible sky obstruction, while blue lines represent the lower sightline boundary defined by surrounding greenery and building geometry. Note: The angle between the red and blue lines is the required minimum opening angle for the sky view. Source: author ZP.

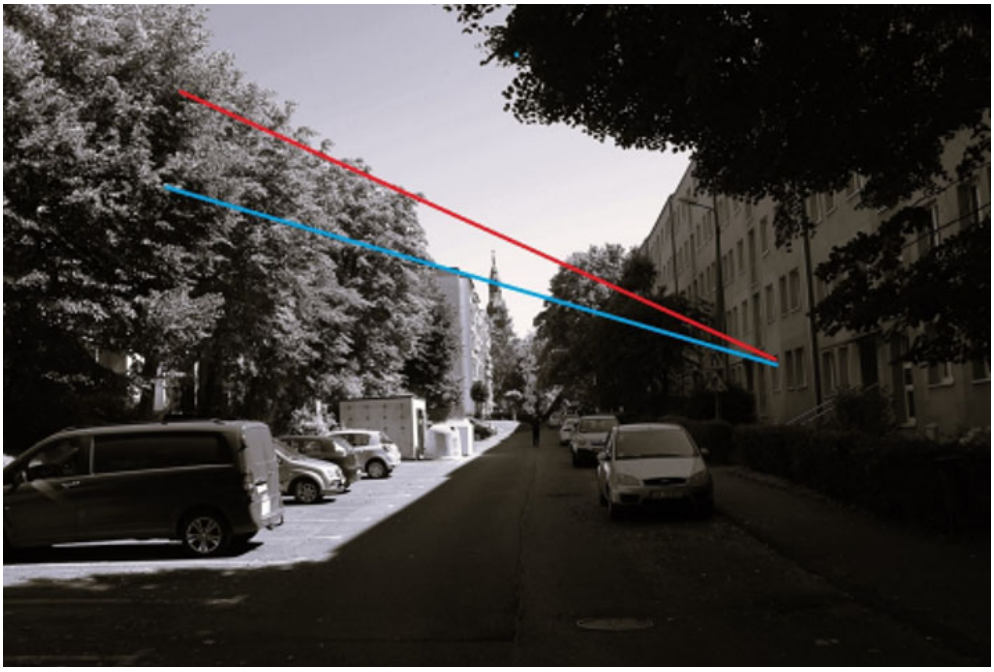


Figure 13. The impact of tall trees on the reduction in access to the sky in a residential building. Note: The angle between the red and blue lines is the required minimum opening angle for the sky view. Source: author ZP.



Figure 14. Photographic analysis. Graphic representation of the minimum sky view angle (7.5° criterion), indicating the limiting condition of directional access to the sky for ground-floor flats and for flats located on the first, second and third floors. The example illustrates the effect of restricted sky visibility caused by tall trees, whose impact is further intensified by their location on an elevated slope. Note: The angle between the red and blue lines represents the adopted minimum opening angle for sky visibility. Source: author ZP.

