Human-Driven Daylighting: research perspectives and outlook

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Abstract

Daylighting opens up a range of topics of investigation at the interface between architecture and building technology, especially when focusing on the integration of building performance in design. While it has a strong impact on human health and well-being, and an undeniable association with (subjective) emotional delight and perceived quality of a space, it is also highly dynamic and variable in nature, based on a combination of predictable (sun course) and stochastic (weather) patterns, which makes it both a challenging and essential aspect of how "performative" a space can be considered. This paper aims to provide an overview of research perspectives regarding how architectural design, building engineering and other domains of science could be more strongly bridged to address the need for meaningful metrics in architectural design and propose approaches to integrate the complexity of human needs in buildings into effective design and decision-making support.

Keywords: daylighting, well-being, design support, visual comfort.

1. Introduction

In the contemporary context of building for sustainability, the integration of building performance criteria into the design process has received a great level of attention in the last two decades. Simulation models of increasing degree of sophistication [1] have been developed to evaluate the energy impacts of satisfying these benchmarks with active electric lighting, heating or cooling to compensate for excessive or insufficient daylight and its associated tradeoff – solar gains – in terms of thermal comfort. A wide range of metrics and of tools are now available and still being developed to support our search for minimizing energy consumption or ecological footprint. It is typically based on the principle that the performance of a space will increase with user satisfaction and decrease with energy consumption [2] (towards discomfort compensation until occupant satisfaction is reached). In today's energy crisis, minimizing this compensation becomes essential but requires a very good understanding of our comfort requirements, used as triggers for (predicted) action on our environment according to still poorly understood interaction patterns with building controls (dimming, thermostats, shading etc) [3,4]. Static comfort thresholds can only provide an incomplete picture and have led, in the 30ies to 60ies, to an era of windowless, air-conditioned offices and classrooms as ultimate symbols of progress specifically because they adhered – under full control – to accepted standards for comfort. We have now realized that our needs far surpass these universal ones [5] and include a longing to bond with our living environment (biophilia hypothesis) as well as a need to stay connected to its ever-changing nature through windows and views [6]. While we share fundamental needs driven by evolution, it is very clear that people value things differently, and have needs far from being monolithic at several levels:

- *diversity*: Individual preferences about privacy, temperature swings, or architectural character e.g. depend on factors ranging from cultural background and social status to health and age.
- *variability*: The temporal variability of our needs results from our inherent attachment – at both the psychological and physiological levels – to a very variable outside environment (seasons, time of day, weather, vegetation, light-dark cycles).
- *boundaries*: In today's urge to design sustainably, we must think within an overarching reality of finite resources; to reduce our carbon footprint and use of non-renewable energy, the building sector – that accounts for 40% of them – plays a pivotal role.

The architect is faced with multiple, highly variable, bounded criteria that can conflict but need to be brought together to lead to a satisfying solution. The ultimate balance cannot be solely based on measurable criteria: a design process does not reproduce conventional optimization because of its inherent non-linearity and reliance on elements that cannot always be objectified. Unlike clothing that can easily and continuously be adjusted to both user preferences and outside conditions, buildings are constrained to a somewhat limited set of materials and to basic adaptation (shading, operable windows), which prevents them from responding to individuals to the same degree of refinement as clothing: preferences have somehow to be synthesized, and the main role of the architect is to do this synthesis. How we can help architects synthesize complex, dynamic and often conflicting goals – regarding function, structure, energy, comfort and many more – into an integrated built form remains a big, and exciting, challenge.

2. Addressing complex human needs in a built environment

Established metrics relevant to daylight penetration have been focusing on finding benchmarks for task illuminance and visual comfort (glare avoidance) [2,4,7,8], with varying degrees of applicability beyond the conditions in which they were measured, and with results that are often difficult to compare [4]. Other studies have also looked at individual preferences [3], or at “light quality” indicators typically derived from luminance averages or ratios [9]. Our own work in this area led to new daylight metrics concepts, associated to entire space areas [10] or viewed scenes [11] rather than individual detection points, and to relative approaches for more complex systems [12]. It hence shifted the focus back on daylight variability, not only its spatial distribution [10,11,13]. These multiple efforts led to a strong interest in assessing the potential of optimization to support design, based on methods ranging from generative design to human-guided search, knowledge-based or expert systems, where our work [14] was instrumental to demonstrate the under-explored potential of iterative processes to increase control and educational value [15].

Where technology can help is in allowing the architect to go beyond his or her own sensitivity: the extent to which a design answers even dynamic and highly refined goals can be determined systematically – though it might require enormous calculation capacities – so that the architect can extract an informed synthesis. And this process starts by defining design or performance goals [10,13], which can then be gauged against more or less refined models or metrics. Human-driven goals have to encompass individual diversity and temporal variability: as we know, to feel comfortable in a space can result in very different constraints depending on the time of day, the season and the location of the building, and human factors will induce diverging preferences for comfort from individual to another. The necessary flexibility and dynamic response of design goals also applies to our cyclic physiological needs or to the ever-changing ambiance of a space that contributes so intimately to its uniqueness. Starting to address such questions will foster a re-thinking of the integration of technology both in the design process and in actual building systems.

