Title

Advocating for view and daylight in buildings: Next steps

Journal
Energy and Buildings, 265(Energy Build. 210 2020)

ISSN
0378-7788

Authors
Lee, Eleanor S
Matusiak, Barbara Szybinska
Geisler-Moroder, David
et al.

Publication Date
2022-06-01

DOI
10.1016/j.enbuild.2022.112079

Peer reviewed

Energy & Buildings 265 (2022) 112079

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Advocating for view and daylight in buildings: Next steps

Eleanor S. Lee [a,*], Barbara Szybinska Matusiak [b], David Geisler-Moroder [c], Stephen E. Selkowitz [a], Lisa Heschong [d]

[a] Energy Technologies Area, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA
[b] Department of Architecture and Technology, Norwegian University of Science and Technology, Sentralbygg 1, Gløshaugen, Trondheim, Norway
[c] Bartenbach GmbH, Rinner Strasse 14, 6071 Aldrans, Austria
[d] Independent, Former Principal of the Heschong Mahone Group, USA

ARTICLE INFO

Article history:
Received 20 November 2021
Revised 26 March 2022
Accepted 1 April 2022
Available online 4 April 2022

Keywords:
Windows
Shading
View
Daylight
Health
Well-being
Building energy efficiency
Bidirectional scattering distribution functions (BSDF)
Electrochromics
Computer-based renderings

ABSTRACT

With the exponential growth in population and commensurate increased density in urban cities, access to daylight and views to nature is being severely curtailed in buildings. In parallel, increasingly urgent demands to sharply reduce building energy use and associated greenhouse gas emissions are being made to mitigate climate change. There are many challenges and performance tradeoffs associated with the building facade (i.e., daylight and view versus solar and glare control); increased prioritization of health and well-being as a fundamental human requirement could adversely affect building energy-efficiency. Given the current state of knowledge on the effects of daylight and view on health and well-being in buildings, we identify critical needs in research, tools and technologies that if satisfied may enable more effective use of daylight and view in buildings within the constraints of climate change. Lack of knowledge regarding the complex causal mechanisms of window views on human factors is a severely limiting factor in forward progress. Current models and methods to derive bidirectional scattering distribution functions (BSDFs) will need to be modified. Developers of energy-efficient window technologies will need more guidance to shape product development. Advanced window technologies and integrated design can enable attainment of both health and well-being and net zero energy goals, but considerable work will be needed to make such options turnkey and broadly available.

1. Introduction

Over the past half century, the increase in high density, built environments has paralleled the exponential growth in population worldwide, resulting in ever denser cities with decreased natural, landscaped areas and buildings with more restricted daylight and views [1]. Financial pressures on real estate development often result in taller, deeper floor-plate buildings, which also have less access per square meter to daylight and views, while those developers with access to prime view properties often build up or out to maximize the view potential of their properties to the detriment of their neighbors. Simultaneously, concern over the energy and carbon impacts of buildings has resulted in increasingly stringent energy efficiency codes and standards [2]. Urban areas account for 67–76% of global energy consumption and 71–76% of greenhouse gas emissions with further expansion expected to be proportional to the projected increase of 2.5 billion people between 2010 and 2050 [3]. Windows affect heating, ventilation, and air conditioning (HVAC) and lighting energy use that when combined comprise 43% of total primary energy use in residential and commercial buildings in the U.S. [4]. Many codes have placed prescriptive constraints on window area to reduce energy use, with a consequence of also restricting design options for daylight and views. For example, the U.S. building energy efficiency standards [5] do not allow a window-to-exterior-wall ratio (WWR_e) greater than 0.40 if the prescriptive path is used. Recommendations for larger window areas, such as are often advocated for sufficient view access (WWR_e = 0.31–0.69[1]) [6,7], conflict with the energy-based recommendations, and generally require more detailed and time-consuming design analysis to qualify a design via performance path tradeoffs [8].

* Corresponding author.
E-mail addresses: eslee@lbl.gov (E.S. Lee), barbara.matusiak@ntnu.no (B.S. Matusiak), David.Geisler-Moroder@bartenbach.com (D. Geisler-Moroder), seselkowitz@lbl.gov (S.E. Selkowitz), lisa@lheschong.com (L. Heschong).

[1] Window-to-*interior*-wall ratio (WWR_i)=0.50–0.80 [7] or WWR_i=0.44–1.0 [8] was converted to WWR_e using a 2.74 m ceiling height and 3.96 m floor-to-floor height assuming commercial buildings.

https://doi.org/10.1016/j.enbuild.2022.112079
0378-7788/Published by Elsevier B.V.

Nomenclature

OF	openness factor (nominally equivalent to $T_{v,n-n}$ in EN 14501)
$R_{v,dir-h}$	direct-hemispherical light reflectance
SHGC	solar heat gain coefficient or g-value
$T_{e,n-h}$	normal-hemispherical solar transmittance
$T_{v,n-dif}$	normal-diffuse light transmittance
$T_{v,n-h}$	normal-hemispherical light transmittance
$T_{v,n-n}$	normal-normal light transmittance
WWR_e	window to exterior wall area ratio

Countering these pressures is an increased awareness of the health benefits of daylight and windows accelerated by recent advances in the understanding of the role of light stimulus at the eye as the primary source of entrainment for human biological rhythms. It is now understood that intrinsically photoreceptive retinal ganglion cells (ipRGCs) in the retina most sensitive to wavelengths at 480 nm, i.e., the color of the blue sky and the peak spectral intensity of daylight, provide essential signals to our circadian biological clock [9–11]. These signals profoundly impact many aspects of human physiology, health, and well-being, including patterns of sleep, alertness, memory formation, hunger, hormone release, blood pressure, body temperature, and immune response. Considerable research has since occurred to better understand the relationship between human physiological and psychological responses to temporal variations in spectrum and intensity of light indoors [12–14]. Recent studies have suggested that newly identified opsins in the eye, most sensitive to violet light, specifically in the 380 nm and 430 nm range, may be involved in early eye development and other metabolic functions [15,16]. Most applied research to date has focused on the potential of dynamic electric lighting to satisfy stimulus requirements as a substitute for daylight exposure rather than studies of actual daylight exposure [17]. In fact, very little is known about daylight[2] exposure patterns for various population types (e.g., age group, occupation, or geographic region).

Ulrich [18] first studied the relationship between view through a window and patients' rates of recovery from surgery, psychological state, and pain relief. Ulrich found for example that gall bladder surgery patients with beds next to an outdoor view of nature (tree view), as opposed to those with a brick wall view, recovered faster, had a better mood, took less pain medication, and had slightly lower scores for minor post-surgical complications. Choi et al. [19] investigated the effect of daylighting on the patient average length of stay (ALOS) in hospitals. It was found that patients in brighter daylit wards had a shorter ALOS. Given such findings about the likely physiological benefits provided by natural light, many health care designers have proposed that buildings with more daylight and/or views may lead to faster recovery or even provide a preventative health measure [20,21]. Greater access to daylight and window views has been advocated in school design to counter the growing myopia epidemic in children [23].

Researchers have also examined the relationship between window views and occupant comfort, satisfaction, and emotional well-being [24–31]. Wilson proposed the biophilia hypothesis as "the urge to affiliate with other forms of life" which has inspired much subsequent work to link buildings to nature [32]. The importance of nature in the context of both the home and workplace has been extensively studied [33–35] and biophilic design has been proposed as a sustainable architectural design strategy that incorporates reconnecting people with the natural environment [36,37]. Views through the window convey information about diurnal and seasonal changes in outdoor content with added visual interest of people, birds, and other fleeting activities, all of which provides cognitive stimulus and relief from the more controlled indoor environment [38].

With the growing interest in the importance of daylight and window views as a contributor to the health and well-being of building occupants, there is concern that changing priorities may adversely affect the energy efficiency and carbon profile of buildings. The objective of this paper is to identify the critical needs in research, simulation tools, and technology to satisfy both concerns. We provide an overview of the current state of knowledge regarding research, metrics, and voluntary standards (Section 2) and simulation tools (Section 3), then identify critical needs (Section 4) that if addressed could enable stakeholders to address daylight and view more effectively within the constraints of climate change. The intended audience are those in the building science field (e.g., researchers, practitioners, regulators, and related stakeholders) not intimately involved in human health and well-being research pertaining to daylight and view.

Note that in this paper, we focus primarily on the implications of view and only secondarily on daylight exposure as a consequence of access to windows and associated views.[3] We define "daylight" generally as exposure to ambient levels of interior daylight illumination (and its associated spectral content), and "view" as meaningful and desirable content of the ground plane, horizon, and/or sky outside and where details and movement of people, animals, landscape, and/or weather can be discerned.

2. Overview of view-related research and metrics

2.1. Existing research on view

Research studies investigating the benefit of windows and view on human physiology, cognitive function, psychological state, and behavior date well back to the early 1960s with comprehensive reviews of literature conducted over the years (e.g., [30,39–46]). Based on a recent comprehensive review of the literature, three distinct characteristics of views as a framework for analysis were proposed by Ko et al. [46]: view access, content, and clarity. In the following sections corresponding to this framework, we provide a limited overview of view research with the intention of a) providing background information to those who are not deeply involved in the topic, and as a result b) enable stakeholders to consider how these characteristics may intersect with operational and design decisions impacting energy use. In general, we focused on outcomes from field studies as we judged these to be methodically

[2] In one of the few studies involving daylight [22], ambulatory measurements of daily light exposure and spectral content were conducted monthly over a year on 15 subjects with results showing significant seasonal and daily variations in light exposure and content. The exact exposure to daylight, however, is unknown as both daylight and electric light were measured with a single device.

[3] Often the two are not well differentiated in the literature, or one is often assumed to function as a proxy for the other. For example, window area may serve as a proxy for daylight exposure, or daylight illumination levels may serve as a proxy for view. While exposure to daylight is closely tied to access to view, the two may have both overlapping and separate causal mechanisms.

most adequate to guide further research on the effects of view on human health.

2.1.1. View access

The first concern, i.e., view "access", is whether an occupant has a window and is in a position in the room to see out the window. Given financial pressures of the real estate industry, as mentioned in Section 1, windows are sometimes entirely omitted in the design of occupied spaces.[4] In a 2020 study [47], test subjects (n = 86) were found to perform better on cognitive tests, have more positive emotions and better thermal comfort after working on office type tasks near a view window than the same subjects working under identical full-scale, controlled environmental conditions but without the view. When working for an hour at a desk with outdoor window views, subjects' performance on cognitive tests improved. They perceived thermal sensation to be cooler and more comfortable,[5] reported more happy and satisfied feelings, and less sad and drowsy feelings.

Early studies of view access focused on simple geometrical relationships between the observer and the window. Proportionally *larger* views were found to predict better performance in office field studies [48]. This was true independent of whether the worker's desk was facing towards or away from the view.[6] Access to "better" views, as defined by the study authors, such as those including vegetation, a view of the sky, or human activity outside, was consistently associated with a number of positive outcomes in office [49] and educational environments [50], including greater working memory capacity in office workers as measured by Digit Span Backwards (n = 201), and greater progress in math and reading in schools, as measured by standardized test scores (n = 9000). In addition, the office workers who had better views had fewer health complaints and greater satisfaction with all other indoor environmental quality factors. While the many positive outcomes related to views are widely studied, the underlying causal mechanisms are less well understood. There may be multiple mechanisms at work, including circadian stimulus, cognitive and emotional mechanisms, along with social and cultural factors [38].

2.1.2. View content

Prior research has focused on how human factors are affected by the specifics of view "content" and suggest that the best views include both foreground and sky, i.e., outdoor content both near and far from the window (depth of field). View preferences may be a result of contemplated evolutionary aesthetics. Dutton argued that perception of beauty is evolutionary determined, i.e., things, places, and landscapes which people consider beautiful are typically found in settings that are likely to support survival of the human's genes [51,52]. According to the prospect-refuge theory [53,54] and later [55,56], an optimal environment for survival is a location where the prospect is substantial (i.e., broad open views of the surrounding landscape to observe potential danger) and where there is a place to hide (refuge). Both are needed to create an optimal environment, which is perceived also as aesthetically pleasurable. Views containing close-up areas as well as far-away areas are needed to create a "prospect" for the viewer.

A good view should include visual complexity, such as is commonly found in natural materials and processes. In [29], researchers gathered survey responses to questions related to psychological and physiological comfort from occupants working in ten office buildings in the Netherlands (n = 333). Occupants were located at varying distances from the window and because window access is mandated in the Netherlands, no workstation partitions blocked access to the view. Views were defined by the aesthetic quality of the view (good or bad rating related to interest and attractiveness of photographs) and view type (nature or urban). Researchers found that psychological and physiological comfort were positively influenced by natural views and good view quality. A "good" view was associated with fewer self-reported discomfort problems. The study also found that the preferred distance was not necessarily closest to the window due to increased thermal and visual discomfort.[7] In the absence of thermal or visual discomfort, a closer distance to the window was associated with higher stress recovery in a study (n = 32) performed in a virtual reality environment [57].

Separately, the results of an international survey (n = 400+) aimed at registering visual conditions in home offices during the COVID-19 pandemic lock-down showed that when people chose the location of their home-office desk, more than 72% chose a distance less than 2 m from the window and of those, 30% chose less than 1 m [59]. In the majority of cases, the view direction was towards the outdoors independent of window orientation. The need for a view weighed more heavily than the need to avoid glare, supporting prior findings [60]. These findings emphasize the need for solar shading solutions that maximize view while controlling visual and thermal discomfort (cf. Section 2.1.3).

Matusiak and Klöckner [61] conducted a study in Norway (n = 106) to investigate how qualitative aspects (beauty, composition, complexity) affect workers' evaluations of view quality at their permanent workplaces and how these aspects compare to quantitative measures related to window design (angular height and width of view aperture, view depth, number of view layers, fragmentation of view by window mullions or separate windows). Aesthetic quality was determined to be the most valued aspect of view. The attributes for a positive evaluation of the aesthetical quality were different for buildings (age, maintenance/upkeep, moderate complexity, historical significance) and landscape (coherence, legibility, moderate complexity, and mystery). The view depth (defined as distance from the window to the most distant visible element in the landscape) and number of view layers also had a strong positive influence on perceived view quality.

2.1.3. View clarity

The cumulative effect of views to the outdoors and the spectral and luminous intensities of an outdoor scene received at the eye is a function not only of window geometry relative to the indoor and outdoor context and the occupants' interest in the view, but also the net effect of 1) glazing and shading materials, and 2) operation of window management systems such as awnings, blinds, shades, and curtains.