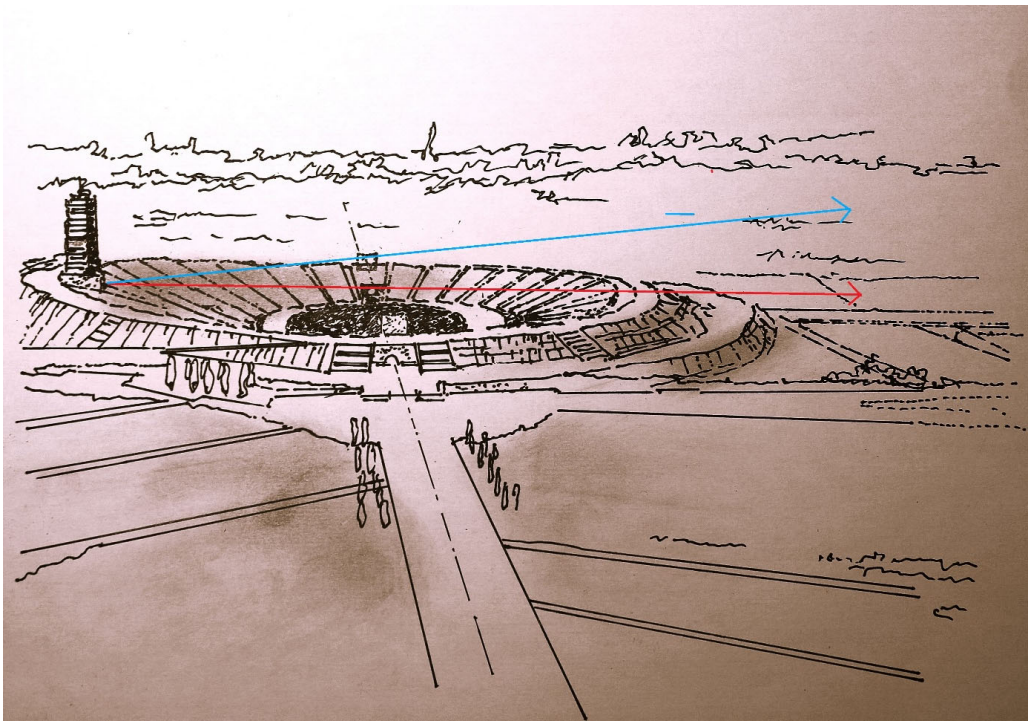


Figure 15. Silesian Stadium in the landscape of Silesian Park (1956). The main functional and spatial assumptions adopted by architect Julian Brzuchowski aimed to achieve the stadium's landscape character. The significant elevation of the western stands above the eastern stands opens up far-reaching views of the park's eastern panorama, including Planetarium Hill, for spectators. The arrows indicate the primary viewing directions opened by the elevation difference between the western and estern stands. Source: author ZP.

4. Results

4.1. Structure of the Sky View

The analysis suggests that geometric visibility of the sky does not always correspond to the way spatial information is processed across different eccentricities of the visual field [5]. In many of the analysed residential locations, the sky is formally visible, yet it is reduced to a narrow strip just above the line of obstruction. Such an opening remains confined to the central field of view and does not engage the peripheral zones that contribute to the perception of large-scale spatial information (Figure 1). In these situations, the visible portion of the sky functions more as a limited source of light than as a clearly structured spatial element, making it harder to assess its height, extent, and relationship to the surrounding buildings. In cases of greater exposure—particularly in diagonal and zenithal sectors—the sky view extends beyond the central eccentricity ranges discussed in the literature in relation to large-scale luminance perception. Under these conditions, the sky may become a more stable spatial reference, supporting the perception of scale and vertical relationships. These differences are not revealed by analyses based solely on averaged indicators but become evident when examined using hemispheric methods.

4.2. Impact of Buildings and Greenery

Buildings and tall greenery modify the structure of the sky view in a direction-dependent manner. These elements do not limit access to the sky uniformly, but selectively eliminate specific sectors of the hemisphere, often those most relevant for spatial perception—particularly the diagonal and zenithal sectors (Figures 8 and 9). As a result, even minor geometric changes in superstructures, balconies or tree crowns may significantly alter the perceptual quality of space.

The analysis indicates that greenery is not inherently a negative factor. When tall tree crowns leave key sky sectors unobstructed, the sky can retain its orientational function. The decisive factor is therefore not the presence of greenery itself, but its geometric relationship to the observer and surrounding buildings.

The discussion of short-wave light absorption by plant tissues, often mentioned in relation to melanopsin sensitivity (~480 nm), is included here solely as contextual background. It does not imply a physiological assessment of light effectiveness, but serves to frame the structural analysis of directional sky exposure. This perspective allows moving beyond a binary "greenery–buildings" evaluation toward a geometry-based assessment of perceptually significant sky sectors.

4.3. Comparative Analysis and Typology of Sky Openings

Based on hemispheric analysis and the values of the RRI-A and RRI-B metrics, three basic types of sky openings were distinguished, differing in their perceptual relevance:

- Sub-perceptual openings—situations in which the visible portion of the sky is confined to very narrow sectors located within the central few degrees of the field of view (Figures 1 and 2).
- Threshold openings—configurations in which the sky aperture begins to extend beyond central viewing ranges (approx. 10° of eccentricity), yet does not fully engage the peripheral zones of the visual field.
- Stable openings—situations involving oblique and/or zenithal sectors exceeding approximately 20° of eccentricity. In such cases, the sky engages peripheral vision and may function as a relatively stable spatial reference supporting the perception of scale and spatial relations.

