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Optimum external shading system for counterbalancing glare probability and daylight illuminance in Sydney's residential buildings

Ehsan Sorooshnia and Maria Rashidi
Centre for Infrastructure Engineering, School of Engineering, Design and Built Environment, Kingswood, Australia
Payam Rahnamayiezekavat
Western Sydney University – Parramatta South Campus, Sydney, Australia, and
Fatemeh Rezaei and Bijan Samali
Centre for Infrastructure Engineering, School of Engineering, Design and Built Environment, Kingswood, Australia

Abstract

Purpose – Optimisation of daylight admission through window is crucial for alleviating glare while maintaining useful daylight levels in order to enhance occupants' health, visual comfort and moderating lighting energy consumption. Amongst various solutions, fixed external shade is an affordable solution for housing spaces that need to be sophisticatedly designed, especially during the period of increasing home spaces as working environments. In the humid subtropical region, daylight control plays an important role in indoor comfort, particularly with areas with a high window to wall ratio (WWR). Due to the insufficient amount of such study on non-office spaces in Australia, shading-related standards are not addressed in Australian building codes.

Design/methodology/approach – The chosen methodology for the research is a quantitative data collection and analysis through field measurement and simulation simultaneously. The first step is a multi-objective optimisation of shading elements through a non-dominated sorting genetic algorithm (NSGA-II) on parametric modelling via Rhino3D CAD and simulation engines (DIVA and ClimateStudio). In the second phase, the Pareto front solutions are validated by experimental measurements within a room with a single north-facing window (the most probable for the daytime glare in Sydney) for the seven most common local window configurations.

Findings – Through the simulation of ten genes, 1,560 values and $2.4 \times 1{,}019$ of search space, this study found an optimum shade for each local common window layout, resulted in $+22\%$ in (UDI) and -16% in views with discomfort glare on average. Moreover, an all-purpose polygonal shade showed an average of 4.6% increase in UDI and a 5.83% decrease in the percentage of views with discomfort glare.

Research limitations/implications – The findings are subject to the room dimensions, window dimensions and layouts, and orientation of windows for selected residential buildings in Sydney.

Originality/value – The study contributes to the development of highly accurate fixed external shading systems with rectangular and tapered-form external shapes. A real-time measurement by luminance-metre sensors and HQ cameras located at six eye levels is conducted to corroborate simulation results of the visual comfort.

Keywords External shade, Daylight glare probability, Useful daylight illuminances, Multi-objective optimisation

Paper type Research paper

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Nomenclature

DGP	Daylight glare probability
NSGA	Non-dominated sorting genetic algorithm
UDI	Useful daylight illuminances
UGR	Unified glare rating
VCP	Visual comfort probability
BGI	Building Research Station Glare Index
EPW	Energy Plus Weather file
BSDF	Bidirectional scattering distribution function
sDG	Percentage of views with discomfort glare (more than 5% of the time)
WWR	Window wall ratio
SWR	Shading window ratio
HDR	High dynamic range
TSW	Total shade area to window area

1. Introduction

Australia is distinguished by the frequent bright and cloudless skies even in winter, whilst European countries experience overcast skies during winter that are deemed critical in terms of daylight illumination and window design (Kittler and Darula, 2019). Useful Daylight illuminances (UDI) has a significant role in the maintenance of indoor comfort. The COVID-19 pandemic, which has brought an increase in indoor home spaces as working environments (Hu, 2020; Wuersch and Neher, 2020; Morawska *et al.*, 2020), is growing the importance of the study on residential indoor visual comfort matters, especially regarding the reciprocal relationship between avoiding glare and indoor daylight access. During the daytime, the primary glare resource is windows which let in direct sunlight. It is advisable to intercept excessive luminance into space. In order to use incoming sunlight effectively, the light sources would be controllable. To alleviate the harsh glare, all fenestration subjected to direct sunlight should have to be equipped to handle glare with some sort of sun control (ASHRAE, 2009), which is the paper's main aim. In addition, efficient use of sunlight illumination convinces us to use shading systems to prevent unsolicited insolation and the connected glare (ASHRAE Design_Guide, 2015).

Much of the current literature on glare pays particular attention to office spaces. So, the dwelling spaces are not studied as much in this context. Qin and Li (2021) simulated a light-controlled shading system on building energy consumption using eQUEST software based on a light environment by Ecotect for a 32-storey office in Wuhan, China, with an average window to wall (WWR) ≈ 0.73 (curtain wall). They provided no field measurement and experimental validation. Garretón *et al.* (2021) conducted an experiment finding the relationship between glare, the view to outside, and daylight availability for a roller blind system using HDRI technique for a 1 × 1 m window was oriented to the north-east in Argentina. Their experiment ran on sunny days between April and May 2019 from 9 a.m. to 4 p.m. (Garretón *et al.*, 2021). Huo *et al.* (2021) conducted a sensitivity analysis of parameters for cooling demand and shading performance for a six-storey residential building in China. Park *et al.* (2021) carried on a field study to investigate the interrelationship between desk workers' satisfaction, workstation lighting, and the working area environmental characteristics. They studied the effect of five shading device types. Sedaghatnia *et al.* (2021) performed a multi-objective optimisation (using Ladybug and Honeybee) as well as on-site measurement to assess glare, daylight and energy saving for an educational building with WWR of 0.3 and 0.6 in Tehran, Iran. Tabadkani *et al.* (2020) analysed an external motorised Venetian blind to control solar radiation to mitigating thermal and visual discomfort. The simulation is performed via EnergyPlus. They used two indoor sensors in a single office room in Melbourne, Australia, with WWR is 90% to assess DGI and task horizontal illuminance in order to adjust the Venetian blinds. They did not validate the simulation result by field measurements. Through a field comparison test, Huo *et al.* (2020) quantified the external shading effect on the southern windows of a five-row residential building with an orientation of 10° south by the west in Zhengzhou, China, in terms of thermal-optical performance. The southern wall WWR is 40%. The parameters were monitored in the hottest period. Wang *et al.* (2020a) investigated the effects of shading and ventilation of windows on an office in a high-rise building energy demand and thermal comfort in China from uncertainty analysis, sensitivity analysis and multi-objective optimisation. The windows, in this case, are oriented south and west. Luo *et al.* (2020) evaluated the automated interior motorised blinds effect on visual comfort, daylighting and electrical energy savings through simulation for an open-plan office in China. The window is oriented south, and the WWR is 72%. Kunwar *et al.* (2020) the effect of dynamic Venetian blinds on Energy savings, glare, and daylight availability in commercial buildings in the US through experimental testing. Their experiment is performed from March 28th to September 14th. The test rooms were oriented East, South, and West. Abidi and Rajagopalan (2020) conducted an investigation on daylight admission into high-rise living spaces in Melbourne, Australia, to find the optimum opening size and shape. Wu *et al.* (2019) studied automated Venetian blinds effect on indoor work-plane illuminance (WPI) and daylight glare probability (DGP) using HDR imaging techniques in Lausanne, Switzerland during winter. Ghadi *et al.* (2017) proposed fuzzy-based controllers with the integration of daylight for institutional buildings in Queensland, Australia (see Figure 1).

So far, far too little attention has been paid to Australian dwellings indoor visual comfort. Most studies in glare and useful daylight have only been carried out in a small number of building types. The research to date has tended to focus on offices rather than dwelling spaces. Hence, the generalisability of much-published research on this issue is problematic. Previous studies of glare have not dealt with residential spaces in much detail. In addition, no research has been found to survey different possible eye levels (including standing and seated) because the majority of studies have considered the working plane level. Apart from Hirning *et al.* (2014), there is a general lack of subjective research, HDR imaging technique and whole-room field measurement. As there have been few empirical investigations into indoor visual comfort in the Australian residential sector, there is no clause regarding glare alleviation. Only a single clause identifies minimum illuminance in the Building Code of Australia (BCA).

