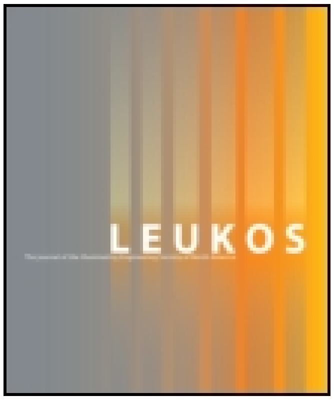

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Analysis of Various Opening Configurations of a Second-Generation Virtual Natural Lighting Solutions Prototype

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ABSTRACT To address the absence of natural light in working spaces, virtual natural lighting solutions (VNLS) can be promising. VNLS are systems that artificially provide lighting as well as a realistic outside view with properties comparable to those of real windows and skylights. This article discusses the evaluation and analysis of various opening configurations of a second-generation VNLS prototype, which features an array of light emitting diode (LED) tiles coupled with a line of linear LED fixtures with adjustable color temperatures that provide direct light. Simulation using Radiance was performed and validated with the measurement results. Various possibilities of placing the prototypes inside the test room were investigated in Radiance to determine the effect on space availability and visual comfort. Based on the comparison of seven configurations of two prototypes with equal total opening size, it was found that nearly all configurations tested yielded a space availability of 100% with a criterion of 200 lx and where space availability is defined as the percentage of points on a horizontal grid that meet or exceed the target illuminance. Taking 300 lx as the criterion, two openings on each short wall facing each other (configuration 2) and four openings on a long wall (configuration 5) yielded space availabilities of more than 90%. Taking 500 lx as the criterion, configurations 2 and 5 yielded space availabilities between 25% and 50%. The highest uniformity ($E_{\mathrm{min}}/E_{\mathrm{avg}}$) was achieved under configuration 2 (0.59), whereas the maximum daylight glare probability (DGP) values under all configurations were between 0.25 and 0.30. Our simulation results suggest that the space availability in a private office can be optimized by placing a VNLS prototype on each short wall facing each other or by placing two on a long wall.

KEYWORDS configuration, prototype, space availability, virtual natural lighting solutions, virtual windows, visual comfort

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1. INTRODUCTION

The benefit of natural light and view from windows in buildings has been widely reported and understood [for example, Aries and others 2010; Berman and others 2008; Chang and Chen 2005; Farley and Veitch 2001; Hartig and others 2003;

Kaplan R 1993; Kaplan S 1995; Kim and Wineman 2005; Markus 1967; Ulrich 1984]. Moreover, a proper use of natural light would potentially save considerable amount of energy from artificial lighting use [for example, Assem and Al-Mumin 2010; Galasiu and Veitch 2006; Hammad and Abu-Hijleh 2010; Yun and others 2010].

However, there are some situations in which natural light is absent or insufficient. For example, the buildings can be too deep to let sufficient daylight reach the entire space [Reinhart 2005; Reinhart and Weismann 2012], and some rooms are not provided with daylight openings or any form of daylight transporting systems; for instance, due to hygienic or safety reasons. Moreover, significant fractions of the working population in the world do their work during nighttime [Lockley and Gooley 2006], and night-shift workers are prone to various discomfort issues due to a lack of synchronization between the shift work schedule and the individual light–dark cycle [Blask 2009; Stevens 2009]. Many studies have also suggested that the value of increased productivity due to an improved indoor climate can be greater than the operational and maintenance costs [for example, Continental Automated Buildings Association 2008; European Commission 2013; Kosonen and Tan 2004; Skåret 1992; Woods 1989]. All of these considerations lead to the demand of having an innovative solution that can bring natural light with all of its qualities to the inside space.

To answer this challenge, the concept of virtual natural lighting solutions (VNLS), which are systems that can artificially provide lighting as well as a realistic outside view with properties comparable to those of real windows and skylights, is proposed. The original concept can be traced back to as far as the middle ages. For example, *trompe l'oeil* is known as an art technique that involves realistic imagery to create the optical illusion that the depicted objects appear in three dimensions, while actually being a two-dimensional painting.

1.1. First-Generation VNLS Prototypes

In the lighting research field, a number of studies have been performed using VNLS prototypes with a simplified view as a method to study various effects of light and view on subjects. In this article, these prototypes are classified as the first-generation VNLS prototypes. Examples of studies using these prototypes can be found in a pilot study of de Vries and others [2009], where two units of emulated windows, each measuring 1.20 m × 1.20 m with 12 rows of tubular fluorescent lamps, were installed in a test room. The experiments focused on the performance of the test subjects ($N = 10$) when looking at daylight openings covered with a diffuse screen. Prototypes of the same type were used in the experiments of Smolders and others [2012], focusing on the effect of eye illuminance on subjective measures, task performance, and heart rate variability. The results showed that a higher eye illuminance could improve not only subjective feelings of alertness and vitality but also objectively measured performance.

Experiments on well-being and subjective tiredness were also conducted by Stefani and others [2012], using a unit of virtual sky, consisting of 34,560 light emitting diode (LED) tiles behind a diffusor foil. Static and two dynamic lighting conditions were compared to each other. Their findings indicate that for test candidates without access to natural light, subjective tiredness after one working day was significantly lower, while the well-being decreased significantly less, under a cloud animation compared to static light.

Experiments on glare sensation from another prototype with a simplified view were conducted by Rodriguez and Pattini [2014], observing its effects on glare-sensitive and glare-insensitive subjects when performing a computer task. The results showed that luminance and size of the window had the same statistically significant effect on glare sensation for both groups, whereas the glare-sensitive subjects had a higher relative risk of being disturbed when occasionally looking directly at the glare source.

Though various VNLS prototypes have been developed, it is observed that most of them do not provide directional (sun-) light. A few examples of those providing sunlight in addition to a simplified sky scene have been developed by ENTPE-EDF Lyon [Enrech Xena 1999; Fontoynont 2011a, 2011b] and Philips [van Loenen and others 2007]. In the latter case, the prototype was a 1.20 m × 1.20 m luminaire with 12 rows of red, green, and blue tubular fluorescent lamps. Each lamp could be tuned to mimic the color gradients of, for example, the sunrise, noon, or sunset. A halogen, parabolic aluminium reflector spotlight was added and could be controlled to mimic direct sunlight. There was a possibility to control the color gradient and to create the impression of having a patch of sunlight inside the space. It is observed, however, that the prototype missed the ground elements and horizon in its display view. It also had a relatively small window-to-wall ratio and used fluorescent light sources instead of more energy-efficient ones. The parabolic aluminium reflector spot lamp also had limited ability to create a realistic impression of sun patches in the space. Therefore, a new-generation prototype is required to observe whether the performance can be improved by adding the missing features and to validate a computational model that can be extended for further development of future VNLS.