2.1.3.1. Glazing and shading materials. Very little research has been conducted explicitly correlating physiological and psychological benefits to modified views as defined by degree of obstruction, optical distortion, within-plane haze or scattering of light, spectral modification, and reduction in the dynamic range of light intensity by glazing and shading materials. Modifications can be a static aspect of the glazing or shading material (e.g., translucent glass) or vary with incident solar conditions (e.g., scattered sunlight off the interstitial openings in a perforated blind). The resulting impacts on the temporal availability and clarity of view can be considerable.

[4] In 2021, the proposed design for a windowless dormitory at the University of California Santa Barbara raised international alarm (e.g., [58]).

[5] Thermal conditions were the same since the tests were performed in a thermally isolated test chamber.

[6] A "primary" view is defined as that visible within 45° of the computer screen (i.e., with a small turn of the head), and "break" view is that seen by making small adjustments to body position (e.g., swiveling an office chair a bit). Office occupants subconsciously glance out windows via primary or break views.

[7] These findings differed from those stated above for [59], which was conducted in a residential setting.

At a fundamental level, research has been conducted to correlate subjective appraisals of view to the optical properties of glazing and shading materials without the added complexity of how the shades were operated. In a study by Konstantzos et al. [62], view "clarity" is defined as the human eye's ability to perceive details of the outdoor environment without subjective interpretation of whether the content is interesting or of aesthetic value. The study requested that participants (n = 18) look at the outdoor view at normal incidence through fourteen different shade fabrics with varying openness factors, visible transmittance, and color and provide their subjective and objective responses on a seven-point Likert scale to questions regarding clarity of view, vividness of colors, and visibility of content (i.e., nearby fence, road, distant power cables, and color of moving vehicles about 30 m away). View clarity was found to be affected significantly by both sky conditions and viewing distance, with a greater distance from the window (2.4 m versus 1.0 m) and cloudy conditions achieving higher view clarity. A view clarity index was proposed which enables assessments of shade materials based on shade properties alone, i.e., fabric openness factor and normal-hemispherical visible transmittance ($T_{v,n-h}$). The index was derived from test conditions with high visible transmittance ($T_{v,n-h}$ = 0.65) windows, when no direct sun was in the occupant's field of view, and with electric lighting providing a minimum indoor workplane illuminance of 500 lx. Separately, view clarity of sample fabric shades and electrochromic windows was assessed using high dynamic range photography under direct sunlit conditions [63]. Scattering of direct sunlight within areas of the fabric shades was determined to obscure view.

Khanie et al. [64] further reduced view to fundamental material aspects by correlating subjects' visual perceptions of images depicted in an immersive virtual reality (VR) environment to chromatic contrast, visual complexity, and amount of view. The contrast and complexity metrics were derived from analysis of chromatic and achromatic contrast between pixels of a transformed (CIE L*a*b* color space), reduced resolution, photorealistic image. Subjects were asked to rate their satisfaction and connectedness when looking at images of fabric roller shades and thin and wide, horizontal and vertical, blinds and louvers with different slat angles. Such research could accelerate visual perception analysis of glazing and shading systems. Given known limitations of VR [65], further studies under real world conditions are planned to support hypotheses to date.

2.1.3.2. Shade operation. Regarding temporal requirements for view access, the benefit of view for mind wandering, relaxation of the eyes, and surveying outdoor conditions can occur anytime throughout the day or night. Few would argue that greater, more frequent access to unobstructed, unmodified outdoor views of nature (absent discomfort or privacy concerns) is undesirable. At minimum, we know that occupants adjust shades for any number of reasons including view. In [66], researchers found that office worker (n = 147) interactions with shading and electric lighting were motivated by view, connection to the outdoors, privacy, and desire for daylight.

While there are many view-focused studies conducted in real buildings, documentation of window and shading conditions affecting view clarity is often missing or of insufficient detail. The following case studies in occupied buildings[8] were not explicitly designed to evaluate the effects of view clarity on occupant health and well-being. The studies were focused on evaluating the performance of emerging energy-efficient fenestration technologies and as such the window or shades were controlled in part to minimize HVAC and lighting energy use. The studies do however lend insights into the practical aspects of view access in real world buildings and provide limited evidence supporting prior hypotheses that greater access to view can lead to greater occupant satisfaction with the indoor environment. Findings also point to qualifiers: if view is achieved at the expense of reductions in lighting quality (i.e., spectral composition, intensity, and distribution of light indoors), dissatisfaction with the glazing and/or shading solution (and associated view) increases.

In a study in a high-rise office building in New York City involving automated roller shades,[9] survey results (n = 665) were analyzed to determine causes of satisfaction with the building [67], which was greater than the norm of surveyed buildings [68,69]. Overall satisfaction and job performance ("ability to get your job done") was strongly correlated to perceived lighting quality, but ambiguously[10] correlated to a private or open plan office, being adjacent or not adjacent to a window, or being on a lower or higher floor above ground. The latter three aspects affect view, which is a psychological variable, and together they were weakly but significantly correlated to each other. Results suggest that automated access to unobstructed views with high lighting quality can create a more satisfactory, productive work environment compared to conventional office environments with less reliable access to view and poor lighting quality.

Given the choice of either an EC window or venetian blind to satisfy visual constraints, each with very different effects on view, which technology did occupants choose to use and which elicited greater satisfaction with the workplace environment? In a six-month monitored study involving south-facing private offices in a partly cloudy Oregon climate [70], 80% of the venetian blinds (opaque, brushed aluminum slat) were observed[11] to be fully raised on the EC test floor whereas only 25–50% were raised on the reference floor with dark tinted, low-emittance windows.[12] The EC windows were automatically controlled to three discrete tint states with the option for manual override with an additional fourth darkest tint state, which was rarely used. Several months after conclusion of the study, there was still less blind use on the EC floor: 52% versus 15% were fully raised. Consistent with observations of blind position, occupants on the EC floor disagreed that "the shades blocked the view" (2.90 on a 9-point Likert scale, n = 21) while occupants on the reference floor slightly agreed (5.38, n = 8). This difference was found to be statistically significant ($p = 0.03$). Occupants also agreed more strongly that the "outside was sufficiently visible through the window" (7.0 EC versus 5.7 reference), although this result was not statistically significant ($p = 0.10$). Subject ratings of the environmental conditions were mixed. Occupants indicated that they experienced less glare with the EC windows (6.23) compared to the reference windows (3.88) with $p = 0.04$, but light levels were perceived to be slightly dark and gloomy in the EC offices (4.15,

[8] Note that the studies were selected not to espouse any one window technology over another but because the studies provided within-subject and/or between-subject analysis of subjective appraisals of a reference versus test case where the window condition was changed, and operation of the window or shade was monitored and/or documented as part of the analysis. Because the studies were not designed explicitly to evaluate view, additional information and statistics (e.g., p-value) were provided for the LBNL studies to facilitate understanding of study outcomes.

[9] New York City: WWR_e=0.76; SHGC=0.30, $T_{v,n-h}$=0.53; north facade shades (Mechoshade ThermoVeil 6020): $T_{v,n-h}$=0.06, $T_{e,n-h}$=0.08, OF=0.03 (=$T_{v,n-n}$), EN 14501 Class 2; south, east, west facade shades (Mechoshade S10480A): No data available, OF=0.02.

[10] New York Times Building: Note that ambiguities can occur if more than one variable is correlated to a result and there is no clear reason for one to be more probable than the other.

[11] Oregon: Approximate height and slat angle of each individual blind was recorded through visual inspections performed approximately once per month. The blinds were fully raised and zip-tied at the start of the study but untied when requested by the occupant(s). All blinds were untied at the conclusion of the study.

[12] Oregon: WWR_e=0.46; reference window: $T_{e,n-h}$=0.06, $T_{v,n-h}$=0.15; EC window: SHGC=0.43–0.09 and $T_{v,n-h}$=0.36–0.02.

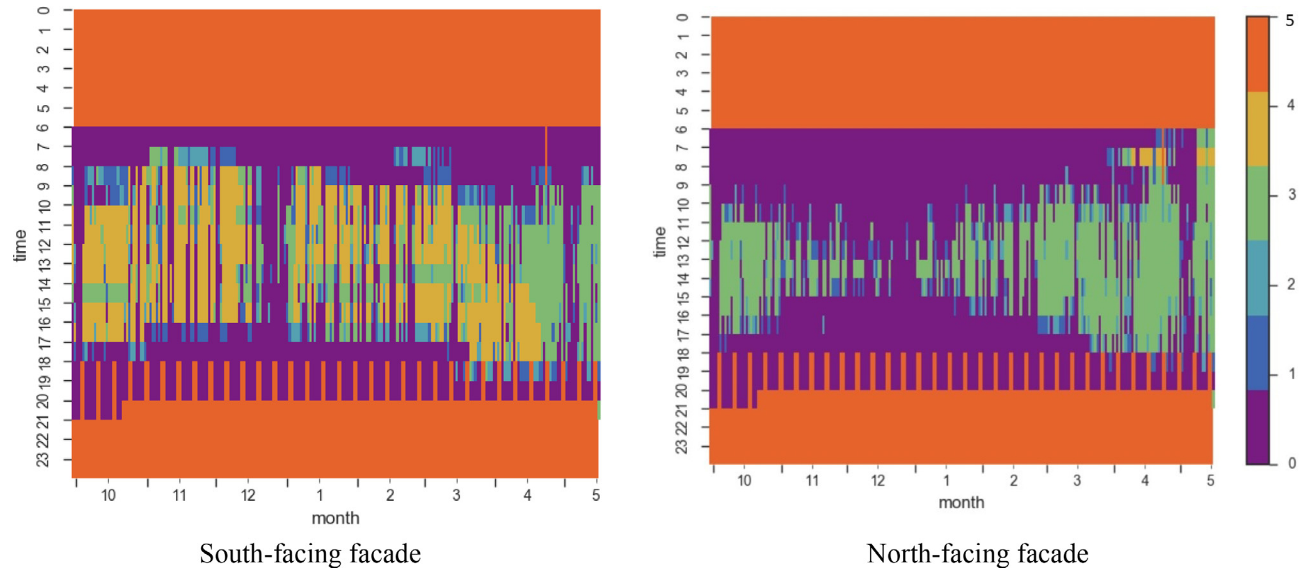

Fig. 1. The position of shades varies for many reasons, including diurnal and seasonal changes in incident solar radiation per window orientation. The plots show the height of an automated roller shade for each day over monitored period from September to May (x-axis) and hour of day (y-axis). The shades were controlled for daylight, glare, solar heat gains, view, and minimizing light pollution for south-facing (left) versus north-facing (right) open plan office areas in a New York City high-rise office tower. Monitored height of the lower edge of the shade above the floor corresponds to: h = 2.97 m (fully raised, position zero), 2.41 m, 1.88 m, 1.35 m, 0.79 m, and 0.25 m (position 5) above floor, respectively. Average seated eye height is 1.2 m above the floor so positions 4 (yellow) and 5 (orange) obstructed views above the horizon. Partial views were discernable through the fabric. Source: [73]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

n = 27) and brighter in the reference offices (5.89, n = 9), p = 0.01. Despite this, 85% of occupants preferred the EC windows over the reference windows, with more view and less glare being contributing factors for the preference. Other relevant findings from field studies of EC windows are available in [71,72].

In a six-month monitored study involving automated roller shades in a high-rise office building [73] where the shade fabric and automatic control differed between two parallel reference and test floors with the same window orientation and outdoor exposure, there was a statistically significant difference in response as to whether the weave ("transparency") of the shades[13] and automated control enabled occupants to see outdoors (p = 0.02). Average ratings on the five-point Likert scale were toward "disagree" (2.0, n = 12) for the test shading system and above neutral toward "agree" (3.25, n = 8) for the reference system. The test shades had different control settings and were perceived to have blocked the view more compared to the reference shades. Note that access to view differed with window orientation and sun and sky conditions (Fig. 1). Views on the north-facing orientation were less obstructed compared to the south, particularly during the winter period, whereas views on the south were more obstructed to control direct sunlight and glare.

2.2. Metrics and standards for view

Recommended guidelines and design standards for minimum window area were common for both educational and healthcare buildings up through the middle of the 20th century both in the U.S. and Europe [74,75]. New metrics for view have resulted from the many quantitative measures identified in research studies for view access and content. Based primarily on architecturally driven research, the metrics tend to focus on geometric aspects of view, such as unobstructed lines of sight, distance from window, and content of view, rather than from a more physiological perspective, such as considering movements of the eye (e.g., [76]), pupil dilation, or neural response. Ideally, standards of performance and their supporting metrics would be derived from carefully vetted examples of best practices, with clearly documented design strategies linked to post-occupancy outcomes via a foundational understanding of physiologic mechanisms.

The following descriptions provide a summary of some of the metrics, guidelines, and standards in use today to enable stakeholders to understand what aspects of view are currently evaluated and how they might affect building energy use. Describing the origin and basis for these metrics is beyond the scope of this article.

2.2.1. Existing metrics, guidelines, and standards

To date, various forms of view standards related to view access and content have been incorporated into design guidelines and recommended specifications, checklists for utility incentive programs, voluntary recognition and certification programs (such as LEED, WELL, Fitwel), building codes, and labor protections and business operations (such as via ISO and OSHA). There is a wide range of specificity, from articulating general good intentions, such as evidenced in many UK and European standards, to highly quantitative requirements used in some U.S. codes.

For example, the EN17037 daylight standard [77] prescribes better-to-best rankings for the width of the window (>14° wide horizontal sight angle minimum), distance to outdoor obstacles (>6 m minimum), and number of layers seen from indoors (at minimum, the landscape layer should be included). Alternatively, the U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) version 4.1 [78] provides one credit if there are unobstructed lines of sight to the outdoors for 75% of regularly occupied floor area and if two of four additional criteria related to view are met, e.g., multiple lines of sight (e.g., use of corner windows), view type (nature), indoor distance to view within three head heights of the window. The 2021 International Green Construction code [79] and ASHRAE 189.1–2020 Standard [80] include new provisions for certain space types that at least 50% of occupied

[13] New York City: WWR_e=0.62–0.70, SHGC=0.35, $T_{v,n-h}$=0.65; reference shade (Mechoshade 6429, dove grey): $T_{v,n-h}$=0.09, $T_{e,n-h}$=0.10, OF=0.03 (=$T_{v,n-n}$), EN 14501:2019 Table 9 Class 1. Test shade (Lutron S0207-E-1, white/ pearl): $T_{v,n-h}$=0.06, $T_{e,n-h}$=0.09, OF=0.01 (=$T_{v,n-n}$), Class 1.

floor area has a direct line of sight 1.07 m above the floor and within 12.2 m from the view window with a glazing area greater than 7% of the floor area (additional glazing area may be required to meet daylighting requirements).

