The design of window shades and fenestration for view clarity

Michael G. Kent[a,b], Won Hee Ko[c], Iason Konstantzos[d], Stefano Schiavon[e], Piers MacNaughton[f] and Arnold J. Wilkins[g]

[a] Singapore University of Social Sciences, School of Business, Singapore
[b] SinBerBEST, Berkeley Education Alliance for Research in Singapore, Singapore
[c] Hillier College of Architecture & Design, New Jersey Institute of Technology, Newark, New Jersey, United States
[d] Durham School of Architectural Engineering & Construction, University of Nebraska – Lincoln, Lincoln, United States
[e] Center for the Built Environment, University of California, Berkeley, United States
[f] View Inc., Milpitas, California, United States
[g] Department of Psychology, University of Essex, United Kingdom

Corresponding author: michaelgeorgek@suss.edu.sg

Abstract

The ability to discern the content of the view through a window is referred to as *view clarity*. It is often overlooked in the design process, and the methods of shading daylight can affect window views. We conducted a narrative review of building standards and the scientific literature to better understand how shades can be designed so as to retain the window view. View clarity was characterised by three main dimensions: 1) the shading solution; 2) the view content; and 3) the observer. Each dimension and the interactions between them influence view clarity. These interactions make it difficult to predict view clarity for all the situations that can occur in buildings. Nonetheless, we highlighted the effects of different shades on the view clarity. Our insights can help designers consider these impacts within the context of overall window design.

Keywords: Window view; Daylighting; Shading; Fenestration; Windows; Design; Architecture

1. Introduction

Views out of buildings connect people to the outside,[1] helping to maintain their health and wellbeing.[2] This connection is responsible for the many benefits that views convey such as student achievement[3,4] and cognitive work performance [5]. Our recent framework defines view quality by three parameters:[6] content, access and clarity. Whilst standards advocate criteria for content[7,8] and support sufficient access for occupants to see nearby windows,[9–11] view clarity is difficult to guarantee. Clarity through windows addresses the ability to see and discern view content.[6] This is a salient issue considering that the optical properties of window shades and fenestration interact with daylight, altering the view content seen through the window.[6,12–14]

Shading plays an important role during building operations.[15] Most shades are installed to control daylight admittance through windows, preventing conditions that lead to thermal[16] or visual discomfort.[17,18] They may also be used to prevent visual privacy,[19,20] for environmental conservation (e.g. bird collisions)[21] or even for energy generation (e.g., semi-transparent photovoltaics).[22] Tinted glass or films that alter the chromatic properties of the glass also serve as shading systems, but these can impact colour visual acuity[23–25] and subjective perception[26] of the observers. Irrespective of shading types, designs will alter the visual connection experienced from the view out.[27] These changes not only influence visual clarity,[14,28] but can impact on other aspects of human vision and psychology that are worthy of investigation.

1.1. Problem overview

Our previous position statement[13] highlighted view clarity as a significant challenge to the successful design of window views, pinpointing façade materials, façade operation, and other factors (e.g., façade maintenance) as emerging problems. This raises important questions about how much and how long views are preserved once shades are used. It was estimated that more than 75% of buildings have over half their glazed area covered, and on average, 59% of the glazed area was covered by window shades or blinds.[29]

Daylight metrics such as Annual Sunlight Exposure[30] could provide insights into how often shade are used. However, the complex relationships between occupant behaviour and the external environment present overt challenges in accurately predicting manual window blind operation.[31] Blinds are not invariably deployed by occupants to avoid glare or overheating. Shades are used more on lower than upper floors to provide visual privacy.[8] This could be overcome by advanced data analytics (e.g., random forest), which yielded high prediction accuracies for different attributes of the view.[32] However, view clarity was not measured.

Designing windows without consideration of view clarity presents challenges for occupant comfort and satisfaction. Designs that meet high-quality criteria for view content (e.g., ground, landscape and sky layers[19]) and view access (e.g., sufficient window opening size[33,34]) will not guarantee overall quality. View clarity can override view content and access if window shades are deployed to account for occupant preferences (e.g., privacy, glare control, thermal comfort).

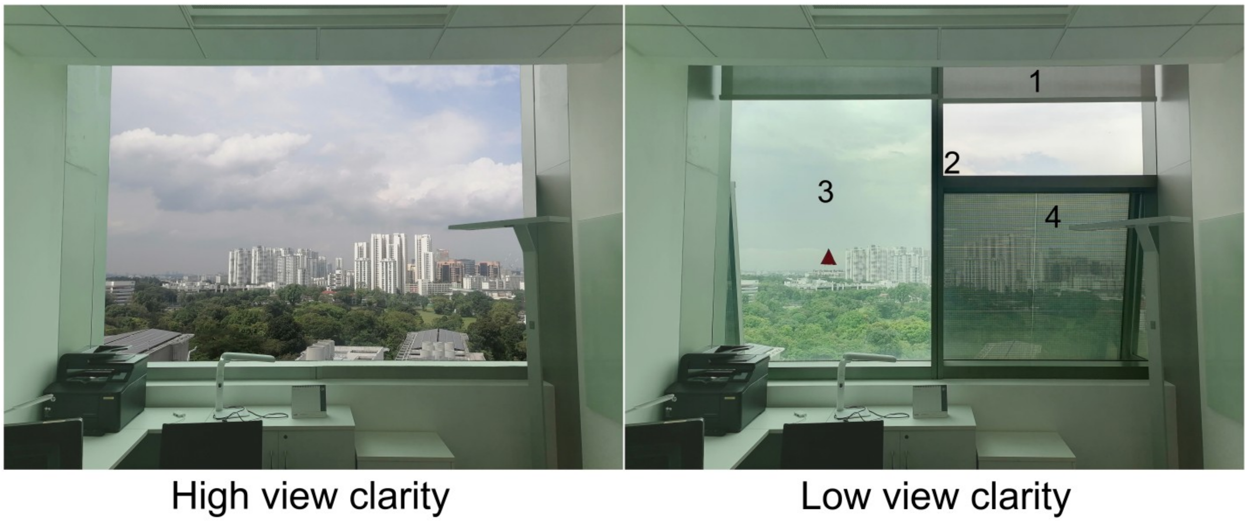

Figure 1 The same window view with high and low view clarity. Reduced view clarity is caused by 1) fabric roller blinds, 2) vertical mullion and horizontal lightshelf, 3) low transmittance glazing, and 4) semi-transparent photovoltaic panel

View clarity is rarely determined by a single obstruction (Figure 1). Clarity is affected by shades and other fenestration objects such as mullions.[6] Therefore, not every object that reduces view clarity was designed with the intent of shading. For example, protective nets in high-rise residential buildings can be installed for anti-theft purposes and/or to protect children or objects from the building. However, the netting creates a mesh pattern that may hinder view clarity. Shades arguably cause the largest shifts in clarity, considering the wide variety of shading products that are available (e.g., fabric roller shades, external louvres and electronic glazing). Both WELL version 1[35] and 2[36] advocate many types of shades (e.g. lightshelves, operable draperies, fritted or electronic blackout glazing). Understanding how each element (e.g., roller blinds, lightshelves, or the glazing), can alter the view content seen by occupants is paramount to understanding how shades can be designed to retain view clarity.

2. Literature review

The Cambridge Dictionary defines clarity as: "*The quality of being clear and easy to understand*".[37] When contextualised to architecture, window views and human vision, clarity becomes a more complex concept. We had previously defined view clarity as the ability to see and discern view content (e.g., buildings and trees).[6] Although our definition does not entirely depend on properties associated with visual clarity (e.g., preferred or perceived brightness and colour[38–40]), it shares some similarities with it that also resemble recognised international lighting vocabulary that also describes "clarity" (i.e., 17-24-131)[41]:

"Characteristic of a transparent or semi-transparent material whereby distinct high-contrast images or high-contrast objects, separated by some distance from the material, are perceivable through the material"

A more granular characterisation of view clarity was proposed by Hill and Markus.[12] They proposed that human vision through window meshes could be described by three main dimensions: 1) obstruction properties (e.g., in their study window meshes); 2) view content properties; and 3) the observer. When generalised these three concepts to other shading typologies, similar distinctions can also be applied (Figure 2).

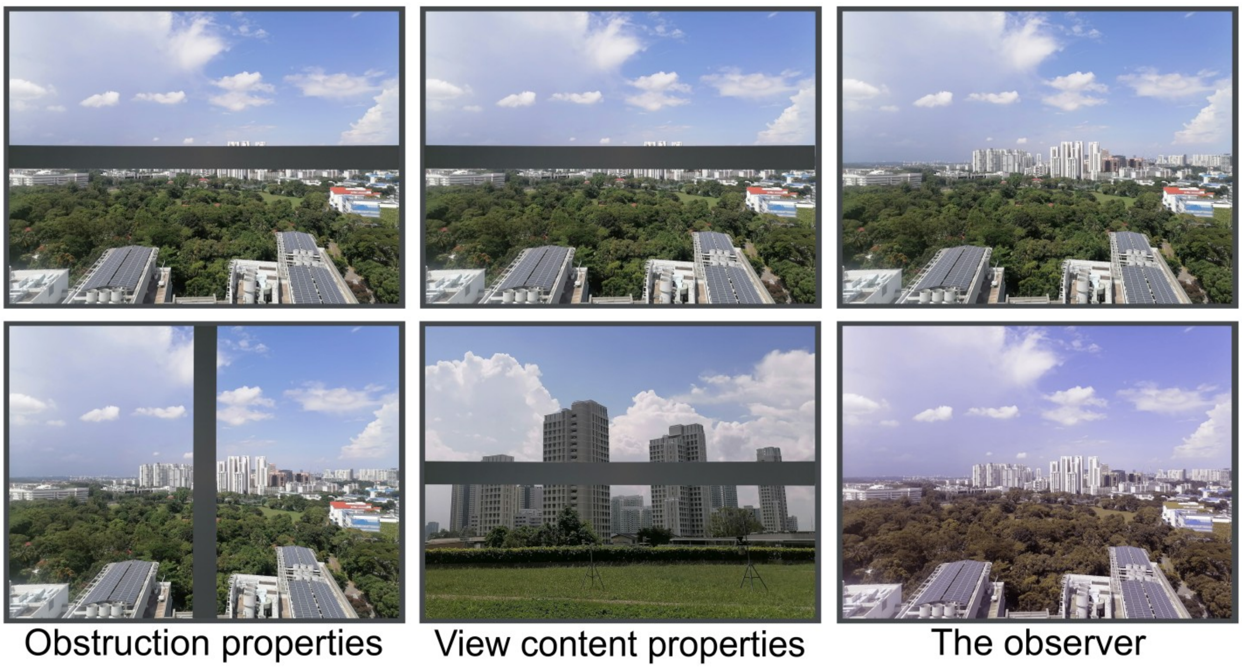

Figure 2 Examples of the three different dimensions of view clarity: 1) obstruction properties, 2) view content properties and 3) the observer (e.g., normal colour vision versus deuteranopia). The views were taken from Kent and Schiavon[1]

