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Visual performance of red luminescent solar concentrating windows in an office environment

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ABSTRACT

The luminescent solar concentrator (LSC) could provide a colorful and adaptable complement to standard silicon solar panels, allowing easier deployment solar energy systems in the urban environment. In order to successfully implement this technological innovation into the built environment, it should also complement the surrounding architecture and be visually acceptable to the user. One prominent feature of the LSC is its bright, fluorescent coloration. Since the devices can be transparent, this opens the possibility of employing the LSC as a power-generating window. Current research on LSCs focused on the energy efficiency and on the theoretical impact on users. So far, the impact of such a colored window on the inhabitants (or users) in spaces using these windows has been largely unexplored. In this work, we study the impact of a red LSC on the visual comfort and impression of volunteer participants. We made the interesting observation that a window covered 25% by an LSC is judged favorably when compared to a normal, clear glass window. Such a window could become a local source of electrical power from sunlight while simultaneously improving the well-being of the room inhabitants.

1. Introduction

The building sector contributes about 30% of global annual greenhouse gas emissions and consumes up to 40% of all produced energy: emissions from the building sector must be tackled if targets for greenhouse gas emissions reduction are to be met [1]. However, the topic sustainability is very broad. Sustainable building is more than environmental friendliness; it must also encompass economic and socio-cultural issues as well, allowing us to 'meet the needs of the present without compromising the ability of future generations to meet their own needs' [2].

The need for energy conservation in buildings has spurred innovations in window technologies. Many devices such as shutters [3], blinds [4], electro- and photochromic windows [5–7], thin-film solar cell windows, polymer dispersed liquid crystals (PDLCs), organic films [8], liquid crystal based windows [9,10], and thin inorganic coatings [11] have all been suggested or have already reached the marketplace.

Another innovative technology that could be employed as a window is the luminescent solar concentrator (LSC). The LSC usually is made of a dye-embedded polymeric lightguide. The luminescent dye absorbs some of the incident sunlight and re-emits this light at a longer wavelength. A fraction of the emitted light is trapped in the lightguide which has a higher refractive index than the surroundings, which transports the light to the edges of the polymer plate via total internal reflection. At the edges of the lightguide photovoltaic (PV) cells may be placed to convert the exiting emitted light into electricity [12–14]. A depiction of the function of the LSC is shown in Fig. 1.

The LSC has the potential to find extended use in an area traditionally difficult for deployment of regular PV panels: the built environment. The device is very flexible in its design since it can be thin (and thus reduce weight), can be cut to shape and can be made in a variety of colors. Furthermore, LSCs do not need to track the sun and work in both direct and diffuse sunlight [15]. These characteristics could offer architects more design freedom in integrating solar-energy systems into the built environment. Transparent LSCs could be included in windows [16,17], and in a dynamic form be capable of switching between 'dark' and 'light' states [9]. Recent examples in architecture already demonstrated the re-invented use of colored glass in contemporary architecture. Not as small, stained glass windows like in cathedrals, but as large colored planes (see references in Fig. 2).

While considerable research has directed to improving energy and cost-efficiency of this device [18–20], very little insight has

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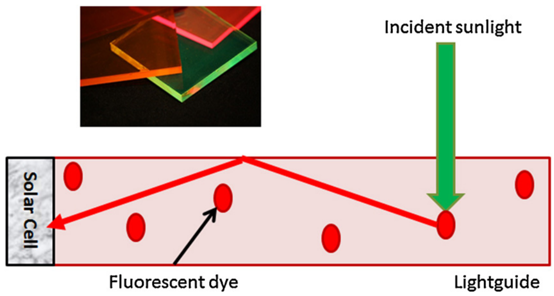

Fig. 1. Schematic visualization of the luminescent solar concentrator. Incident light (green arrow) is absorbed by a fluorescent dye which re-emits the light at a longer wavelength (red arrow). The light is trapped by total internal reflection in the lightguide and exits an edge where an attached solar cell concerts the emission light into electricity. (Inset) Photograph of three LSC lightguides exposed to ultraviolet light from above. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

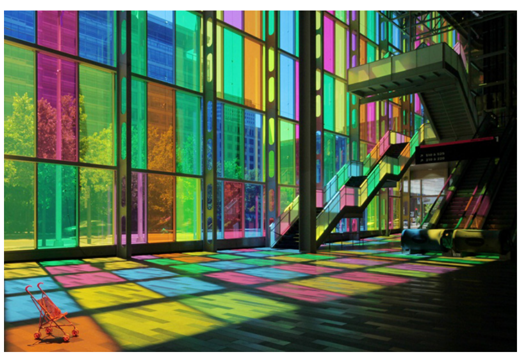

Fig. 2. Interior view of the Palais des Congrès, Montreal, Canada (photo courtesy M. Nguyen).