View clarity is in part addressed by the EN 140501 Standard [81], which defines a method for classifying shading devices based on their capacity to provide visual contact with the outdoors when fully extended. The underlying intent of the classification system is to provide a more favorable rating if the shade allows shape recognition, minimizes modification and distortion of direct vision, and avoids parasitic luminance (scattering) within the constituent material (e.g., fabric) when illuminated by the sun. Performance classifications are defined by direct and diffuse visible transmittance at normal incidence ($T_{v,n\text{-}n}$ and $T_{v,n\text{-}dif}$ measured according to EN 14500 [82]). Note that while the standard acknowledges that visual contact is affected by different light conditions during the day and therefore view quality requirements (e.g., for north- versus south-facing facades), the classification system is based on normal incidence irrespective of outdoor daylight conditions for practical purposes. The standard also notes that distribution and shape of openings as well as reflectance properties at the inward side of the device (i.e., side opposite of incoming radiation) might affect the view properties but does not take these aspects into account in the classification.

2.2.2. Proposed metrics and analysis methods

Other view metrics related to view access and content have been proposed. Mardaljevic [83] defined a metric that quantifies the view available from the outdoor surface of a given window plane, where the percentage of the hemispherical view from a window or skylight is calculated for the ground, landscape, and sky. The method has the distinct advantage that it is not dependent on the occupants' position from within the space and is based entirely on geometric factors relative to outdoor surroundings. In [84], Turan et al. proposed a spatially distributed view access metric for open unobstructed floorplans based on calculations for a grid of viewpoints throughout an indoor space. The metric indicates the potential for view without consideration of the quality of view. Li and Samuelson [85] proposed a workflow for design teams that use satellite imagery to create a panoramic image of the view from any arbitrary point on the floorplate.

Ko et al. [46] proposed an assessment framework and view quality index derived from a comprehensive review of the literature and view-related standards. All three variables, view access, content, and clarity, are included in the index and are normalized to a value between zero and one. The access variable includes a saturation threshold for the viewing angle that reflects no further need for additional outdoor view, potentially placing an upper limit on window area. The content variable accounts for view layers, content distance from the window, movement or dynamic features of the content, and features of nature in the field of view. The clarity variable is computed from the observer's position in the room and is also constrained by a minimum and saturation threshold for achieving an acceptable level of clarity. The framework acknowledges time-varying aspects of view clarity but the index reflects a single view clarity value for variable conditions that occur over a year.

3. Overview of simulation models

Most of the metrics and standards described under Section 2.2.1 are based on geometrical relationships which can be calculated using existing simulation tools. For example, the metrics and methods proposed by Turan et al. [84] or Li and Samuelson [85] require sophisticated computer simulations to trace rays to outdoor elements, but the underlying raytracing methods are well established. For EN 14501, classification of the shading systems is based on laboratory measurements of visible transmittance at a normal angle of incidence.

View clarity, however, is affected by site-specific, spatial- and time-varying conditions of direct sunlight and diffuse skylight on the window glass, state and position of shading system, and angle of view within the indoor space (i.e., see Section 2.1.3). To model such conditions, existing simulation models, supporting data, and analysis methods will likely need to be modified to make complete and equitable assessments, whether for the purpose of weighing design alternatives for a specific project or for the development of a generic classification system. In this section, we discuss the capabilities of existing tools to a) render photorealistic views of the outdoors for windows with shades or other optically complex materials and systems (e.g., for comparison against a gold standard reference such as unobstructed, clear, non-reflective glass), and b) model control of operable shades for view and other contextual variables. In Section 4.2, we then discuss what work needs to be done to enable such analysis in support of metrics, standards, and/or building design simulations.

3.1. Modeling view clarity

Modeling view through optically complex, scattering materials represents a unique challenge irrespective of whether the images are being used to develop new view clarity metrics using VR appraisals or for climate-based analysis of facade designs. The ability to discern details of the outdoor view through shades is affected by the light scattering and spectral properties of glazing and shading materials. Renderings must be able to replicate the dynamic range of luminance intensities (1.0 to 1e + 09 cd/m^2), complex luminance distributions, and color of the view through windows and optically complex shading and daylighting materials.

If point-in-time photorealistic renderings are the sole requirement for evaluation, then use of physically based, ray tracing rendering methods with analytical or geometrical descriptions of transparent glazing and macroscopic shading systems may suffice (e.g., venetian blind slats with Lambertian, homogeneously diffusing finish). If climate-based daylight modeling (CBDM) is required to evaluate the temporal variations in view clarity, then there are limits as to how clearly views can be rendered when matrix algebraic simulation methods are used. Matrix simulations use analytical models or tabulated bidirectional scattering distribution function (BSDFs)[14] data to describe the optical properties of shading materials [86,87]. With tabular BSDFs, matrix simulations effectively discretize and average areas of the scene, creating a blurred effect on the view. To reduce this effect, high-resolution BSDFs combined with peak extraction (PE)[15] [88,89] can be used to increase resolution of the rendered image (Fig. 2 upper plots). For macroscopic systems, such as venetian blinds, the view through the open portions between slats can be rendered with clarity if the geometry of the shading system is provided as input (Fig. 2 lower plots).

Degradation in view image quality occurs due to an imbalance between direct and scattered radiation. This is represented in the standard EN 14501 by classification by direct and diffuse transmittance (see above) and can be caused, e.g., by haze from sunlight

[14] BSDFs describe how incident solar radiation is scattered (transmitted and reflected) by a simple or composite surface, such as a window shade. Tabular BSDFs describe these data with a discrete set of values for a defined number and set of directions. High-resolution BSDFs use a high number of hemispherical subdivisions (average patch size with cone opening angles of less than 10°) to represent scattering data whereas low-resolution BSDFs use a low number (10-24°).

[15] Peak extraction is an algorithm in Radiance v5.3 that identifies peaks in the specular, direct-through direction of a tabulated BSDF so that the "vision" component and unscattered, directly transmitted sun component can be separated in the simulation.

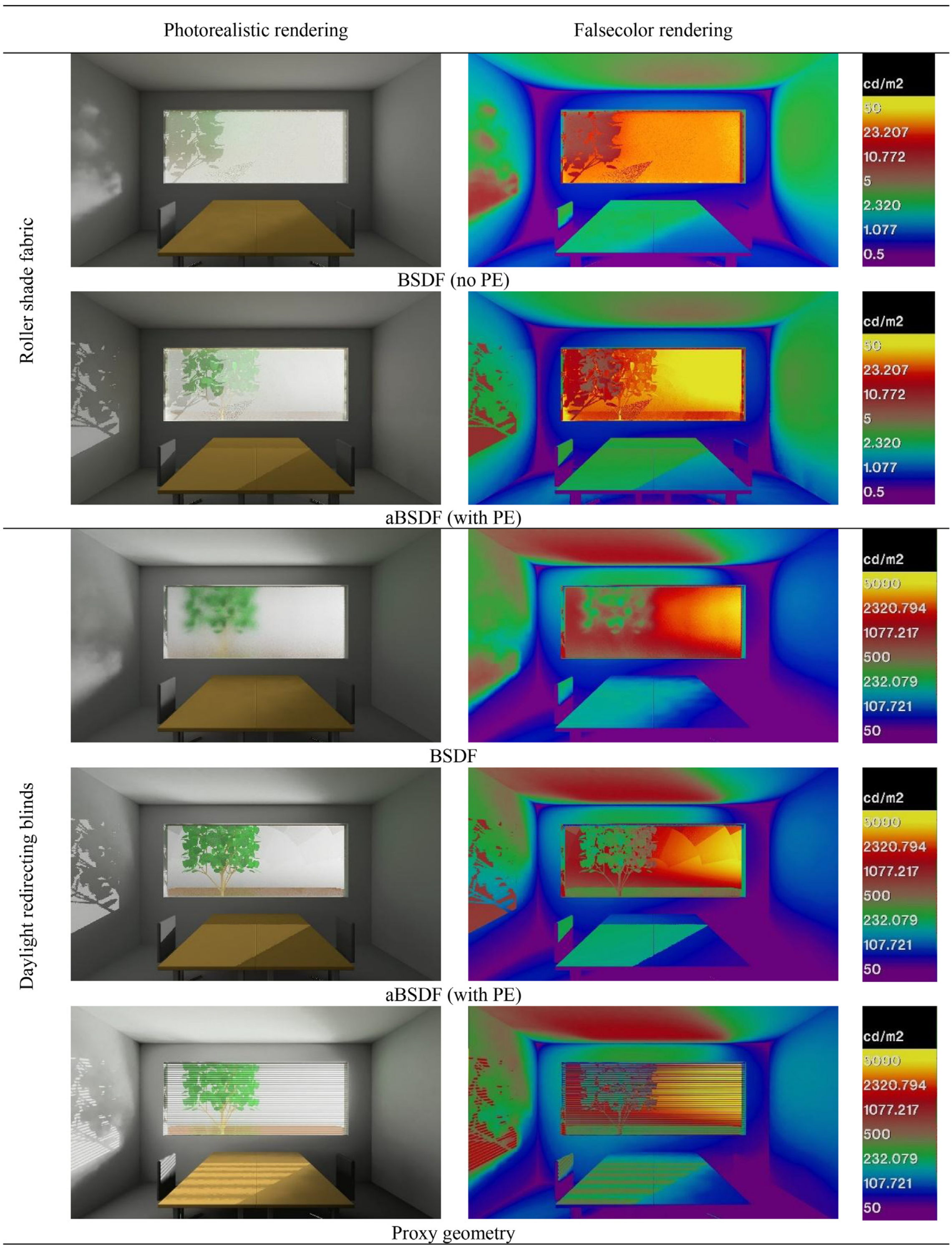

Fig. 2. Renderings of views through fabric shade (upper) and redirecting blinds (lower). For the fabric, the BSDF results in a blurred view while use with PE results in shaper clarity of the tree outside the window. For the blinds, the BSDF-generated images are insufficient for evaluation of view irrespective of how high the BSDF resolution is (blurred or choppy). Proxy geometry of the blind slats must be provided to clearly resolve the view. Source: D. Geisler-Moroder.

incident at an oblique angle or through glare effects from scattering caused by minute, shiny, aluminum holes in perforated venetian blinds. In both examples, the ratio of scattered and unscattered light is not constant; it changes depending on the conditions of irradiation. CBDM simulations offer the possibility to calculate the direct and scattered shares of light flux and thus a way to consider and evaluate temporal and annual dynamics in the quality of the view.

Image resolution, whether it be a photograph of an actual view or simulated image, limits the degree of clarity of distant rendered objects (Fig. 3). High resolution, photorealistic, physically based images take longer to render. An equiangular fisheye projection at 2000 × 2000 pixel resolution is typically used for glare analysis; here, the orb of the sun with an apex angle of 0.53° is rendered with approximately 34 pixels. It is unclear whether this degree of resolution is sufficient to discern the type of bird 20 cm high on

Fig. 3. Photograph of the view of trees through horizontal venetian blinds (716x1120 pixel image taken in a real space). Source: D. Geisler-Moroder.

a tree 25 m away or recognize a person on the sidewalk from a third story window. Borrowing from the EU standard EN 62676-4 for video surveillance, resolution might be clustered into so-called (M)DORI[16] zones (i.e., Monitoring (12 ppm), Detection (25 ppm), Observation (62 ppm), Recognition (125 ppm), and Identification (250 ppm)) according to pixel densities on target objects in pixels per meter (ppm). Transferring this to our bird example, the 20 cm animal on the tree 25 m away in a 2000 $\times$ 2000 pixel equiangular fisheye image would correspond to just above 25 ppm. If the tree is 50 m, 10 m, 5 m, or 2.5 m away, the same bird would be mapped at about 13 ppm, 64 ppm, 127 ppm (recognition), or 254 ppm (identification), respectively.

The naturalness of the view is affected by the spectral composition [90] of transmitted daylight[17]. To accurately evaluate color rendering of outdoor objects, spectral rendering methods are required. State-of-the-art three channel color (RGB) calculations allow estimations, which might be close enough for evaluation in the context of view quality in many real-world scenarios, especially if advanced approaches like spectral prefiltering or superior color spaces like sharpRGB are used. However, if spectrally selective materials such as colored (e.g., electrochromic) glazing or systems with saturated colors are involved, then higher resolved spectral calculations may be needed. Also, if contrast and complexity metrics such as those proposed by Khanie [64] are used for assessments, then images rendered with spectrally resolved data may also be needed. Spectrally resolved data for transparent glass are available, however, spectrally resolved BSDF data for shades are not yet available. Moreover, simulation tools to evaluate color rendition from spectral renderings were investigated in the past [91,92], but did not find their way into commonly used software. Recent developments for spectrally resolved daylight simulations [94,95] and underlying spectral sky models [96] are targeted towards the evaluation of non-image forming effects but could potentially be extended for color rendering evaluations.

The eye's neural sensitivity to spatial frequency[18] of the stimulus affects visual perception [97,98]. Shading materials may affect the spatial frequency of the viewed image, acting as a bandpass filter that reduces contrast of the viewed image. Modeling this aspect would require empirical models of human vision as an overlay to rendered images. Replicating stereoscopic vision for depth perception is yet another challenge. Methods for generating such renderings for a single direction of view are straightforward but the technical challenges of generating omni-directional stereo images [99] and the influence of BSDF data resolution needs to be investigated.

Views can also be obscured by veiling reflections produced by interior reflections of white or bright objects off the indoor glass surface of the window. Here again, it is not clear what the needs are from the view metrics and research community; a limited set of point-in-time simulations or a proxy contrast metric (e.g., R.D. Clear method presented in Appendix A in [100]) may be sufficient to evaluate climate-based view under this condition. Detailed patterns of sunlight on indoor surfaces can be modeled with high-resolution BSDFs with proxy geometry or peak extraction (for specular transmission), but sunlight on nearby outdoor (e.g., balconies, non-coplanar shades) surfaces would need to be rendered using conventional raytracing.

3.2. Integrated analysis

Research, case studies, and our own experience in the real-world points to the logical conclusion that when designing for view, all other considerations associated with the window should also be taken into account. Integrated analysis is ideal if the goal is to satisfy health and well-being as well as stringent building energy efficiency requirements. Such analysis can occur at a variety of scales ranging from analysis on a small project to broad scoping studies for regional analysis: e.g., codes and standards development, general design guidance, technology R&D (e.g., [101,102]), and other applications. Multi-objective optimization algorithms (e.g., Pareto front) can be used to efficiently identify optimal solutions (e.g., [103,104,105]). Parametric analysis can help guide designers toward better solutions.