The properties of obstructions inside or near the window reduce view clarity.[19] Variations in shading shape, size and orientation and glazing properties are among the factors designers use to retain the view. Other architectural features (e.g., mullions) and window maintenance (e.g., cleanliness) also matter. View content can also influence clarity: view content that has high contrast (e.g., a dark building façade contrasted against a bright sky) will be more visible than low contrast information. Although the underlying relationships for the above are generally understood,[42] they have not been applied to view clarity. Lastly, view clarity can depend on the visual acuity, psychological state of the observer, and individual differences. Observers with induced positive moods generally looked long and more often at positive images located in their peripheral vision and reduced their attention onto negative information.[43]

Current green certification labels for shading do not mention view clarity (Table 2 and Appendix A1). While the absence or inclusion of view clarity recommendations could be explained by diverging design intent (e.g., glare control, overheating avoidance, or view provision) or a general lack of understanding, designers will inevitably use different criteria to inform the design of shades. Nonetheless, view clarity is a concept that is largely understudied and not well understood,[6,13] making it difficult to provide comprehensive guidance for designers to follow. This motivated us to perform a narrative review[44] to understand how current literature and standards can support a better understanding the design process for view clarity.

Table 1 Certification systems that provide informed guidance for the design of shading

Certification scheme and feature	Design intent
WELL version 1, Solar Glare Control[35]	View window shading – at least one required a) Internal window shading or blinds that can be controlled or automated to minimise glare b) External shading to minimise glare c) Variable glazing transmittance (e.g., electrochromic glass), which can be reduced by more than 90%
BREEAM New Construction, Glare Control[9]	Compliant shading measures – can include any or a combination a) Building integrated measures (e.g., fins) b) Operable devices (e.g., Venetian blinds or close weave fabric shades), with openness factor is ≤1%, and fabric light transmittance is <0.1 (10%) c) External shading or brise soleil

3. Shading solution properties

We considered the influence different shades have on view clarity. We grouped shades into following categories: fabric, solid, and glazing solutions (Figure 3).

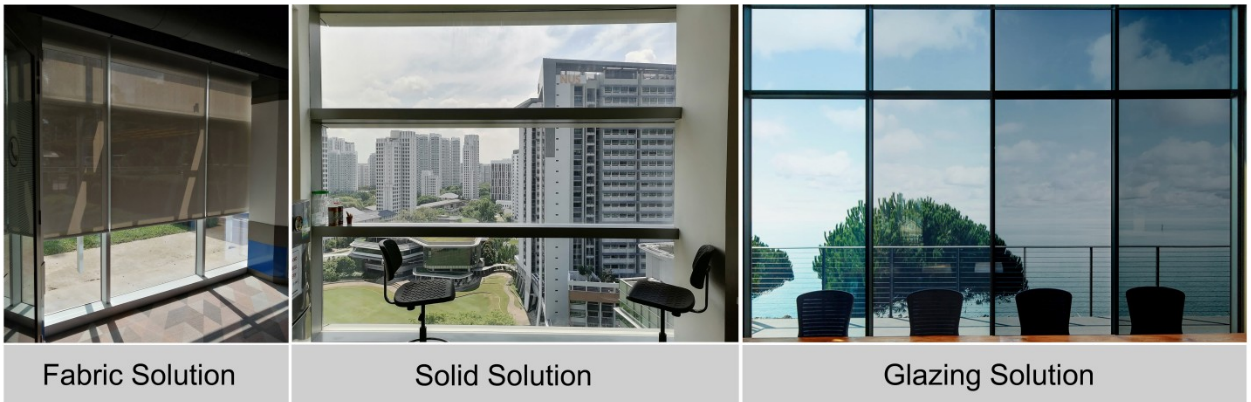

Figure 3 Examples each shading solutions: fabric (roller blind at the Building and Construction Authority in Singapore), solid (louvres) and glazing (electrochromic glass) applied on different building façades

Our categorisation describes the occlusion properties and not the operational characteristics of the shades, which vary considerably across occupant preferences.[45] Occlusion properties are easier to define. Fabric and solid shades refer to the material of the shade. Roller shades are an example of shades that use woven fabrics to restrict daylight admittance, whereas solid shades (e.g., louvres) are typically structures that intermittently block daylight across the window area. The opening areas can be larger for solid structures than fabric shades, but the occluded areas are opaque. Glazing solutions will distort the optical properties of daylight through the material.

3.1. Fabric Shading Solutions

Fabric woven shades are the most common shading solution currently in use. The EN 14501[46] classifies the "visual contact with the outside" for these shading devices (Table 2) based on two visual transmittance (τ_v) parameters: 1) normal-to-normal ($\tau_{v,n-n}$); and 2) the diffuse-to-normal ($\tau_{v,n-dif}$). Table 2 is applied when the shade is fully deployed and has a small opening surface.

Table 2 European Norm for blinds and shutters [46] that provides performance criteria describing 'visual contact with the outside' for solar shades based on five class thresholds

Normal visible transmittance ($\tau v_{,n-n}$)	**Diffused visible transmittance ($\tau v_{,n-dif}$)**		
	$0 < \tau v_{,n-dif} \leq 0.04$	$0.4 < \tau v_{n-dif} \leq 0.15$	$v_{,} \tau_{n-dif} > 0.15$
$\tau v_{,n-n} > 0.10$	Very good effect	Good effect	Moderate effect
$0.05 < \tau v_{,n-n} \leq 0.10$	Good effect	Moderate effect	Little effect
$\tau v_{,n-n} \leq 0.05$	Moderate effect	Little effect	Very little effect
$\tau v_{,n-n} = 0$	Very little effect	Very little effect	Very little effect

According to Flamant *et al.*[28], $\tau_{v,n-n}$ and $\tau_{v,n-dif}$ are related to the openness factor (OF) and fabric colour. High values of $\tau_{v,n-n}$ (typical of high OF) generally allow better shape recognition, while high values of $\tau_{v,n\text{-}dif}$ (typical of light colours) distorts the view and generates a parasitic luminance on the fabric when the sunlight hits the surface. Transmittance of light through fabrics additional occurs through two more pathways:[12] inter-reflections between fibres and diffraction (Figure 4). However, manufactures only provide values for OF and fabric visible transmittance. An experiment under controlled artificial lighting identified visible light transmission and reflectance as the two primary variables that determined view clarity through fabric shades.[25]

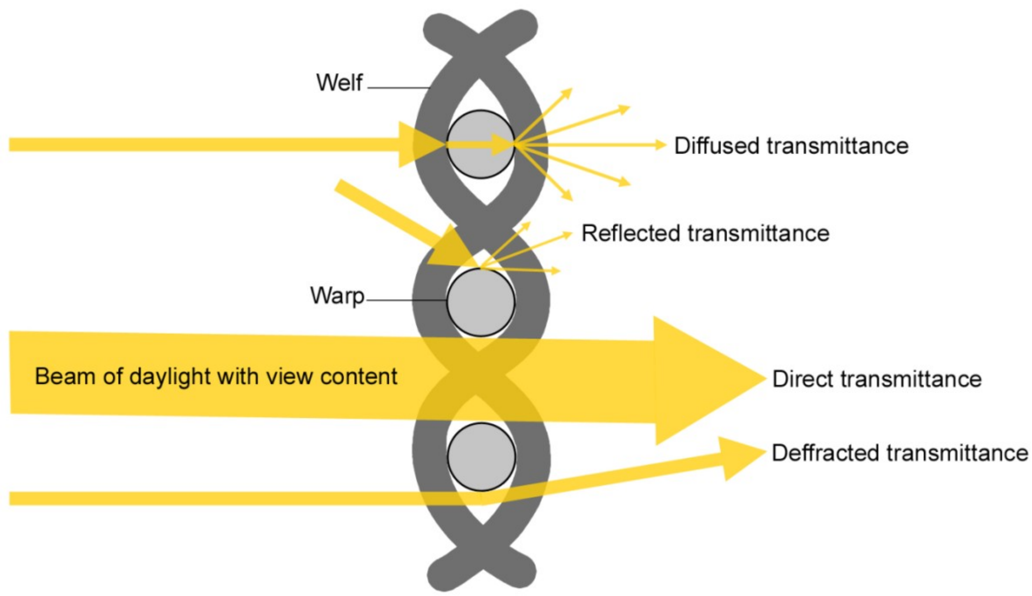

Figure 4 Four pathways of visible daylight transmittance through woven fabric blinds. Adapted and redrawn from Hill and Markus.[12] Edited by the authors

The outdoor daylight will strongly influence view clarity through fabric shades.[28] A study by Konstantzos *et al.*[14] showed that high OF produced the highest view clarity, and dark fabrics outperformed light fabrics. Darker fabrics reduced the reflected transmittance between the fabric warp to allow the transmission of direct daylight, containing view content, to be more easily seen through the fabric.[25] Because lighter fabric colours scattered the light across its surface, under excess daylight exposure the surface will appear brighter and may cause discomfort glare (Figure 5). When strong illumination is received, light will be transmitted to other parts of the material, reducing overall contrast[47] and masking the view content.