been gained on the acceptance and visual comfort impact of using LSCs, which is a vital aspect to understand before attempting widespread integration of the device in the built environment. A major issue in the use of LSC as a window could be the coloration of the lightguide, which has not only a direct influence on the energy-efficiency of the LSC, but an effect on the daylight penetrating into the room in terms of illuminance of surfaces, spectral distribution and luminance distribution, all of which may affect the perception and quality of a space and therefore the acceptance of the user [21,22]. A current study by Aste et al. analyzed the impact of LSC on the visual effects of the colored daylight in a room [21]. To do so, they analyzed the different light characteristics like illuminance, correlated color temperature, and color rendering index (CRI) of a yellow LSC under two dominant daylight conditions. They concluded that due to a reduced CRI, care should be taken when applied in the built environment. These are theoretical based conclusions and indicate the care one should take when applying colored daylight openings. In this study we want to answer the question of how much colored window is really acceptable for the users.

While there has been work performed to produce colorless LSC devices for window application [23–25], the efficiencies will be necessarily limited since they may only utilize light from the ultraviolet and infrared portions of the spectrum. The most promising LSCs in terms of electrical output generally are colored orange or red, although a deep blue panel with infrared overtone has also been demonstrated [18,20,26].

Among the many environmental attributes of a workplace, lighting is considered as one of the most important [27,28]. Studies have shown lighting and color not only influences an individual's perception of work-related tasks [29], but also affects their general emotional and motivational states. It impacts their physical and mental health and thus potentially has both psychological and emotional as biological and physiological effects [30]. A combination of light quantity (illuminance and luminance) and light quality (spectral distribution expressed in correlated color temperature (CCT) and color rendering index (CRI)) makes various psychological impressions on humans as well [31]. For electric lighting, for example, a higher color temperature (4000 K, blue) and illuminance of a clear midday sky creates an energetic mood, and are associated with cool, air, sky and water while lower color temperatures (2700 K, orange) and illuminance creates a relaxed mood, generally associated with sun and fire [32]. In addition, the color temperature can also influence perceived brightness of a space [33]. When color light is experienced for a longer period of time, it may physically affect bodily functions, like brain activity and hormone production [34]. Studies have indicated that the characteristics of glass used on office façades paired with daylight quality and quantity could have an impact on the well-being of the occupants as well as their level of arousal and performance at work [35]. A modification of the spectral distribution of daylight may affect visual performance (acuity) as well and research exploring the effects of electrical lighting has indicated that the spectral distribution of daylight may affect visual fatigue or discomfort [36]. Light with a high color temperature resulting in a bright, luminous environment in particular, stresses and activates the autonomic nervous system (specifically, the sympathetic nervous system) and the central nervous system [37].

While a considerable body of work exists concerning the spectral characterization of light from artificial source (see, for example, [38]), studies specifically focused on the effect of window glazing type on daylight quality are scarce or confounding. Some studies suggest that tinted glazing has no effect on the visual environment due to adaptation of the visual system [39], while in contradiction another study indicates that the glazing type has a significant effect on the perception of the visual environment: for example, a window with a green shift makes the room feel more enclosed and gives an appearance of weaker daylight and drab color [40]. Another study showed that people tend to prefer bronze glazing when compared to blue or neutral glazing [35].

The characteristics of any LSC used as part of a window should meet the needs for visual comfort of the people living or working in the space employing the LSC device. The objective of this research is to study the influence of red LSCs as daylight opening on the visual impression and preference in an office environment.

2. Experimental

The experiment used a full scale $1.8 \times 2.7 \times 3.9\,m^3$ room and 3 identical scale models with internal dimensions of $0.3 \times 0.45 \times 0.65\,m^3$ (scale 1:6) (see Fig. 3). The interior of the scale models was painted with a diffuse white finish (reflectance value 90%) and had a crème-colored carpeting (reflectance value 28%) and furnished with scaled wooden table, wooden chair, laptop, houseplant, a silver teaspoon (on the table), a piece of broccoli and a baby tomato. These objects were chosen because they offered a variety in colors, shapes and textures people were familiar with. A colored print was placed on one of the lateral walls as well as a black song text on white background. Previous evaluations comparing full-scale space and scale models replicating the full-scale space showed that the evaluations did not differ significantly [41]; similarly, glare assessments in scale models with those obtained in full-scale rooms under real sky conditions showed the same discomfort glare assessments [42].

The three scale models were located on the second floor of the Vertigo building at the Eindhoven University of Technology with a true West-facing facade (270°) which offers a view over the green