Prior to the development of advanced simulation tools, evaluation, and comparative analysis of building designs as an integrated whole would have been impractical. The raytracing algorithms for daylighting were far too slow to be included with building energy simulation engines and radiosity algorithms were deemed too limiting. Today, climate-based daylighting simulations have become routine and are used even during the frenetic early design process. Annual evaluations of daylight, glare, solar radiation, and view can be accomplished efficiently using matrix-based raytracing software tools (i.e., view defined as percentage of obstruction by shade, not view clarity as described in Section 3.1). Modeling operable shades can be included via scheduled inputs, heuristic logic, or model-based control algorithms provided by the simulator.[19] Evaluation of daylight metrics, thermal comfort, and energy use and demand can be accomplished by coupling daylight and building energy simulation tools for run time data exchange, e.g., Spawn of EnergyPlus [106]. The software architecture enables both within-timestep feedback loops and predictive forecasting across multiple time steps for demand responsive [107] and resilient design solutions. These capabilities will enable designers to better address both health and building-to-grid performance criteria with an integrated tool set.

Including all aspects of view clarity as delineated in Section 3.1 in run-time simulations is likely not feasible and/or computationally efficient with today's tools and available optical data at this

[16] An example from video surveillance depicting the different levels is shown online by IPICA Software [93].

[17] The spectral content of transmitted daylight and solar radiation (intensity per wavelength across the solar spectrum) is modified by the spectral properties of the window glass and shading system. Spectral content determines the color of objects viewed through the window and shading system.

[18] Spatial frequency is a measure of periodic grating across a position within a given distance from the retina [97]. The visual cortex has multi-dimensional spatial filters with narrow bandwidths. Different spatial frequencies can cause visual discomfort depending on sensitivity of individuals to physical stimulus. Such discomfort can render a view to the outdoors unpleasant, e.g., moire effect when looking at superimposed gratings (closely spaced, horizontal lines on fritted glass).

[19] Control models for manually operated shading systems are limited (e.g., [108,109]) and represent a serious limitation in the evaluation of view in buildings with conventional shades.

time. In the short term, lower cost metrics (computationally) will need to be derived or gold standard renderings will have to be used judiciously in evaluations.

4. Advocating for healthy, energy efficient buildings

As evidenced by activities delineated in Sections 2 and 3, enormous progress has been made over the past few years in raising the architectural industry's awareness on the importance of daylight and view in buildings with voluntary or mandatory standards now in effect in some countries to ensure consideration of health and well-being criteria. In support of these standards, simulation tools have been developed to automate calculation of daylight and view metrics, window and shading manufacturers are taking steps to evaluate how their products can be designed or redesigned to support view criteria, and those influencing city and urban planning are advocating for incorporating nature and greenery in dense, urban areas with greater purpose. Manufacturers have developed and now offer a wide range of new glazing and shading materials to provide design teams, owners, and occupants with improved physical solutions to optimize view while addressing the energy and carbon impacts of façade design decisions.

Acknowledging the current limitations of our research and metrics, what are the critical needs going forward to better support health and well-being in buildings? Within the view and daylight research community, research needs have been assessed, e.g., [44,46]. Within the broader building science context, what are the research needs? Given our current understanding of causal mechanisms, what impacts do we anticipate will occur with respect to building energy use and associated carbon emissions if view and daylight requirements are met and what further enhancements to tools, technologies and building operations, if any, are needed to mitigate these impacts? In this section, we provide various perspectives on these questions with respect to critical needs in the areas of research, tools, and technological advances.

4.1. Research needs

The overall aim of further research should be to develop methods and solutions that maximize the positive health and well-being effects of view and daylight, minimize thermal and visual discomfort, and satisfy energy and carbon emission reduction goals. Research should result in measurable outcomes related to human performance (cognition, working memory capacity), physiology (parasympathetic function, cortisol, and melatonin for circadian health (i.e., sleep quality and alertness)), and well-being (stress, restoration, satisfaction, quality of life). Questions of interest pertain to physical aspects of design: e.g., how much view, when, for whom? and how frequently? Are the well-being outcomes of view predicted by occupant satisfaction with the view? This research question is worth considering, because if so, data collection in the field could be greatly simplified by simply surveying the occupants. Ultimately, it would be ideal if observable features of a view could be shown to be predictive of different types of occupant outcomes.

If visual substitutes for the real world (i.e., photographs, virtual reality) are determined to be insufficient due to physical limitations of the media (e.g., limited dynamic range in intensity of image, inability to replicate angle-dependent visual phenomena), then field studies may be the only alternative. For studies conducted in real-world buildings, ideally, the actual daylight and view seen through the window should be monitored and reported in studies so that physical attributes of the window (i.e., geometry, glazing and shading spectral and transmission properties, operating state, etc.) and other site-specific factors that affect the view (i.e., orientation, direct and diffuse solar, precipitation) can be correlated to effects on health and well-being. Such specificity enables other researchers and industry to link outcomes to related building performance, i.e., energy use. There is a paucity of information on the real-world window conditions that produce positive outcomes in much of the view-related research. Research methods for studies in the real world must be designed carefully since there are many contextual variables and environmental stimuli that influence measured outcomes. Schweiker et al. [110] identified limitations of the majority of existing research studies which use a single-domain approach to relate a single environmental influence to human perception and behavior. Multi-domain approaches acknowledge that humans receive information from a combination of sources in the environment, which then affects perception and behavior in the environment. Facade design variables were identified as amongst the most crucial. New methods may be needed to understand the complexity and interplay of contextual variables. Meta-analysis of existing studies, particularly in occupied buildings, may help to support cohesive hypothesis formulation and direct research efforts.

To create a view that has a positive effect on health, specifically one that reduces stress and increases cognitive restoration, the elements of natural outdoor landscape especially greenery and water *must* be included in the view. To date it is widely agreed that some amount of greenery is positive, but the specifics are not well researched or understood [111]. Further research should focus on the question: What *amount* of greenery in the view is necessary to generate the restoration effect? A small area of ordinary lawn will not make a difference. What are the important *qualities* of the greenery and natural landscape needed to create the restoration effect? Variety of texture, lushness, formalism, and color composition of the landscaped areas should be considered in addition to size, location, and distance from the viewer. Assuming a nice view out with greenery or water, what is the *minimum acceptable size* of view that would still promote health and well-being? The answer will give important design clues about the maximum view distance of occupants from the window as a function of window size and number of windows needed, both of which affect building design and energy use (i.e., perimeter-to-core ratio, window-to-wall ratio).

Research to date seems to suggest that only the most clear, transparent, unobstructed window can afford such natural views to the outdoors, which for many parts of the world is challenging given the need for solar shading. Transparency of glazing materials *is* especially important: view distance and view angle should be considered as important parameters. Are partially obstructed or modified views of greenery sufficient for restorative effect? Research should aim at developing a theoretical ground for creation of new glazing and shading systems and materials, which could better address site-specific conditions, such as latitude and orientation of the window as well as the shape of the room. Answering such questions regarding the amount and qualities of greenery needed would enable others to better understand how best to develop energy-efficient, technological solutions and architectural designs, particularly for dense urban environments.

How much of a window with its associated health benefits can be obstructed by e.g., shading devices, both temporally (in time) and spatially (in area)? Sunlight is an important contributor to health and well-being. There are an increasing number of research studies examining the effect of light exposure on circadian rhythm related health aspects, but little is scientifically proven regarding the positive impact of sunlight on psychological aspects, i.e., mood, feelings, emotions. More research is needed to determine the necessary timing, duration, intensity, and patterns of sunlight needed to produce desired positive psychological effects. This work must

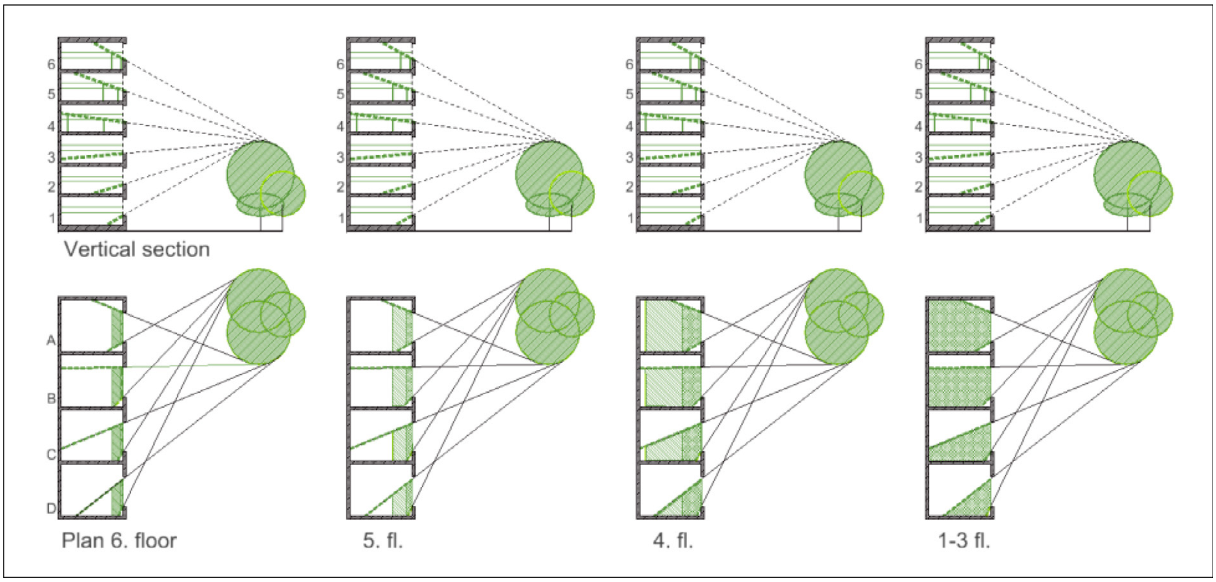

Fig. 4. No-greenery lines indicated with thick, stippled and green on the vertical section and floor plans. The area of the room with the view to the greenery is marked on the floor plans for floors 1–6 with dark and light hatch for 1.2 m and 1.75 m eye height, respectively. Source: [113]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

be done with regard to visibility of sunlight within indoor and outdoor views, as people may tolerate north-oriented rooms (in the Northern Hemisphere) if significant parts of the outdoor view are frequently sunlit in rich detail. Climate and culture will affect responses to view and could be taken into account [112]. Such work will inform design and control of shading systems, which must manage other aspects of building performance (i.e., visual and thermal comfort, solar gains, privacy).

Research needs to define adequate measures, the simplest one being a "green view percentage", i.e., percentage of the view image (as taken by a camera from the interior viewpoint). This solution is not so straightforward, however, as a series of additional questions arise, especially what should be the position of the viewpoint in different room types for a fair comparison of rooms and buildings [83]. To create districts and cities with "healthy" views at an urban scale, recommendations for design of green areas (i.e., outdoors, in atria, on the facades of buildings?) should follow the research results. One possible measure could be the greenery-view factor [113], calculated as a percentage of occupied area in the building enabling greenery-view. Similar to the No-sky line (a simple design tool used by architects) that divides the interior into a part that "sees the sky" and a part that does not, a No-greenery line divides a room into a part that "see the greenery" and the other that does not (Fig. 4).

4.2. Models and tools

The main – and partly contradicting – requirements for daylighting design (daylight provision, glare protection, exposure to sunlight / sun protection / solar gain utilization, and view) are not only represented in standards and codes but must also be considered in the utilized design tools. While daylight provision has been the main part of daylight simulation software from the beginning, glare evaluations or sunlight exposure calculations have been added gradually as new metrics emerged. The evaluation of view has long been limited to geometric analysis (mostly in CAD software) to prove compliance with codes and has only recently found its way into design tools. ClimateStudio [114] for example now enables view analysis according to LEED v4 and EN 17037.

However, there are important questions that remain when trying to evaluate view within the daylighting design aspects of the broader building design process. A main issue is the consideration of shading and daylighting systems in the calculations and in the metrics. This includes:

– Is view through a shade (e.g., a fabric with openness, venetian blinds at various tilt angles, slightly frosted glass, electrochromic glazing at different tint states) a pure material or system property and can thus be evaluated and categorized on that level following standards like EN 14501? Or do outdoor daylight conditions contribute significantly to the perception of the view (e.g., direct and diffuse scattering of incident radiation within shading materials, etc.) and we therefore need to evaluate view through the system under variable solar conditions within the site and building context and thus in building simulations?
– Daylighting and shading systems are commonly represented through their BSDF for analysis of solar control, daylight, and visual comfort performance. For view, is it possible to evaluate view using a BSDF? Or does either proxy geometry or a proxy analytical model for view evaluations need to be provided? If proxy geometry must be provided, what level of detail is necessary or sufficient? What neurocognitive models for the human visual system can then be used to convert simulated images to those created in the mind (i.e., self-assembly of partially obstructed views), and how can the result be related to the stress-reducing, restorative effects of view?
– Do we have appropriate characterization and simulation methods for all types of shading systems? Do we for example need new or adapted methods[20] for inhomogeneous structures that

[20] SHGC can either be calculated (WINDOW, ISO 9050, EN 410, ISO 15099, ISO 52022) or measured via calorimeter (ISO 19467–1 and –2; [118]) when no validated calculation method exists (e.g., for complex fenestration systems that can only be measured). Methods for characterizing scattering properties at higher angular resolution for glare and potentially view analysis are currently under development [87,88,115].

Table 1
Simulation of various window conditions and relationship to view.