Within the adopted geometric framework, RRI-A quantifies the vertical angular aperture of the sky, primarily corresponding to central viewing directions (approx. 5–10°). RRI-B evaluates the visibility of a predefined peripheral angular band (42–69° relative to the gaze axis), treated as a representative geometric interval beyond central vision.

Accordingly:

- In sub-perceptual openings, RRI-A may take non-zero values while RRI-B remains low;
- In threshold openings, RRI-B indicates partial visibility of the peripheral band;
- In stable openings, RRI-B approaches values corresponding to full visibility of the adopted peripheral wedge.

4.4. Case Study: The Józefowiec Housing Estate and Similar Post-War Complexes

As a result, many spaces have moved from the category of stable openings to threshold or sub-perceptual ones, despite formally meeting classic planning criteria such as sunlight requirements or SVF values. These phenomena may be interpreted as perceptual effects of contemporary urban densification processes, in which point interventions—such as the growth of tall greenery—are not fully captured by averaged geometric indicators and gradually degrade the directional structure of the sky view.

An extreme case of restricted access to the sky, affecting both ground-floor and upper-floor flats, is documented through photographic analysis in which the minimum sky view angle (7.5° criterion) has been reduced to its limiting condition (Figure 14).

Similar processes can be observed in other post-war housing estates, such as the Tysiąclecia and Paderewskiego estates in Katowice, Ursynów in Warsaw, as well as modernist estates in Berlin, Prague and Budapest. The common denominator here is a gradual departure from the original principles of spatial design—strongly linked to the industrial landscape of the city

and the need for light—in favour of denser development and uncontrolled growth of greenery, leading to the loss of the directional structure of the sky view.

An analysis of the Józefowiec housing estate showed that the originally open urban structure is undergoing gradual perceptual degradation as a result of the development of greenery (Figures 10–14).

5. Discussion

5.1. Perceptual Interpretation of Results

Retinocentric analysis suggests that the quality of spatial perception depends not only on the amount of available daylight but also on the directional structure of the sky view and the way in which it engages the functional zones of the field of vision. Shifting the emphasis from average measures to directional analysis allows us to better explain why urban layouts that formally meet classic lighting criteria can be perceived as overwhelming, while others promote orientation and spatial clarity.

From this perspective, the loss of directional access to the sky may imply not only a reduction in the amount of daylight but also a weakening of contact with its most stable and spatially dispersed environmental component; this aspect is treated in this study solely as an interpretative context.

In the literature, the short-wave component of daylight is sometimes associated with circadian processes, but in this study these references serve only a contextual function and are not the subject of direct analysis.

From this point of view, the analysis of directional exposure to sky light may also be of interpretative importance for the organisation of study and work stations, where access to daylight is often assessed solely in quantitative terms. Taking into account peripheral directions of light exposure can provide a complementary context for the discussion of indoor environmental quality without formulating normative design recommendations.

5.2. Short-Wave Light and the Role of Greenery

Short-wave light (approximately 460–490 nm) is frequently discussed in the literature in relation to perceptual and circadian processes. Data on the spectral sensitivity of the visual system, including melanopsin mechanisms, are treated here as established scientific knowledge and are not directly analysed within this study. In the context of the urban environment, it is important to note that both urban greenery and typical building glazing selectively absorb part of the short-wave radiation. Standard window panes may reduce the transmission of short-wave light, which means that unobstructed sky sectors may acquire relatively greater perceptual relevance within the adopted geometric framework. This observation supports considering the directional structure of sky exposure in daylight analysis within dense developments, without implying normative or health-related design prescriptions.

In the long term, the context of decades of green growth and its spatial effects is also important. The panorama of Silesian Park (Figure 15) documents the positive, long-term transformation of plantings on industrial wastelands into a dense and ecologically valuable forest complex. The park's layout was created as a result of the reclamation of degraded post-industrial areas, mainly through the planting of millions of trees between 1955 and 1965. Now, after 60–70 years, they form a dense tree stand. This is an example of an exceptionally positive landscape transformation, in which, in addition to the natural environment, the wide openness allowing full contact with the sky plays an important role. Awareness of the importance of natural composition inspired the designers of the Silesian Stadium, leading to an architecture that coexists with the landscape and introduces

attractive openings to the park complex. This approach was also evident in the unrealized "Saturn 2005" roofing project.