Pierson *et al.* (2018a, b) claimed that as of 2018, regardless of glare effect rankings, there are no current indices on human glare discomfort perception. They found that it might be because the discomforting glare governing mechanism is not rightly understood since there is no plausible scientific justification for it. They also state that current predicting indices cannot determine an absolute threshold of an occupant's glare perception. In 2021, the most cited Pierson *et al.* (2021) concluded, whereas "more than 20 models for predicting discomfort from daylight glare have been developed, none accurately predict it." These indices portend the grade of perceived discomfort glare approximately. This approximating function has been the best means to assess glare comfort as of 2018 (Pierson *et al.*, 2018a). Bellia *et al.* (2008) expounded the indexes related to artificial lighting (VCP [1], BGI [2], and UGR [3]) are not applicable to evaluating glare from windows because of the excessive solid angle to the glare source as well as greater luminance of the seen sky rather than an equivalent artificial lighting fixture with the same size. Nazzal has also found that UGR and VCP are not valid for daylight glare evaluation (Nazzal, 2001). Therefore, based on mentioned discussion, the DGP [4] formula is used to assess glare in this paper. Daylight Glare Probability (DGP) was the more recent index developed by Jan Wienold and Jens Christoffersen in 2006 to assess glare

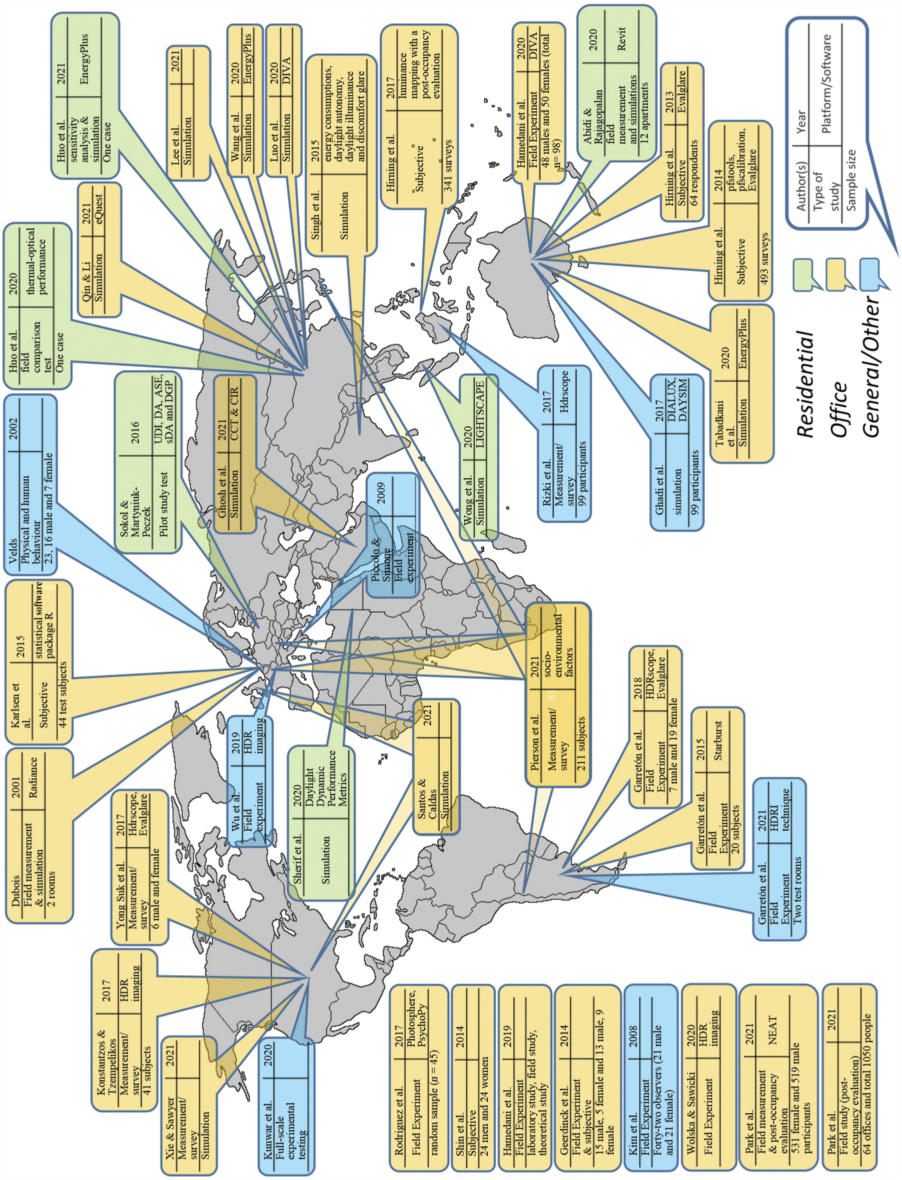


Figure 1.
Similar recent studies according to building type, study type, location, etc.

(Equation 1). Unlike other indexes that express perception glare, DGP indicates an occupant's probability of being caught by glare (Pierson *et al.*, 2018a).

$$\mathrm{DGP} = \left(5.87 \times 10^{-5} E_V\right) + \left(9.18 \times 10^{-2} \log_{10}(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 * \omega_{s\ ,i}}{E_V^{1.87} \times P_i^2})\right) + 0.16 \quad (1)$$

Where:

E_V is vertical eye illuminance [lux];

$L_{s,i}$ is luminance of ith source (window) [$\mathrm{cd}_{/\mathrm{m}}{}^2$];

$\omega_{s,i}$ is the solid angle (angular size of the glare source as seen by the eye) of ith source (window) [sr];

P_i is the position index relative to the ith source (window).

As Nazzal claims, the procedure of Equation (1) can be used regardless of window size, shape and position (parameters w, h, e and f in Figure 3) are assumed constant in every case simulation (Nazzal, 2005).

However, a significant problem with applying fixed shading is finding the optimum features that alleviate discomfort factors while maximising comfort parameters. The issue has grown in importance in light of recent studies trying to devise movable shading systems (Kim *et al.*, 2019; Wang *et al.*, 2020b). In the sense of glare reduction, internal shading devices are less contributive since they block the sun rays after penetrating the room. But the exterior shades show the more efficient performance due to blocking the direct radiation and abating heat transmission simultaneously (Khoroshiltseva *et al.*, 2016). Previous studies of daylight-related matters concerning Australian construction have not been dealt with in much detail regarding Australia's local conditions and construction (González and Fiorito, 2015; Lavin and Fiorito, 2017). The research to date has tended to focus on offices (Scott Linney, 2008; Iwata, 2010; Wienold, 2010; Atzeri *et al.*, 2013; O'Brien *et al.*, 2013) rather than dwellings (Wong and Istiadji, 2004; Babaizadeh *et al.*, 2015). Although extensive research has been carried out on glare, no studies have been found applying field tests to comprehensively delineate the relationship between daylight glare and daylight illuminance and external fixed shading system for dwelling spaces in the sub-tropical climate of Australia.

The major objective of this study is to find an affordable and easy-to-install external shading system alleviating glare in Sydney residential spaces while not sacrificing useful daylight illuminance. This shading system does not need any sophisticated mechanical fixtures or occupants' operation. Therefore, this study sets out to assess the effect of adding shading on moderating glare and daylight illuminance. Simulations were performed by plug-ins DIVA (Jakubiec and Reinhart, 2011) and ClimateStudio (Sollema, 2020). The method used in this project is a genetic-algorithm based approach (Tuhus-Dubrow and Krarti, 2010; Omidfar, 2011), which connects a parametric design to simulation engines like Radiance, Daysim, OpenStudio, etc., to simulate daylight and glare, and are validated by experimental measurements.

Recent trends in indoor visual comfort have led to a proliferation of studies that try to find optimum shading systems or shading strategies concerning daylight access (Wang *et al.*, 2020b; Wong and Istiadji, 2004; Samadi *et al.*, 2020; Al Dakheel and TabetAoul, 2017; Do and Chan, 2020; Luo *et al.*, 2020) through computer simulation (Alzoubi and Al-Zoubi, 2010; Bueno *et al.*, 2020; Athienitis and Tzempelikos, 2002; Gugliermetti and Bisegna, 2006; Wienold, 2007; Littlefair *et al.*, 2010) and performing experiments (Tokura *et al.*, 1996; Iwata *et al.*, 1991; Kim *et al.*, 2009).