	Simulation of:	Assessment of:	Tools and product data available?
1	Geometrical relationship between the envelope aperture to the outdoors	View access: How much can be seen through an aperture in the wall from an indoor viewpoint	Yes, geometry based.
2	View elements at gross level (ground, landscape, sky)	View content: What one sees through an aperture in the wall from an indoor viewpoint; potential for relaxation of eye, mind wandering; prospect/ refuge	Yes, geometry based.
3	View of near and far content at adequate detail (e.g., bird on nearby tree, cars passing on road, fog on distant mountain)	View clarity: Potential for relaxation of eye, mind wandering; prospect/ refuge; visual perception; assessment of pleasantness of view	Yes, if modeling clear glass or CFS with BSDF + geometric model (e.g., louvered blinds), high-resolution tabular BSDF with proxy geometry, or high-resolution BSDF with peak extraction (PE) (e.g., fabrics). Computational demands of high image resolution images may limit CBDM analysis.
4	View with reflections on window under low daylight or nighttime conditions	View clarity: Obscures details of view	Point in time, raytracing calculation only. Current matrix methods not applicable. Derive analytical function for view clarity using point in time simulations under representative sun/ sky conditions?
5	Haze or glare from an imbalance of within-system diffuse and direct light	View clarity: Obscures details of view	Point in time raytracing based on geometric model or BSDF with peak extraction; or advanced matrix methods separating direct and diffuse contribution (5-phase method).
6	Spectral shift in colour rendition of view elements due to tinted glazing	View clarity: change in perceived naturalness of view, e.g., changes assessment of outdoor weather conditions; changes non-visual effects of incoming light	Point in time, raytracing calculation only. Current matrix method not applicable, mainly due to missing spectral representation in BSDF data and data availability.
7	Partial obstruction of view elements by macro- and microscopic-scale opaque shadings	View clarity: Obscures details related to prospect/ refuge; clarity and retinal spatial frequency dependent on distance from window	Point in time, raytracing calculation only. Macroscopic system: geometry only. Microscopic systems: high-resolution BSDF with PE*. Neurocognitive model needed for spatial frequency.
8	Frequency and degree of obstruction of transparent portion of the window by operable shades	View clarity: Obscures details of view	Yes. Can use existing CAD if simple geometry-based control logic or matrix algebraic methods if shade is controlled based on direct sun, glare, daylight, or area of unobstructed window.

* Here the open research question is the circumsolar area – without peak extraction (PE): which BSDF resolution do we need? And with PE: how to decide how much of the circumsolar to put into the peak?

vary spatially over the area of the system and thus cannot be represented using BSDFs which homogeneously specify an averaged behavior of the overall system?
– How can such optical data be utilized in today's applied matrix calculation methods, which are used for efficient annual daylighting simulations? Can we derive integrated solutions using parametric climate-based optimizations if we use simplified models for view or are more complex models needed?
– Do we need to perform annual simulations on an hourly basis as commonly applied in building simulations to evaluate view? Or can the simulations be reduced to a number that is representative of the range in outdoor luminance and solar conditions?
– To what extent must view clarity be evaluated? Connecting to the concept of (M)DORI zones for video surveillance, how can this be translated into image rendering requirements to evaluate view clarity? Do current daylight simulation tools provide the capabilities and performance to render images at appropriate resolutions? Or is there a need for a stronger link to the field of Computer Graphics with photorealistic but not necessarily physically correct renderings at a high resolution and at a reasonable speed?
– Are spectral simulations required for color rendering calculations to also evaluate how color affects perceived views? Are the necessary foundations in place for this, i.e., multi-spectral rendering software, spectral data not only for glazings but also shading and daylighting systems, and appropriate metrics accounting for these effects?
– How should the simulation software systems be extended and how do we prioritize modeling needs so that we achieve the best overall outcome for health and wellbeing and building performance?

Table 1 summarizes simulation capabilities needed to support analysis of view access, content, and clarity. Development of BSDF libraries containing optical characterization data of light scattering properties of shading and daylighting materials and systems is underway [115,116]. It is imperative that view-related requirements be included in the development of these new libraries.

4.3. Technological advances

Building occupants experience the benefits of window views and daylight that result from the selection of specific technology solutions incorporated into building designs. These solutions are not static over long periods of time – they evolve incrementally based on traditional improvements in materials and methods of manufacture but can also change more rapidly when new performance demands arise. In the context of our discussion of occupant needs related to view, there is a pressing need and a great opportunity to rethink the relationships between available and emerging[21] glazing, window, and shading technologies and their impacts on views and building energy use.

Windows have always served multifunctional roles in buildings. They manage thermal transfer, modulate solar gain, admit, or restrict air flow, provide daylight to interior spaces and provide view. They are also part of the larger building envelope that separates and protects building occupants from undesirable outdoor elements: wind, rain, animals, dust, air pollution, noise, etc. While this paper focuses on view, the cumulative impact of windows and the building envelope on building energy use and carbon emissions is large, in the range of 20–40%. Buildings account for ~40% of energy and carbon impacts globally, and ~75% of electricity use in the U.S. and similar fractions in other industrialized countries [4]. The 2021 United Nations Climate Change Conference of the

[21] Emerging technologies are those that have not yet been introduced to the market or which have low market adoption.

Parties (COP26) highlighted new global efforts to dramatically reduce carbon emissions over the next 20–30 years, a task that cannot be accomplished without dramatically reducing building energy use. So, as we explore the potential for windows to provide enhanced views and daylight, we must ask if those window and building design solutions can be executed in a manner that supports the critical global need to reduce building energy use and carbon emissions.

Numerous window technological innovations have occurred over the last 30 years, and they now provide an enhanced range of window performance in terms of durability, energy management, aesthetics, cost, operability, etc. Much of the driver for this innovation has been the more traditional concerns of energy impacts and this is expected to continue as nations chart a path to carbon neutral buildings by 2050. Some of this investment in new technology development can be harnessed and refocused to address the challenges of occupant views if those needs can be clarified and translated into functional criteria for material properties and operations.

These glazing and facade innovations have been introduced into buildings via three primary pathways:

1. Improving intrinsic properties of each window element, e.g., a spectrally selective coating on glass that provides daylight and allows clear view but rejects 30–70% of incident solar energy; or highly insulating glazings that provide view with minimal net thermal impact;
2. Providing enhanced operational control over how window properties are managed over time, e.g., dynamic shading systems, or electrochromic glass whose light transmittance can change from 70% to less than 1% to provide view but manage glare and solar gain; and,
3. Integrating window systems with smart controls that manage the state of multiple elements to optimize occupant and building performance, e.g., active facade/shading systems that admit daylight through an upper clerestory to brighten a space and reduce lighting energy use while providing glare free view access through a lower vision glazing strip.

A survey of state-of-the-art products and R&D trends [117] suggest that many of the technology improvements to windows needed to improve energy performance can be made with little or no adverse impact on view using certainly the first innovation pathway above and possibly the second, depending on spectral and scattering transmission qualities and/or obstruction when actuated. Whether potential market opportunities will drive manufacturer R&D investment for such solutions and lead to their widespread use is an issue that cannot be as easily assessed; discussion of these aspects are deferred to another study. We outline five areas of active technology R&D that should improve the energy performance of buildings and may impact view access and view quality for occupants.

4.3.1. Thermal losses

Conventional double glazed, low-emittance windows which comprise the current standard in most industrialized countries have a U-factor of approximately 1.8 W/m^2-K. Many cold climate countries now have code requirements of approximately 1.0 W/m^2-K which are achieved typically with low-E coatings and insulating gas fills in double or triple glazing. The next generation of triple- or quadruple-glazed window technology, or vacuum insulating glazing, will drop window U-factors to approximately 0.6 W/m^2-K (i.e., R9.5) and reduce the center glass U-factor to approximately 0.4 W/m^2-K [119]. With these levels of thermal performance, the heating impacts of windows (which globally are the largest energetic impacts of windows) can be minimized in even the coldest climates, allowing some increase in window area if needed to provide views without incurring a significant energy or comfort penalty. These thermal properties can be achieved while maintaining a $T_{v,n-h}$ of about 0.5 or greater without significant haze or color, effectively achieving minimal loss of view clarity.

4.3.2. Solar control

Managing and improving window solar control functions while providing view has been one of the greatest challenges because the most direct historic methods to provide such control also obscured view, e.g., wooden shutters over windows. Much of the growth in world population and associated building construction over the next 30 years is projected to be in equatorial regions with high cooling loads driven in large part by solar impacts [120]. Developing improved building solutions that provide access to daylight and view in these regions without cooling penalties will be critical. At higher latitudes, the sun path is lower, mandating difficult tradeoffs between comfort, daylight, and view. Solar control technology continues to evolve over three distinct but overlapping pathways.

4.3.2.1. Spectrally-selective, low-emittance windows. Reducing solar impacts on cooling was initially achieved using dark tinted or reflective glazings that resulted in low visible light transmission and significant impacts on view. In the current generation of glazings with spectrally selective, low-emittance coatings, the coatings can reject virtually all of the solar near-infrared energy with only a modest loss of daylight using complex multilayer coatings that can be color neutral if desired. Fig. 5 shows a plot of calculated $T_{v,n-h}$ versus SHGC for approximately 5000 commercially available, double glazed products based on data from the International Glazing Database (IGDB) [121]. Even when SHGC is reduced to as low as 0.15, these glazings will still have $T_{v,n-h}$ values of $\sim$ 0.3 which may be adequate for view under many but not all conditions. The best color-neutral, spectrally selective glazings have reached optimal performance limits (i.e., light-to-solar-gain ratio (LSG = $T_{v,n-h}$/SHGC of approximately 2.5) meaning that glazing with a $T_{v,n-h}$ of approximately 0.5 can have an SHGC as low as approximately 0.2. The glazings with the highest LSG begin to reduce transmittance in the 300–400 nm range. Since the spectral content of transmitted daylight affects melanopic and violet light exposures for physiological requirements, this aspect of spectral selectivity should be further investigated.

4.3.2.2. Smart switchable glass. The latest generation of switchable transparent electrochromic (EC) glass modulates visible transmittance and solar heat gains over a wide dynamic range with continuous tinting rather than a small number of preset states, within-pane variable tint zones, and more neutral gray appearance instead of Prussian blue when tinted. With a $T_{v,n-h}$ range of 0.60 to 0.01, the current generation of EC windows sacrifice some aspects of view and daylight quality to manage energy and glare. Here spectral transmission is also of concern but since the tint varies, the hours of operation of the EC windows in each optical state will also need to be taken into account, as discussed in case studies above (Section 2.1.3). Research advances in EC coating technology promise independent control of near infrared and visible light [122], potentially improving transparent view when limited solar load control is needed. Other new promising EC material solutions are neutral colored and reflective rather than absorptive and fast switching to even lower visible transmittance levels that provide privacy, e.g. $T_{v,n-h}$ < 0.001 [123,124]. Ultimately continued refinement in the underlying manufacturing processes will enhance durability and cost effectiveness as well.

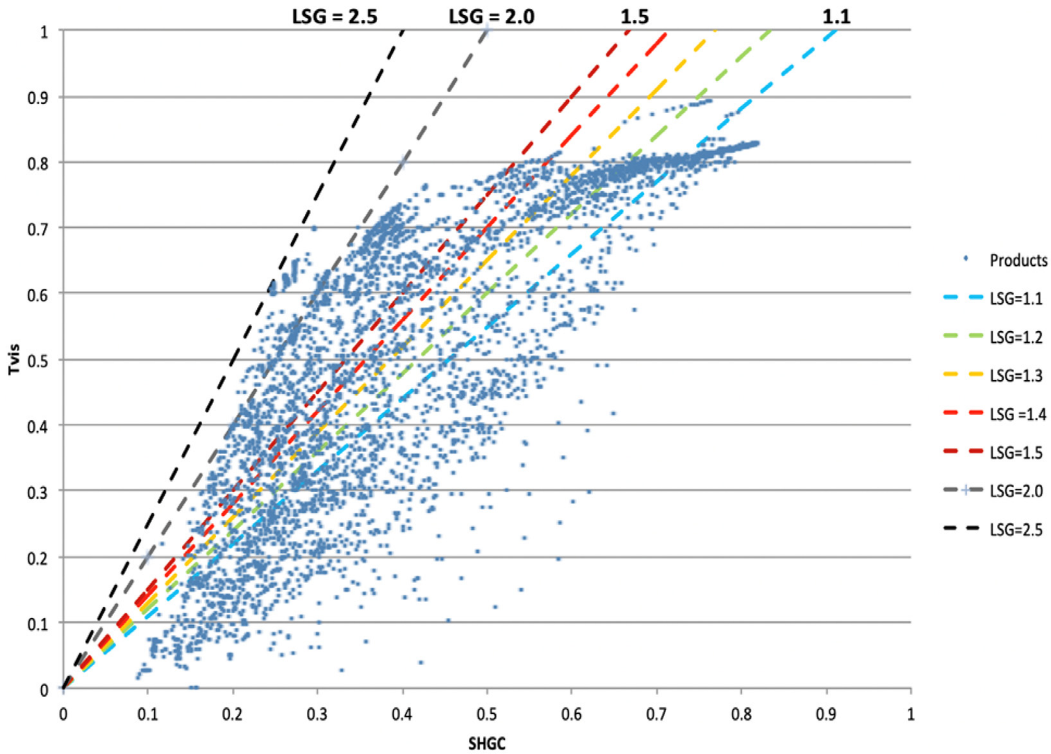

Fig. 5. Visible light transmittance (T_{vis} = $T_{v,n-h}$) versus SHGC for approximately 5000 types of commercially available, double glazed, insulating glass units. The optimal performance limit has an LSG ratio of 2.5 (i.e., spectral selectivity). Source: LBNL.

4.3.2.3. Optically complex shading systems. Blinds and louver systems have evolved from simple slatted assemblies to geometrically complex slats with perforations and surface finishes to better manage incident sunlight. Shades have evolved from single layer fabrics to more complex multilayer, honeycomb structures with coplanar fabric layers, with and without coatings. The combination of weaves, coating materials, honeycomb structures and novel elements, such as electrochromic threads to change transparency [125], make the field of shade design a subject of new interest. Views through any of these systems will always be compromised compared to an unobstructed window. But emerging materials technologies might allow the underlying opacity or transparency of the threads to change with passive or active intervention, or the geometry of the weave to change on demand, using new shape memory alloys [126,127] thus altering the transparency and view based on temperature, light level, or on demand. Scattering of sunlight within the shading material itself can obscure the view. Care must be taken to evaluate new designs and materials under variable sunlit conditions. Avoiding luminance contrast within spatial frequencies where we are most sensitive will ensure visual comfort (Fig. 6). Patterns inspired by nature were evaluated as calming, interesting and pleasant, which raises the question on how such elements could be applied in design to support stress recovery (Fig. 6) [128,129]. Perforated scrims are used architecturally and can provide slightly modified views but may provide inadequate control of solar glare [130]. Materials researchers and architects who are exploring new material and design options can usually calculate, visually inspect, or measure the optical properties of these new options but would welcome more guidance on the impact of shading materials, systems, and designs on view quality and occupant acceptance.