1.2. Aim and Objectives

The aforementioned state of the art shows that an ideal VNLS does not yet exist at the moment. In order to approach the ideal condition, a number of evaluation stages must be performed, including theoretical analysis, initial design, numerical testing of the design, prototype construction, physical testing, subjective laboratory testing, field trials, and so forth. In the early design stage, computational modeling and simulation is a powerful tool to predict the system performance in an efficient way, in terms of time and cost, and with regards to the relevant physical phenomena.

It is noticed from the literature review that objective studies addressing the indoor lighting and visual comfort aspect of the VNLS prototypes are relatively rare. This study therefore aims to find how a certain VNLS prototype influences the indoor lighting condition and visual comfort. Therefore, there is a need to create a representative model of the prototypes and to predict their performance by mean of computational modeling and simulation.

In particular, this study focuses on lighting measurement and simulation of a second-generation VNLS prototype, which is described in Section 2. Two objectives are defined: the first one is to validate the illuminance distribution results obtained from Radiance simulation [Ward and Shakespeare 1998] with the ones obtained from measurement, by evaluating the interior lighting condition inside the test room. The second objective is to determine the effect of various configurations of the prototypes inside the test room on the space availability, uniformity, and visual comfort.

The measurement and simulation protocols are described respectively in Sections 3 and 4. The simulation settings of various opening configurations are given in Section 5, and the results are discussed in Sections 6. The article is concluded in Section 7.

2. CASE DESCRIPTION

A second-generation VNLS prototype has been built in the new ExperienceLab of Philips Research at the High Tech Campus in Eindhoven, The Netherlands. The light sources of this prototype were arrays of LED tiles, considering its relatively long lifetime, high efficacy, high flexibility, and possibility to individually control and to display multiple colors. Moreover, LED technology has a great potential for saving energy consumption in buildings [for example, Jenkins and Newborough 2007; Pandharipande and Caicedo 2011].

A total of eight Philips Origami BPG762 luminaires (Koninklijke Philips N.V., Amsterdam, the Netherlands), each measuring 0.595 m × 0.595 m × 0.050 m (*L* × *W* × *D*), were incorporated to provide the light as well as to construct the view of the prototype. Each luminaire houses four smaller tiles consisting of 108 LUXEON RGB (Koninklijke Philips N.V., Amsterdam, the Netherlands) power LEDs and can display colors in red, green, and blue (RGB) components. It is designed to be a uniform edge-free lighting tile and can be combined to form an array and perform as a pixel unit. Each tile can be independently controlled by a digital addressable lighting interface or digital multiplex (DMX) protocol. A total of eight (2 rows × 4 columns) Origami BPG762 luminaires were installed. The rear view of the arrays is illustrated in Fig. 1.

For the purpose of mimicking direct sunlight, the Philips iW Cove MX Powercore (Koninklijke Philips N.V., Amsterdam, the Netherlands) (wide beam [100°–110°] version) module was installed. It has independent channels of warm, neutral, and cool white LEDs that can be individually controlled to produce adjustable color temperatures in a range from 2700 K to 6500 K. The individual size is 0.305 m long with a diameter of 0.042 m and can be connected in a line with other lamps of the same type. Therefore, there were in total eight lamps that were installed to simulate sunlight.

The prototype could display a diffuse, 32 (that is, 8 columns × 4 rows) pixel view, with an aspect ratio of 2:1

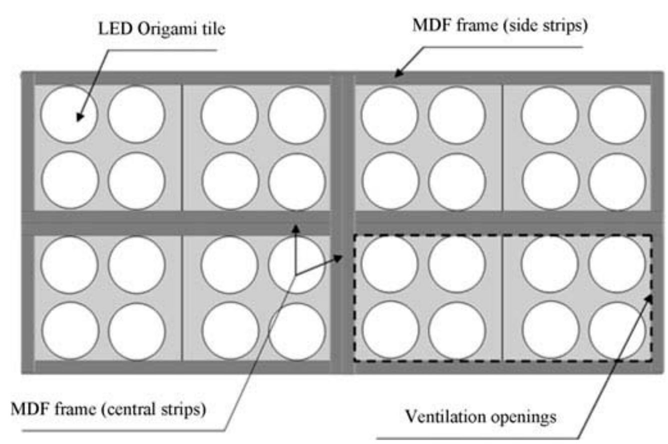


Fig. 1 **Rearview illustration of the 2 × 4 Origami BPG762 arrays in the prototype.**

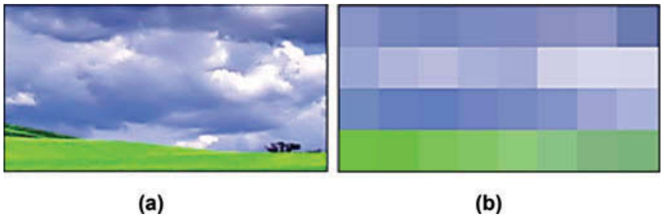


Fig. 2 (a) Original displayed view and (b) displayed view after applying a mosaic filter.

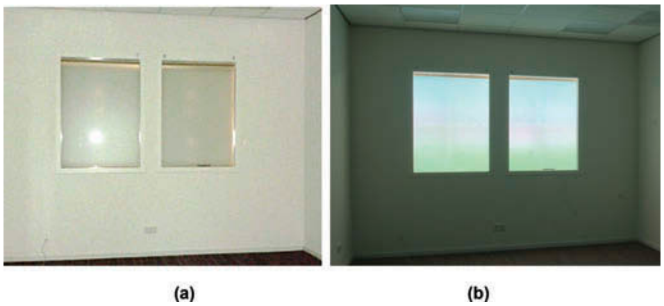


Fig. 3 Prototype appearance from inside the test room at (a) off and (b) on conditions.