This case provides an interpretative background for the problem of the gradual, unintentional degradation of directional access to the sky in residential structures, such as the Józefowiec housing estate (Figures 10 and 11).

The collected supplementary literature suggests that directional access to the sky benefits from an interdisciplinary approach, combining knowledge from the fields of neurophysiology, visual optics, environmental psychology and urban planning. This subchapter therefore serves to interpret the results presented earlier, without introducing new theses or duplicating the literature references used in the main part of the article. All references to the biological significance of light are descriptive in nature and do not imply an assessment of physiological or health effects.

5.3. Behavioural Context and Spatial Preference

The importance of the view of the sky is supported by behavioural studies indicating a preference for places near windows in public spaces [13]. This behaviour can be interpreted as a spatial preference related to environmental stimuli, including access to daylight with a clear directional structure.

Similar implications arise in educational spaces, where the orientation of workstations relative to windows can affect the perceptual conditions and comfort of users. These considerations concern the organisation of space, not direct teaching effects.

5.4. Design Implications and Directions for Further Development

From a design perspective, the results of the retinocentric analysis indicate the need to supplement classic environmental assessment tools with methods that enable the analysis of users' actual directional exposure to daylight. It seems particularly important to distinguish between the formal availability of light and its perceptual significance for spatial orientation.

The proposed framework should be understood as a geometry-based extension of existing environmental performance indicators addressing the directional structure of sky exposure. In this sense, the RRI metrics represent a geometry-based abstraction inspired by biological evidence rather than a physiological simulation.

In this context, it is reasonable to treat future research on spectral measurements as a supplement to geometric analyses of directional access to the sky. This approach should be understood as a direction for research, rather than a direct technological or normative postulate.

Any considerations regarding shortwave light should be treated as analytical descriptors rather than regulatory tools imposing specific design restrictions. The literature on environmental psychology suggests that limited access to daylight may affect the subjective well-being of users; however, the health implications remain outside the direct scope of this study.

The integration of retinocentric analyses into design practice and planning tools may, in the future, enable more informed shaping of the residential environment, while maintaining a cautious, empirical approach to biological issues.

Another important direction for further research is the analysis of the spectral transmission of transparent partitions. Future work could focus on comparing standard glazing packages with solutions with different spectral characteristics, especially in the short-wave range, which is discussed in the literature in relation to melanopsin-mediated processes.

This research should not lead to direct normative postulates, but to a better understanding of the relationship between the geometry of access to the sky, spectral filtering of light by partitions, and the actual directional distribution of sky-related light within the defined geometric viewing frame. Another direction for further analysis is to deepen the re-

lationship between the eccentricity of the field of view and the actual topography of ipRGC cells in the human retina, taking into account potential individual differences. A better understanding of these relationships could, in the future, allow a more precise comparison between geometric angular thresholds and retinal topography, without implying direct physiological conclusions. However, this issue is beyond the scope of this article.

References to biologically active light and peripheral vision serve an interpretative function in this chapter, providing context for the geometric results without entering into detailed neurophysiological considerations. At the same time, they point to a potential direction for further research, consisting of a more precise correlation between the geometry of access to the sky and the actual exposure of users to light stimuli of biological significance.

Recent sustainability-oriented research increasingly highlights the limitations of single averaged environmental indicators and emphasises the need for multi-criteria, performance-based assessment frameworks in urban design. Computational studies addressing climate resilience and adaptive urban form demonstrate that environmental quality cannot be adequately described using one-dimensional metrics, but requires direction-sensitive and geometry-based analyses that reflect actual human–environment interactions [20].

Future research may explore the integration of geometric sky-access analysis with spectral transmission studies of glazing systems and façade materials. Such investigations could clarify how spatial geometry and material filtering jointly influence the directional distribution of sky-related light within interior environments. These directions should be understood as research extensions rather than normative design prescriptions.

In the context of sustainability research, the proposed retinocentric approach should be understood as a perceptual-performance indicator rather than a normative design rule, and references [20,21] are used to frame this approach within broader computational and multi-criteria sustainability assessment paradigms.

6. Conclusions

The analyses suggest that contact with the sky in a residential environment is not only physical but also perceptual in character [2]. The sky may function as a relatively constant, large-scale reference element supporting spatial orientation, a sense of scale and the legibility of the surroundings. Its presence in the field of vision—especially in sectors involving peripheral vision—promotes stable perception of space, even when the user is not consciously focusing on it.

