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Citation for published version (APA):

Document status and date:
Published: 01/01/2014

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Evaluating the experience of daylight through a virtual skylight

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Introduction

People generally have a clear preference for daylight over electric lighting as a source of illumination (Boyce et al., 2003). For example, in an office setting people prefer to have daylight for enhanced psychological comfort, a more pleasant office appearance, increased productivity, and assumed health benefits (Heerwagen & Heerwagen, 1986). Moreover, daylight affects humans psychologically and physiologically and has been associated with many positive health and wellbeing effects such as improved mood, enhanced morale, lower fatigue, and reduced eyestrain (Edwards and Torcellini 2002). However, in current times, people spend most of their time indoors in rooms with no or limited daylight entrance. This raised the questions whether it is possible to create electric lighting solutions that mimic daylight in spaces where there is no or limited access to real daylight. For example, in bathrooms, meeting rooms, basements, hotels, or shopping malls.

Virtual skylight

Some attempts to create virtual daylight sources and virtual windows have been made (e.g. Van Loenen et al. 2007; Fraunhofer, 2012; Skyfactory, 2014). These solutions proved successful in creating a virtual outside view, but typically are less successful in mimicking the daylight. Most existing solutions provide an outside view using displays, printed translucent sheets, or coloured light sources, resulting in light effects in the room that are typically not appreciated by people. For example, due to the unnatural colours of the skin when being exposed in coloured light. Another problem is that these solutions typically do not provide sufficiently bright white light for functional use.

User experience test

Goal of this study is to investigate the user experience of a virtual skylight, focusing on the experience of the light effect. For this study, the virtual skylight was prototyped using a commercially available 600x600 LED module (Philips SmartPanel, 4000K, 3400lm). This product was adapted by adding an optical structure to provide a blue sky effect. The virtual skylight (VS) was...
compared with the standard panel without the optical structure (SP) and the same module with a blue filter to mimic a blue sky (BF). The BF concept was created by a local lighting designer using an additional translucent blue acrylic filter under the LED panel, a common method to create a blue sky effect.

Since the main focus of this study is the user experience of the light effect created by the VS (blue sky view combined with white sun light) compared to alternative solutions (SP and BF), as much of the other factors were kept the same between the three conditions VS, SP and BF. Identical diffuse LED light panels (Philips SmartPanel, 3400lm, 4000K) were used in all three conditions, but in the VS and BF the aforementioned modifications (optical structure / blue filter) were made. All light panels were installed in identical positions in equal size rooms and all modules were slightly recessed in the ceiling to provide the illusion of a ceiling window / skylight. As it was decided to compare the 3 concepts using the same LED panels with and without modifications, the resulting illuminance and CCT levels varied per condition. Also, the light distribution varied between the three conditions with the SP and BF having a more uniform distribution in the room (brighter walls), while VS had a more directional white light output (darker walls). It was decided not to control for these differences, but compare the total light effects resulting from the 3 product concepts.

Three test rooms were prepared on the 17th floor of an office building in Shanghai, China, one for each condition. The rooms were at the inner side of the building with limited daylight entrance. The test rooms had almost identical dimensions (see Figure 2). In each room, four lighting modules of 600x600 mm each were installed at similar locations in the room in a 1x2 configuration (see Figure 2). In each room, illuminance and spectral measurements were taken horizontally at the desk and vertically at position of participants’ eyes to objectively specify the lighting conditions in each room.

Table 1: Light measurements in experiment rooms

<table>
<thead>
<tr>
<th></th>
<th>VS</th>
<th>SP</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illuminance desk (lux)</td>
<td>675</td>
<td>1286</td>
<td>413</td>
</tr>
<tr>
<td>Illuminance eye (lux)</td>
<td>379</td>
<td>809</td>
<td>252</td>
</tr>
<tr>
<td>CCT desk</td>
<td>5158</td>
<td>3903</td>
<td>12895</td>
</tr>
<tr>
<td>CCT eye</td>
<td>5637</td>
<td>3907</td>
<td>12830</td>
</tr>
<tr>
<td>CRI desk</td>
<td>85</td>
<td>82</td>
<td>60</td>
</tr>
<tr>
<td>CRI eye</td>
<td>81</td>
<td>82</td>
<td>60</td>
</tr>
</tbody>
</table>

Three Chinese participants were recruited via an external agency with the following profile: 25-40 years old (male and female); office workers of foreign companies, state-owned companies, and local companies; no...
eye/sight problems. All participants received a monetary compensation for participating in the test through the agency.