(width: height). The original displayed view was a scene of nature, composed of a green ground and a bluish, cloudy sky (see Fig. 2a). The horizon was set approximately at the eye height (1.20 m for sitting viewers); therefore, the ground element occupied only approximately 0.25 of the total view height. Using an image processing software, a mosaic filter was applied to turn the image into 32 pixels (see Fig. 3b). The DMX512 protocol was employed to realize the control function. Each color channel can be dimmed from the full RGB value of 255 to 0. The RGB values of each pixel were obtained as the input for the DMX. The DMX values addressed for each pixel of the display at the maximum setting (that is, the highest luminance) are given in Table 1. RGB values of [255, 255, 255] correspond to a full-white color display.

To provide a suggestion of a blurred view, a 5-mm-thick PLEXIGLAS Satinice colorless diffuser (type 0F00 SC) (Evonik Industries AG, Essen, Germany) was mounted in front of the Origami arrays, replacing the original separate outer diffusers, to eliminate the visibility of LED spots and tile boundaries. The PLEXIGLAS diffuser had a one-sided matte surface and was made of frosted surface material. Finally, a window glass and frames were put in front of the display. The layers of Origami array–diffuser–window glass formed the basic structure of the prototype display.

Figure 3 displays the appearance of the prototype from inside the test room, at off and on conditions, showing the displayed view in Fig. 2 and Table 1, after applying the diffuse panel and window glass.

3. MEASUREMENT PROTOCOL

The prototype was placed in a test room of 6.81 m × 3.63 m × 2.70 m ($L \times W \times H$). There were two real window openings on one of the short walls, but during the experiments, they were blocked with two white covers of

TABLE 1 DMX values addressed for each pixel on the display at the maximum setting

Position	D1	D2	D3	D4	D5	D6	D7	D8
Red	20	220	255	26	25	220	220	25
Green	255	255	230	233	255	255	255	248
Blue	230	255	255	255	255	255	255	227
Position	C1	C2	C3	C4	C5	C6	C7	C8
Red	230	220	230	220	220	230	200	220
Green	255	255	255	255	255	255	255	255
Blue	255	255	255	255	255	255	255	255
Position	B1	B2	B3	B4	B5	B6	B7	B8
Red	255	255	225	205	200	180	230	200
Green	255	255	255	255	255	255	255	255
Blue	255	255	255	255	255	255	255	255
Position	A1	A2	A3	A4	A5	A6	A7	A8
Red	0	0	0	0	0	0	0	0
Green	200	216	221	215	227	224	225	229
Blue	100	10	10	10	10	10	10	10

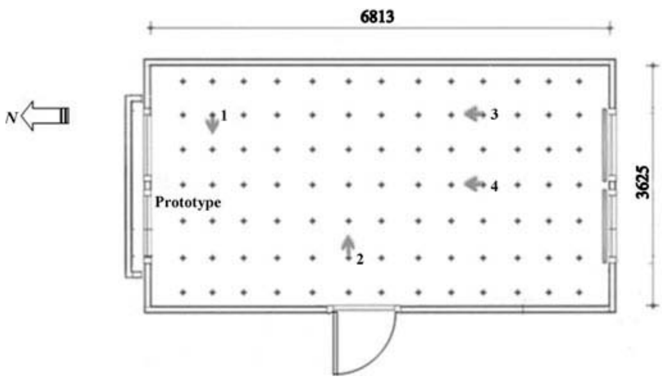


Fig. 4 Floor plan and view of the test room.

the same color and reflectance as the surrounding wall finishing. The VNLS prototype was installed on the opposite wall. 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, and the height of the window bottom was 0.93 m from the floor. The distance between the frames of the two openings was 0.14 m. Figure 4 illustrates the floor plan view of the test room.

To evaluate the actual lighting performance of the prototype, a number of data were collected at three settings; that is, 25% (representing a low setting), 62.5% (representing a medium setting), and 100% (see Table 1) of the maximum. The DMX values were proportionally scaled, and the display showed the view image in Fig. 3b. Horizontal illuminance data on the workplane were collected for 91 points (see Fig. 4), using a Lutron LX-1118 light meter (Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan), at a height of 0.75 m from the floor. Reflectance of interior surface materials data were measured using Konica Minolta CM-2600D spectrophotometer (Konica Minolta Holdings, Inc., Tokyo, Japan). Furthermore, the horizontal illuminance data were post-processed to obtain the average illuminance values (E_{av} [lx]), uniformity (U_0), and space availability (%A [%]).

These three indicators can be expressed as follows:

$$E_{\text{av}} = \frac{\sum_{i=1}^{N} E_i}{N} \tag{1}$$

$$U_0 = \frac{E_{\min}}{E_{av}} \tag{2}$$

$$\%A = \frac{N_{E \geq E_{\text{crit}}}}{N} \times 100\%, \tag{3}$$

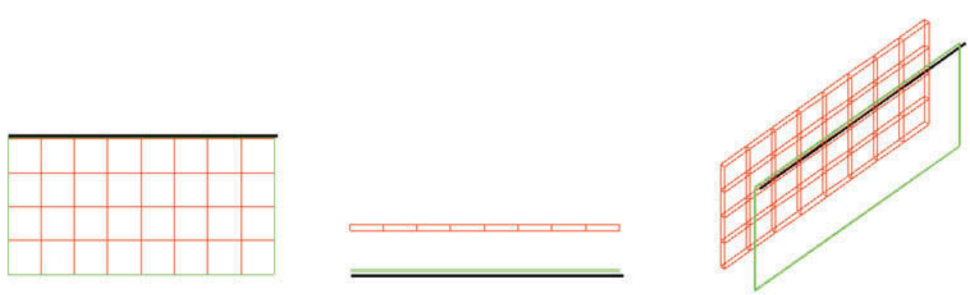
where E_i (lx) is the horizontal illuminance on each measuring point, $E_{\min}$ (lx) is the minimum horizontal illuminance, $N_{E \geq E_{\text{crit}}}$ is the number of measuring points satisfying the criterion of minimum illuminance value of E_{crit}, and N is the total number of measuring points, which in this case is 91.

To evaluate the visual comfort in this case, the daylight glare probability (DGP) [Wienold and Christoffersen 2006] was used as an indicator, which can be expressed as follows:

$$\text{DGP} = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log 2 \left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right), \tag{4}$$

where E_v is the total vertical eye illuminance (lx), ω_s is the solid angle of the glare source (sr), L_s is the glare source luminance (cd/m^2), and P is the position index; that is, a weighting factor based on the position in a viewing hemisphere.