6.1. Design Recommendations and Directions for Action

In light of the results, it is reasonable to formulate recommendations that extend beyond the mere description of geometric phenomena and address design practice and spatial policies in a cautious and scope-consistent manner.

Firstly, contemporary urban and architectural design should take into account not only quantitative access to daylight but also the directional structure of views of the sky. Oblique and zenithal sectors—identified in the retinocentric analysis as perceptually significant for spatial orientation and environmental legibility—may therefore be considered in spatial planning. Criteria based solely on averaged indicators (e.g., Sky View Factor) can be complemented with geometry-based metrics relating to functional fields of view, such as RRI-B (Figure 6), in order to better reflect the directional organisation of sky exposure experienced by users.

Secondly, environments intended for children require careful spatial consideration. Age-related differences in optical transmission and visual system characteristics are acknowledged in the literature; however, such aspects are not analysed in the present study and are

mentioned solely as general contextual background. The current framework remains strictly geometry-based and does not derive age-specific biological or health-related implications.

The present analysis remains strictly within a geometric and perceptual framework. Therefore, any age-related differences in spectral sensitivity should not be interpreted as direct design determinants, but rather as contextual considerations that may inform future interdisciplinary research.

Within the scope of this study, maintaining clear and unobstructed directional access to the sky is discussed as a geometric-perceptual factor associated with spatial legibility and environmental orientation, without formulating explicit biological or health-related claims.

Thirdly, the results highlight the relevance of semi-open spaces, particularly balconies and loggias. These spaces enable contact with the sky without the mediation of glazing, whose spectral transmission characteristics may vary depending on material composition and construction. In many flats, they constitute the only locations where users can experience direct sky exposure without additional optical filtering or reflections. The balcony thus functions not merely as a utilitarian architectural element, but as a transitional interface between interior space and the broader hemispheric structure of the sky. The geometric relationship between balustrade height, loggia depth, and neighbouring buildings can determine whether directional sky exposure remains sub-perceptual or becomes spatially legible and structurally integrated within everyday visual experience (Figure 3).

Fourthly, it is worth noting the broader tendency toward reduced daily contact with the open sky among urban populations. Contemporary glazing systems may limit the transmission of short-wave components of daylight; however, the present study treats such spectral aspects exclusively as contextual background and does not formulate performance- or health-based criteria related to spectral control. Compared to historical living conditions, contemporary city dwellers spend a significant portion of their time in enclosed environments, where visual contact with the sky is often restricted to brief episodes or narrow openings between buildings. Within the geometric interpretative framework adopted in this study, such spatial reduction in directional sky exposure may influence perceptual legibility, the readability of spatial depth, and the clarity of environmental orientation.

A fully repeatable geometric protocol is provided in Appendix A.

6.2. Interdisciplinary Implications

It should be emphasized that the approach proposed in this article is interdisciplinary and combines geometric analysis with architectural design experience. In the case of the Silesian Stadium modernization, one of the guiding spatial assumptions was to preserve a directional view from the western stands toward the panorama of Silesian Park and the open sky above the eastern stands (Figure 15).

The gap between the horizontal roof and the upper edge of the stands was shaped so as to maintain visual contact between spectators and the sky–landscape horizon. In a venue of considerable perceptual scale, such reference elements may contribute to spatial orientation and environmental legibility. At the same time, this example is presented as an illustrative case of large-scale spatial design.

The relationship between spectator, sky, and landscape evokes an architectural analogy with historical amphitheatres, where the stepped auditorium—often integrated into natural terrain—allowed events to unfold against the backdrop of the open sky and surrounding topography. The reference here is conceptual rather than formal, and serves to underline the long-standing architectural intuition that open sky exposure can structure large collective spaces.

Taken together, geometric analysis, perceptual interpretation, and design practice support considering directional access to the sky as a relevant component of environmental

quality in residential and public spaces. Within the scope of this study, this proposition remains interpretative and geometry-based, without extending into physiological or normative claims.

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Abbreviations

The following abbreviations are used in this manuscript:

RRI	Relative Retinal Image
SVF	Sky View Factor
ipRGC	intrinsically photosensitive retinal ganglion cells

Appendix A. Repeatable Geometric Protocol for RRI-A and RRI-B

Appendix A.1. Purpose and Scope of the Protocol

This appendix provides a fully repeatable geometric procedure for calculating the RRI-A and RRI-B indicators introduced in the main text.