Konstantzos *et al.*[14] emphasized the complex relationships between OF, colour and visible transmittance, as a product of weave formation. This research led to the proposal of the View Clarity Index (VCI), quantifying the clarity performance from OF and visible transmittance tested on commonly listed fabric labels (equation 1). This equation was later revised to model the relationships between the VCI, OF and diffused transmission ($\tau_{v,\ n-diff}$ is the diffuse-to-normal that is closely related to the fabric colour) in equation 2:[28]

$$VCI = 1.43 \cdot OF^{0.48} + 0.64 \cdot \frac{OF}{\tau_v}^{1.1} - 0.22 \qquad 0 \le \text{VCI} \le 1 \qquad (1)$$

$$VCI_{modified} = -0.461 \cdot e^{-66.6 \cdot \tau_{v,n-n}} - 0.467 \cdot \frac{\tau_{v,n-dif}^{0.296}}{\tau_{v,n-n}^{0.222}} + 0.921 \qquad (2)$$

Values for VCI range from 0 (diffused shading) to 1 (no shading). The total transmission (τ_v) is from both the normal-to-normal ($\tau_{v,n-n}$) and the diffuse-to-normal ($\tau_{v,n-dif}$) in equation 1.

Figure 5 The influence parasitic luminance caused by direct sunlight incident on a fabric roller shade

3.2. Solid Shading Solutions

Solid shading solutions include Venetian blinds, external louvers, grills, and pergolas, typically varying both in terms of shape, size, and even orientation. However, the layout of the shade relative to its view content matters. Horizontal occlusions (e.g., Venetian blinds) running parallel to a skyline will occlude clarity more than vertical obstructions with comparable dimensions.[6] The same effect occurs when vertical Venetian blinds are installed against a view with high-rise buildings. Blinds that resemble the pattern or layout of its view content will make it difficult for occupant to distinguish between both. This causes a visual camouflage effect).[48,49]

Some solid solutions create inoperable obstructions (e.g., grills), which pose significant disadvantages to view clarity because reductions in clarity are permanent.[19] Other shades (e.g., external louvres and switchable blinds) can be configured to provide a congruent balance between daylight, visual comfort and view clarity,[50] but this may come at the expense of increased cost and maintenance.[51] Occupants generally prefer adjustable systems that can reduce glare and maintain view retention.[52–54] Shades that reduce glare or overheating beyond minimum acceptable levels of comfort are not preferred, since they offset other requirements such as view clarity.[55] Lightshelves that permanently occluded the view out from a core open-plan office zone were a significant source of dissatisfaction.[56]

3.3. Glazing Solutions

Glazing solutions include, but are not limited to, frosted/satin/opal glass, textured/patterned glass and frits, tinted glass and films, and smart (e.g., electrochromic and thermochromic glass).

Glazing solutions can facilitate the design of certain spaces (e.g., bathrooms) that require reduced clarity.[20] Translucent obstructions (e.g., frosted glass) provide privacy while allowing light admittance into the space.[57] The physical effects of translucency are generally better understood than how the visual system processes translucent images.[58] Reflections and refractions change the received visual information depending on its passage through the material when light passes through the glass.[59] Light is scattered both at the surface and sub-surface of the material,[47] creating visual blur through the material that persists even when contrast remains unchanged across the translucent region.[60] Both the form of the view content and the colour of the original object are distorted. Hue, saturation and brightness, all vary according to the distance light travels through the material.[47]

Reductions in view clarity caused by other types of shade can be offset by chromatic glazing.[61] However, ensuring view clarity may not the primary motivation underlying why designers use glazing solutions. A survey revealed that only 21% of 10407 LEED accredited professionals assumed that shading and view preservation were important criteria,[62] behind energy efficiency (81%), daylighting (73%) and aesthetics (33%). Chromatic glazing is glass that produces distinct colours (e.g., blue or bronze) when they are tinted,[24] which necessitates colour vision for the observer to correctly distinguish between the colour differences. These types of glazing can retain the view out even when daylight gains are reduced to protect from overheating or glare. Moeck *et al.*[63] anecdotally stated that at low transmission rates electrochromic glazing will diminish the connection experienced to the outside, yet this reduction is still superior to reductions in clarity produced by conventional shades. A study by Ko *et al.*[25] showed that films and electrochromic glass generally outperformed fabrics shade in terms of view clarity measured by visual acuity, contrast and colour sensitivity tests.

Electrochromic glazing solutions will generally ensure higher view clarity than roller blinds. Electrochromic glazing is able to preserve distant views, and fewer incidents of eyestrain and headaches have been attributed to the visual relief.[64] Electronic glass that enabled better daylight and view quality leveraged a 42% increase in decision-marking tests compared to blinds, and higher quality in sleep for office works.[65] However, window films and electrochromic glazing can reduce chromatic acuity (e.g., colour discrimination).[25] Thermochromic films that produced a bronze tint elicited higher perceived visual assessments (e.g., comfort), while blue tints were more conducive for work performance (e.g., alertness), and few errors when discerning colours were found.[23,24]

Studies completed on tinted lenses (e.g., for helmets and sunglasses) have examined the effects of tint colour on view clarity and can be useful also in the architectural context. Tinted lenses reduce high brightness, improve our ability to see reflective and relatively less detailed content.[66,67] Comparable improvements were not revealed for chromatic tasks that contained colour visual stimuli. Shaik *et al.*[67] found the greatest performance reductions were caused by blue tinted spectacles, with grey lenses showing some improvements over the former and brown. While achromatic view clarity could be enhanced by colour tinted glass under excessive daylight, tint colour may need to be selected based on outdoor content. For example, yellow tints improve contrast for bright content against a blue background,[68] similarly to how the landscape contrasts against the sky layer.

Unlike fabric shades that have perforated holes that permit daylight and the outdoor view to be transmitted through the material (i.e., Openness Factor), the optical properties of the entire glass (e.g., visible transmission) control view clarity through EC glazing. The spectral properties of daylight admitted through glass may also be altered[24,69] as well as the colour properties of the view seen of the building. Since colour acuity is not currently embedded in any available metrics and the Openness Factor cannot be applied to glass, the VCI cannot be used to measure view clarity through glazing solutions.

4. View content properties

Clarity seen through the window depends also on view content. Hill and Markus[12] explained by visual camouflage or masking that results in a loss in outdoor content, particularly when the geometric characteristics of a window shade or fenestration (e.g. perforated meshes) coincide with the prevailing texture of the view. Similarities in colour, brightness and pattern, between animals and their immediate surroundings, also hinder visual detection.[70]

4.1. Spatial frequency

To detect real-world information the visual system needs to distinguish subtle differences in luminance without defined borders that can separate the target object from its background.[71] Views contain an assortment of content that varies in contrast and size. This applies for chromatic (coloured) and achromatic content.[72] This could be best explained by the ability of the visual system to discern periodic distribution patterns of light and dark (i.e., contrast thresholds) contained in the scene that are projected at different sizes.[73] This is known as spatial frequency.

Spatial frequency refers to the variation across space for a particular pattern, usually measured in terms of repeated cycles per unit distance.[74] The spatial structure can be used to gauge contrast sensitivity.[75] High spatial frequencies represent abrupt spatial changes (e.g., edges and small fine details) that necessitates greater contrast to be visible.[76] Low spatial frequencies represent global information about the shape, orientation and proportion.[77] Scenes with nature contain high frequency patterns and less nuanced colours, allowing the eye to process visual information more efficiently and comfortably.[78] Urban environments often have low spatial frequencies,[79] which often exhibit unnaturally larger variations in colour.[80] For example, most images from nature (e.g., a forest) will typically contain a lower local contrast of surface colours (e.g., subtle variations of green) compared to man-made urban environments, which can contain an abrupt contrast of unnatural colours (e.g., urbanised city billboards).

Figure 6 Comparison between two views under the same weather and time of day: both when the windows were unobstructed and when fabric roller shades were drawn. One view shows a nearby building that produce low spatial frequency content (left) and the other view has more nature (greenery) that produces high spatial frequency content (right)

Lighter fabric shades spread daylight across its surface and reduces the overall contrast of view, explaining why the fabric blinds masked the high spatial frequency content of nature (Figure 6) while retaining low spatial frequency nearby building content. Other attributes such as spatial frequency and size of the shade also matter. When the spatial frequency of superimposed grating patterns is close to 3 cycles per degree subtended at the eye (i.e., the pattern became finer), greater visual contrast is required to detect objects covered by the grating.[81]

Tinted glazing reduces both the overall contrast and difference in chromaticity of the view.[80] Blue and purple tinted lenses proved to be effective in reducing large contrast differences produced by glare, leading to notable improvements in both contrast sensitivity and clarity.[66] Similar findings also advocated the use of blue or clear lenses in situations necessitating increased contrast sensitivity at high spatial frequencies.[67] This study revealed that the most prominent improvements were in relation to low spatial frequency content, while were subdued for high spatial frequencies. Preferences to lens colour also depended on the content viewed. Out of nine different tint colours, observer preferred clear glasses when viewing photographs of nature while purple lens were generally preferred when viewing paintings.[82] However, chromatic preferences tend to vary considerably for observers with aura migraines.[83]

4.2. Content distance

Spatial frequency can be used to describe how a repeated pattern changes over certain distance.[84] If an observer is far away from the target object, visual content will take up fewer degrees of a visual angle.[85] Therefore, distant views will appear smaller and shading poses a greater risk of obstructing this content than for nearby elements (Figure 7). Atmospheric perspective will also decrease contrast at increased distances (i.e., the farther an object is from an observer the lower its clarity due to the molecules and particles in the air).[73] Light transmission at greater distances is attenuated,[86,87] requiring greater contrast for the distant object that is being viewed to become visible.