Vertical illuminance and luminance perceived by the observer were measured by taking 20 photographs (ISO 400, f/5.6, shutter time varied from 4 s to 1/8000 s), at a height of 1.20 m, with the view direction specified by the arrows in Fig. 5a. For this purpose, a Canon EOS50D digital single-lens reflex camera (Canon Inc., Tokyo, Japan)



(a) (b) (c)

Fig. 5 (a) Front, (b) top, and (c) perspective views of the modeled prototype.

+ Sigma 4.5mm fisheye lens (Sigma Corporation of America, Ronkonkoma, NY, USA) was employed for taking multiple photographs in equiangular 180° view with various exposure values, which in turn were postprocessed to obtain the luminance pictures. The luminance values were calibrated with the SpectraDuo PR-680 photometer (Photo Research, Inc., Chatsworth, CA, USA). The obtained photographs were exported to Radiance, combined into high dynamic range images using the Hdrgen programme and analyzed using Evalglare [Wienold and Christoffersen 2006].

4. SIMULATION PROTOCOL

4.1. Model Description

The first objective of this article is to validate the illuminance distribution results obtained from simulation using Radiance with the ones obtained from measurement, because the computational model is to be extended for development of future (not yet existing) VNLS. Therefore, the actual conditions under the three lighting scenes were also modeled and simulated, to provide insight into the difference between simulation and actual measurement. Comparison was made between the simulated and measured values of horizontal illuminance at 13 points in the middle row (see Fig. 4).

The front, top, and perspective views of the modeled prototype are displayed in Fig. 5. Each of the small Origami tiles was modeled as boxes of 0.30 m × 0.30 m × 0.05 m ($L \times W \times D$), constructed with a light material. The eight iW Cove lamps were modeled as a continuous row of eight cylinders, with a length of 0.30 m each and a diameter of 0.016 m, also constructed with a light material. Each lamp had various red, green, and blue radiance components (W/m^2/sr), depending on the row position and the sky scene. The assigned values for each component under the maximum settings in Radiance are defined in Table 2, which is fine-tuned proportionally to the actual DMX values in Table 1. For other settings, the assigned values are proportionally scaled. The detailed values assigned for the window construction and the room's interior surfaces reflectance as obtained from the measurement are specified in Table 3.

4.2. Validation

To validate the model, simulations were run for the three settings—that is, 100%, 62.5%, and 25%—by addressing the input defined in Table 3. Calculation was performed for the 91 measuring points on the workplane, referring to Fig. 4. One-to-one comparison between measurement and simulation was done for all values of horizontal illuminance at the central line where point 4 was located. This line, at which there were 13 measuring points, was located directly in the central projection of the windows. Furthermore, simulation parameters in Radiance were set as shown in Table 4.

TABLE 2 Red, green, and blue irradiance components of light material defined in Radiance for the 12 TL5 lamps in the prototype

Position	D1	D2	D3	D4	D5	D6	D7	D8
Red	4.70	51.8	60.0	6.12	5.88	51.8	51.8	5.88
Green	60.0	60.0	55.1	46.6	54.8	60.0	60.0	58.3
Blue	55.1	60.0	60.0	60.0	60.0	60.0	60.0	53.4
Position	C1	C2	C3	C4	C5	C6	C7	C8
Red	55.1	51.8	55.1	51.8	51.8	55.1	47.1	51.8
Green	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Blue	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Position	B1	B2	B3	B4	B5	B6	B7	B8
Red	60.0	60.0	60.0	48.2	47.1	42.3	55.1	47.1
Green	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Blue	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Position	A1	A2	A3	A4	A5	A6	A7	A8
Red	0	0	0	0	0	0	0	0
Green	47.1	50.8	52.0	50.8	53.4	52.7	52.9	53.9
Blue	23.5	2.35	2.35	2.35	2.35	2.35	2.35	2.35

TABLE 3 Material definitions in Radiance for the window construction and room's interior

Material	Red	Green	Blue	Specularity	Roughness	Diffuse transmission	Transmittance specularity
Diffuse panel	0.25	0.25	0.25	0	0	0.55	0
Window glass	0.90	0.90	0.90	—	—	—	—
Window frame	0.79	0.79	0.79	0	0	—	—
Ceiling	0.91	0.91	0.91	0	0	—	—
Walls	0.79	0.79	0.79	0	0	—	—
Floor	0.13	0.08	0.03	0	0	—	—
Door	0.79	0.79	0.79	0	0	—	—

TABLE 4 Radiance simulation parameters

Parameter	Description	Value
−ab	Ambient bounces	4
−aa	Ambient accuracy	0.08
−ar	Ambient resolution	128
−ad	Ambient divisions	1024
−as	Ambient supersamples	256

In order to assess whether the simulation results are fit for the purpose of reproducing the actual scene, several criteria can be applied, but there is no definitive agreement on an acceptable degree of accuracy [Ochoa and others 2012]. For example, Slater and Graves [2002], CIE [2005], and Maamari and others [2006] suggested a criterion of approximately ±21% from the true value. According to Fisher [1992], an acceptable criteria range would be 10% for average illuminance calculations and 20% for measured point values. Moreover, in view of subjective lighting perception, the European Standard EN 12464-1 [Comité Européen de Normalisation 2002:7] mentions that "a factor of approximately 1.5 represents the smallest significant difference in subjective effect of illuminance," as given in the recommended scale of illuminance (lx) for various conditions in workplaces. This is approximately in line with the findings of Slater and others [1993] in their subjective study, where illuminance ratios between two workstations of at least 0.7 (or 1.4 if the ratio is inversed) were "generally acceptable." They mentioned that even though there was a trend of decreasing acceptability at lower illuminance ratios, there were indications that lower illuminance ratios may also be acceptable under some conditions.

Taken this recommendation into account, the criterion of which the difference between simulation (E_{sim} [lx]) and measurement (E_{mea} [lx]) values do not lead to a significant difference in their subjective effect, is

$$0.67 < \frac{E_{sim}}{E_{mea}} < 1.50. \qquad (5)$$

In other words, the ratio of simulation and measurement values at any measuring point should not be less than 2:3 (or approximately 0.67) and not more than 3:2 (or 1.50), so that the values do not lead to a significant difference in their subjective effect. This criterion is applied in the following sections to evaluate the simulation results.