3. The ‘human’ challenge

The ultimate objective is to provide building designers with the means necessary to assess critical parameters in a successful design and efficiently combine qualitative and quantitative criteria in the solution search process. This must be approached from two perspectives: from what we have and from what we need. Of course the resources available to work with (i.e. the building’s environment whether natural and/or built, its localisation, climate etc) must be analysed, and we must process this information to inform us about how the building should respond to it; but first, we have to identify the needs of the building’s occupants, to determine whether and how these can be met.

The ‘human’ challenge at hand is two-fold. It comes from the human nature of the designer, which remains the main driver of a design process: the ultimate balance between multiple, often-conflicting criteria cannot solely be based on measurable parameters, thus the design process must remain non-deterministic. And it comes from the human nature of the occupants, with diverse and variable needs. This perspective actually asks us to move away from evaluating performance as an absolute value ranging from good to bad, because the concept of performance itself becomes dynamic: performance should be measured against goals that might vary over time (variability), by occupant profile (diversity) and/or be subjective (designer’s intent). This therefore opens up new research perspectives as to how we could can empower the designer with computation, with a focus on educational potential rather than performance optimization, and further investigate the relationships between occupants and a built environment with a focus on their dynamics.

4. Decision support for human designers

Although it remains the way design support technology has been developed to date, architectural design cannot be replicated by a well-defined computational process: optimization does not respond well to the non-deterministic, ill-defined and unpredictable nature of the design process, which is exactly where its creativity lies. To get technology to support human-centered design, we must put designers back into their essential role, which is not to test and optimize – tasks for which a computer might be more efficient indeed – but to know what to look for.

4.1 Ill-defined design dialog

Towards this end, we should maintain the ill-definition inherent to the creative design process and build a dialog with the user respectful of implicit design intents, that avoids splitting the problem into smaller or alternative well-defined ones [16]. The ambition of such a system would thus be to emphasize educational potential around a goal-based structure where performance objectives can be implicit (subjective, e.g. preference) or explicit (objective, e.g. relative to prescribed thresholds), and which offers an iterative, open-ended platform to engage the user in the exploration of an inherently incomplete problem-space.

A preliminary concept for this kind of platform would be to build a shareable knowledge-base of design effects, where performance impacts can be stored and where model similarities are evaluated to predict effects on performance. The idea would be to integrate user inputs through an immersive interface that includes a case-based 'Machine Learning' structure to collect and later match user inputs, and a 'Clustering' engine for design changes classification into representative groups. This should lead to an iterative adoption of design changes, similarly to an iterative expert system we developed for a full-year interactive daylighting design support platform called Lightsolve [13-15] but with a more efficient balancing of requests to the knowledge-base and to the calculation engine.

4.2 Bridging the gap between technology users and technology developers

In parallel, more research is needed to advance the state of the art in façade technologies for high-performance buildings and in more refined approaches to measure light and heat in buildings; perhaps most importantly, a lot of effort should also be spent on figuring out how this information can be efficiently represented to support decision making. This means developing new assessment capabilities – both experimental and simulation based – for cutting edge technology solutions in combination with new approaches in integrating performance considerations in the design process.

4.2.1 Meaningful metrics for advanced envelope systems

An exemplar platform to bridge the gap between the priorities designers have when making such decisions for their project, and the data that technology manufacturers generate and make available about their products, is illustrated by the interactive search and selection platform called D-LITE [17] (http://www.d-lite.org). Along the same perspective of facilitating decisions regarding complex façade systems and technologies for designers or building owners and occupants, we devised a unique set of synthetic performance metrics aiming to provide intuitive, relative scores regarding their energy impact, visual comfort and view through potential to allow them to be compared to one another [12].

4.2.2 Advances in façade technology

On the other hand, new technologies are being developed by both industries and research groups. An example is the deep-daylighting technology – now patented – that our group designed and, through an industry partnership, successfully brought to be installed on a 10 stories office building in Downtown Tokyo; in parallel, we are currently investigating devices based on shape memory alloys and capable of reacting adaptively to sun availability or opportunities provided by mirrored assemblies within the building skin to mitigate view and solar control simultaneously. In the long run, further developments on smart, adaptive building control systems (lighting, shading) and on new performance evaluation models could further catalyze the identification of the proper (existing) systems for a given project, and help hierarchizing priorities for new technology developments.

5. Decision support for human occupants

To embed the diversity and variability of human needs as foundational elements of design and put human occupants back at the core of the building question, we need to reach out to fundamental discoveries from neuroscience, biology and other fields, which will bring new insights and a deeper understanding of how we interact with our environment.