Figure 7 An unobstructed and obstructed (by louvres) window view with a distant landscape layer. Another window view with an unobstructed window view, but partially obstructed sky layer

Distant content is mostly concentrated within the landscape layer (Figure 7), which gauges the distance of the view.[1] Faraway landscape layers have a smaller visual angle and a higher chance of shades obstructing the content. Current standards recommend having content that is at least 6 m away to satisfy "sufficient" window view quality requirements,[7,8] coinciding with the distance view acuity tasks are deployed to gauge "normal" vision.[88] Nonetheless, the inability of shades to retain distant content could counteract their intended benefits (e.g., reduced eyestrain).[89,90] Therefore, shades should avoid fracturing the view to maintain high view clarity [91]. Fractures can occur when shades impede areas where that the three layers intersect each other. Horizontal shades pose significant problems. Since the landscape layer intersects with the ground and sky layers, retaining this layer is needed to achieve high view clarity.

For smaller windows this may not be feasible. Glazing solutions (e.g., solar films or chromatic glass) could offset these constraints, but it is not clear if they will invariably retain high clarity for every view. This will be dependent on the colour of the glass and view content. For example, studies have shown that blue tinted films hinder our ability to see blue visual stimuli.[23,24] This could affect how the sky or blue spaces are perceived. Yap[92] generally showed that contrast sensitivity was improved at most spatial frequencies under photopic vision when a yellow filter was compared to no filter. This could be due to the 40% increase in perceived brightness yellow filters create, despite reduced light transition.[93] However, Luria[94] showed that yellow filters increased the contrast between a yellow target against a blue background. If there the target stimulus is blue, there is no improvement to clarity when a yellow filter is applied.

5. The observer

A caveat to some studies is the large differences that are exhibited amongst individuals. Colour preferences towards tinted filers for optimal comfort and clarity can vary based on neurological diagnoses.[80] For example, colour preferences vary between observers that do or do not experience migraines.[83] Individuals that have an exaggerated sensitivity to visual discomfort (e.g., photophobia)[83] are more sensitive to certain patterns (e.g., stripes created by Venetian blinds) or colours (e.g., chromatic changes caused by different tinted films) created by shades.

Other visual (e.g., acuity) and non-visual (e.g., mood) states of the observer influence view clarity. Cultural differences create diverging expectations that inform the design and operation of windows for privacy.[95] Privacy concerns can override other window functions (e.g., view out) for Arab population groups.[96] Consequently, this results in veiled windows (i.e., mashrabiya) being used that prevent people from seeing into the building but also reduces view clarity . Significant differences in visual perception between male and female observers have been identified.[97] For example, males required a shorter time to identify the direction of low and high contrast visual stimuli.[98] These individual differences could influence perceived view clarity for dynamic content (e.g., people or traffic) seen in the view.

5.1. Ocular performance

The visual system allows us to see and process visual information. Differences in object contrast, brightness or colour, seen against the visual background, determine how clearly we can identify visual stimuli.[74] This can be crucial for seeing essential features of the window view that are composed of different brightness, contrast, and colour. Deficiencies in ocular ability will prevent people from being able to see many essential features, particularly at low- to mid-range spatial frequencies (e.g., road signs and facial features).[85] Visual acuity, contrast sensitivity and detection speed, are among the factors that determine ocular performance, but decrease when the eye ages due to macular degeneration, cataract, diabetes, and glaucoma.[99]

Window views are often believed to maintain health ocular performance by counteracting symptoms that reduce how clearly the observer can see distant content. Many green certification labels (Table 3) encourage design credits to promote certain qualities of the window view. The main motivation that supports their design intent is the positive benefits they could convey to reduce eyestrain.

Table 3 List of green building certifications that state that the purpose of awarding credit(s) to the design of window views is to reduce visual eye strain. Note: the phrasing across different versions differs slightly but the overall intent of the credit(s) award is the same

Certification system	Design intent for window view credit(s)
BREEAM-Netherlands version 1.1[100]	To encourage adequate provision of an external view in all relevant workplaces. This is in order to prevent eye strain and break the monotony of the indoor environment.
BREEAM-Norway versions 1.1[101], 1.2[102] and 6.0[103]	The view out is of a landscape or buildings (rather than just the sky) at seated eye level (1.2 – 1.3 m) within the relevant building areas and should ideally be through an external window. A view into an internal courtyard or atrium will comply provided the distance from the opening to the back wall of the courtyard/atrium is at least 10 m (therefore allowing enough distance for the eyes to refocus).
BREEAM-Sweden versions 1.1[104] and 2.0[105]	To allow occupants to refocus their eyes from close work and enjoy an external view, thus reducing the risk of eyestrain and breaking the monotony of the indoor environment.
Green Building Index version 1.0[106] and 3.0[107]	To reduce eyestrain for building occupants by allowing long distance views and provision of visual connection to the outdoor environment, which includes greenery and/or water bodies.
Greenship versions 1.1[108] and 1.2[109]	To reduce eye fatigue by providing long-distance views that gives a visual connection to the outside of the building.
greenstar NZ[110] and greenstar NZ version 3.1[111]	To encourage and recognise reduced eyestrain for building occupants by allowing long distance views and the provision of visual connection to the outdoors.

5.2. Aging

Less blue light is admitted into the eye that results in the lens forming a yellow appearance,[112] deepening in colour with age. Colour filtering caused by the yellowing of the lens distorts blue and green colours.[113] Other similar aging processes that diminish blue wavelength transmission can be accelerated by high exposure to ultra-violet-B radiation, causing the lens to become denser and less transparent (i.e., brunescence).[114] No significant effects of age on clarity were found through blue and green tinted windshield glazing across two cohorts of dissimilar age, ranging between ages of 22 to 30-years and 65 to 89-years.[115] The null result could be explained using a visual acuity test (i.e., Landolt task). Another study[116] showed that contrast sensitivity measured through yellow filters under glare conditions improved, albeit this improvement only occurred for older (51-60 years) than young observers.

Other age-related factors decrease ocular performance. Maximum contrast sensitivity occurs around 20-years of age within the intermediate frequency range (i.e., 2-8 cycles per degree).[117] This then declines at an increasing pace with age. Older observers (≥ 60-years) have a lower sensitivity to frequencies above 4-cycles per degree.[118,119] Therefore, elderly occupants may not be able to see high frequency content (e.g., nature) and only lower frequency content that shows the outline (e.g., buildings or the skyline) of window view is visible. This may be exacerbated when shades are used (Figure 6). Vision can decline sooner with ocular pathology (e.g., cataracts or diabetic retinopathy). Brannan *et al.*[120] showed that contrast sensitivity decreased from 37% to 19%, prior to and 6-months after cataract surgery. A study applied tinted colour films to observers with cataracts.[121] An increase in contrast thresholds under glare conditions was found regardless of tint colour, but the differences between the colours on contrast sensitivity were not statistically significant.

5.3. Colour vision

Colour blindness reduces our ability to see colour view content. It is estimated that one in 12 men and one in 200 women have a colour deficiency in northern Europe,[122] and that protan and deutan (collectively termed as "red-green") visual defects account for about 8-10% of males in the United States.[123] However, we were not able to find research that looked at how colour blindness impacts view clarity.

Observers with colour deficiencies had significantly longer response times and had more errors when asked to identify the colour of traffic signals than individuals with normal colour vision.[124] This not only occurred when they wore clear eye lenses, but also applied and intensified when they wore different glass tints:[125] the authors recommended against the use of tinted eye lenses with colour-blind observers as it slowed their ability to detect red traffic signals. This means that people with colour-blindness may have a reduced view quality. Figure 2 shows a comparison across the same view as seen by an observer with normal colour vision and another with deuteranopia. This is the most common form of "red-green" colour vision deficiency, making certain nuances of green appear more red.[126] This will cause green view content (e.g., nature) to appear more yellow.

6. Discussion

6.1. Designing for view clarity

Table 4 summarises some of the most important occlusion parameters we reviewed that can influence view clarity according to the three types of shades. One generalised model may not be able to fully comprehend how view clarity is affected by every type of shade. Our narrative review revealed that view clarity is strongly influenced by interactions between the three parameters (i.e., obstruction, view content, and observer properties). Clarity can be substantially reduced for one view, yet the same shade applied to another window, could retain more view content. For example, Figure 2 compared the affect the same lightshelf had on view clarity for two views. The clarity of the view with three horizontal layers (i.e., ground, landscape, and sky), where the landscape layer extended into the distance, was notably reduced. However, greater visual coherence was preserved when the content predominantly consistent of vertical features (i.e., high-rise buildings) situated nearby.