In this study, any slight change in each independent parameter (dimensions and inclination of shading elements) is compared using NSGA-II (non-dominated sorting genetic algorithm for multi-objective optimisation) introduced by Deb *et al.* (2000). This algorithm "finds any Pareto optimal solution in a finite number of solution evaluations" (Deb, 2001). The analysis in this study is conducted through Wallacei evolutionary engine (Makki and Showkatbakhsh, 2018) to find the Pareto front [5] for near-optimum shading elements and their features. The first and second fitness objectives are daylight glare probability (to be minimised) and UDI (to be maximised), respectively. For each predefined window layout, the objectives are deeply sensitive to the subject's relative horizontal and vertical position to the window as well as the time of year. The form-finding process is done for two options for each window configuration case, first, a set of rectangular elements and second, a tapered irregular shade. Geometrical parameters of shading elements such as size, inclination and cutting angles are optimised accurately in order to minimise glare probability and ample solar radiation, holding outdoor view and useful daylight illuminances.

1.1 Indoor comfort assessing methods

International Commission on Illumination (CIE) defines glare as "the condition of vision in which there is discomfort or a reduction in the ability to see significant objects, or both, due to an unsuitable distribution or range of luminances or to extreme contrasts in space or time" (Commission_Internationale_de_l'Eclairage, 1983). Daylight glare assessment is more complicated than artificial lighting due to dynamically changing sky luminance distribution over time (Torres and Verso, 2015).

Regarding the lack of a standardised dependent measure and global consensus of opinions on glare's statement of meaning (Clear, 2013), useful daylight illuminances (UDI), proposed by Nabil and Mardaljevic (2005), is the method to evaluate daylight illuminance in this paper. In this method, illuminance greater than 2000 [lux] leads to the emergence of glare (Nabil and Mardaljevic, 2005, 2006). When horizontal illuminance over a work plane reaches over 3,000 [lux], this unlocks the potential for glare (Torres and Verso, 2015). The daylight availability metric of UDI divided hourly time into three main categories: 0–100 lux (failing), 100–2000 lux (useful) [6] and over 3,000 lux (excessive) (Nabil and Mardaljevic, 2006; Mardaljevic, 2015). The purpose of the UDI system is "to approach the data first from a human factors perspective, and then reduce it to compact metrics". and making output from a climate-based simulation comprehensible without renunciation of the vital performance-revealing content of the raw data. It disengages researchers from analysing the extensive mass of data gathered through conventional means, such as frequency histograms, cumulative plots, etc. (Mardaljevic, 2017). This is the main reason for choosing the UDI metric (out of three main metrics of spatial daylight autonomy, annual sun exposure (ASE) and UDI). Nazzal believed most glare evaluation formulae only consider horizontal illuminance, which is inadequate for assessing a subject's comfort (Nazzal, 2001).

Pierson *et al.* (2018b) analysed subjective glare ratings and the values of discomfort glare indices as the most common approach to evaluating the glare. The main physical quantities are (1) the glare source(s) luminance in people's field of view (Figure 2), (2) the solid angle of the glare source(s) (see Figure 3) (3) the luminance of the background (Figure 2) and (4) the position index of the glare source(s) (Commission_Internationale_de_l'Eclairage, 1983; Einhorn, 1969) (see Figure 5). A glare index is defined as an analytical assessment of HDR [7] images using numerical formulae educed from experimentation on human subjects (Reinhart and Wienold, 2011). According to previous studies, the main categories of glare are *imperceptible*, *perceptible (noticeable)*, disturbing and *intolerable* (Pierson *et al.*, 2018b).

In addition to the *factor method*, *threshold method* and *task area method*, a point-in-time glare analysis method is used in some daylight-simulation software (Pierson *et al.*, 2018b). The latter is the method utilised to analyse glare in this paper.

2. Methodology

This research critically examines the probability of glare and useful daylight for local residential buildings in Sydney, Australia, then analysing the external shading effect on these matters. With a realistic and thorough assessment, the authors considered six possible occupant's eye levels (both seated and standing positions) in eight view directions within a room. Therefore, this research project has aimed to try to establish the optimum external shade that does not need to be operated by occupants. The project starts with comprehensive care of local climate and window layouts to find the discomfort situations, then simulating best shading features to bring optimum regulated glare and daylight access. Every single solution gained from the Pareto front is validated by field measurement before and after adding shading elements. Therefore, this paper leaves two final options of shading system for designers and practitioners in NSW, Australia to have visually comfortable residential spaces: a single rectangular shade on each side of a window or an elaborated tapered form of shade.

The research framework comprises four phases: (1) Gathering meteorological data and local window layouts; (2) Measure indoor parameters through field measurement; (3) multi-criteria optimisation simulation, and (4) Validation of optimum solution by field measurement. All these steps are followed for both rectangular and tapered polygonal shading elements. Figure 2 illustrates the block diagram of the research.

2.1 Building modelling and simulation

Different shading feature alternatives for a North orientation have been calculated for a single dwelling room located in Sydney (33°51′ S 151°12′ E), in the south-eastern part of Australia, to assess the glare and daylight illuminance. To simulate annual glare analysis and hourly DGP, the authors have assumed a single room of 4 × 6 × 3 m with a single north-facing window located at Sydney Olympic Park (33.8465° S, 151.0722° E) (Table 1). With only one side (4 × 3 m) facing outdoors (Table 1). The room is modelled in Rhino3D [8] and then analysed by DIVA (daylighting and energy modelling plug-in for Rhino3D) using Radiance and Energy Plus, trusted by the industry under different window layouts setup. The effectiveness of various dimensions and tilt angles for shading elements are simulated and analysed.

A multi-objective simulation is used to obtain empirical results about the performance of fixed shading elements. Local weather data were gathered from EPW [9] files. Finding the optimum shading systems and shading element features, which is the fundamental property

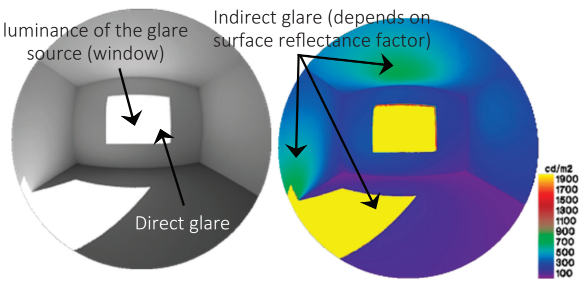


Figure 2.
Perceptible glare on May 3rd 10:00 a.m. under clear sky condition for a north-facing window located at Sydney Olympic Park shows 36% perceptible glare using DIVA

