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Lighting performance and electrical energy consumption of a virtual window prototype

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HIGHLIGHTS

- We discuss the design and evaluation of a virtual window prototype.
- The prototype was built using LED tiles simulating light and view of a window.
- Lighting performance and power consumption were evaluated in a test room.
- Three daily usage profile scenarios and two annual modes were considered.
- The normalised, total annual electrical energy consumption is found 0.63–0.79.

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ABSTRACT

This article discusses the design and evaluation of a virtual window prototype, built using arrays of LED tiles to simulate the light as well as the view of a window. Arrays of white light LED fixtures with adjustable colour temperatures were incorporated to provide direct light into the test room. Lighting performance was evaluated by measuring horizontal illuminance on the workplane, vertical illuminance on the observer's eye plane, and luminance perceived by the observer at four vertical points. For estimating the electrical energy consumption, real-time power consumption of the entire system was measured, and three daily usage profile scenarios and two annual modes were considered. In addition, five locations were chosen to represent various climate types. The results show that under the maximum setting, the average workplane illuminance was 239 lx for the test room used, whereas discomfort glare at the observer's positions was classified as imperceptible. Patches of direct light on the side walls could be created as an intended effect from installing the direct light source arrays. Variation of average annual space availability within a given location as a function of usage profile is found to be very small; the values are however sensitive to the chosen criterion of workplane illuminance. Based on the designated daily usage profiles and annual modes, the normalised, total annual electrical energy consumption in all climate types is on average within the range of 0.63–0.79, relative to the total electrical energy consumed by the prototype when it constantly displays the maximum intensity setting.

1. Introduction

Research has shown the important role of windows in the indoor environment, and that building occupants feel windows are important due to the preference for having natural light over electric light, e.g. [1,2]. Several studies have reported on beneficial and restorative effects of views onto a natural scene [3], whereas views onto human-built environments yield effects which are similar to having no window at all [4]. Kim and Wineman [5] empirically showed that views and windows have psychological and economic values. With regards to energy use for lighting in buildings, a proper use of natural light from windows can potentially save a considerable amount, e.g. [6–11].

Despite the aforementioned advantages, the quality and quantity of daylight is highly variable, and its availability is limited in space and time. For example, daylight is absent during nighttimes; the buildings can be too deep to let sufficient daylight reach the entire space [12–14]; and some rooms are not provided with

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Nomenclature

Abbreviations

DALI	Digital Addressable Lighting Interface
DGP	Daylight Glare Probability
DMX	Digital Multiplex
HD	High Definition
HDR	High Dynamic Range
ISO	International Standard Organisation (for measuring film speed)
LED	Light-emitting Diode
MRI	Magnetic Resonance Imaging
RGB	Red, Green, Blue
VNLS	Virtual Natural Lighting Solutions

Symbols

$\%A$	space availability (%)
E_v	total vertical eye illuminance (lx)
L_s	glare source luminance (cd/m^2)
P	position index (–)
U_0	uniformity (–)
W_{real}	real-time power consumption (W)
x	normalised DMX value, range 0–1 (–)
ω_s	solid angle of the glare source (sr)

windows, skylights, or any form of daylight transporting systems. Another important fact is that significant fractions of the working population in the world do their work during nighttimes [15]. Night shift workers experience various discomfort issues, due to a lack of synchronisation between the shift work schedule and the worker's light–dark cycle [16–17]. Moreover, many studies have reported that the value of increased productivity due to an improved indoor climate can be greater than the operational and maintenance costs [18–22]. These considerations lead to the demand of having an artificial, or virtual, solution that can bring natural light with all of its qualities to the inside space, while still aiming for a sustainable energy source and/or energy conservation.

To address this issue, the concept of Virtual Natural Lighting Solutions (VNLS), in the form of virtual windows or virtual skylights, has been proposed for some time. Early efforts were mainly focused on bringing view of an outside condition into the room. For example, *trompe l'oeil* is known as an art technique involving imagery which creates an optical illusion that the displayed scenes appear in three dimensions, while actually being only a two-dimensional painting.

More recently, a number of commercial efforts have been developed to provide a virtual view from a window or skylight, using static, translucent photographs in front of a light source. In line with findings of Ulrich et al. [23], the application of virtual windows and skylights can be found particularly in windowless healthcare environments such as critical care units and magnetic resonance imaging (MRI) environments to reduce anxiety of the patient.

Research regarding a virtual window prototype in the form of a backlit, translucent printed image has been performed by Shin et al. [24] with focus on subjective discomfort glare from the view. Investigation on virtual windows in the form of screen projection has been done, for instance by Tuaycharoen and Tregenza [25], also focusing on subjective discomfort glare; and by IJsselsteijn et al. [26], focusing on depth perception cues.

Next to the backlit and projection image technique, other researchers and manufacturers have utilised electronic large, high definition (HD) displays for the purpose of simulating window-views in a more flexible manner, e.g. [27,28]. In particular, evaluation data obtained from test subjects by Radikovic et al. [28] suggested their prototype was a better window substitute than a static image, and had significantly more positive effects on the observers' arousal ($p = 0.009$), positive affect ($p = 0.007$), and interest ($p = 0.032$). The test subjects judged the system prototype as an acceptable replacement for a real window, and gave it higher ratings for realism and preference than a static image ($p < 0.001$).

Subject-based research on HD monitor displays was also done by Friedman et al. [29] and Kahn et al. [30]. The monitors were installed on the walls of seven inside offices of faculty and staff at a university, and displayed a real-time view of the immediate outside scene. The results showed that users deeply appreciated many aspects of the experience, such as the increase in connection to the natural world, psychological wellbeing, and cognitive functioning.

While various virtual window prototypes have been developed, it is observed that most of them do not provide directional (sun-)light, as expected from a real window. Examples of virtual window prototypes that provided sunlight in addition to a simplified sky scene have been developed by ENTPE-EDF Lyon [31–33] and Philips [34]. In the latter, there was a possibility to control the colour gradient and to create the impression of having a patch of sunlight inside the space. It is noticed that the prototype possessed several shortcomings, particularly its relatively small window-to-wall ratio and the use of fluorescent light sources instead of more energy-efficient ones. The virtual sun of that prototype had a relatively low ability to create the impression of a real sun patch in the space.

Therefore, this study aims to design and build a new virtual window prototype with an improved lighting performance and energy consumption compared to the earlier ones. The objectives are twofold; the first one is to evaluate the interior lighting condition inside a test room under various daily settings, and the second one is to estimate the influence of various operating scenarios on the average space availability and total annual electrical energy consumption that would respectively be produced and consumed when applying such prototypes.

2. Design steps

2.1. Test environment

The test environment was built in the new ExperienceLab of Philips Research at the High Tech Campus in Eindhoven, the Netherlands. The dimension of the test room was 6.81 m × 3.63 m × 2.70 m ($L \times W \times H$), slightly longer than the standard reference office room [35]. Two original real window openings were placed on a short wall (south) to enable daylight admission. The virtual window prototype was installed on the opposite wall (north).

In order to avoid daylight entering from outside during the measurements, in the entire experiments, the two real windows were blocked with two white covers of the same colour and reflectance as the surrounding wall finishing. Fig. 1 illustrates the floor plan and section view of the test room.

There were two openings for the prototype; each had a dimension of 0.90 m × 1.20 m ($W \times H$) excluding the window frames,