5. ANALYSIS OF VARIOUS CONFIGURATIONS

The second objective of this article is to determine the effect of various configurations of the prototype inside the test room on the space availability, uniformity, and visual comfort. In order to maximize the light distribution on the workplane, two prototypes were modeled inside the test room and were placed either on the short walls or on the long walls. Seven configurations were introduced, named configurations 1 through 7; the floor plans are illustrated in Fig. 6. Note that in most configurations, the prototype was split into two equal parts; each consisted of 4 × 4 tiles. Each opening had a dimension of 0.90 m × 1.20 m ($W \times H$), and the height of the window bottom in all configurations was 0.93 m from the floor, which is the same as in the tested configuration.

Using the properties in Tables 2 and 3, simulations in Radiance and Evalglare were run to obtain the space availability, uniformity, and DGP at the defined four observer's positions. The test room can be assumed as a typical office room that requires workplane illuminance of 500 lx, but in practice it can also be used for other purposes; for instance, waiting rooms in health care facilities, which require a lower workplane illuminance. Therefore, for this analysis, the space availability was evaluated not only for the criterion of 500 lx but also for 300 and 200 lx.

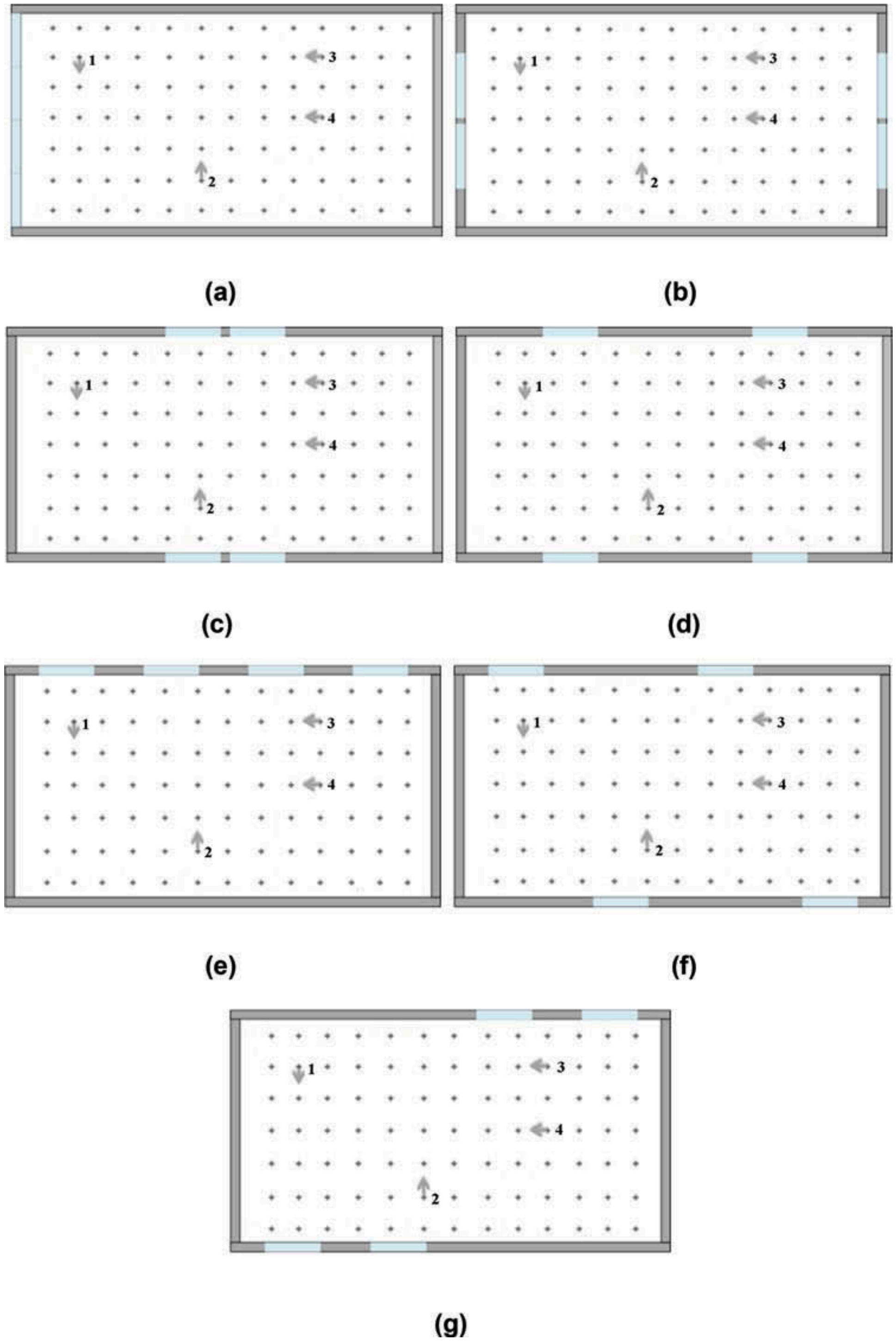


Fig. 6 **Floor plan of the test room with the prototypes in configurations (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, and (g) 7.**

6. RESULTS AND DISCUSSION

Results of the measurement and simulation of the actual test room and prototype are given in Sections 6.1 and 6.2. Results of the analysis of various configurations are given in Section 6.3.

6.1. Measurement of Actual Test Room

Table 5 gives the measurement results of the average work-plane illuminance, uniformity, and space availability at 25%, 62.5%, and 100% of the maximum setting in the test room. Under the maximum setting (Table 1) of the

TABLE 5 **Measurement results of the average illuminance (E_{av}), uniformity (U_0), space availability with 500, 300, and 200 lx criterion (%A_{500lx}, %A_{300lx}, %A_{200lx}), together with the maximum DGP and its position in the test room at 25%, 62.5%, and 100% of the maximum setting**

Setting (%)	E_{av} (lx)	U_0	%A_{500lx} (%)	%A_{300lx} (%)	%A_{200lx} (%)	DGP_{max}	Position
25	49	0.37	0	0	0	0.13[a]	1
62.5	136	0.33	0	11	20	0.21	1
100	239	0.30	11	29	43	0.26	1

[a]Values are lower than 0.20; that is, the minimum defined for DGP.