In simple terms, the protocol explains how to determine which parts of the sky are visible from a given point inside a room, and which parts are geometrically blocked by surrounding buildings or vegetation.

The method is designed so that it can be reproduced either:

- manually (by graphic construction in a vertical section), or
- computationally (using ray–obstruction intersection routines).

The procedure evaluates directional sky visibility within a window-limited viewing frame. It does not require full-hemisphere integration and does not rely on physiological measurements. All quantities are defined geometrically.

In practical terms, this means that we translate spatial relationships into measurable angular intervals.

The geometric logic underlying this protocol is consistent with established methods of angular sightline analysis used in architectural design, particularly in the study of stadium stand profile geometry and visibility optimization [3]. In that publication, the reader can find detailed information concerning graphic and computational procedures for angular visibility assessment in large-scale spatial systems. The present protocol applies a comparable angular-analytical approach to the assessment of directional sky visibility in residential interiors.

Certain schematic figures reproduced in the main text retain extended graphical notation originally developed in [3]. For the purposes of the present study, only the angular definitions and computational steps explicitly specified in this appendix are operative for RRI-A and RRI-B calculations.

Appendix A.2. Input Parameters

The procedure requires three groups of input parameters: observer parameters, viewing-frame parameters, and obstruction parameters.

These parameters describe:

- where the observer is located,
- how they are looking,
- and what may block the view.

Appendix A.2.1. Observer Parameters

Eye height (h_eye)

Vertical position of the observer's eye above finished floor level.

In everyday terms, this represents whether we analyse the view from a seated position, or a standing adult position.

In this study, two representative values are used:

- 1.2 m (seated/child reference),
- 1.6 m (standing/adult reference).

The chosen value must be explicitly reported for each analysed scenario.

Distance from the window (d_win)

Horizontal distance between the observer and the interior window plane.

This parameter defines how far the person stands from the window—a factor that influences which angles are visible.

In this study:

- 1.0 m is adopted as a typical near-window position.

Vertical gaze direction (α_gaze)

Angle between the central line of sight and the horizontal plane.

This parameter reflects whether the observer looks straight ahead, slightly upward, or slightly downward.

Three habitual gaze states are considered:

- α_gaze = 0° (horizontal),
- α_gaze = $+25^\circ$ (upward),
- α_gaze = -25° (downward).

Each scenario must clearly state which gaze direction is analysed.

Appendix A.2.2. Viewing Frame Parameters

Horizontal viewing limitation

The analysis is limited to a window-centered horizontal viewing frame of:

$\pm 30^\circ$ from the window normal (i.e., 60° total horizontal opening).

In other words, we do not analyse the entire sky dome, but only the portion that can realistically be seen through the window.

Obstructions outside this horizontal sector are not included in the RRI evaluation.

Vertical viewing frame

In the vertical section, the viewing frame is defined by straight rays drawn from the eye point toward:

- the upper limiting element (upper window edge, balcony slab, overhang), and
- the highest external obstruction in the direction of view (opposite building edge, tree crown, etc.).

These rays define the vertical limits of visible sky.

Appendix A.2.3. Obstruction Parameters

All relevant obstructions are represented by their angular elevation as seen from the observer point.

These may include:

- opposite building façades,
- balcony slabs,
- roof overhangs,
- vegetation silhouettes.

Each obstruction must be represented consistently in the same vertical section.

In practical terms, anything that blocks the line of sight before it reaches the sky is treated as an obstruction.

Appendix A.3. Output Definitions

Two geometric descriptors are calculated.

These descriptors allow us to quantify how different parts of the visual field are affected.

Appendix A.3.1. RRI-A (Relative Retinal Image–Aperture)

RRI-A quantifies the vertical angular aperture of visible sky within the defined window-limited viewing frame. It is calculated as the angular difference between the upper and lower boundary rays constructed in the vertical section ($\Delta\alpha$_sky).

This value represents the absolute geometric opening through which the sky is visible from a given observation point. Unlike RRI-B, which measures the proportion of a predefined peripheral wedge, RRI-A expresses a directly measured angular interval and is therefore reported in degrees.

Within the interpretative framework of the present study, RRI-A primarily relates to central and near-central viewing directions (approximately 0–10° of eccentricity). It provides a geometric basis for comparing the minimum vertical sky aperture available in different spatial configurations, without implying any physiological or luminance-based assessment.