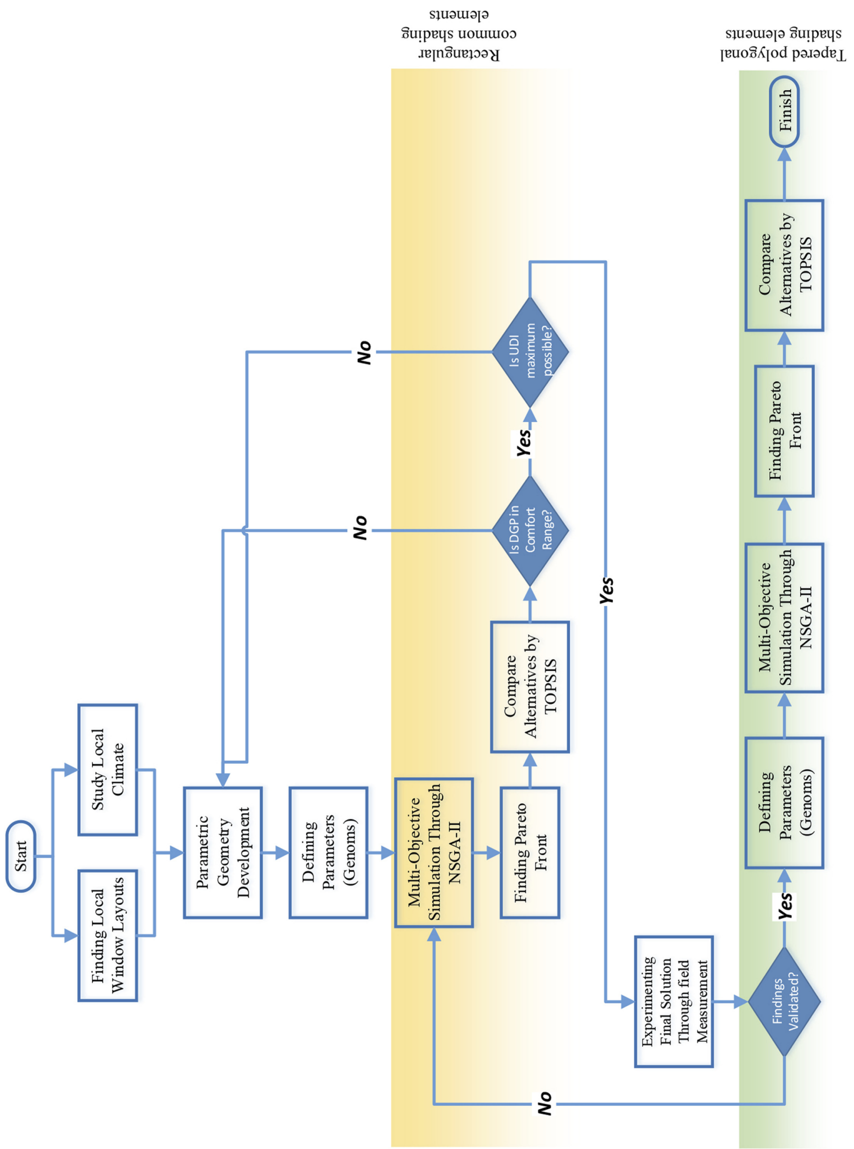


Figure 3.
Block diagram of the research

of this project, begins with simulation. It will then go on to experimental measurement. The solution sought is a local optimum solution for Sydney's climate.

2.2 Experimental setup

To analyse annual glare and daylight illuminance analysis for a north-facing window (for seven different cases), a room of $4 \times 6 \times 3$ m with a full-façade north-facing window located in Sydney Olympic Park, NSW, Australia is chosen. To measure the metrics for each window layout, the authors covered the remaining surface of the window with a completely opaque multilayer cardboard. As the simulation and measurement mainly focus on daylight, the cover sheets' thermal properties are not important. Table 1 shows the material properties for the given room.

Within the given project, a network of virtual and accurate sensors considered to measure DGP, illuminance, etc., are located on a 1×1 m grid at different eye levels (see Appendix) to assess the glare and daylight parameters and compare the position index. The virtual sensors provide input for simulation through ClimateStudio, DIVA (which use RADIANCE), and the findings are validated by data gathered from the actual sensors (field measurement).

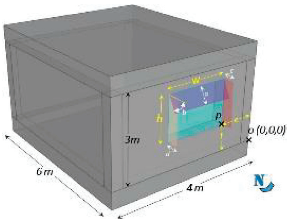
Regarding the window layout, De Luca *et al.* (2016) stated that with the aim of optimising the result for the Northern Hemisphere, the horizontal layout is the efficient choice for south-facing façades but for the east and west-facing ones, the vertical layout is better. The solar altitude is too low during the entire year, making horizontal shades ineffective or very long. Therefore, in these situations, the better option could be vertical fins (Haglund, 2010).

To assess the glare probability for each position, eight view directions were considered (four cardinal directions and for inter-cardinal), meaning for each position index, eight different possible fields of view were simulated. To ensure a comprehensive simulation, the six most common ergonomically eye levels are deemed as 1.1 , 1.2 and 1.3 m for seated people as well as 1.5 , 1.6 and 1.7 m for standing individuals (see Appendix). Hence, for each hourly-basis analysis, there are 1,680 subjective virtual eyes to evaluate DGP. The results demonstrate that under clear sky conditions, for almost all eye levels, an intolerable or disturbing level of glare is possible all year long. On the contrary, the simulation of annual glare analysis for a south-facing, east-facing and west-facing window shows there is a limited range of daytime/dates of occurring discomfort glare, which reiterates the importance of developing solutions for north-facing windows. Since glare is not critical for other directions in Southern Hemisphere, this research focuses on north-facing windows.

2.2.1 Simulation parameters. The vertical illuminance is simulated before and after adding shade, measured by accurate sensors and a luminance metre. Figure 4 depicts the direct correlation between vertical illuminance at the eye level and glare probability. Such data collecting by field measurement were used to validate the simulation result as well.

Three parameters that can affect the solid angle and position index are shown in Figure 5. w is the width of window [m], h is the height of window [m], d is the perpendicular distance from the observation place to the centre of the window area [m], g is the transverse distance

Table 1.
A single residential room located at Sydney Olympic Park



	Material	Roughness	Reflectance	Specular	Diffuse		Colour
Walls	Gypsum board	0.20	83.40%	1.01%	82.39%		White painted
Ceiling	Plaster	0.20	82.20%	0.44%	81.76%		White painted
Floor	Wooden	0.20	4.93%	0.74%	4.19%		Brown
	Material	*U-value*	*SHGC*	*TVIS*	*RVIS front*	*RVIS back*	*Colour*
Window	Single layer clear float glass (6mm)	5.82	0.818	0.877	8.4%	8.5%	Clear

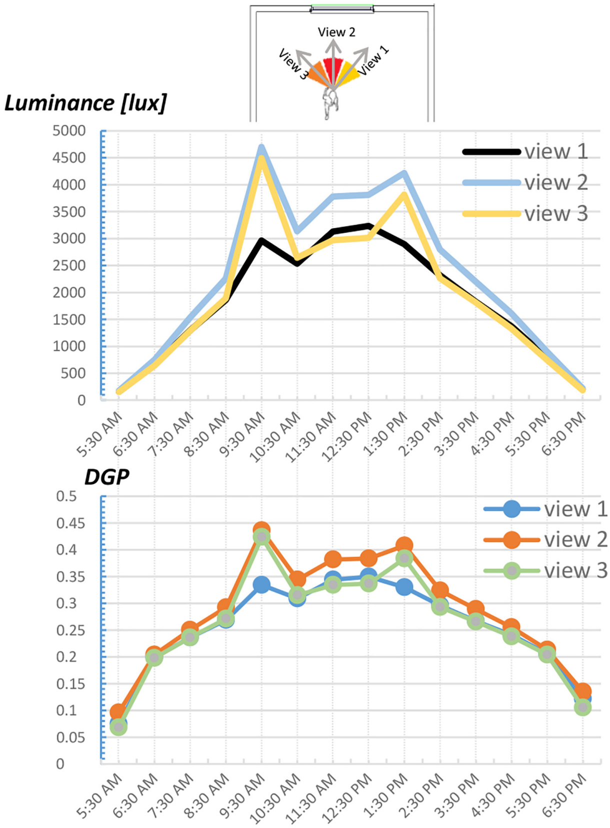


Figure 4.
Vertical eye luminance [lux] at a level of 1.7 m on January 1st for a north-facing room at Sydney Olympic Park under *clear sky condition with the sun* (left); DGP for three views at the same position, location and time to left graph, which shows the direct correlation between L_v and DGP (right)

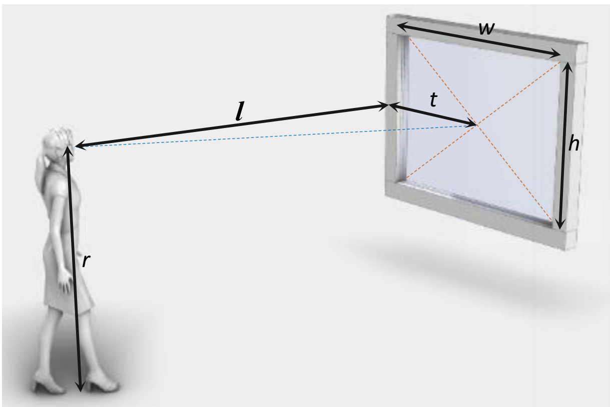


Figure 5.
Parameters to calculate the configuration factor of a window

between the subject's eye and the centre of window and *c* is the subject's eye height (Figure 5 and Table 2). The window-related variables are considered constant for each case, and the position-related ones are defined as genomes.