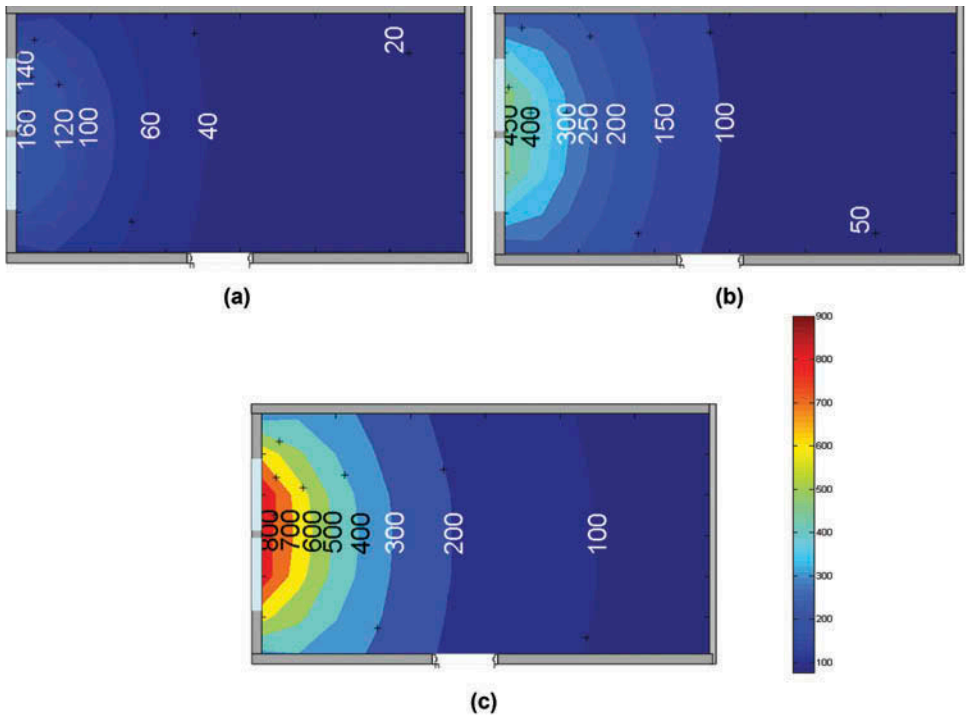


Fig. 7 **False color maps of the measured workplane illuminance (lx) under (a) 25%, (b) 62.5%, and (c) 100% of the maximum setting.**

defined display, approximately 11% of the workplane met the target illuminance of 500 lx, 29% met the target of 300 lx, and 43% met the target of 200 lx. Under the lower settings, the space availability becomes zero; that is, there are no points on the workplane that satisfy the illuminance criterion. The uniformity is 0.30, 0.33, and 0.37, under 25%, 62.5%, and 100% of the maximum setting, respectively.

Figure 7 displays false color maps of horizontal illuminance values on the workplane under the three settings.

The measurement results show that at the nearest point to the window, the workplane illuminance value reaches approximately 800 lx under the maximum setting, yielding a space availability (taking 500 lx as the minimum criterion) of around 11%. Under 62.5% and 25% settings, none of the points receives illuminance larger than 500 lx, which is required for typical office work. However, if the test room would be occupied for different activities that require lower illuminance criteria, the space availability would then be higher. For instance, taking 300 lx as the criterion, approximately 30% space availability can be achieved under the maximum setting, as observed from the isolux contour in Fig. 7c. The light distribution is symmetrical along the windows' central axis.

6.2. Simulation of Actual Test Room

The lighting simulation and measurement results of the prototype generally show a good agreement, with a maximum relative difference of 28% at the farthest point under the 25% setting, possibly dominated by measurement accuracy limits, because the absolute difference is only 5 lx. However, the ratio of the simulated value to the measured one at all points is actually always between 0.67 and 1.5, which represents the smallest significant difference in subjective effect of illuminance [Comité Européen de