How critical are views of the sky? Many shading systems such as overhangs, awnings, and fixed horizontal louver systems or screens block views of the sky. This is as yet unknown but pragmatically speaking a view horizontally and downward is certainly better than no view. Views to the sky may be important for stimulus to the eye and circadian system. Satisfaction with limited views may very much depend on the user group, e.g., in a study involving visually impaired, light-sensitive subjects, the best view direction was toward the ground even under overcast sky conditions [131]. On the other hand, for most people, the view towards the sky without solar glare is very much appreciated and views

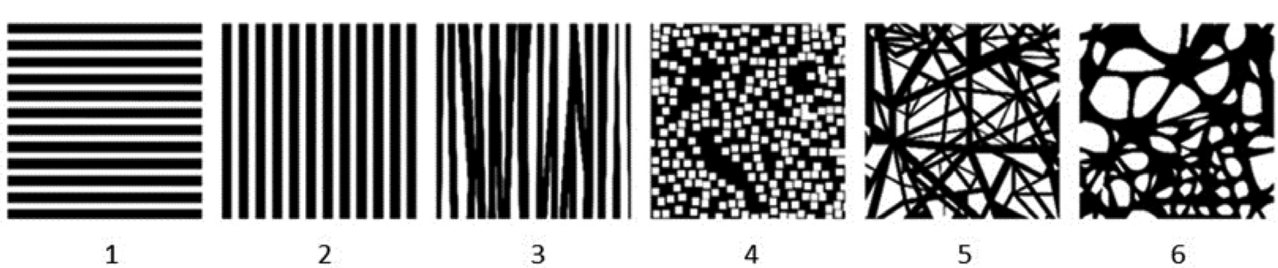

Fig. 6. Disorientation and discomfort due to spatial frequency were reported for Patterns 1 and 2. Pattern 3 was evaluated as the most calming in one study, and Patterns 3 and 6 as calming, interesting and pleasant in another study. Source: [128,129].

without the visible sky were evaluated significantly lower (e.g., [132]).

Significant effort has been invested in developing automated control systems for shades and dynamic glazing. These systems have been designed to manage direct sunlight, solar heat gains, glare, daylight, and view by changing the position or state of the shade or glass but are not widely used. The question is how to include view more proactively, e.g., what should be prioritized at a given time, protection against solar radiation or maintaining view? If glare tolerance is greater with view, can the shade be raised despite occurrence of glare and increased cooling energy from solar gains? Research in carefully controlled testbeds and larger studies in occupied buildings can provide insights into this complex challenge. But even the smartest automated systems will likely never provide solutions that will meet all occupant needs, so ideally systems will permit occupant overrides in a manner that balances occupant preferences for view with building operational needs.

Are there alternative control concepts that we should consider? Shading functions for the sun versus bright sky could be separated. A single operable shade obstructs view for the entire room when lowered (Fig. 7) when perhaps only a few users are disturbed by glare. An opaque element within the plane of the window could follow the movement of the sun and protect a single user or designated area while a separate, more transmissive shade (allowing a certain degree of view) could be operated according to preferences of the rest of the occupants. Liquid crystal device (LCD) windows have the potential to offer this sun tracking capability. They can be subdivided into an array of individually controlled sub-elements, where each sub-element can be switched to modulate transmitted solar intensity, offering the capability to control small sub-areas of the window for daylight and glare [133]. More pragmatically, local sun shades at the location of individual users would enable view for the remainder of the occupants [134,135]. Vertical and horizontal operable shading elements combined on the same window may give additional advantages, especially on east- and west-oriented windows where there is asymmetry in the diurnal path of the sun. The vertical shading device could be controlled to block the sunlight, while the horizontal device could be used only to protect against the bright sky.

Separation of view from daylight apertures enable control of shades for independent purposes [136–138] (Fig. 8). Such architectural solutions may have the advantage of providing greater access to the view per single aperture and perhaps reduce the need for larger-area windows that are ultimately obstructed with conventional shades. Open plan spaces with windows on two- or three sides of the space allow views out when one facade orientation is shaded. An additional view window may be proposed just to enable access to a more informative, interesting, or beautiful view. When daylight and view align, the window could be enlarged just because of the more desirable view content at that location. These design strategies for both daylight and view could result in larger total window glass area – which impacts energy consumption. Hence, a higher precision in the window design is necessary to balance daylight, view, and energy use.

Fig. 8. Design of apertures to serve different functions provides more opportunities for unobstructed views out. The south windows (left) can be shaded from direct sun while the north skylights and windows (right) provide views to the sky [136]. Source: D. Geisler-Moroder.

4.3.3. Daylight redirection or transport

Over the last 50 years much of the interest in admitting more daylight in buildings was driven by the goal to reduce electric lighting use. With LED lighting and advanced controls, lighting energy use has been reduced significantly in new building designs and retrofits, but there is still concern regarding a rebound or increase in energy use to meet circadian entrainment requirements. The relative value of daylight-redirecting technologies and view needs to be better understood within this context since both daylight and view affect health and well-being. For example, a light shelf or prismatic glazing in the clerestory portion of the window will redirect daylight to the ceiling deeper into a room, lowering energy use and supporting circadian health but will block or obscure views of the sky [139]. A skylight or light pipe collects sunlight at the exterior wall or roof and transports daylight and/or sunlight to the core or below-ground spaces that have no access to windows or views. Such technologies may be beneficial for circadian entrainment, reduced energy, resiliency, and providing visual clues to changing outdoor sun and sky conditions but pro-

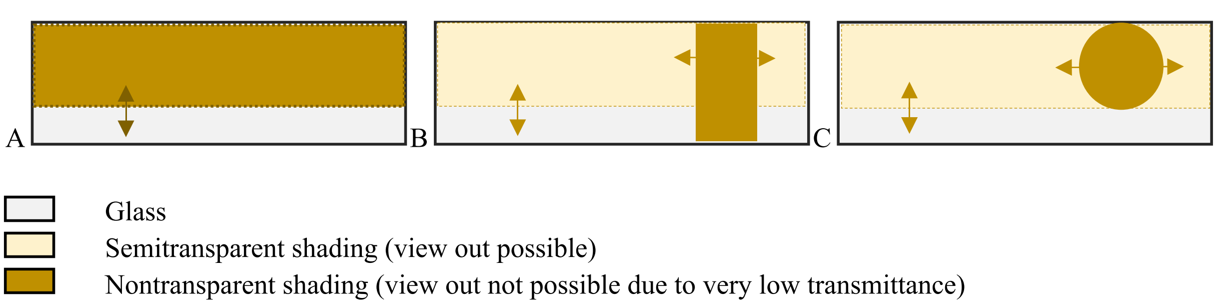

Fig. 7. Principles of sun-shading use. A: equal for all users; B and C: adjusted to one user and equal for the rest. Source: B.S. Matusiak.

vide no view. The relative energy impacts versus health-related trade-offs needs to be better understood.

4.3.4. Building integrated photovoltaics (BIPV)

There is tremendous interest in generating renewable power on site to minimize utility grid dependency in light of increasing power outages and improve resilience. Building integrated photovoltaics (BIPV) are attracting attention as costs decline and efficiency improves. Some opaque and semi-transparent BIPV materials are installed as a shading element on a view window or even within the view glazing in the window [140]. When used as window glazing, the current commercial technologies (both traditional silicon cells and amorphous silicon) have a significant impact on the color and clarity of view out of windows. There are several startups making good progress on PV windows that convert solar near infrared and ultraviolet light to electricity and maintain a transparent view with minimal impacts on visible transmittance [141]. These "clear" PV windows provide less power but do not interfere with view.

4.3.5. Integrated controls

The third innovation pathway, "integrated systems with smart controls" is critically important because of the diversity of performance needs, the wide range of technologies available to meet those needs, and perhaps most importantly the diverse and time-varying nature of how occupants live and work in buildings. The desire for a view and response to views is not uniform amongst occupants nor constant across time. The nature of views can change dramatically over time and the occupant's level of interest in and reaction to the views can be equally highly variable. Accordingly, it is not surprising that the window system, which is the (potentially) controllable physical intermediary and interface between a building occupant and the view to the outdoors becomes a key focus of interest. While basic HVAC functions have always been "automated", even with a controller as simple as a thermostat, control of shading, daylight and views has largely been manual and ad hoc, left to the desire and whim of the occupants. A new generation of smart sensors and building controls that sense occupancy, thermal conditions, utility rates, building energy use history, and occupant preferences can now, in principle, evaluate and optimize control of operable glazing and shading systems to maximize or optimize some end use function, e.g., occupant view or building carbon emissions. Machine learning, adaptive controls indicate promise particularly given the complexity of this multi-objective problem [107,142–144]. There is a critical need to understand how to incorporate view metrics and criteria into simulation models (Section 4.2) and integrated automated control algorithms to achieve both energy-efficiency and health and well-being goals.

Assuming we understand how to create robust, implementable business solutions around the technologies described above in this section, the reality is that speculative developments based on maximizing narrowly defined return-on-investments will likely continue to drive the mainstream real estate market in most industrialized nations. Decisions on whether to use more advanced technologies, to advocate for health and well-being in buildings, and for more occupant friendly conditions in indoor environments where people spend the majority of their time will often come down to how the real estate market values these new perspectives. A better understanding of the relationship between window views, occupant satisfaction and building performance will help strengthen the economic rationale for these investments. While fundamental codes and standards will be needed to ensure minimum working conditions for all, we will require clear research evidence supported by empirical data, accurate and efficient tools for practitioners, and turnkey, intelligent technological solutions in order to meet the new stringent COP 26 net zero targets over the coming decades, while capturing the window views that building occupants desire and deserve.

5. Conclusions

There is a considerable body of evidence indicating that outdoor views of nature and ample daylight produce significant positive health and well-being impacts on building occupants. Recent research on view access and content has focused on determining the underlying causal mechanisms that relate physical attributes to occupant outcomes (e.g., distance from window, window size); however, temporal aspects of view access (timing and duration) has not been studied and very little research has been conducted to determine how views modified by glazing and shading materials, i.e., view clarity, affect physiological and psychological health. Case studies in occupied buildings reviewed in this study indicate that greater, more frequent access to transparent outdoor views can lead to greater occupant satisfaction if lighting quality and/or daylight availability are not negatively affected. Metrics for view clarity are under development using subjective appraisals of shading materials in field studies or in immersive virtual reality environments. Careful research will be required to better understand how static and operable shading affect and can balance the complex and interactive effects of view, daylight, discomfort glare, and solar control as related to health and well-being.

Simulation tools are available to calculate geometric-defined relationships between occupants and outdoor view content. Tools to evaluate view clarity are limited. For some shades (e.g., operable venetian blinds with matte-finished slats), view clarity defined by degree of obstruction of transparent view can be evaluated efficiently using existing tools on a single point-in-time and annual basis. For optically complex scattering materials, such as fabric shades, the current BSDF data and modeling tools are limited and will require modifications to enable computationally efficient evaluations. Achieving spectral accuracy in renderings will also require model and input data updates, particularly if view clarity is based on visual perception metrics (e.g., contrast and complexity). Tools that support and potentially direct development of integrated design solutions in combination with technological advances (e.g., via multi-objective optimization algorithms or artificial intelligence) will be needed to significantly lower energy use to desired net zero levels needed to mitigate climate change.

Technological advances in static insulated windows, solar control, and daylighting systems are available to counter potential increased energy use associated with increased view and daylight. New materials and systems R&D can produce exciting new high-performance options, but technology innovators will need guidance from the human factors research community to direct development efforts. Dynamic shading and switchable windows provide additional, more complex solutions that will require additional research to ensure that the active control of these optical elements results in a net positive effect on health and well-being, while achieving energy use targets. Incorporating human factors into the cost-benefit analysis conducted by the real estate industry will be necessary to move these technologies beyond the early adopter's stage of the adoption curve.

Field studies show that users interact with building systems (lighting, shading, etc.) only at the beginning of the day or in the case of prolonged discomfort [145,146]. Users adapt to uncomfortable conditions by trying to improve them on their own, e.g., anti-reflective film on the computer display, changing the primary view direction by turning the head or body away from a bothersome light source, etc. But an individual's access to the view can be difficult to fix, especially in a landscape office. Therefore, it is extremely important that industry takes responsibility for view access for end users.

Legislative pressures on city and planning agencies are largely responsible for increased densification in urban areas as a result of housing and transportation crises: regulations allow narrow lot sizes and minimal setbacks from property lines with consequent degradation in daylight and views even when a window aperture is provided. Strong, evidence-based advocacy is needed to counter the pressures these agencies face to increase health and well-being in our built environment. These explorations of how to rethink and reuse indoor space might have another salutary effect. As we discuss meeting energy and carbon goals for 2050, it will be interesting to explore how the design of new spaces might accommodate our new approaches to addressing window views. But we often forget that, in the developed world, 80% of the buildings we will occupy in 2050 are in place now. So, it will be essential to determine how to revitalize and reuse most of the world's existing building stock, but in a manner that enhances occupant experience and view, as well as meeting our new COP26 energy and carbon targets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding contributions were provided by: Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 (Lee); ENOVA SF, a Norwegian government enterprise responsible for promotion of environmentally friendly production and consumption of energy (Matusiak); "Early Stage: Tageslicht-Blendung und Virtual Reality" project financed the Austrian Research Promotion Agency FFG (Geisler-Moroder).