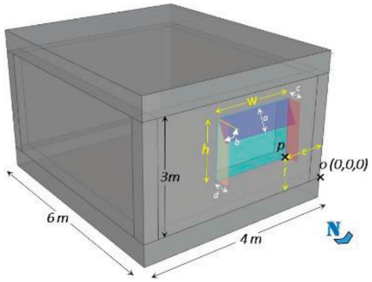


Table 2.
Independent parameters breakdown

Category	Sub-category	Description	Symbol	Unit	Range
Window	window dimensions	window length	***w***	m	1≤ w ≤3.8
		window height	***h***	m	1≤ h ≤3
	window-to-wall relative position	horizontal relative coordinate	***e***	m	0.1≤ e ≤3.5
		vertical relative coordinate	***f***	m	0≤ f ≤2
Local climate	sun position	hour	***x***		5:30≤ x ≤18:30
		day	***y***		1≤ y ≤31
		month	***z***		1≤ z ≤12
Subject's position	solid angle	subject's eye relative distance perpendicular to the window	***l***	m	50≤ l ≤550
		subject's eye relative position to the centre of the window	***t***	m	0≤ t ≤300
		subject's eye height	***r***	m	110≤ r ≤190
Shading system	Horizontal shade element	horizontal element depth	***a***	m	0≤ a ≤2
		horizontal element inclination	***b***	degree	0≤ b ≤45
	Vertical shade element	vertical western-side shade element depth	***c***	m	0≤ c ≤1.5
		vertical eastern-side shade element depth	***d***	m	0≤ d ≤1.5

The apparent solid angle ω_N subtended by the window can be calculated accurately by Equation (2).

$$\omega_N = \frac{w \times h \times \cos(arctg(w/2l))\cos(arctg(h/2l))}{l^2} \quad (2)$$

For w, h, and l, refer to Figure 5. This formula can be applied to the whole window.

The solid angle subtended by the window (Ω_{pN}) to the point of observation is (Nazzal, 2001) [10]:

$$\Omega_{pN} = 2\pi\phi_i \quad (3)$$

To measure the luminance window gains from sunlight, some internal parameters assumed the window length (w), window height (h), and the window corner (p) coordinates (e and f) define the relative position of the window to the building envelope. The effective height of the room (3 m) is assumed constant, as there is no wide range of options regarding codes and standards. Internal parameters mean variables are related to the building's features.

To create the worst-case scenario, the reflectance ratio of the window is considered equal to 1, which means all sunlight can pass through the glass pane, and the sky conditions are set as "clear sky with sun" all year long.

The external parameters include the time (hour, day and month) of a given year. Narrowing down the possible times for glare, the authors excluded the period in which the sun is under the horizon from the time-related genome range. Therefore, daytime (5:30 a.m. to 6:30 p.m.) with 30-min increments has been considered the time parameters. Table 2 provides the breakdown of parameters.

Any slight change in each independent parameter (mentioned in Table 2) created by the DIVA plug-in is compared using NSGA-II (non-dominated sorting genetic algorithm for multi-objective optimisation) introduced by Deb; this algorithm "finds any Pareto optimal solution in a finite number of solution evaluations" (Deb *et al.*, 2000; Deb, 2001). The sensitivity of the NSGA-II technique was demonstrated in a report by Deb, Agrawal, Pratap and Meyarivan in 2000 (Deb, 2001). The objectives defined through Wallacei X™ analytic engine (Makki *et al.*, 2019) are *DGP* and *UDI* due to finding the most probable daylight glare while not sacrificing daylight autonomy. Setting the window dimensions and position (w, h, e, and f in Table 2) as constant, the authors have created 7 cases which are commonly used locally to Sydney Olympic Park (see Table 3); 10 genes (*a, b, c, d, x, y, z, l, t and r*), 1,560 values, 2 fitness objectives and 2.4×10^{19} of search space are defined in the optimisation simulation process. The fitness objectives in the multi-objective simulation are:

(1) Maximising *Useful Daylight illuminances* (decreasing the need for artificial lighting).

(2) Minimising *Daylight Glare Probability* (to mitigating discomfort glare probability).

This optimisation process finding situations with a high probability of glare is undertaken for every cardinal and inter-cardinal direction. Unlike the typical optimisation problem solving, in this research, the authors tracked every single generation (which is at least 100 generations) to find a wide range of near-optimum shade. Only cases that include north-facing windows are reported in this paper due to the prevailing adverse condition of DGP and UDI. In addition, to find the worst-case scenario, it is assumed there is no existing shading effect (buildings, trees, shading elements, etc.) exists.

2.2.2 Field measurement. According to Bellia *et al.* (2008), calculating the glare source (and window) is not so lucid to be assessed by luminance meter or by videography techniques. Having a reliable assessment of this factor, in addition to photography, surface luminance uniformity should be taken into account.

Parallel to simulations, data were collected from multiple sources at various time points during the experiment. It was considered that quantitative measures would usefully supplement and extend the Simulation results. Luminance meter, light sensors (Figure 6 and Table 4), NoIR [11] camera and high-quality fish-eye camera (Figure 7), as well as the human

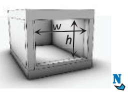
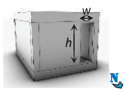
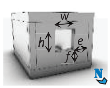
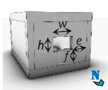
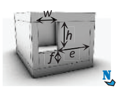
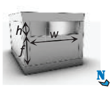
Case ID	Case Room (North-facing)	Parameters	Window	
N-01		$w = 3.8$m $h = 2.9$m $e = 0.1$m $f = 0.1$m	Full-height full-width multi-pane sliding	
N-02		$w = 1$m $h = 3$m $e = 0.1$m $f = 0$	Full-height vertical single-pane hinged	
N-03		$w = 2.8$m $h = 1$m $e = 0.6$m $f = 1$m	In the middle multi-pane hinged	
N-04		$w = 1.5$m $h = 1.5$m $e = 1.2$m $f = 1$m	In the middle double-pane hinged	
N-05		$w = 1.5$m $h = 1$m $e = 1.2$m $f = 1$m	In the middle double-pane hinged	
N-06		$w = 1.5$m $h = 2$m $e = 2.4$m $f = 1$m	On top double-pane hinged	
N-07		$w = 3.8$m $h = 1$m $e = 0.1$m $f = 2$m	Full-width horizontal multi-pane hinged	

Table 3. Penetration parameters for $4 \times 6 \times 3$ m north-facing rooms

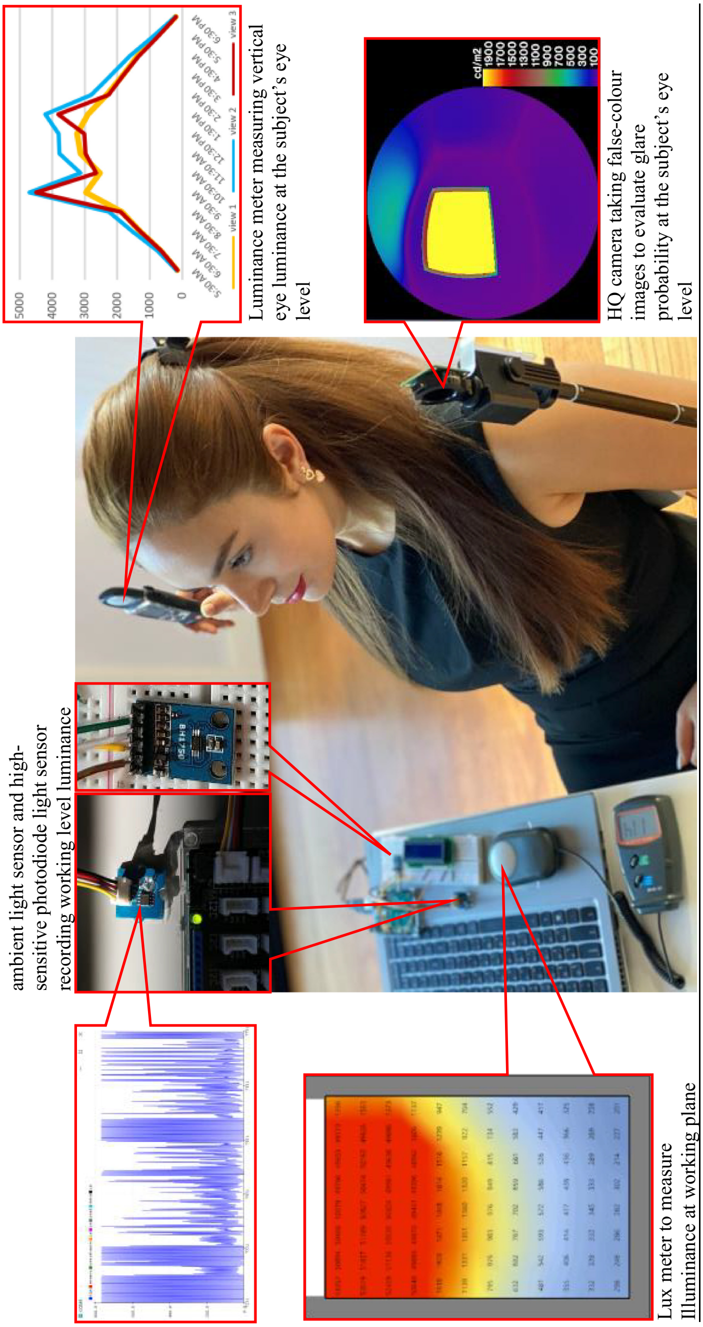


Figure 6.
To validate data, light-dependent resistor sensor [12] and ambient light sensors [13] positioned at the points that virtual sensors