Table 4 Summary of parameters and impacts the types of shading have on view clarity

Shade type	Parameter	Impact on view clarity
Fabric solutions		

	Spatial frequency	Reduces high spatial frequency (e.g., nature) and retains low spatial frequency (e.g., urban) view content
	Parasitic luminance	Light fabrics increase parasitic luminance when exposed to direct daylight and shade can become the new glare source. Darker fabrics reduce this effect and improve clarity, but the fabric will have a low surface albedo that could overheat the space
	Operational characteristics	Shading deployment is usually ephemeral and can be manually or automatically operated. Reductions to view clarity can be temporary
Solid solutions		
	Visual camouflage	Shading patterns (e.g., horizontal blinds) that coincide with the composition of the view (e.g., horizontal layers) significantly reduce view clarity and can evoke visual stress
	Fracturing the view	Impeding areas where the three layers meet can fracture the view. Distant views have an elevated risk of being obscured as the landscape will appear smaller and there is a greater chance shades will block this layer
	Immobile	Reductions to view clarity are generally more permanent. This includes automated shades (e.g., rotatable louvres)
Glazing solutions		
	High tint state	High luminance contrast across window will be reduced and view clarity is improved. However, interior reflections on glass can reduce clarity if room has strong interior lighting and light colours. Turning lights off will result in bleached daylight being transmitted into the room
	Tint and view content colour	May improve or reduce the ability to see certain colours in the view. The level of view clarity will depend on the tint colour of the glass and dominant colour of the view content
	Unwanted view clarity	Some types of glass may be selected to deliberately reduce view clarity (e.g., frost glass) for privacy, but still allow daylight into the room (e.g., bathrooms)

Nonetheless, designers can still consider the complex interplay between the obstruction properties and view content to safeguard view clarity. Figure 7 shows that view retention is much higher when louvres only shade the sky layer and not distant content in the landscape layer. If the view does not contain high-quality content (e.g., nearby urban features), the designer could shade the entire window with louvres, particularly if the intent was to reduce glare or overheating. When high-quality view content such as nature is present, designers may want to avoid using fabric shades, if feasible. Nature is the most important of the five environment information criteria,[127] which are supported by daylight standards.[7,8] However, shades that are not able to support high spatial frequency information such as nature, may result in loss of important visual information once the shading solutions is deployed. Tinted glazing reduces the overall differences in chromaticity in the view. Therefore, they will exert a greater influence on the urban content, which has an unnatural and more nuanced colour gradient, as oppose to nature.[83]

Although Table 4 summarised the main design characteristics we had covered in earlier sections of our work, other arguably more apparent impacts caused by shades (e.g., reduced daylight illuminance when using darker fabric shades), still need to be considered. Even though some design characteristics are less relevant to, or do not directly affect, view clarity, a holistic outlook towards view clarity is still required to balance different design objectives. This may include building aesthetics that is influenced by the type of shading deployed and operated, which may even become potential barriers to view clarity, particularly when the shading system does not compliment the overall design of the building. For example, manually operated fabric blinds are often drawn to different heights that could give an undesired staggered appearance from both the inside and outside of the building. However, Automated blinds can be configured to provide a more uniform look while also providing similar levels of view clarity to their manually operated counterparts.

Venetian blinds and louvres will also contrast against their background (i.e., the window view or shaded façade surface, creating stripe patterns that are uncomfortable to look at.[78] When the slats are spaced 5 cm apart, the pattern has a spatial frequency of 3 cycles per degree at a distance of about 8 m which is the most aversive.[78] To design louvres that are not stressful is difficult because the range over which stripes are stress extends from 0.7-15 cycles per degree. Stripes formed by the warp and weft of roller blinds will also coincide with spatial frequencies less than 10 cycles per degree,[128] causing elevated visual stress that is more likely to be a problem for occupants sitting close to the window.

Another important consideration would be when view clarity conflicts with other important design requirements, which could be with unrelated window view criteria (e.g., thermal comfort or discomfort glare[129] or criteria related to the window view (e.g., view content or access). For example, our previous work recommended a WWR and horizontal view angle of at least 25% and 35o, respectively, to meet minimum view access requirements that are independent of daylight performance.[33] For glazed facades that provide sufficient view access but are unable to achieve Daylight Glare Probability values below the minimum threshold ($\leq$ 0.35) in the European daylight standard,[7] ensuring sufficient view clarity could be a challenge when the designer is unable to modify the size or position of the window opening. Window shades may be deployed for prolonged periods to avoid visual discomfort, causing conflicts between design requirements for view access, discomfort glare and view clarity.

6.2. Temporal changes to view clarity

The VCI[14] is a metric that quantifies view retention for fabric shades. However, this does not consider every shade type covered in Table 4 or the dynamic operation of certain shades. The EN 14501[46] recommends clarity is measured when the shades fully obscure the window opening. However, this does not necessarily reflect how occupants will operate adjustable shades (e.g., fabric shades or smart glazing). Although adjustable shades, such as fabric shades, still obstruct the view out,[130] their reductions in view clarity can be short-term and optional compared to inoperable shades, and the view became a motivating reason to reopen blinds, particularly once discomfort sources subsided.[131] A conceptual dynamic view quality metric has been proposed to extend the VCI for situations that deploy dynamic shading,[132] although this has yet to be calibrated by human-subjects experimentation to verify its accuracy.

Occlusion patterns that minimise view clarity could be understood from glare control schedules or behaviours that are informed by automated or manually operated blinds. Façade irradiation measurements have previously been used to predict manual blind occlusion patterns.[133] Blind occlusion patterns are easier to discern when the blinds are automated. Not only does this strategy significantly reduce (i.e., 45% to 79%) building energy loads,[134] reductions in view clarity directly correlate to blind deployment schedules.

Automation integrated into dynamic control strategies has been applied to tint states for chromatic glass.[135] Occlusion patterns for view clarity could also correspond to the Annual Sunlight Exposure metric,[30] creating synergies between daylighting and view targets with the same daylighting performance indicator. In other words, designers will aim to minimise excess daylight exposure to maximise view clarity, which in turn, subsidises the utility for this performance metric. A caveat to these approaches is that shades are only deployed in response to high daylight admittance, but not other reasons that motivate blind use. Nearby buildings or ground floor spaces increase the risks of privacy[1,8] that also cause blinds to be deployed. Electrochromic glazing and automated blinds also can provide occupant control through physical switches or digital apps for conditions not accounted for through an automated system.

6.3. Drawbacks of view clarity

A significant drawback of high view clarity is the increased likelihood of bird collisions.[21] Approximately one billion birds die annually when they collide with windows,[136] which is exacerbated by unobstructed fully glazed facades.[137] LEED Canada[138] recommends placing nature (e.g., trees) either nearby (<0.9 m) to avoid reflections on the glass or far away from the building to avoid birds mistaking reflections for vegetation, and also the use of exterior shades or other façade treatments (e.g., etched or fritted patterns).LEED version 3[139] uses Threat Factors to gauge the risk the façade has to birds (Figure 8). Designs are referenced against a Threat Factor, ranging from 0 for opaque glazing to 100 for clear glass,[140] and when the Threat Factor exceeds 15, the bird collision deterrence requires collision ratings to be calculated. While solutions reduce the risk of bird collisions,[138,141] these also minimise view clarity. Other bird safe glass solutions reduce the Threat Factor without comprising view clarity. Since many birds can see light within the ultraviolet spectrum (320-400 nm),[142] windows with ultraviolet reflective films allow them to see visible patterns that are otherwise invisible to humans.[143]

Figure 8 Three different facades showing: solid shading solutions created by external louvres with low view clarity and a Threat Factor of 5; bird-safety glazing installed on an airport façade[144] with continuous frit patterns and a Threat Factor of approximately 25; and unobstructed fully glazed façade with high view clarity and a Threat Factor of 100

Another important consideration is at night. Window views are transmitted into the building by daylight reflected from outdoor view content.[145] If the view content is brighter than the surface of the shade material, the fabric will appear more transparent. This phenomenon is reversed at night-time, when electrically lit spaces are brighter than outdoors, making it easier to see into the building, rather than out. Reduced or no view clarity has important consequences at night, when reducing visibility into the building may be equally important as being able to see out during the day. External views into the building are much clearer to render when interior lighting exceeds exterior lighting, posing an increased privacy issue. Dynamic glazed solutions can be installed to include a "night mode" setting, preventing light spillage by up to 98% while also controlling for light trespass and pollution into the neighbourhood.[146]

7. Conclusion

View clarity describes how clearly view content can be seen through windows. We reviewed current building standards and scientific literature to highlight how view clarity can be considered into the design process of window views, thereby ensuring that the benefits views convey to building occupants (e.g., health and wellbeing) are achievable.

We introduced three parameters that underpin view clarity: 1) obstruction properties, 2) content view properties and 3) the observer. Our work discussed how each influenced view clarity. Our work revealed interactions amongst each property that cannot be overlooked. The impact the same shade component has on view clarity is contingent upon the visual characteristics of the view content (e.g., its distance or colour). Designers should carefully consider how different types of shades interact with the available view content to optimise clarity. To facilitate this decision-making process, we categorised the shades into three unique groups, namely: fabric, solid and glazing solutions. The impacts each shade group along with its corresponding impacts to view clarity were outlined in Table 4.

View clarity cannot be accurately defined by one prediction model given the nuanced requirements that need to be included into the design process. While high view clarity generally conveys benefits to most buildings, certain exceptions arise from privacy being a more important consideration than clarity in some spaces (e.g., bathrooms or office space) and at night time. View clarity is also multifaceted, requiring designers to consider both the duration and amount of view that remains clearly visible during building operation. Lastly, the pursuit of high view clarity has notable drawbacks, with the heightened occurrence of bird-related threats being a noteworthy issue when designing large unobstructed glazed facades.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This work was supported by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a centre for intellectual excellence in research and education in Singapore.

References

1. Kent M, Schiavon S. Evaluation of the effect of landscape distance seen in window views on visual satisfaction. *Build Environ* 2020; 183: 107160.
2. Veitch JA, Farley KMJ, Farley KMJ, et al. *A room with a view: A Review of the effects of windows on work and well-being*. 2001.
3. Heschong L. *California energy commission windows and classrooms: A study of student performance and the indoor environment*. 2003. Epub ahead of print 1 October 2003. DOI: 10.13140/RG.2.2.26759.44964.
4. Kuhlenengel M, Konstantzos I, Waters CE. The effects of the visual environment on K-12 student achievement. *Buildings* 2021; 11: 498.
5. Ko WH, Schiavon S, Zhang H, et al. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Build Environ* 2020; 175: 106779.
6. Ko WH, Kent MG, Schiavon S, et al. A Window View Quality Assessment Framework. *LEUKOS* 2022; 18: 268–293.