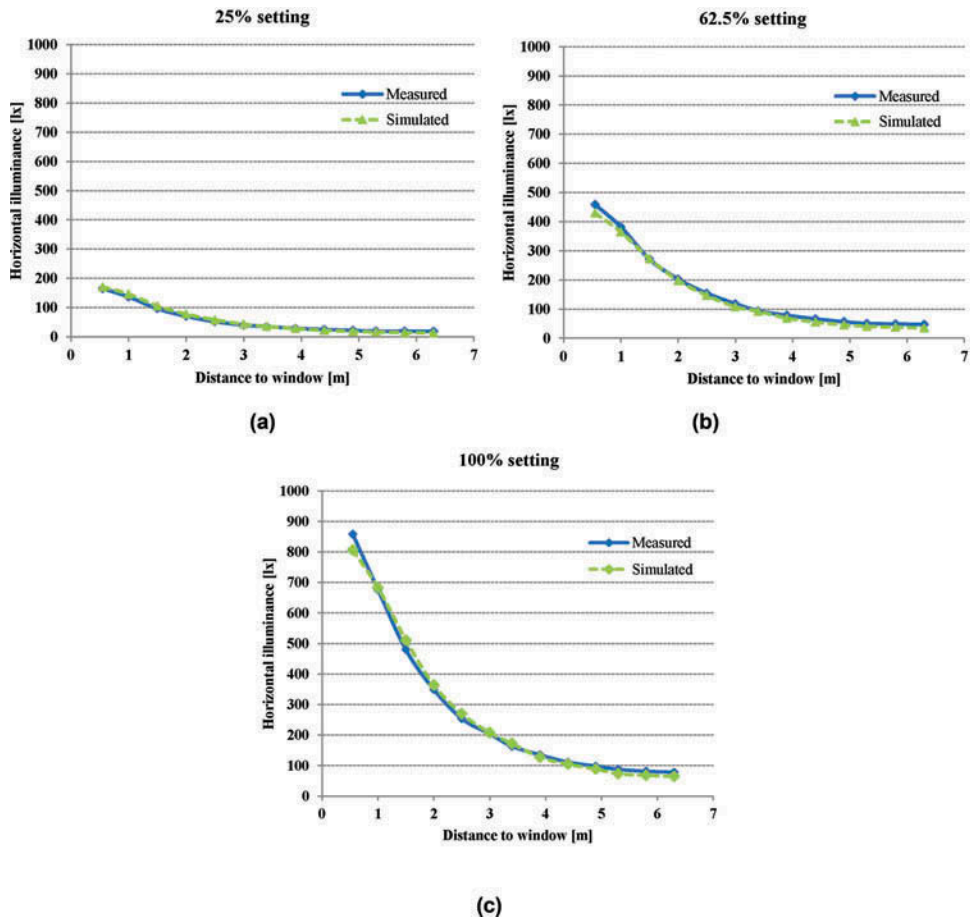


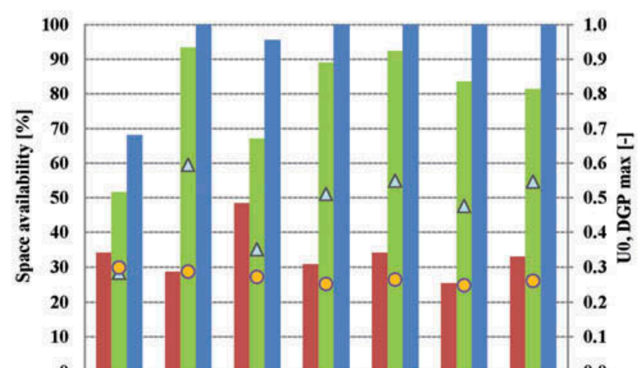
Fig. 8 **Graphs showing the relationship between horizontal illuminance at the central line on the workplane and distance to windows under the (a) 25%, (b) 62.5%, and (c) 100% of the maximum setting.**

Normalisation 2002]. Therefore, the computational model is considered sufficient for the purpose of reproducing the scenes without a significant subjective difference and can be further extended for nonexisting solutions.

Figure 8 displays the graphs showing the relationship between horizontal illuminance and the distance to the windows under the three defined settings, based on the measurement and simulation.

6.3. Comparison of Various Configurations

The relationship between space availability, uniformity, and maximum DGP in the test room under the simulated configurations (Fig. 6) is illustrated in Fig. 9. It is observed that when 200 lx is taken as the criterion for workplane illuminance, nearly all configurations yield a space availability of 100% or very close to it, except configuration 1, in which all of the four openings are placed on a short wall. Consequently, the far side of the room is left without sufficient light. When 300 lx is taken as the criterion, only configuration 2 (two openings on each short wall facing each other) and configuration 5 (four



	C1	C2	C3	C4	C5	C6	C7
%A 500lx	34	29	48	31	34	25	33
%A 300lx	52	93	67	89	92	84	81
%A 200lx	68	100	96	100	100	100	100
U0	0.28	0.59	0.35	0.51	0.55	0.48	0.55
DGP max	0.30	0.29	0.27	0.25	0.26	0.25	0.26
Position	1	1	3	1	2	2	1

Fig. 9 **Graphs showing the relationship between space availability, uniformity, and maximum DGP in the test room under the simulated configuration scenes.**

openings on a long wall) yield space availabilities of more than 90%. When 500 lx is taken as the criterion, all configurations yield space availabilities of less than 50%, the highest being configuration 3 (two openings on each long wall facing each other, 0.14 m distance between openings on the same wall).

The highest uniformity is achieved under configuration 2 (0.59), and second to that are configurations 5 and 7 (0.55). The maximum DGP values under all configurations range are very similar, within the range of 0.25–0.30, mostly found at the observer's positions that are the closest to the openings or those that are able to view the entire four openings. The highest value is found at position 1 under configuration 1, because the position is located near the wall where both of the prototypes are placed. Under configuration 2, the observer at the same position would experience the second highest DGP value, because each prototype is placed on the short walls, one of which is at a distance of 1.0 m to the observer's position. According to Wienold [2009] and Reinhart and Wienold [2011], a DGP value of less than 0.35 is considered "imperceptible"; therefore, no discomfort glare should be expected from the tested configurations. Nonetheless, care should be taken because DGP, in its current definition, is apparently not robust enough to be used as a stand-alone daylighting visual comfort design guide, because it may underestimate glare sensation in some cases [Van Den Wymelenberg and Inanici 2014].

Figure 10 displays false color maps of horizontal illuminance values on the workplane under all configurations.