Reported value:

- $\Delta\alpha$_sky (in degrees)

Appendix A.3.2. RRI-B (Relative Retinal Image–Directional Band)

RRI-B evaluates the visibility of a predefined directional sky wedge within the peripheral field of view.

The wedge has a fixed angular width of 27° and is positioned between 42° and 69° relative to the current gaze axis. Its geometric definition corresponds to the schematic cross-sectional representation shown in Figure 2 of the main text, which provides the angular basis for the construction described in Appendices A.3.2 and A.4.4.

The selection of the 42–69° interval follows the adopted retinocentric assumption that the analysis focuses on a directional band geometrically associated with the retinal equatorial region (approximately ±20° around the retinal mid-periphery). Within this framework, the wedge represents a geometrically defined peripheral exposure zone rather than a physiological model. Alternative angular intervals (e.g., ±5° or other eccentricity ranges) could be adopted by other researchers depending on the specific retinal region

or perceptual function under investigation. In the present study, a constant 27° wedge is maintained to ensure methodological consistency and comparability across cases.

Because RRI-B measures the proportion of this predefined wedge that remains unobstructed, it is expressed as a percentage rather than as an absolute angular value. This formulation allows a direct comparison of peripheral sky exposure across different spatial configurations while keeping the angular reference interval constant.

Appendix A.4. Manual Graphic Procedure (Vertical Section)

The following steps are performed in a 2D vertical section passing through the observer and the window centerline.

This construction translates spatial geometry into measurable angles.

Appendix A.4.1. Step 1—Define the Observer Point

Place the eye point (EP):

- at height h_eye above the floor,
- at horizontal distance d_win from the window plane.

This point becomes the origin for all angular measurements.

Appendix A.4.2. Step 2—Define the Central Gaze Line

From EP, draw the central gaze line with angle α_gaze relative to the horizontal.

This line represents the current direction of attention.

Repeat the following steps separately for each selected gaze state if comparative analysis is required.

Appendix A.4.3. Step 3—Determine the Sky Opening Boundaries (For RRI-A)

From EP, draw two rays:

- an upper tangent ray to the upper limiting element,
- a lower tangent ray to the highest external obstruction.

The angular interval between these two rays represents the visible vertical sky opening.

In perceptual terms, this is the sky that fits within the central viewing frame.

Step 4—Compute RRI-A

Measure the angular difference:

$$\Delta\alpha_sky = \alpha_upper - \alpha_lower$$

This value (in degrees) is reported as RRI-A.

It expresses how wide the visible sky aperture is.

Appendix A.4.4. Step 5—Define the Directional Wedge (For RRI-B)

For the selected gaze direction α_gaze, define two additional rays:

- α_gaze + 42°
- α_gaze + 69°

The angular interval between these rays is 27°.

This interval defines the peripheral directional wedge.

Appendix A.4.5. Step 6—Determine Wedge Obstruction

Check which portions of the 27° wedge are intersected by obstructions.

If a ray reaches the sky without intersection, that portion is considered visible.

If it intersects a building or vegetation before reaching the sky, that portion is considered obstructed.

Appendix A.4.6. Step 7—Compute RRI-B

Measure the visible part of the wedge:
Visible_wedge_angle
Then compute:

$$\text{RRI-B (\%)} = (\text{Visible_wedge_angle}/27^\circ) \times 100$$

This value expresses the percentage of the peripheral band that remains unobstructed.

Appendix A.5. Optional Sensitivity Variant

To assess the sensitivity of RRI-B to the assumed retinal directional band, the angular position of the 27° directional wedge (defined in Appendices A.3.2 and A.4.4) may be shifted relative to the gaze axis.

Instead of the baseline interval:
α_gaze + 42° to α_gaze + 69°,
an alternative 27° interval may be analysed, for example:
α_gaze + 10° to α_gaze + 37°,
α_gaze + 25° to α_gaze + 52°,
or any other fixed 27° band defined relative to α_gaze.
In all sensitivity variants:
the wedge width (27°) remains constant,
only its angular position relative to the gaze axis changes.

This allows researchers to test whether the RRI-B result is robust with respect to assumptions about retinal eccentricity or peripheral exposure zones.

All alternative intervals must be explicitly reported to ensure reproducibility.

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