7. EN 17037. *Daylight in buildings*. Brussels, Belgium: European Committee for Standardization, 2018.
8. Society of Light and Lighting. *Lighting guide 10: Daylighting - A guide for designers*. London, United Kingdom: Chartered Institution of Building Services Engineers (CIBSE), 2014.
9. BRE. BREEAM UK New Construction 2018. 2018; 398.
10. U.S. Green Building Council. *LEED v4.1: Building design and construction*. United States: U.S. Green Building Council, https://www.usgbc.org/leed/v41?creative=340432438239&keyword=building%20certificate&matchtype=b&network=g&device=c&gclid=Cj0KCQiA0fr_BRDaARIsAABw4Es2urPKusFY8pT8HHRRE3rp9ED4UET5XWh5uz6nDq_CnkP7KgcsAj8aAv5rEALw_wcB (2020).
11. International WELL Building Institute. *Standard | WELL V2*. Version 2 pilot. International WELL Building Institute pbc, https://v2.wellcertified.com/v/en/light/feature/5 (2020, accessed 17 March 2020).
12. Hill AR, Markus TA. Some factors influencing vision through meshes. *Hum Factors* 1968; 10: 531–551.
13. Ko WH, Schiavon S, Altomonte S, et al. Window view quality: Why it matters and what we should do. *LEUKOS* 2022; 18: 259–267.
14. Konstantzos I, Chan Y-C, Seibold JC, et al. View clarity index: A new metric to evaluate clarity of view through window shades. *Build Environ* 2015; 90: 206–214.
15. Tzempelikos A, Athienitis AK. The impact of shading design and control on building cooling and lighting demand. *Sol Energy* 2007; 81: 369–382.
16. Arens E, Hoyt T, Zhou X, et al. Modeling the comfort effects of short-wave solar radiation indoors. *Build Environ* 2015; 88: 3–9.
17. Hopkinson RG. Glare from daylighting in buildings. *Appl Ergon* 1972; 3: 206–215.
18. Kent M, Jakubiec J. An examination of range effects when evaluating discomfort due to glare in Singaporean buildings. *Light Res Technol* 2021; 14771535211047220.
19. Markus TA. The function of windows— A reappraisal. *Build Sci* 1967; 2: 97–121.
20. Veitch JA, Christoffersen J, Galasiu AD. Daylight and view through residential windows: Effects on well-being. In: *LD+A Magazine*. Krakow, Poland: Illuminating Engineering Society, 2012, pp. 1–6.
21. American Bird Conservancy. *Bird-friendly building design*. American Bird Conservancy, 2015.
22. Liu D, Sun Y, Wilson R, et al. Comprehensive evaluation of window-integrated semi-transparent PV for building daylight performance. *Renew Energy* 2020; 145: 1399–1411.
23. Liang R, Kent M, Wilson R, et al. The effect of thermochromic windows on visual performance and sustained attention. *Energy Build* 2021; 236: 110778.
24. Liang R, Kent M, Wilson R, et al. Development of experimental methods for quantifying the human response to chromatic glazing. *Build Environ* 2019; 147: 199–210.

25. Ko WH, Burgess I, Schiavon S, et al. Assessing the effects of films, electrochromic glass, and fabric shades on visual acuity, contrast and color sensitivities. Under Review.
26. Chinazzo G, Wienold J, Andersen M. Effect of indoor temperature and glazing with saturated color on visual perception of daylight. *LEUKOS* 2021; 17: 183–204.
27. Bellia L, Marino C, Minichiello F, et al. An overview on solar shading systems for buildings. *Energy Procedia* 2014; 62: 309–317.
28. Flamant G, Bustamante W, Tzempelikos A, et al. Evaluation of view clarity through solar shading fabrics. *Build Environ* 2022; 212: 108750.
29. Archambault J. Seduced by the view. *Urban Green Council*, https://www.urbangreencouncil.org/seduced-by-the-view/ (2013, accessed 15 August 2023).
30. Daylight Metrics Committee. *IES LM-83-12*. New York, United States: Illuminating Engineering Society of North America, 2012.
31. Nezamdoost A, Wymelenberg K. Blindswitch 2017: Proposing a new manual blind control algorithm for daylight and energy simulation. 2017.
32. Kim J, Kent M, Kral K, et al. Seemo: A new tool for early design window view satisfaction evaluation in residential buildings. *Build Environ* 2022; 214: 108909.
33. Ko WH, Schiavon S, Santos L, et al. View access index: The effects of geometric variables of window views on occupants' satisfaction. *Build Environ* 2023; 234: 110132.
34. Ne'Eman E, Hopkinson RG. Critical minimum acceptable window size: a study of window design and provision of a view. *Light Res Technol* 1970; 2: 17–27.
35. International WELL Building Institute. Solar glare control | WELL Standard - v6. *International WELL Building Intitute*, https://standard.wellcertified.com/v6/light/solar-glare-control (2016, accessed 10 June 2022).
36. International WELL Building Institute. Daylight design strategies | WELL Standard. *WELL Standard*, https://v2.wellcertified.com/en/wellv2/light/feature/5 (2022, accessed 10 June 2022).
37. Cambridge Dictionary. Clarity | meaning in the Cambridge English Dictionary, https://dictionary.cambridge.org/dictionary/english/clarity (2022, accessed 6 May 2022).
38. Aston SM, Belichambers HE. Illumination, colour rendering and visual clarity. *Light Res Technol* 1969; 1: 259–261.
39. Hashimoto K, Nayatani Y. Visual clarity and feeling of contrast. *Color Res Appl* 1994; 19: 171–185.
40. Thornton WA, Chen E. What is visual clarity? *J Illum Eng Soc* 1978; 7: 85–94.
41. CIE. *The international standard CIE S 017:2020 ILV: International Lighting Vocabulary*. 2nd Edition. Vienna, Austria: Commission Internationale de L'Eclairage, 2020.
42. Rea MS, Ouellette MJ. Relative visual performance: A basis for application. *Light Res Technol* 1991; 23: 135–144.
43. Wadlinger HA, Isaacowitz DM. Positive mood broadens visual attention to positive stimuli. *Motiv Emot* 2006; 30: 87–99.

44. Snyder H. Literature review as a research methodology: An overview and guidelines. *J Bus Res* 2019; 104: 333–339.
45. Bennet I, O'Brien W, Gunay HB. Effect of window blind use in residential buildings: Observation and simulation study. 2014; 14.
46. EN 14501. *Blinds and shutters - Thermal and visual comfort - Performance characteristics and classification*. Brussels, Belgium: European Committee for Standardization, 2021.
47. Fleming RW, Jensen HW, Bülthoff HH. Perceiving translucent materials. *J Vis* 2004; 4: 119.
48. Merilaita S, Scott-Samuel NE, Cuthill IC. How camouflage works. *Philos Trans R Soc B Biol Sci* 2017; 372: 20160341.
49. Troscianko T, Benton CP, Lovell PG, et al. Camouflage and visual perception. *Philos Trans R Soc B Biol Sci* 2009; 364: 449–461.
50. Bian Y, Chen Y, Sun Y, et al. Simulation of daylight availability, visual comfort and view clarity for a novel window system with switchable blinds in classrooms. *Build Environ* 2023; 235: 110243.
51. Kim JT, Kim G. Advanced external shading device to maximize visual and view performance. *Indoor Built Environ* 2010; 19: 65–72.
52. Karmann C, Chinazzo G, Schüler A, et al. User assessment of fabric shading devices with a low openness factor. *Build Environ* 2023; 228: 109707.
53. Kent MG, Altomonte S, Wilson R, et al. Temporal effects on glare response from daylight. *Build Environ* 2017; 113: 49–64.
54. Konstantoglou M, Tsangrassoulis A. Dynamic operation of daylighting and shading systems: A literature review. *Renew Sustain Energy Rev* 2016; 60: 268–283.
55. O'Brien W, Kapsis K, Athienitis AK. Manually-operated window shade patterns in office buildings: A critical review. *Build Environ* 2013; 60: 319–338.
56. Sanati L, Utzinger M. The effect of window shading design on occupant use of blinds and electric lighting. *Build Environ* 2013; 64: 67–76.
57. Hutchison D, Kanade T, Kittler J, et al. Seeing through obscure glass. In: Daniilidis K, Maragos P, Paragios N (eds) *Computer Vision – ECCV 2010*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 364–378.
58. Anderson BL. Visual perception of materials and surfaces. *Curr Biol* 2011; 21: R978–R983.
59. Fleming R, Jäkel F, Maloney L. Visual perception of thick transparent materials. *Psychol Sci* 2011; 22: 812–20.
60. Singh M, Anderson BL. Photometric determinants of perceived transparency. *Vision Res* 2006; 46: 879–894.
61. Eldin WS. Smart Glazing Systems for Low Energy Architecture, https://www.semanticscholar.org/paper/Smart-Glazing-Systems-for-Low-Energy-Architecture-Eldin/2f5fffab5cb73d9444febef026be393d043ad3b5 (2011, accessed 28 June 2022).