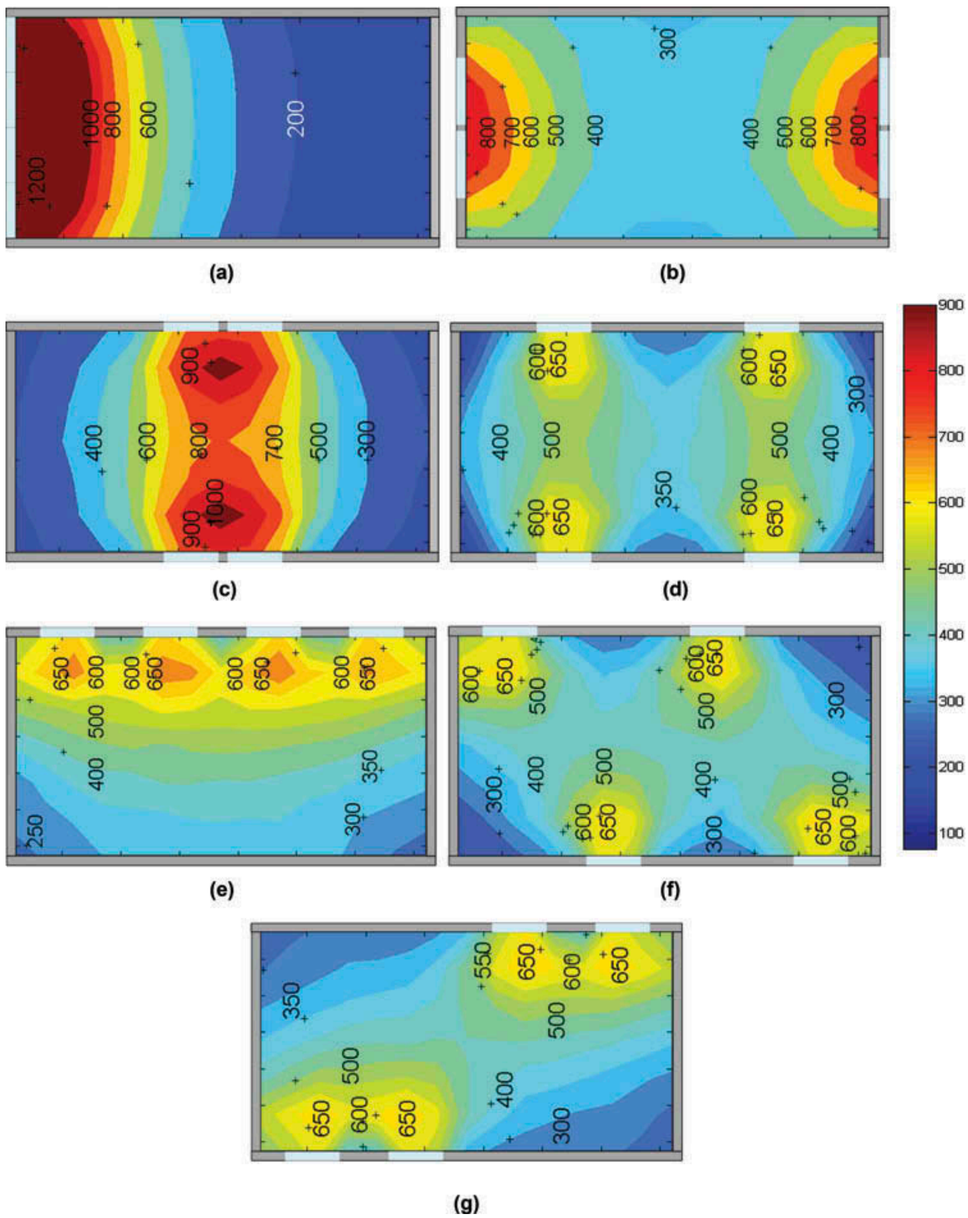


Fig. 10 False color maps of the simulated horizontal illuminance (lx) under configurations (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, and (g) 7.

The simulation results show that at the nearest points to the openings, the workplane illuminance values are approximately 800 lx under configuration 2 (Fig. 10b), whereas the values are between 600 and 650 lx under configuration 5 (Fig. 10e). The distance between two adjacent openings is 0.14 m in configuration 2 and 0.80 m in configuration 5. In the latter, the individual prototype (4 × 8 tiles) is split into two parts; each consisted of 4 × 4 tiles. Therefore, the maximum illuminance in configuration 5 is less than that in configuration 2, because the light is spread more evenly and is not concentrated as much as in configuration 2. As shown in Fig. 9, both configurations have a space availability of 100% for 200 lx criterion and approximately 90% for 300 lx criterion. For 500 lx criterion, the satisfying workplane area in configuration 5 is slightly larger than that in configuration 2.

Configuration 3 (Fig. 10c) yields the largest space availability for 500 lx criterion but not the largest for 300 lx criterion. Under this configuration, the prototypes are placed in the center of the long walls; therefore, the light is more concentrated in the middle part of the room and drops toward the edges. Configuration 7 (Fig. 10g) is close in terms of performance to configuration 5; only the light is less concentrated at the nearest points to the openings, and there is less workplane area with illuminance higher than 300 lx.

Under configuration 5, the highest DGP value (0.26) is observed at position 2 (see Fig. 4), which directly faces four openings, whereas under configuration 2, the highest DGP value (0.29) is observed at position 1, as mentioned earlier. This finding leads to a suggestion of placing workstations and viewing directions that will give the least discomfort glare perception. For instance, under configuration 2, the viewing direction at position 2 is recommended, whereas position 3 or 4 is recommended under configuration 5.

In general, this study gives an insight on the effect of placing VNLS prototypes with various configurations on the lighting performance of a standard office room. The presented results are, however, limited to the specified prototype under the defined settings. Other factors should also be considered in the approach of optimizing space availability; for instance, by increasing the beam angle of the light source [Mangkuto and others 2014]. Despite the limitation, this study has clearly demonstrated the benefit of applying VNLS in a windowless space, which is applicable, among others, in operating rooms in hospitals and in control rooms in industrial plants due to hygienic or safety considerations. The obvious advantage of having VNLS is the possibility to put them on any wall or ceiling surface, while gaining some daylit space and a view. The optimization result can therefore be used by lighting designers to get an insight on how to position the existing and/or future VNLS to obtain a large space availability and uniformity on the workplane, while keeping the visual discomfort as low as possible.

7. CONCLUSIONS AND OUTLOOK

A second-generation VNLS prototype has been designed and built by installing arrays of LED tiles, providing a blurred view and diffuse light, and a line of LED linear fixtures, providing direct light into a test room with a standard office size. This particular prototype has an important role in validating the computational model that can be extended for further development of not-yet-existing VNLS. Simulation and measurement values of horizontal illuminance at certain distances from the prototype were compared under three settings. The maximum relative difference is 28%, found at the farthest point under the tested minimum (25%) setting. The ratio of the simulated value to the measured one at all points is always between 0.67 and 1.50, ensuring no significant difference in subjective effect of illuminance. Therefore, the computational model is considered sufficient for the purpose of reproducing the scene without creating a significant subjective difference.

Based on the comparison of seven configurations of two prototypes with equal total opening size in the test room, it is found that nearly all configurations, except configuration 1 (four openings on a short wall), yield a space availability of 100%, taking 200 lx as the criterion. When 300 lx is taken as the criterion, configuration 2 (two openings on each short wall facing each other) and configuration 5 (four openings on a long wall) yield space availabilities of more than 90%. When 500 lx is taken as the criterion, the configurations yield space availabilities between 25% and 50%. The highest uniformity was achieved under configuration 2 (0.59) and configurations 5 and 7 (0.55). The maximum DGP values under all configurations were between 0.25 and 0.30. Therefore, our simulations suggest that space availability in a standard office room can be optimized by placing a prototype on each short wall facing each other or by placing two prototypes on a long wall.

This article focuses on better understanding of how VNLS influence the indoor lighting performance and visual comfort and how to design better solutions to improve the light and view qualities. For that purpose, the study in this article is based on a combination of physical measurement, computational modeling, and simulation of VNLS prototypes. Future work should assess subjective users' perceptions of the particular prototypes. As solutions become more complex and sophisticated, further evaluation and analysis on how people actually appraise VNLS in real settings will be necessary, before proceeding to the design implementation.

Furthermore, by applying the latest lighting technology, it would be possible to create a more detailed view on the display with higher light output, while consuming less energy. A dynamic view could be introduced by applying a digital communication network to automate the display variation at every given (small) time step. Research into dynamic lighting is in line with the roadmap of the European Commission [2013], which has put healthy and comfortable indoor environment, including lighting, as one of its cross-platform target areas for the year 2020. Future research and innovation topics under this target area should be directed, among others, toward creating efficient and comfortable indoor lighting; for example, by developing flexible lighting based on LEDs.

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