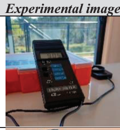
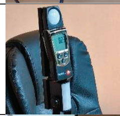
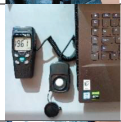
Light Meter	*Range*	*Resolution*	*Accuracy*	*Specification*	*Experimental image*
Digital Lux Meter-LX10B	0-50,000[lux]	1/10/100[lux]	±(5%+2d)	Sampling time 0.4 seconds	
Testo 540 Pocket Lux Meter	0-99999[lux]	1[lux]	±3[lux] ±3% of mv		
Tenmars TM202 Light Meter	200,2000,20000,200000 [lux]	1/10/100[lux]	±3%		
Lutron LX 108 Lux Meter	0-19990[lux]	0.1[lux]	±(5%+2d)		
Light Intensity Sensor	*Range*	*Resolution*	*Accuracy*	*Specification*	
BH1750 digital ambient light sensor	1-65535[lux]		+/-20%	Minimal effect of IR radiation	
Light Sensor v1.2 is an analog module (a high-sensitive photodiode)			Light resistance: 20KΩ; Dark resistance: 1MΩ	Response time 20-30 milliseconds; Peak Wavelength	
HD Camera	*Quality*	*Sensor Resolution*	*Pixel Size*	*Field of view*	
Raspberry Pi NoIR Camera Module v2	8 megapixel (1080p30)	3280 × 2464 pixel static images	1.12μm×1.12μm	62.2° Horizontal & 48.8° Vertical	
Raspberry Pi HQ Camera	12.3 Megapixels (1080p30)	4056 × 3040 pixels	1.55μm×1.55μm		

Table 4.
Equipment used to measure metrics

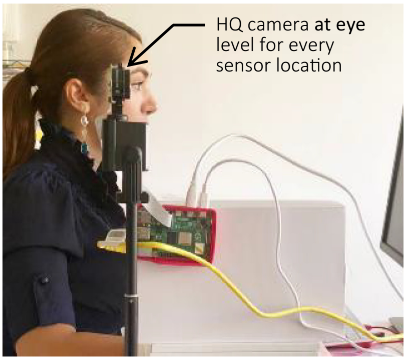


Figure 7.
Validating DGP simulation data by taking HDR images of HQ cameras and human subjects' assessment. Every virtual sensor in simulation is replaced with a camera and human subject to assess data gathered from simulation

subject survey analysis used to gather experimental data. Comparing data gathered from the experiment with simulation results showed a deviation of 7, 5.3, 4.2, 6.1, 5.2, 4.1, and 2.3% for cases *N*-01 to *N*-07, respectively.

3. Result and discussion

Two main fitness objectives in the simulation are Daylight Glare Probability (DGP) and UD. UDI is a metric that evaluates daylight availability, which is the "percentage of the operation time, when illuminance values between 100 [lux] to 2,000 [lux] are received by natural light in a space" (Nabil and Mardaljevic, 2006). Assuming cardboard material (reflectance: 87.56%, specular: 3.83%, diffuse: 83.74%, roughness: 0.1) for shading element focusing on extreme situations using NSGA-II algorithm found the near-optimum shade elements dimension minimising discomfort glare while not affecting daylight autonomy significantly. Table 5 shows the results.

The findings of near-optimum shading elements (Table 5) are

(1) For full-width windows, the ratio of the total shade area to the window area is nearly 90%;

(2) There is no clear relationship between WWR (window to the wall) and TSW (total shade area to window area) ratio;

(3) To avoid glare discomfort, existing vertical shade on the eastern edge of the window is inevitable, but there is no need for the western edge. As Sedaghatnia *et al.* (2021) stated, for all orientations, the glare probability patterns are similar all year long except the west.

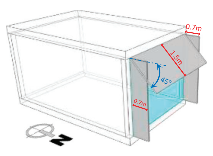
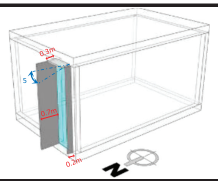
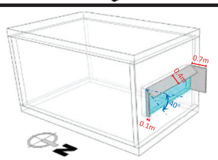
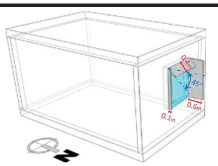
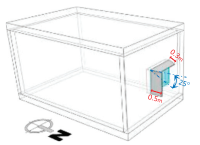
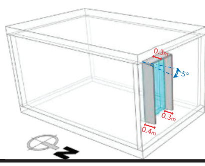
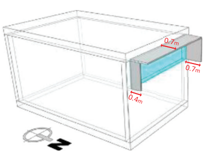
Park *et al.* (2021) reported that regarding overall lighting conditions, desk worker's visual satisfaction is at the highest level (90%) in the offices with external and internal shading devices. The optimised external shading elements shown in Table 5 brings an increase in UDI for all cases, from +2% to +57% for case N-05 and case N-07, respectively. The average increase in UDI is 21.57%, which means receiving adequate daylight illuminance obviates the need for switching lights when the sky is clear more than 20% of operation time. It is worth noting that the reflected sunlight from the inner side of shading elements plays a significant role in illuminating indoor.

Abidi and Rajagopalan measured the horizontal illuminance at desk 80 cm above the floor in 12 bedrooms located in Melbourne. For NW, large windows 2,093 [lux] and 78 [lux] were measured for the point next to the window and the farthest corner from the window, respectively (Abidi and Rajagopalan, 2020). Adding the shading elements in Table 5 brings an average of 3,608 [lux] for all cases in Sydney (from 1,375 to 8,236 for the case N-05 to case N-01, respectively). This average luminance is adequate for performing a job as well as a living. Abidi and Rajagopalan reported sDA = 84% for the mentioned room (Abidi and Rajagopalan, 2020).

For cold regions in China, Huo *et al.* (2020) reported that the external shading could reduce the glare probability, but it brings no significant advantage to alleviating indoor discomfort glare. They also stated, "if an external shading device greatly decreases the indoor luminance, the external shading may increase the indoor glare risk" (Huo *et al.*, 2020). Sedaghatnia *et al.* (2021) reported a 68% glare decrease and a 70% increase in daylight access. They declared, "a space with higher illuminance values does not lead to disturbing glare if shading based on climate and sky conditions is in place". This study proves adding suggested external shades reduces sDG by an average of 16% (from zero to 37.5% reduction for case N-01 and case N-05, respectively) which means discomfort glare probability reduction for Sydney. Figure 8 summarises the changes that external shade brings for each case. It is worth mentioning for the full-façade window (case N-01), the added shade increases discomfort glare probabilities. Building Code of Australia (BCA), Vol. 2 identifies the external shading "is capable of restricting at least 80% of the summer solar radiation" (ABCD, 2019). The shading elements in Table 5 comply with the national code.

The shade illustrated in Table 5 is a single solution that satisfies all-year daytime needs. When the task plane (desk, kitchen counter, etc.) is fixed, the results of analysing the task-plane are as shown in Table 6.