62. Sottile G. Cleantech daylighting using smart glass: A survey of LEED accredited professionals. *TechConnect Briefs* 2008; 201–204.
63. Moeck M, Lee ES, Rubin MD, et al. Visual quality assessment of electrochromic and conventional glazings. *Sol Energy Mater Sol Cells* 1998; 54: 157–164.
64. Hedge A. Worker reactions to electrochromic and low e glass office windows. *Ergon Int J*; 2. Epub ahead of print 1 January 2018. DOI: 10.23880/EOIJ-16000166.
65. Boubekri M, Lee J, MacNaughton P, et al. The impact of optimized daylight and views on the sleep duration and cognitive performance of office workers. *Int J Environ Res Public Health* 2020; 17: 3219.
66. Lee JE, Stein JJ, Prevor MB, et al. Effect of variable tinted spectacle lenses on visual performance in control subjects. *CLAO J Off Publ Contact Lens Assoc Ophthalmol Inc* 2002; 28: 80–82.
67. Shaik M, Majola PD, Nkgare LM, et al. The effect of tinted spectacle lenses on contrast sensitivity and colour vision. *Afr Vis Eye Health* 2013; 72: 61–70.
68. Wolffsohn JS, Cochrane AL, Khoo H, et al. Contrast is enhanced by yellow lenses because of selective reduction of short-wavelength light. *Optom Vis Sci Off Publ Am Acad Optom* 2000; 77: 73–81.
69. Cuttle K. Subjective assessments of the appearance of special performance glazing in offices. *Light Res Technol* 1979; 11: 140–149.
70. Troscianko J, Skelhorn J, Stevens M. Quantifying camouflage: how to predict detectability from appearance. *BMC Evol Biol* 2017; 17: 7.
71. Owsley C, Sekuler R, Siemsen D. Contrast sensitivity throughout adulthood. *Vision Res* 1983; 23: 689–699.
72. Mullen KT. The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings. *J Physiol* 1985; 359: 381–400.
73. Roark MW, Stringham JM. Visual performance in the “Real World”: Contrast sensitivity, visual acuity, and effects of macular carotenoids. *Mol Nutr Food Res* 2019; 63: 1801053.
74. Dowling JE, Dowling Jr. JL. *Vision: How It Works and What Can Go Wrong*. MIT Press, 2016.
75. Peli E. Contrast in complex images. *JOSA A* 1990; 7: 2032–2040.
76. Kauffmann L, Ramanoël S, Peyrin C. The neural bases of spatial frequency processing during scene perception. *Front Integr Neurosci*; 8, https://www.frontiersin.org/articles/10.3389/fnint.2014.00037 (2014, accessed 2 September 2022).
77. Bar M. Visual objects in context. *Nat Rev Neurosci* 2004; 5: 617–629.
78. Wilkins A. A physiological basis for visual discomfort: Application in lighting design. *Light Res Technol* 2016; 48: 44–54.
79. Flitcroft DI, Harb EN, Wildsoet CF. The spatial frequency content of urban and indoor environments as a potential risk factor for myopia development. *Invest Ophthalmol Vis Sci* 2020; 61: 42.

80. Wilkins AJ, Evans BJ, Plant GT. Potential uses for precision tinted lenses in a neurology clinic. *TouchREVIEWS Neurol*, https://touchneurology.com/headache-disorders/journal-articles/potential-uses-for-precision-tinted-lenses-in-a-neurology-clinic/ (2022, accessed 27 August 2023).
81. Chronicle E, Wilkins AJ. Gratings that induce perceptual distortions mask superimposed targets. *Perception* 1996; 25: 661–668.
82. Huang L, Seiple W, Park RI, et al. Variable tinted spectacle lenses: a comparison of aesthetics and visual preference. *CLAO J Off Publ Contact Lens Assoc Ophthalmol Inc* 2001; 27: 121–124.
83. Wilkins AJ, Haigh SM, Mahroo OA, et al. Photophobia in migraine: A symptom cluster? *Cephalalgia* 2021; 41: 1240–1248.
84. Kalloniatis M, Luu C. Visual acuity. In: Kolb H, Fernandez E, Nelson R (eds) *Webvision: The organization of the retina and visual system*. Salt Lake City (UT): University of Utah Health Sciences Center, http://www.ncbi.nlm.nih.gov/books/NBK11509/ (1995, accessed 8 June 2023).
85. Owsley C, Sloane ME. Contrast sensitivity, acuity, and the perception of 'real-world' targets. *Br J Ophthalmol* 1987; 71: 791–796.
86. Duntley S. The reduction of apparent contrast by the atmosphere. Epub ahead of print 1948. DOI: 10.1364/JOSA.38.000179.
87. Houghton HG. The transmission of visible light through fog. *Phys Rev* 1931; 38: 152–158.
88. Caltrider D, Gupta A, Tripathy K. Evaluation of visual acuity. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing, http://www.ncbi.nlm.nih.gov/books/NBK564307/ (2023, accessed 27 August 2023).
89. Jong PTVM de. Myopia: its historical contexts. *Br J Ophthalmol* 2018; 102: 1021–1027.
90. Sheppard AL, Wolffsohn JS. Digital eye strain: prevalence, measurement and amelioration. *BMJ Open Ophthalmol* 2018; 3: e000146.
91. Wilson MP. Comment 2 on 'Discomfort glare from interesting images' by N Tuaycharoen and P Tregenza: *Light Res Technol*; 37. Epub ahead of print 2005. DOI: 10.1177/136578280503700415.
92. Yap M. The effect of a yellow filter on contrast sensitivity. *Ophthalmic Physiol Opt* 1984; 4: 227–232.
93. Kelly SA. Effect of yellow-tinted lenses on brightness. *JOSA A* 1990; 7: 1905–1911.
94. Luria SM. Vision with chromatic filters. *Am J Optom Arch Am Acad Optom* 1972; 49: 818–829.
95. Al-Kodmany K. Residential visual privacy: Traditional and modern architecture and urban design. *J Urban Des* 1999; 4: 283–311.
96. Abdelwahab S, Kent MG, Mayhoub M. Users' window preferences and motivations of shading control: Influence of cultural characteristics. *Build Environ* 2023; 240: 110455.
97. Shaqiri A, Roinishvili M, Grzeczkowski L, et al. Sex-related differences in vision are heterogeneous. *Sci Rep* 2018; 8: 7521.

98. Murray SO, Schallmo M-P, Kolodny T, et al. Sex differences in visual motion processing. *Curr Biol* 2018; 28: 2794-2799.e3.

99. Schierz C. Lighting for the elderly: Physiological basics and their consequences. *Light Eng* 2011; 19: 19–27.

100. Dutch Green Building Council. *BREEAM-NL 2010: Label for sustainable real estate*. Version 1.11. Neverlands: Dutch Green Building Council, 2010.

101. Norwegian Green Building Council. *BREEAM-NOR new construction 2016: Technical manual SD5075NOR - Ver: 1.1.* Version 1.1. Norway: Norwegian Green Building Council, https://byggalliansen.no/wp-content/uploads/2018/11/BREEAM-NOR-2016_New-Construction_-_Endringer-i-versjon-1_1.pdf (2017).

102. Norwegian Green Building Council. *BREEAM-NOR 2016 new construction: Technical manual SD5075NOR - Ver: 1.2.* Version 1.2. Norway: Norwegian Green Building Council, https://byggalliansen.no/wp-content/uploads/2019/06/SD-5075NOR-BREEAM-NOR-2016-New-Construction-v.1.2.pdf (2019).

103. Norwegian Green Building Council. *BREEAM-NOR v6.0: New construction*. Version 6.0. Norway: Norwegian Green Building Council, https://byggalliansen.no/wp-content/uploads/2022/04/BREEAM-NOR-v6.0_ENG.pdf (2022).

104. Sweden Green Building Council. *BREEAM®SE: BREEAM-SE New construction 2017*. Version 1.1. Sweden: Sweden Green Building Council, https://www.sgbc.se/app/uploads/2018/06/BREEAM-SE-2017-1.1-English-version.pdf (2018).

105. Sweden Green Building Council. *BREEAM®SE: English manual for new construction and refurbishment*. Version 2.0. Sweden: Sweden Green Building Council, https://www.sgbc.se/app/uploads/2018/10/BREEAM-SE-eng-publ-130501-2.0-160223.pdf (2013).

106. Green Building Index Sdn Bhd. *green building index: GBI assessment criteria for non-residential new construction*. First edition. Malaysia: Green Building Index, https://www.greenbuildingindex.org/Files/Resources/GBI%20Tools/GBI%20NRNC%20Non-Residential%20Tool%20V1.0.pdf (2009).

107. Green Building Index Sdn Bhd. *green building index: GBI assessment criteria for residential construction*. Version 3.0. Malaysia: Green Building Index, https://www.greenbuildingindex.org/Files/Resources/GBI%20Tools/GBI%20RNC%20Residential%20Tool%20V3.0.pdf (2013).

108. Green Building Council Indonia. *Greenship new building: Version 1.1*. Version 1.1. Indonesia: Green Building Council Indonesia, 2021.

109. Green Building Council Indonia. *Greenship for new buildings: Version 1.2 summary of criteria and benefits*. Version 1.2. Indonesia: Green Building Council Indonesia, 2013.

110. New Zealand Green Building Council. *greenstar: Technical Manual. Office design & built 2009. Now including existing buildings.* Auckland, New Zealand: New Zealand Green Building Council, 2014.