References

[1] N.B. Grimm, S.H. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X. Bai, J.M. Briggs, Global change and the ecology of cities, Science 319 (5864) (2008) 756–760.
[2] K.C. Seto, J.S. Golden, M. Alberti, B.L. Turner, Sustainability in an urbanizing planet, Proc. Natl. Acad. Sci. USA 114 (2017) 8935–8938, https://doi.org/10.1073/pnas.1606037114.
[3] B. Güneralp, Y. Zhou, D. Ürge-Vorsatz, M. Gupta, S. Yu, P.L. Patel, M. Fragkias, X. Li, K.C. Seto, Global scenarios of urban density and its impacts on building energy use through 2050, Proc. Natl. Acad. Sci. 114 (34) (2017) 8945–8950.
[4] U.S. Energy Information Administration, 2021.Annual Energy Outlook 2021. Washington, D.C. https://www.eia.gov/outlooks/aeo/ (accessed September 15, 2021).
[5] ANSI/ ASHRAE/ IES, 2019. ANSI/ASHRAE/ IES Standard 90.1-2019, Energy Efficiency Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
[6] A.M. Ludlow, The functions of windows in buildings, Light. Res. Technol. 8 (2) (1976) 57–68.
[7] I.T. Dogrusoy, M. Tureyen, A field study on determination of preferences for windows in office environments, Build. Environ. 42 (10) (2007) 3660–3668.
[8] M. Andersen, Unweaving the human response in daylighting design, Build. Environ. 91 (2015) 101–117.
[9] J.L. Price, J. Blau, A. Rothenfluh, M. Abodeely, B. Kloss, M.W. Young, double-time is a novel Drosophila clock gene that regulates PERIOD protein accumulation, Cell 94 (1998) 83–95.
[10] Nobel Assembly at Karolinska Institutet, 2017. "Nobel Prize in Physiology or Medicine, Jeffrey C. Hall, Michael Rosbash and Michael W. Young, for their discoveries of molecular mechanisms controlling the Circadian rhythm", https://www.nobelprize.org/prizes/medicine/2017/press-release/ (accessed September 15, 2021).
[11] N. Šprah, M. Košir, Daylight provision requirements according to EN 17037 as a restriction for sustainable urban planning of residential developments, Sustainability 12 (1) (2020) 315.
[12] S.W. Lockley, G.C. Brainard, C.A. Czeisler, High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light, J. Clin. Endocrinol. Metab. 88 (9) (2003) 4502–4505.
[13] R.J. Lucas, G.S. Lall, A.E. Allen, T.M. Brown, How rod, cone, and melanopsin photoreceptors come together to enlighten the mammalian circadian clock, Prog. Brain Res. 199 (2012) 1–18.
[14] M.H. Smolensky, L.L. Sackett-Lundeen, F. Portaluppi, Nocturnal light pollution and underexposure to daytime sunlight: Complementary mechanisms of circadian disruption and related diseases, Chronobiol. Int. 32 (8) (2015) 1029–1048.
[15] H. Calligaro, O. Dkhissi-Benyahya, S. Panda, Ocular and extraocular roles of neuropsin in vertebrates, Trends Neurosci. (2021), https://doi.org/10.1016/tins.2021.11.008.
[16] M.T.T. Nguyen, S. Vemaraju, G. Nayak, Y. Odaka, E.D. Buhr, N. Alonzo, U. Tran, M. Batie, B.A. Upton, M. Darvas, Z. Kozmik, An opsin 5–dopamine pathway mediates light-dependent vascular development in the eye, Nat. Cell Biol. 21 (4) (2019) 420–429.
[17] J. van Duijnhoven, M.P. Aarts, H.S. Kort, The importance of including position and viewing direction when measuring and assessing the lighting conditions of office workers, Work 64 (4) (2019) 877–895.
[18] R. Ulrich, View through a window may influence recovery from surgery, Science 224 (4647) (1984), https://doi.org/10.1126/science.6143402.
[19] J.H. Choi, L.O. Beltran, H.S. Kim, Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility, Build. Environ. 50 (2012) 65–75.
[20] R.S. Ulrich, C. Zimring, X. Zhu, J. DuBose, H.B. Seo, Y.S. Choi, X. Quan, A. Joseph, A review of the research literature on evidence-based healthcare design, HERD: Health Environ. Res. Des. J. 1 (3) (2008) 61–125.
[21] E.M. Sternberg, Healing spaces: The science of place and well-being, Harvard University Press, 2010.
[22] M. Adamsson, T. Laike, T. Morita, Annual variation in daily light exposure and circadian change of melatonin and cortisol concentrations at a northern latitude with large seasonal differences in photoperiod length, J. Physiol. Anthropol. 36 (1) (2017) 1–15.
[23] R. Hobday, Myopia and daylight in schools: a neglected aspect of public health?, Perspect Public Health 136 (1) (2016) 50–55.
[24] E. Ne'eman, Visual aspects of sunlight in buildings, Light. Res. Technol. 6 (3) (1974) 159–164.
[25] E. Ne'eman, S. Selkowitz, Windows, skylights, and atria – Occupants' visual/subjective comparison. Proceedings of the ASHRAE International Symposium on the Interface between the Building Envelope and HVAC Systems, Kansas City, MO, June 17-20, 1984. https://escholarship.org/content/qt14k3w4d6/qt14k3w4d6.pdf (accessed September 15, 2021).
[26] E. Ne'eman, R.G. Hopkinson, Critical minimum acceptable window size: a study of window design and provision of a view, Light. Res. Technol. 2 (1) (1970) 17–27.
[27] P. Boyce, C. Hunter, O. Howlett, The benefits of daylight through windows, Rensselaer Polytechnic Institute, Troy, New York, 2003.
[28] Commission Internationale de ÍEclairage (CIE), 2009.Ocular lighting effects on human physiology and behaviour. Vienna, Austria: CIE, 2004/2009, ISBN CIE 158:2009.
[29] M.B. Aries, J.A. Veitch, G.R. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (4) (2010) 533–541.
[30] J.A. Veitch, J. Christoffersen, A.D. Galasiu, Daylight and view through residential windows: effects on well-being, in: Proceedings of Lux Europa, 12th European Lighting Conference, 2013, pp. 1–6.
[31] A. Jamrozik, N. Clements, S.S. Hasan, J. Zhao, R. Zhang, C. Campanella, V. Loftness, P. Porter, S. Ly, S. Wang, B. Bauer, Access to daylight and view in an office improves cognitive performance and satisfaction and reduces eyestrain: A controlled crossover study, Build. Environ. 165 (2019).
[32] E.O. Wilson, Biophilia, Harvard University Press, Cambridge, MA, 1984.
[33] R. Kaplan, The role of nature in the context of the workplace, Landscape Urban Plann. 26 (1–4) (1993) 193–201.
[34] E. Karjalainen, T. Sarjala, H. Raitio, Promoting human health through forests: overview and major challenges, Environ. Health Prev. Med. 15 (1) (2010) 1–8.
[35] H. Frumkin, G.N. Bratman, S.J. Breslow, B. Cochran, P.H. Kahn Jr, J.J. Lawler, P.S. Levin, P.S. Tandon, U. Varanasi, K.L. Wolf, S.A. Wood, Nature contact and human health: A research agenda, Environ. Health Perspect. 125 (7) (2017).
[36] Stephen R. Kellert, Judith H. Heerwagen, Martin L. Mador, Biophilic Design: The Theory, Science, And Practice of Bringing Buildings to Life, 1st ed., Jon Wiley & Sons Inc, New Jersey, 2008.
[37] Sustainable architectural design, see https://en.wikipedia.org/wiki/Sustainable_design (accessed September 15, 2021).
[38] L. Heschong, Visual Delight in Architecture: Daylight, Vision, and View, Routledge, 2021.
[39] T.A. Markus, The function of windows—A reappraisal, Build. Sci. 2 (2) (1967) 97–121.
[40] B.L. Collins, Review of the psychological reaction to windows, Light. Res. Technol. 8 (2) (1976) 80–88.
[41] A.D. Galasiu, J.A. Veitch, Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review, Energy Build. 38 (7) (2006) 728–742.
[42] H.I. Hellinga, "Daylight and View: The Influence of Windows on the Visual Quality of Indoor Spaces", 2013. Available at: http://resolver.tudelft.nl/uuid:2daeb534-9572-4c85-bf8f-308f3f6825fd (accessed September 15, 2021).

[43] L. Mirza, Windowscapes: A study of landscape preferences in an urban situation, 2015. PhD diss., University of Auckland. https://researchspace.auckland.ac.nz/handle/2292/26068 (accessed September 15, 2021).
[44] M. Knoop, O. Stefani, B. Bueno, B. Matusiak, R. Hobday, A. Wirz-Justice, K. Martiny, T. Kantermann, M.P.J. Aarts, N. Zemmouri, S. Appelt, Daylight: What makes the difference?, Lighting Res Technol. 52 (3) (2020) 423–442.
[45] M. Waczynska, N. Sokol, J. Martyniuk-Peczek, Computational and experimental evaluation of view out according to European Standard EN17037, Build. Environ. 188 (2021).
[46] W.H. Ko, M.G. Kent, S. Schiavon, B. Levitt, G. Betti, A window view quality assessment framework, LEUKOS (2021) 1–26.
[47] W.H. Ko, S. Schiavon, H. Zhang, L.T. Graham, G. Brager, I. Mauss, Y.W. Lin, The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build. Environ. 175 (2020).
[48] Heschong Mahone Group, 2003.Windows and Offices: A Study of Office Worker Performance and the Indoor Environment. Technical report, California Energy Commission, P500-03-082-A-9, October 2003. http://h-m-g.com/downloads/Daylighting/A-9_Windows_Offices_2.6.10.pdf (accessed September 15, 2021).
[49] L. Heschong, Windows and office worker performance. In: Croomes, D. (editor), Creating the Productive Workplace; Taylor & Francis: London, UK, 2006, p.277.
[50] L. Heschong, R.L. Wright, S. Okura, Daylighting impacts on human performance in school, J. Illum. Eng. Soc. 31 (2) (2002) 101–114.
[51] D. Dutton, Authenticity in art, The Oxford Handbook of Aesthetics (2003) 258–274.
[52] D. Dutton, The Art Instinct: Beauty, Pleasure, & Human Evolution, Oxford University Press, USA, 2009.
[53] J. Appleton, Landscape Evaluation: The Theoretical Vacuum, Trans. Inst. Br. Geogr. 66 (1975) 120–123.
[54] J. Appleton, Prospects and Refuges Re-Visited, Landscape J. 3 (2) (1984) 91–103.
[55] R.S. Ulrich, Natural versus urban scenes: Some psychophysiological effects, Environment and behavior 13 (5) (1981) 523–556.
[56] S. Kaplan, Aesthetics, affect, and cognition: Environmental preference from an evolutionary perspective, Environ. Behav. 19 (1) (1987) 3–32.
[57] F. Abd-Alhamid, M. Kent, J. Calautit, Y. Wu, Evaluating the impact of viewing location on view perception using a virtual environment, Build. Environ. 180 (2020).
[58] C. Bethea, Nightmare of the Windowless Dorm Room. The New Yorker, November 22, 2021.
[59] B.S. Matusiak, C. Amorim, S. Sibilio, J. Martyniuk-Peczek, Y. Koga, Home office survey in the scope of the IEA SHC Task 61, The lighting conditions for students. International Commission on Illumination, CIE 2021, Kuala Lumpur, Malaysia, September 27-29, 2021, https://malaysia2021.cie.co.at/sites/default/files/cie_2021_abstract_booklet_0.pdf (accessed September 15, 2021).
[60] N. Tuaycharoen, P.R. Tregenza, View and discomfort glare from windows, Light. Res. Technol. 39 (2) (2007) 185–200.
[61] B.S. Matusiak, C.A. Klöckner, How we evaluate the view out through the window, Architect. Sci. Rev. 59 (3) (2016) 203–211.
[62] I. Konstantzos, Y.C. Chan, J.C. Seibold, A. Tzempelikos, R.W. Proctor, J.B. Protzman, View clarity index: A new metric to evaluate clarity of view through window shades, Build. Environ. 90 (2015) 206–214.
[63] W.H. Ko, G. Brager, S. Schiavon, S. Selkowitz, Building envelope impact on human performance and well-being: experimental study on view clarity. University of California, Berkeley, California, October 15, 2017. https://escholarship.org/content/qt0gj8h384/qt0gj8h384.pdf (accessed September 15, 2021).
[64] M.S. Khanie, Image-based characterization of view in virtual reality. Build for Life conference 2021, Daylight Symposium, November 17, 2021. https://buildforlife.velux.com/daylight-symposium-stage/ (accessed September 15, 2021).
[65] K. Chamilothori, J. Wienold, M. Andersen, Adequacy of immersive virtual reality for the perception of daylit spaces: comparison of real and virtual environments, Leukos 15 (2–3) (2019) 203–226.
[66] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study, Build. Environ. 97 (2016) 177–195.
[67] R.D. Clear, Technical Memo: Post-occupancy evaluation of The New York Times Headquarters Building: An examination of causes for occupant satisfaction and dissatisfaction with the energy-efficiency measures. Lawrence Berkeley National Laboratory, Berkeley, California, October 8, 2010. https://eta-publications.lbl.gov/sites/default/files/nyt-lbl-occu-satisfaction.pdf (accessed September 15, 2021).
[68] Lee, E.S., Fernandes, L.L., Coffey, B., McNeil, A., Clear, R.D., Webster, T., Bauman, F., Dickerhoff, D., Heinzerling, D., Hoyt, T., 2013. A post-occupancy monitored evaluation of the dimmable lighting, automated shading, and underfloor air distribution system in The New York Times Building. Lawrence Berkeley National Laboratory LBNL-6023E, Berkeley, California, January 2013. https://escholarship.org/content/qt3km3d2sn/qt3km3d2sn.pdf (accessed September 15, 2021).
[69] A. Hinge, Post occupancy study of The New York Times Building: Survey findings assessing occupant comfort and satisfaction. Sustainable Energy Partnerships, Tarrytown, New York, November 10, 2010. https://eta-publications.lbl.gov/sites/default/files/nyt-sep-survey-results.pdf (accessed September 15, 2021).
[70] Lee, E.S., Fernandes, L.L., Touzani, S., Thanachareonkit, A., Pang, X. and Dickerhoff, D., 2016. Electrochromic Window Demonstration at the 911 Federal Building, 911 Northeast 11th Avenue, Portland, Oregon. Lawrence Berkeley National Laboratory, LBNL-2001195, Berkeley, California. https://www.osti.gov/servlets/purl/1506249 (accessed September 15, 2021).
[71] Fernandes, L.L., Lee, E.S., Dickerhoff, D., Thanachareonkit, A., Wang, T. and Gehbauer, C., 2018. Electrochromic Window Demonstration at the John E. Moss Federal Building, 650 Capitol Mall, Sacramento, California.Lawrence Berkeley National Laboratory, LBNL-2001183, Berkeley, California. https://escholarship.org/content/qt8qk0m5vb/qt8qk0m5vb.pdf (accessed September 15, 2021).
[72] R.D. Clear, V. Inkarojrit, E.S. Lee, Subject responses to electrochromic windows, Energy Build. 38 (7) (2006) 758–779.
[73] E.S. Lee, L.L. Fernandes, T. Wang, S.E. Selkowitz, S. Mesh, Y. Frank, R. Yancey, Demonstration of energy efficient retrofits for lighting and daylighting in New York City office buildings, Lawrence Berkeley National Laboratory, Berkeley, California, 2017, https://eta-publications.lbl.gov/sites/default/files/nyc-living-lab-final-report.pdf (accessed September 15, 2021).
[74] D. Philips, Daylighting, Routledge, London, 2004.
[75] N. Baker, K. Steemers, Daylight Design of Buildings, A Handbook for Architects and Engineers, Routledge, London, 2002.
[76] M.L. Amundadottir, S. Rockcastle, M.S. Khanie, M. Andersen, A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior, Build. Environ. 113 (2017) 5–21.
[77] CEN, 2018. European Standard EN17037 Daylight in buildings. Brussels: Comité Européen de Normalisation, December 2018.
[78] USGBC, Leadership in Energy and Environmental Design (LEED) version 4.1, U.S. Green Building Council, Washington, D.C., 2019.
[79] ICC, International green construction code (IgCC): A comprehensive solution for high-performance buildings, International Code Council, Washington, D. C., 2021, p. 2021.
[80] ASHRAE, ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2020 Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Peachtree Corners, Georgia, 2020.
[81] CEN, CEN/TC 33 European Standard, CSN EN 14501 Blinds and shutters - Thermal and visual comfort - Performance characteristics and classification, Comité Européen de Normalisation, Brussels, 2021.
[82] CEN, CEN/TC 33 European Standard, CSN EN 14500 Blinds and shutters - Thermal and visual comfort - Test and calculation methods, Comité Européen de Normalisation, Brussels, 2021.
[83] J. Mardaljevic, Aperture-based daylight modelling: Introducing the "view lumen", 2019. Loughborough University, https://repository.lboro.ac.uk/articles/conference_contribution/Aperture-based_daylight_modelling_Introducing_the_View_Lumen_/9458474 (accessed September 15, 2021).
[84] I. Turan, A. Chegut, D. Fink, C. Reinhart, Development of view potential metrics and the financial impact of views on office rents, Landscape Urban Plann. 215 (2021).
[85] W. Li, H. Samuelson, A new method for visualizing and evaluating views in architectural design, Dev. Built Environ. 1 (2020).
[86] G. Ward, R. Mistrick, E.S. Lee, A. McNeil, J. Jonsson, Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within Radiance, Leukos, J. Illumin. Eng. Soc. North America 7 (4) (2010).
[87] E.S. Lee, D. Geisler-Moroder, G. Ward, Modeling the direct sun contribution in buildings using matrix algebraic approaches: Methods and validation, Sol. Energy 160 (2018) 380–395.
[88] G.J. Ward, T. Wang, D. Geisler-Moroder, E.S. Lee, L.O. Grobe, J. Wienold, J.C. Jonsson, Modeling specular transmission of complex fenestration systems with data-driven BSDFs, Build. Environ. 196 (2021) 107774.
[89] Geisler-Moroder, D., Ward, G.J., Wang, T., Lee, E.S., 2021.Peak extraction in daylight simulations using BSDF data. Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.
[90] S. Arbab, B.S. Matusiak, F.A. Martinsen, B. Hauback, The impact of advanced glazing on colour perception, J International Colour Association 2017 (17) (2017) 50–68.
[91] A.I. Ruppertsberg, M. Bloj, Creating physically accurate visual stimuli for free: Spectral rendering with RADIANCE, Behav. Res. Methods 40 (1) (2008) 304–308.
[92] Geisler-Moroder, D., Dür, A., 2009. Color-rendering indices in global illumination methods. Journal of Electronic Imaging 18, 4, 043015–1–043015–12.
[93] IPICA Software LLC, 2021. Pixel Density, PPM and PPF in Video Surveillance. https://www.jvsg.com/pixel-density/ (accessed September 15, 2021).
[94] Inanici, M., ZGF Architects, 2015. Lark spectral lighting.https://faculty.washington.edu/inanici/Lark/Lark_home_page.html (accessed September 15, 2021).
[95] Solemma, 2017. ALFA Adaptive Lighting for Alertness. A new circadian lighting design software. https://www.solemma.com/alfa (accessed September 15, 2021).
[96] A.K. Diakite-Kortlever, M. Knoop, Forecast accuracy of existing luminance-related spectral sky models and their practical implications for the