Finally, finding an all-purpose single shade feature could keep DGP and UDI needs within the acceptable range for all types of windows (case N-01 to N-07) and consolidates all results

	Annual metrics for no shade				*Shade features*	*Annual metrics for shade added*				*Result*
Case N-01	Average Hourly DGP	59.5%	Imperceptible	13.59%		Average Hourly DGP	46.9%	Imperceptible	24.44%	*79% Increase*
			Perceptible	4.43%				Perceptible	10.06	*127% Increase*
	sDG[1]	100%	**Disturbing**	**9.51%**		sDG	100%	**Disturbing**	**14.69**	***54% Increase***
			Intolerable	**72.47%**				**Intolerable**	**50.80%**	***30% Decrease***
	Average UDI	**13.1%**				**Average UDI**	**18.8%**			***43% Increase***
	Average luminance	15,945 [lux]				Average luminance	8,236 [lux]			*49% Decrease*
Case N-02	Average Hourly DGP	27.1%	Imperceptible	73.99%		Average Hourly DGP	24.9%	Imperceptible	80.14%	*8% Increase*
			Perceptible	6.63%				Perceptible	5.52%	*17% Decrease*
	sDG	79.7%	**Disturbing**	**7.40%**		sDG	66.1%	**Disturbing**	**5.69%**	***14% Decrease***
			Intolerable	**11.97%**				**Intolerable**	**8.65%**	***28% Decrease***
	Average UDI	**70.1%**				**Average UDI**	**75.4%**			***7% Increase***
	Average luminance	3,343 [lux]				Average luminance	2,731 [lux]			*19% Decrease*
Case N-03	Average Hourly DGP	32.1%	Imperceptible	61.65%		Average Hourly DGP	27.8%	Imperceptible	72.61%	*17% Increase*
			Perceptible	7.99%				Perceptible	6.91%	*14% Decrease*
	sDG	88.5%	**Disturbing**	**9.38%**		sDG	79.7%	**Disturbing**	**7.73%**	***18% Decrease***
			Intolerable	**20.99%**				**Intolerable**	**12.75%**	***40% Decrease***
	Average UDI	**55.5%**				**Average UDI**	**67.0%**			***20% Increase***
	Average luminance	6,069 [lux]				Average luminance	4,228 [lux]			*31% Decrease*
Case N-04	Average Hourly DGP	26.5%	Imperceptible	75.65%		Average Hourly DGP	23.6%	Imperceptible	83.57%	*10% Increase*
			Perceptible	6.34%				Perceptible	5.06%	*21% Decrease*
	sDG	78.6%	**Disturbing**	**7.19%**		sDG	64.1%	**Disturbing**	**5.49%**	***24% Decrease***
			Intolerable	**10.81%**				**Intolerable**	**5.88%**	***56% Decrease***
	Average UDI	**68.9%**				**Average UDI**	**77.4%**			***12% Increase***
	Average luminance	4,136 [lux]				Average luminance	2,898 [lux]			*30% Decrease*
Case N-05	Average Hourly DGP	22.5%	Imperceptible	86.3%		Average Hourly DGP	17.8%	Imperceptible	96.93%	*12% Increase*
			Perceptible	4.26%				Perceptible	1.25%	*71% Decrease*
	sDG	48.4%	**Disturbing**	**4.56%**		sDG	10.9%	**Disturbing**	**1.16%**	***75% Decrease***
			Intolerable	**4.88%**				**Intolerable**	**0.66%**	***87% Decrease***
	Average UDI	**79.5%**				**Average UDI**	**81.4%**			***2% Increase***
	Average luminance	2,780 [lux]				Average luminance	1,375 [lux]			*51% Decrease*
Case N-06	Average Hourly DGP	26.5%	Imperceptible	75.40%		Average Hourly DGP	23.8%	Imperceptible	83.49%	*10% Increase*
			Perceptible	6.58%				Perceptible	4.92%	*26% Decrease*
	sDG	81.3%	**Disturbing**	**7.15%**		sDG	59.9%	**Disturbing**	**5.18%**	***28% Decrease***
			Intolerable	**10.87%**				**Intolerable**	**6.42%**	***41% Decrease***
	Average UDI	**67.2%**				**Average UDI**	**74.5%**			***10% Increase***
	Average luminance	3,976 [lux]				Average luminance	2,957 [lux]			*26% Decrease*
Case N-07	Average Hourly DGP	33.1%	Imperceptible	58.47%		Average Hourly DGP	24.8%	Imperceptible	83.04%	*42% Increase*
			Perceptible	7.68%				Perceptible	5.11%	*34% Decrease*
	sDG	100%	**Disturbing**	**9.55%**		sDG	86.5%	**Disturbing**	**5.90%**	***39% Decrease***
			Intolerable	**24.29%**				**Intolerable**	**5.95%**	***76% Decrease***
	Average UDI	**47.0%**				**Average UDI**	**74.1%**			**57% Increase**
	Average luminance	5,741 [lux]				Average luminance	2,828 [lux]			51% Decrease

Note(s): [1]Percentage of views with discomfort glare (more than 5% of time)

Table 5.
Found near-optimum solution for each case using DIVA simulation (for more details, see Appendix)

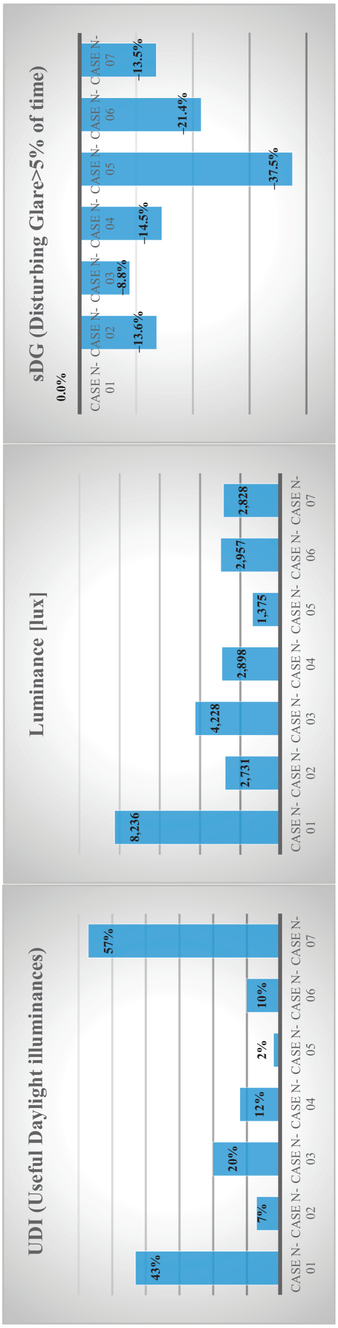


Figure 8.
Changes optimum shading system brings to each case

	Working plane distance from window	Eastern shade length	Western shade length	Horizontal shade length	Horizontal shade angle
Case N-01	Up to 2 m	0.3–0.4 m	0.6 m	1.4–1.5 m	Inclined 5–15° towards glazing
	2–3 m	0.3 m	0.1 m	1.4–1.5 m	Inclined 15° towards glazing
	3–4 m	0.2–0.3 m	0.5–0.6 m	1.4–1.5 m	Inclined 5–15° towards glazing
	4–5 m	0.3 m	0.5–0.6 m	1.4–1.5 m	Inclined 40° towards glazing
	>5 m	0.7 m	0.6–0.7 m	1.5 m	Inclined 40° towards glazing
Case N-02	Up to 2 m	0.6–0.7 m	No shade needed	0.3–0.5 m	Horizontal
	2–3 m	0.2–0.5 m	No shade needed	0.5–0.7 m	Inclined 15° towards glazing
	3–4 m	0.5 m	No shade needed	0.4 m *OR* 1 m	0.4 m horizontal *OR* 1 m inclined 5° towards glazing
	4–5 m	0.6 m	No shade needed	0.4–0.6 m	15–35°
	>5 m	0.6 m	0.1 m	0.4 m	Horizontal
Case N-03	Up to 2 m	0.6 m	0–0.1 m	0.4–0.5 m	Inclined 0–10° towards glazing
	2–3 m	0.6 m	0.6 m	0.4 m	Inclined 15–20° towards glazing
	3–4 m	0.2 m *OR* 0.6 m	0.1 m *OR* 0.6 m	0.4 m	Inclined 0–5° towards glazing
	4–5 m	0.1–0.2 m	0.1 m	0.4 m	Horizontal
	>5 m	0.1–0.2 m	0–0.1 m	0.3–0.4 m	Inclined 0–5° towards glazing
Case N-04	Up to 2 m	0.6 m	No shade needed	0.4–0.5 m	Horizontal
	2–3 m	0.1–0.2 m	0.2–0.4 m	0.3–0.5 m	Horizontal
	3–4 m	0.1–0.2 m	0.4–0.6 m	0.3–0.4 m	Horizontal
	4–5 m	0.1–0.2 m	0–0.2 m	0.3–0.4 m	Inclined 0–15° towards glazing
	>5 m	0.1–0.2 m	0.5–0.6 m	0.3–0.4 m	Inclined 0–5° towards glazing
Case N-05	Up to 2 m	0.6 m	No shade needed	0.5–0.6 m	Horizontal
	2–3 m	0.6 m	0–0.1 m	0.4 m	Inclined 0–5° towards glazing
	3–4 m	0.1–0.2 m	0.6 m	0.4 m	Horizontal
	4–5 m	0.1–0.2 m	No shade needed	0.3 m	Inclined 15° towards glazing
	>5 m	0.4 m	No shade needed	0.3 m	Inclined 5° towards glazing
Case N-06	Up to 2 m	0.1 m	No shade needed	0.3 m	Inclined 5° towards glazing
	2–3 m	0.2 m	0–0.2 m	0.7 m *OR* 1.4 m	0.7 m inclined 45° towards glazing *OR* 1.4 m horizontally
	3–4 m	0.1 m	0.1 m *OR* 0.8 m	0.3 m	Inclined 10° towards glazing
	4–5 m	0.1 m	0–0.1 m	0.3 m	Inclined 10–15° towards glazing
	>5 m	0.1 m	0.1 m	0.3 m	Inclined 5° towards glazing