111. New Zealand Green Building Council. *greenstar: Technical Manual v3.1*. Version 3.1. Auckland, New Zealand: New Zealand Green Building Council, 2016.
112. Mellerio J. Yellowing of the human lens: nuclear and cortical contributions. *Vision Res* 1987; 27: 1581–1587.
113. Hammond BR. The visual effects of intraocular colored filters. *Scientifica* 2012; 2012: 424965.
114. Weale RA. Age and the transmittance of the human crystalline lens. *J Physiol* 1988; 395: 577–587.
115. Shi W, Lockhart TE, Arbab M. Tinted windshield and its effects on aging drivers' visual acuity and glare response. *Saf Sci* 2008; 46: 1223–1233.
116. Mahjoob M, Heydarian S, Koochi S. Effect of yellow filter on visual acuity and contrast sensitivity under glare condition among different age groups. *Int Ophthalmol* 2016; 36: 509–514.
117. Patching GR, Jordan TR. Spatial Frequency Sensitivity Differences between Adults of Good and Poor Reading Ability. *Invest Ophthalmol Vis Sci* 2005; 46: 2219–2224.
118. Derefeldt G, Lennerstrand G, Lundh B. Age variations in normal human contrast sensitivity. *Acta Ophthalmol (Copenh)* 1979; 57: 679–690.
119. Ross JE, Clarke DD, Bron AJ. Effect of age on contrast sensitivity function: uniocular and binocular findings. *Br J Ophthalmol* 1985; 69: 51–56.
120. Brannan S, Dewar C, Sen J, et al. A prospective study of the rate of falls before and after cataract surgery. *Br J Ophthalmol* 2003; 87: 560–562.
121. Naidu S, Lee JE, Holopigian K, et al. The effect of variably tinted spectacle lenses on visual performance in cataract subjects. *Eye Contact Lens* 2003; 29: 17–20.
122. Katsnelson A. Colour me better: fixing figures for colour blindness. *Nature* 2021; 598: 224–225.
123. Neitz M, Neitz J. Molecular genetics of color vision and color vision defects. *Arch Ophthalmol* 2000; 118: 691–700.
124. Dain SJ, Wood JM, Atchison DA. Sunglasses, traffic signals, and color vision deficiencies. *Optom Vis Sci Off Publ Am Acad Optom* 2009; 86: e296-305.
125. Pun HW, Brown M, Lui R. Tinted contact lenses slow reaction time in colour defective observers. *Clin Exp Optom* 1986; 69: 213–218.
126. National Eye Institute. Types of color vision deficiency | National Eye Institute, https://www.nei.nih.gov/learn-about-eye-health/eye-conditions-and-diseases/color-blindness/types-color-vision-deficiency (2023, accessed 14 August 2023).
127. Kent MG, Schiavon S. Predicting window view preferences using the environmental information criteria. *LEUKOS* 2022; 0: 1–20.
128. Wilkins A, Nimmo-Smith I, Tait A, et al. A neurological basis for visual discomfort. *Brain J Neurol* 1984; 107 (Pt 4): 989–1017.
129. Konstantzos I, Kim M, Tzempelikos A. An integrated method and web tool to assess visual environment in spaces with window shades. *Sci Technol Built Environ* 2018; 24: 470–482.

130. O'Brien W, Gunay HB. Mitigating office performance uncertainty of occupant use of window blinds and lighting using robust design. *Build Simul* 2015; 8: 621–636.

131. Gunay HB, O'Brien W, Beausoleil-Morrison I. A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. *Build Environ* 2013; 70: 31–47.

132. Konstantzos I, Tzempelikos A. Design recommendations for perimeter office spaces based on visual performance criteria. In: *Proceedings of CISBAT 2015 International Conference on Future Buildings and Districts*. Lausanne, Switzerland: Lausanne, EPFL Solar Energy and Building Physics Laboratory, 2015, pp. 271–276.

133. Mahdavi A, Mohammadi A, Kabir E, et al. Occupants' operation of lighting and shading systems in office buildings. *J Build Perform Simul* 2008; 1: 57–65.

134. Daum D, Morel N. Assessing the total energy impact of manual and optimized blind control in combination with different lighting schedules in a building simulation environment. *J Build Perform Simul* 2010; 3: 1–16.

135. Woo M, MacNaughton P, Lee J, et al. Access to daylight and views improves physical and emotional wellbeing of office workers: A crossover study. *Front Sustain Cities*; 3, https://www.frontiersin.org/articles/10.3389/frsc.2021.690055 (2021, accessed 6 September 2022).

136. Basilio LG, Moreno DJ, Piratelli AJ. Main causes of bird-window collisions: a review. *An Acad Bras Ciênc* 2020; 92: e20180745.

137. Borden W, Lockhart O, Jones A, et al. Seasonal, taxonomic, and local habitat components of bird-window collisions on an urban university campus in Cleveland, OH. *Ohio J Sci* 2010; 110: 44–52.

138. Canada Gfeen Building Council. *LEED Canada: Reference guide for green building design and construction 2009*. Ottawa, Canada: Canada Green Building Council, 2009.

139. U.S. Green Building Council. Bird collision deterrence | U.S. Green Building Council. *LEED BD+C: New Construction*, https://www.usgbc.org/credits/core-shell-existing-buildings-healthcare-new-construction-retail-nc-schools/v2009/pc55 (2009, accessed 23 June 2022).

140. American Bird Conservancy. Bird collision deterrence: Summary of material Threat Factors, https://abcbirds.org/wp-content/uploads/2015/05/Docs10397.pdf (2011, accessed 27 June 2022).

141. Hong Kong Green Building Council. *BEAM Plus New Buildings*. Hong Kong: BEAM Society Limited, https://www.hkgbc.org.hk/eng/beam-plus/file/BEAMPlus_New_Buildings_v2_0.pdf (2019).

142. Rajchard J. Ultraviolet (UV) light perception by birds: a review. *Veterinární Medicína* 2009; 54 (2009): 351–359.

143. Swaddle JP, Emerson LC, Thady RG, et al. Ultraviolet-reflective film applied to windows reduces the likelihood of collisions for two species of songbird. *PeerJ* 2020; 8: e9926.

144. View, Inc. Designing buildings with smart bird-safe windows. *View, Inc.*, https://view.com/blog/save-millions-of-birds (2019, accessed 5 October 2022).

145. Tregenza P, Wilson M. *Daylighting: Architecture and lighting design*. Milton Park, United Kingdom: Routledge, 2013.

146. View, Inc. Night mode benefits people and wildlife | View, Inc. *Going Dark – Night mode benefits people and wildlife*, https://view.com/blog/night-mode-benefits-people (2019, accessed 17 August 2023).

147. Philippine Green Building Council. *BERDE GBRS - New construction*. Version 2.2. Philippines: Philippine Green Building Council, https://docs.berdeonline.org/userguide/v2.0.0/berde-nc/#copyright (2017).

148. Energy & Environmental Canada Ltd. *Green Globes: Design for new buildings and retrofits: Rating system and program summary*. Canada: Energy & Environment Canada Ltd., 2004.

149. BCA. *GM RB: 2016 Green Mark for residential buildings*. Singapore: Building and Construction Authority, https://www1.bca.gov.sg/ (2017).

150. Green Building Council South Africa. *Green Star SA*. Version 2. South Africa: Green Building Council of South Africa, https://gbcsa.org.za/wp-content/uploads/2020/05/Green-Star-Africa-Mauritius-Revision-2-Final-04-10-2017.pdf (2017).

151. New Zealand Green Building Council. *greenstar: Technical Manual v3.2*. New Zealand: New Zealand Green Building Council, https://www.nzgbc.org.nz/Attachment?Action=Download&Attachment_id=2126 (2017).

152. IGBC. *IGBC Green New Buildings Rating System*. Versio 3.0. Hyderabad, India: Indian Green Building Council, 2014.

153. Indian Green Building Council. *LEED 2011 for India: Green building rating system for new construction & major renovations*. India: Indian Green Building Council, http://www.indiaenvironmentportal.org.in/files/LEED2011forIndia-NC.pdf (2011).

Appendix A: Green certification systems that recommend shading

Table A1 List of green certification systems that assign credits and criteria for shading devices

Certification system	Credit	Purpose	Criteria
BEAM version 2.0[141]	SS7: Sustainable site	Wildlife-friendly building	Design that avoid bird collision on windows (e.g. use pattern on glass/ façade/ shades, translucent glass)
BERDE GBRS version 2.2[147]	EQ-05: Glare control	Glare control	Install a user-controlled shading system to all windows, glazed doors and roof lights in all regularly occupied spaces of the project
BREEAM NC:2018[9]	HEA-01: Visual comfort	Glare control	Ensuring the use or location of shading does not conflict with the operation of lighting control systems
Green Building Index version 1.0[106]	EQ9: Lighting, visual & acoustic comfort	Glare control	Where blinds or screens are fitted on all glazing and atrium as a base building
Green Globes: Design for New Buildings and Retrofits[148]	G.3: Lighting	Natural light exposure, and promote well-being and comfort.	Specify solar shading devices to enable occupants to control brightness from direct daylighting
Green Mark for Residential Buildings:2016[149]	Part 4 – Smart and Healthy Building	Glare control	Provision of any of the strategies for at least 90% of residual units with glare: ● Blinds and screens ● Light shelf ● Glazing treatments
Green Star: South Africa version 2[150]	IEQ-05: Daylight Glare Control	Glare control	Daylight glare control is usually in the form of internal blinds. Other sun shading solutions are used on projects that reduce daylight glare.
Green Star: New Zealand version 3.2[151]	IEQ-9: Daylight Glare Control	Glare control	For each typical glazing configuration on each façade, fixed shading devices shade the working plane OR Blinds or screens are fitted on all glazing and atriums as a base building provision
IGBC Green New Buildings Rating System version 3[152]	SA Credit 3: Passive Architecture	Minimise negative environmental impacts	Climate-responsive concepts and design features (e.g. shading devices, extended louvres)
LEED India: 2011[153]	IEQ Credit 8.1: Daylight and Views – Daylight	Promote outdoor connection through	Designs that incorporate view-preserving automated shades for glare control may demonstrate compliance

		daylight and views	for only the minimum 25 fc (270 lux) illuminance level
WELL version 2[11]	L05 Part 2: Integrate Solar Shading	Indoor daylight integration for visual tasks along with electric lighting. Promote outdoor connection through windows	All vertical transparent envelope glazing has shading that meet one of the following: ● Manual shading controllable by regular occupants at all times. Shades are regularly opened once a day for all days that the project is in use ● Shading is automated to prevent glare

 https://doi.org/10.1177/14771535241261270