5.1 Reaching out to new research fields

The multiplicity and variability of our needs regarding (day)light exposure, for instance, have been a topic of investigation for years now in photobiology and psychophysics, though have not yet penetrated the design realm as dynamic models of human response. A new research field in non-image forming lighting has emerged in photobiology from the recent discovery of a specialized photoreceptor in our eye's ganglion cells – named melanopsin –, responsible for synchronizing our internal circadian pacemaker. In addition to our pioneering work in starting to engage design with this field [13,18,19], efforts have been put on finding absolute thresholds for light exposure that would lead to health benefits; but no mathematical model exists yet to predict the direct non-visual light effects as a function of spectrum, timing and history. Recent advances in eye-tracking methods from psychophysics, that have so far focused on local stimulus-driven saliency, open up opportunities to uncover relationships between gaze and glare in realistic scenarios; results from a set of pilot studies we conducted [20] holds promise for getting a better grip on the dynamics of visual comfort and of ocular light exposure for non-visual effects. These findings also open up new research pathways on how a space is experienced visually (i.e. what attracts our eye), where investigations have remained limited to search for main preference trends. Daylight as a subjectively perceived visual effect is actually very hard to use as a design factor, yet is often what drives decisions; our early investigations of this perspective have so far led to a promising taxonomy of daylight contrast and variability effects [11], but have an even greater potential if they could be considered from a dynamic, intent-driven design framework.

5.2 Human-centered research perspectives for daylight performance

It is time to bring these exciting new research perspectives back into the design realm in a way it can interactively, dynamically and effectively fuel the creative design process: we have access to the essential ingredients of human-responsive design, now we need to cook. In lieu of recipe, we could start by considering three interpretations of "well-being" in a space: as a human inhabitant of a living space, as a user of a (work)space, and as a witness of a delightful space, as discussed in the examples provided below of our group's current research directions.

5.2.1 Healthy living

Humans needs to be in an environment conducive to health and have physiological light exposure needs, whose time- and spectrum-dependent non-visual effects we only start to understand thanks to photobiology findings [21]. Based on the discovery of the novel photoreceptors in our eye's ganglion cell layer, responsible for synchronizing our internal circadian clock, light has become not only a therapeutic tool but also an essential element of healthy living. Drawing from the latest findings in photobiology in terms of non-image-forming effects of light exposure, we intend to take the intensity, spectrum, duration/pattern, history, and timing of light exposure as variables to evaluate non-visual responses to light (i.e. affecting health) based on user-specific performance goals. The goal is thus to integrate time-dependencies of spectral response and light patterns, including space-related color effects and behavior patterns, into a dynamic mathematical model of the non-visual system from a goal-based perspective.

5.2.2 Comfortable work

Users of a space often need to perform tasks for which comfortable visual conditions are needed, to which we respond with head and gaze dynamics that psychophysics can help us better recognize. To embed these dynamics, we need to develop new research methods vis-à-vis visual comfort. Existing glare models indeed assume a fixed line of gaze (i.e. static view direction) and are based exclusively on subjective assessments (self-rated comfort) [8]. These simplifications fail to reflect the dynamics of a real visual environment, which has important consequences for predicting comfort in workspaces; hence, ultimately, for promoting productive environments. To address this, we want to add a new dimension to visual comfort analysis by integrating eye-tracking methods to construct a dynamic model of glare to reflect the fact that we behave dynamically in a space [20]. Resorting to eye-movement tracking methods from psychophysics, we aim to integrate objective inter-dependencies between gaze patterns and visual context in a dynamic glare model, so as to create a robust and more realistic predictor of perceived comfort that accounts for gaze dynamics.

5.2.3 Delightful experience

Finally, any attentive witness to a space seeks to enjoy its play of light and dark. Perception of daylight is the primary interpreter of the materiality and dynamism of any architectural space. However, the perceived qualitative aspects of daylight in a varying indoor space are underserved by the simplistic metrics currently available to designers. How then does a designer integrate changing light into design intentions? To provide design support regarding these inherently emotional aspects, we must seek to interpret subjective contrast and variability perception as design factors without objectifying them. Existing studies on quantifying 'light quality' have tried to correlate perceived interest and satisfaction with luminance averages or some measure of their variability over static scenes. The goal here would be to deepen our understanding of perceptual daylight through a dynamic analysis of spatial contrast and its variability over time [11], and to create a novel intent-driven approach, based on qualitative design intentions regarding the luminous character of a space and an annualized taxonomy of contrast effects inspired from contemporary architecture typologies. By first analyzing the relationship between perceived and objectifiable contrast or variability, we would then integrate these as dynamic guiding factors for matching a (subjective) design intent.

6. Conclusion

This area of investigation brings the promise of high impact research both on how we design buildings and how the design process can interface with fundamental discoveries about humans and their behavior. The strong inter-disciplinary nature of this work will create fundamental connections with fields as far from design as neuroscience and psychophysics, brought together around a human-centered perspective. This also includes investigating technological solutions that could optimize the control of daylight and solar radiation, using the newest technologies in façade design and materials. But beyond searching for technological solutions, building technology should cease to be considered as an add-on and should instead become an inherent part of the design process that focuses on the reason we build buildings in the first place: to shelter complex, diverse occupants.

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