(*continued*)

Table 6. Detailed shading element based on working plane distance to the window

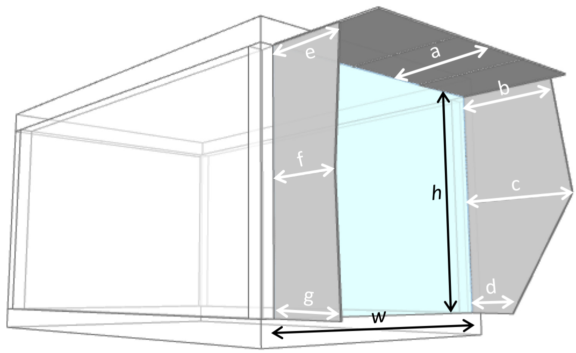
	Working plane distance from window	Eastern shade length	Western shade length	Horizontal shade length	Horizontal shade angle
Case N-07	Up to 2 m	0.3 m	0.3–0.4 m	0.3 m	Inclined 0–10° towards glazing
	2–3 m	0.5 m	0.4 m	0.4 m *OR* 0.5 m	0.4 m inclined 20° towards glazing *OR* 0.5 m horizontally
	3–4 m	0.6 m	0.6 m	0.4 m	Inclined 0–20° towards glazing
	4–5 m	0.2–0.3 m	0–0.2 m	0.3 m *OR* 0.4 m	0.3 m inclined 15° towards glazing *OR* 0.4 m inclined 25–35° towards glazing
	>5 m	0.6 m	0.3 m	0.4 m	Inclined 25–30° towards glazing

Table 6.

from Table 6, resulting in a shading system depicted in Figure 8. This final result was put in simulation again. The final results showed a deviation of 6.5 and 8.2% for DGP and UDI, respectively in case N-01; 5.3 and 5.2% for DGP and UDI, respectively in case N-02; 3.5 and 6.2% for DGP and UDI, respectively in case N-03; 5.3 and 5.9% for DGP and UDI, respectively in case N-04; 3.1 and 4.7% for DGP and UDI, respectively in case N-05; 4.2 and 4.7% for DGP and UDI, respectively in case N-06; 4.3 and 5.9% for DGP and UDI, respectively in case N-07 (see Figure 9).

4. Conclusion

This study determined the effect of an external shading system on a north-facing window located in Sydney, Australia, aiming to mitigate discomfort glare and maintain daylight provision at the highest possible level. Several attempts have been made to evaluate and quantify indoor visual comforts within the buildings. The majority of studies focus on office spaces for some limited window layouts (see Figure 1). To the authors' knowledge, only a few studies have discussed the impact of shading systems on residential indoor visual comfort for Sydney, Australia, which takes all year long daytime hours into account. In this study, we conducted a thorough simulation and experiment that validates the shading system attributes. This study is not limited to a particular time of year and considers all common window layouts that designers use. Two-step simulation (before and after adding the shading



a: 0.53h or 0.43w which is greater;
b: 0.42h or 0.34w which is greater;
c: 0.50h or 0.14w which is greater;
d: 0.20h or 0.17w which is greater;
e: 0.34h or 0.29w which is greater;
f: 0.30h or 0.24w which is greater;
g: 0.32h or 0.25w which is greater.

Figure 9.
A single solution of shading system could be assumed to be installed on all layout north-facing windows in Sydney, alleviating DGP while keeping UDI at the highest possible level

elements) was utilised to assess the shading effect on the parameters. Two-step field measurement (before and after) confirms the design validity. A set of multiple sensors and measuring devices on different eye levels measured the metrics thoroughly. Considering eight directions to assess DGP at six different eye levels (three seated and three standing) and measuring illuminance at different possible working levels make this research a rigorous study on home offices. According to the literature review, some studies on the effect of shading systems, evaluate mentioned objectives individually but not integratedly. Therefore, there has not been done before for Australian dwelling spaces.

This research can benefit architects to determine an affordable optimal shading of different window layout at decision-making stages for residential buildings in Sydney, guiding the efficient application of external shade to maximise indoor visual comfort and decrease daytime electric lighting requirements.

Few studies have been carried out using field measurements to meticulously demonstrate the relationship between external fixed shading systems and indoor glare probability and useful daylight illuminances in Australia. Accordingly, this study addresses the gap by quantifying the effect of external shading on the indoor visual comfort for the most common window layouts in Sydney, Australia. According to the results achieved by the field measurement and simulation, the main conclusions are drawn as follows:

Adding a three-element external shading system (two vertical on eastern and western sides and a horizontal one on the top edge of the window) can regulate indoor spaces visual discomfort (glare and excessive daylight). The most prominent finding to emerge from this study is that a horizontal shade element of at least a length of 50% window height is helpful in alleviating mid-day visual discomfort. Depending on window layout, the vertical elements of length 20–30% window height on the eastern and western sides of the windows significantly affect visual comfort while not blocking the view to the outside and not intercepting useful daylight. Taken together, findings suggest a role for external fixed shade in promoting indoor visual comfort.

Therefore, it seems that exerting external shading elements as an affordable solution (rather than motorised shadings, phase-changing materials) – that is operation-free – contributes to the existing knowledge of designers in Sydney, Australia.

The findings in this report are subject to at least three limitations. First, the room dimensions; second, window-customised dimensions and layout; third, the orientation of the window and forth, shading effect cast from surrounding objects (building and trees). The current study has only examined two visual comfort parameters–glare and useful daylight–and some other factors like spatial thermal comfort, daylight autonomy, energy usage and carbon footprint are excluded. Therefore, the current investigation was limited by daylight illuminance and glare probability. What is now needed is a cross-national study involving the view to the outside factor, which evaluates the external shade effect on obstructing the view to the outside. This research has thrown up many questions in need of further investigation. It is recommended that more research be carried out in the following areas: dynamic shading, shading effect of surrounding objects and integrated indoor comfort assessment.

Notes

1. Visual comfort probability.
2. Building Research Station Glare Index.
3. Unified glare rating.
4. Daylight glare probability.
5. "A set of non-dominated solutions, being chosen as optimal, if no objective can be improved without sacrificing at least one other objective." (Reddy and Kumar, 2015).

6. 100–300[lux] as supplementary which means additional artificial lighting *may* be needed; 300–500 [lux] as autonomous.
7. High Dynamic Range.
8. A 3D computer graphics and CAD "can create, edit, analyse,… and translate NURBS curves, surfaces and solids, subdivision geometry (SubD), point clouds, and polygon meshes. There are no limits on complexity, degree, or size." [Robert McNeel and Associates, https://www.rhino3d.com/features/]
9. Energy Plus Weather file.
10. This parameter is accurate to 1% when $w/2d < 01$ $h/2d < 01$ and accurate to 5% when $w/2d < 1h/2d \; < 1$ (see Figure 5).
11. No Infra-Red.
12. Low dark current and low working lux.
13. Near human eye spectral response and very low IR sensitivity.

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Appendix
The appendix is available online for this article.

Corresponding author
Ehsan Sorooshnia can be contacted at: e.sorooshnia@westernsydney.edu.au