assessment of the non-image-forming effectiveness of daylight, Light. Res. Technol. (2021), https://doi.org/10.1177/1477153520982265.
[97] D. Durmus, Spatial frequency and the performance of image-based visual complexity metrics, IEEE Access 8 (2020) 100111–100119.
[98] A.J. Wilkins, O. Penacchio, U. Leonards, The built environment and its patterns: a view from the vision sciences. Journal of Sustainable Design and Applied Research in Innovative Engineering of the Built, Environment 6 (1) (2018) 5.
[99] A. McNeil, Rendering omni-directional stereo images with Radiance and more, 2016 Radiance Workshop, 2016.
[100] J. Carmody, S. Selkowitz, E.S. Lee, D. Arasteh, T. Willmert, Window system for high-performance buildings, W.W. Norton and Company Inc, New York, 2004.
[101] L. Fernandes, E.S. Lee, A. McNeil, J.C. Jonsson, T. Nouidui, X. Pang, Angular selective window systems: Assessment of technical potential for energy savings, Energy Build. 90 (2015) 188–206.
[102] S. Hoffmann, E.S. Lee, A. McNeil, L. Fernandes, D. Vidanovic, A. Thanachareonkit, Balancing daylight, glare, and energy-efficiency goals: An evaluation of exterior coplanar shading systems using complex fenestration modeling tools, Energy Build. 112 (2016) 279–298.
[103] A. Shehabi, N. DeForest, A. McNeil, E. Masanet, J. Greenblatt, E.S. Lee, G. Masson, B.A. Helms, D.J. Milliron, US energy savings potential from dynamic daylighting control glazings, Energy Build. 66 (2013) 415–423.
[104] Griffith, B., Long, N., Torcellini, P., Judkoff, R., Crawley, D. and Ryan, J., 2007. Assessment of the technical potential for achieving net zero-energy buildings in the commercial sector (No. NREL/TP-550-41957). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://www.nrel.gov/docs/fy08osti/41957.pdf (accessed September 15, 2021).
[105] J. Langevin, C.B. Harris, J.L. Reyna, Assessing the potential to reduce US building CO2 emissions 80% by 2050, Joule 3 (10) (2019) 2403–2424.
[106] Wetter, M., Nouidui, T.S., Lorenzetti, D., Lee, E.A. and Roth, A., 2015. Prototyping the next generation EnergyPlus simulation engine. Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, Hyderabad, India, December 7-9, 2015.
[107] C. Gehbauer, D.H. Blum, T. Wang, E.S. Lee, An assessment of the load modifying potential of model predictive controlled dynamic facades within the California context, Energy Build. 210 (2020) 109762.
[108] C.F. Reinhart, K. Voss, Monitoring manual control of electric lighting and blinds, Light. Res. Technol. 35 (3) (2003) 243–258.
[109] Inkarojrit, V., 2005. Balancing comfort: occupants' control of window blinds in private offices. Doctoral dissertation, University of California, Berkeley. https://escholarship.org/content/qt3rd2f2bg/qt3rd2f2bg.pdf (accessed September 15, 2021).
[110] Schweiker, M., Ampatzi, E., Andargie, M.S., Andersen, R.K., Azar, E., Barthelmes, V.M., Berger, C., Bourikas, L., Carlucci, S., Chinazzo, G. and Edappilly, L.P., 2020. Review of multi-domain approaches to indoor environmental perception and behaviour. Building and Environment, 176, p.106804.
[111] M.D. Velarde, G. Fry, M. Tveit, Health effects of viewing landscapes–Landscape types in environmental psychology, Urban For. Urban Greening 6 (4) (2007) 199–212.
[112] Rodriguez, F., 2021."Cultural perspectives in view quality assessment: Testing adaptive responses to urban views in a VR experiment".Build for Life conference 2021, Daylight Symposium, November 17, 2021. https://buildforlife.velux.com/daylight-symposium-stage/ (accessed September 15, 2021).
[113] B.S. Matusiak, No-Greenery Line and Greenery-View Factor, New Architectural Design Tools, J. Daylighting 7 (2) (2020) 282–286.
[114] Solemma, 2021. ClimateStudio View Analysis. https://climatestudiodocs.com/docs/viewAnalysis.html (accessed September 15, 2021).
[115] Geisler-Moroder, D., Lee, E.S., Ward, G., Bueno, B., Grobe, L.O., Wang, T., Deroisy, B., Wilson, H.R. (2021). BSDF generation procedures for daylighting systems. White paper. T61.C.2.1 - A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77, https://task61.iea-shc.org/publications (accessed September 15, 2021).
[116] Geisler-Moroder, D., Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Jonsson, J.C., Lee, E.S., Tian, Z., Wang, T., Ward, G.J., Wilson, H.R., Wu, Y., 2021. Analysis and evaluation of BSDF characterization of daylighting systems. T61.C.2.2 – A Technical Report of Subtask C, IEA SHC Task 61 / EBC Annex 77, https://task61.iea-shc.org/publications (accessed September 15, 2021).
[117] B.P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey, R. Hart, Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities, Sol. Energy Mater. Sol. Cells 96 (2012) 1–28.
[118] T.E. Kuhn, Calorimetric determination of the solar heat gain coefficient g with steady-state laboratory measurements, Energy Build. 84 (2014) 388–402.
[119] R. Hart, S. Selkowitz, C. Curcija, February. Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings, Build. Simul. 12 (1) (2019) 79–86.
[120] https://www.cleancoolingcollaborative.org/ (accessed September 15, 2021).
[121] International glazing Database, https://windows.lbl.gov/software/igdb (accessed September 15, 2021).
[122] N. DeForest, A. Shehabi, J. O'Donnell, G. Garcia, J. Greenblatt, E.S. Lee, S. Selkowitz, D.J. Milliron, United States energy and CO2 savings potential from deployment of near-infrared electrochromic window glazings, Build. Environ. 89 (2015) (2015) 107–117.
[123] S. Selkowitz, Reflections on surface morphology, Nat. Energy 6 (5) (2021) 456–457.
[124] Lee, E.S., 2018."Innovative glazing materials" in Desideri, U. and Asdrubali, F. eds., 2018. Handbook of energy efficiency in buildings: a life cycle approach. Butterworth-Heinemann. https://escholarship.org/content/qt4qj376pk/qt4qj376pk.pdf (accessed September 15, 2021).
[125] R.J. Mortimer, Switching colors with electricity: Electrochromic materials can be used in glare reduction, energy conservation and chameleonic fabrics, Am. Sci. 101 (1) (2013) 38–46.
[126] F. Fiorito, M. Sauchelli, D. Arroyo, M. Pesenti, M. Imperadori, G. Masera, G. Ranzi, Shape morphing solar shadings: A review, Renew. Sustain. Energy Rev. 55 (2016) 863–884.
[127] Schneider, M., Fransén Waldhör, E., Denz, P.R., Vongsingha, P., Suwannapruk, N. and Sauer, C., 2020. Adaptive textile façades through the integration of Shape Memory Alloy. Proceedings of Acadia 2020, Distributed Proximities, October 24-30, 2020. http://papers.cumincad.org/data/works/att/acadia20_360.pdf (accessed September 15, 2021).
[128] Chamilothori, K. (2019). Perceptual effects of daylight patterns in architecture (Doctoral dissertation, Ecole polytechnique fédérale de Lausanne, Lausanne, Switzerland). doi:10.5075/epfl-thesis-9553.
[129] Chamilothori, K., Chinazzo, G., Rodrigues, J., Dan-Glauser, E.S., Wienold, J. and Andersen, M., 2019. Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality. Building and Environment, 150, pp.144-155.
[130] K. Konis, Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California, Build. Environ. 59 (2013) 662–677.
[131] Matusiak, B., Fosse, P. and Sørgjerd, A.E., 2009. Daylighting/lighting preferences for subjects with visual impairment and for subject with normal vision. A full-scale study in a room laboratory. Norges teknisk-naturvitenskapelige universitet. Trondheim (Norway): Fakultet for arkitektur og billedkunst. DOI: 10.13140/2.1.4168.6723, Report number: ISBN: 978-82-7551-050-9.
[132] F. Rodriguez, V. Garcia-Hansen, A. Allan, G. Isoardi, Subjective responses toward daylight changes in window views: Assessing dynamic environmental attributes in an immersive experiment, Build. Environ. 195 (2021).
[133] Haase W, Husser M, Sobek W. Potential of structured switchable glazing, Proceedings for Glass Performance Days, Tampere, Finland, June 28-30, 2017, pp. 206-210.
[134] K.G. Van Den Wymelenberg, Visual comfort, discomfort glare, and occupant fenestration control: developing a research agenda, Leukos 10 (4) (2014) 207–221.
[135] Van Den Wymelenberg, K.G., 2021.Taskshade, https://www.thetaskshade.com/ (accessed September 15, 2021).
[136] Gentile, N., Osterhaus, W. et al. 2021. Integrating daylighting and lighting in practice. T61.D – A Technical Report of Subtask D. IEA SHC Task 61 / EBC Annex 77, IEA SHC. https://task61.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task61–Technical-Report-D3-D4-Integrated-Solutions-for-Daylighting-and-Electric-Lighting.pdf (accessed September 15, 2021).
[137] Ruck, N., O. Aschehoug, S. Aydinli, J. Christoffersen, G. Courret, I. Edmonds, R. Jakobiak, M. Kischkoweit-Lopin, M. Klinger, E.S. Lee, L. Michel, J.L. Scartezzini, S. Selkowitz. 2000. Daylight in buildings: A source book on daylighting systems and components. LBNL-47493, https://facades.lbl.gov/sites/default/files/daylight-in-buildings.pdf (accessed September 15, 2021).
[138] L.L. Fernandes, E.S. Lee, G. Ward, Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort, Energy Build. 61 (2013) 8–20.
[139] A. McNeil, E.S. Lee, J.C. Jonsson, Daylight performance of a microstructured prismatic window film in deep open plan offices, Build. Environ. 113 (2017) 280–297.
[140] J. Peng, D.C. Curcija, A. Thanachareonkit, E.S. Lee, H. Goudey, S.E. Selkowitz, Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window, Appl. Energy 242 (2019) 854–872.
[141] C.J. Traverse, R. Pandey, M.C. Barr, R.R. Lunt, Emergence of highly transparent photovoltaics for distributed applications, Nat. Energy 2 (11) (2017) 849–860.
[142] A. Guillemin, N. Morel, An innovative lighting controller integrated in a self-adaptive building control system, Energy Build. 33 (5) (2001) 477–487.
[143] Zarkadis, N., Morel, N. and Scartezzini, J.L., 2015. A novel occupant-adapted and fuzzy logic-ready visual comfort modelling approach using machine learning algorithms. In Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale (No. CONF, pp. 419-424). LESO-PB, EPFL.
[144] Gehbauer, C., Rippl, A., Lee, E.S., Advanced Control of Dynamic Facades and HVAC with Reinforcement Learning, Proceedings of Building Simulation 2021, International Building Performance Simulation Association, Bruges, September 1-3, 2021.
[145] International Energy Agency, Task 61, A Subtask, User perspective and requirements, A.2 Use cases https://task61.iea-shc.org/publications.
[146] International Energy Agency, Task 61, A Subtask, User perspective and requirements, A.3 Personas https://task61.iea-shc.org/publications.