**Results**

The first impressions of VS and SP were similarly positive. The main difference between VS and SP in initial participant responses was that VS was perceived to give a natural light effect and SP was considered to give a bright and warm light effect. The first impression of BF was very different and less positive. It was often described as giving a cold and depressing light effect, although some people also referred to it as refreshing.

Participants (N=30) rated the lighting experience in the room on a 5-point scale for 13 items. For the first three items, bi-polar scales were used. For example, for brightness in the room, 1 would mean too dim, 3 would be optimal, and 5 would be too bright. For the other items, Likert scales were used where 1 is the worst rating and 5 the most positive rating. For each item, the mean scores per condition (VS, SP, BF) are presented in the second column of Table 2. To test whether the means for the VS condition were significantly different from the SP and BF condition, paired t-tests with a confidence interval of 95% were conducted. The third column ‘VS versus SP’ presents the direction of the difference. For example, if VS scores better than SP this is denoted with VS > SP. Furthermore, it lists the p-values. Similarly, the fourth column presents the results of the comparison between VS and BF. It should be noted that in total 26 paired t-tests were done which introduces the risk of type I errors due to multiple testing. Even if there would be no differences between the conditions, one could expect 1 significant result by chance (0.05 x 26). In our study, 19 out of the 26 comparisons showed significant difference. No formal correction for multiple testing was done, due to the known problems with these methods (i.e. Nakagawa, 2004).

After being exposed to all three conditions, the participants were asked which concept provided the strongest skylight effect. 57% of the participants believed the VS provided the strongest skylight experience, versus 30% for BF and 13% for SP. Some illustrative remarks participants made about the VS (translated from Chinese) are: “Yellow sunlight”, “Blue sky”, “Feeling of depth”, “Feels like the sun is coming through the window”, “Bright”, and “Sun effect.” Based on their comments, the main reason they choose the VS is that it could best mimic the effect of daylight passing through a ceiling window, combining the yellow sunlight with the blue sky.

**Tab. 2: Mean scores light experience questionnaire for three conditions including direct comparisons (t-test)**

<table>
<thead>
<tr>
<th>N=30</th>
<th>Mean score</th>
<th>VS versus SP</th>
<th>VS versus BF</th>
<th>Direction</th>
<th>p</th>
<th>Direction</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness room</td>
<td>2.73 3.4 2.2</td>
<td>VS &gt; SP* 0.000</td>
<td>VS &gt; BF* 0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brightness desk</td>
<td>2.83 3.37 2.4</td>
<td>VS &gt; SP* 0.025</td>
<td>VS &gt; BF* 0.025</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color tone room</td>
<td>3.2 2.6 3.7</td>
<td>VS &gt; SP* 0.004</td>
<td>VS &gt; BF* 0.014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfortable light</td>
<td>3.33 3.7 2.83</td>
<td>SP &gt; VS 0.110</td>
<td>VS &gt; BF* 0.019</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naturalness of objects</td>
<td>3.5 3.67 3.03</td>
<td>SP &gt; VS 0.455</td>
<td>VS &gt; BF* 0.008</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naturalness of skin tone</td>
<td>3.6 4.07 3</td>
<td>SP &gt; VS* 0.008</td>
<td>VS &gt; BF* 0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I feel this room has a ceiling window</td>
<td>3.43 2.93 3.07</td>
<td>VS &gt; SP* 0.037</td>
<td>VS &gt; BF 0.054</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I feel daylight is entering the room</td>
<td>3.47 3 2.77</td>
<td>VS &gt; SP 0.060</td>
<td>VS &gt; BF* 0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural light</td>
<td>3.4 3.37 2.83</td>
<td>VS &gt; SP 0.856</td>
<td>VS &gt; BF* 0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make me feel relaxed</td>
<td>3.6 3.6 2.97</td>
<td>VS &gt; SP 1.000</td>
<td>VS &gt; BF* 0.006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makes me feel energetic</td>
<td>3.23 3.77 2.67</td>
<td>SP &gt; VS* 0.013</td>
<td>VS &gt; BF* 0.002</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makes me feel pleasant</td>
<td>3.5 3.77 2.97</td>
<td>SP &gt; VS 0.234</td>
<td>VS &gt; BF* 0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall light quality</td>
<td>3.5 3.97 2.93</td>
<td>SP &gt; VS* 0.014</td>
<td>VS &gt; BF* 0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates statistical significance at 95% confidence.

1Please note that these items were scored on a bi-polar scale, meaning that 3 is the best possible score.
Discussion and conclusion

Overall, the results clearly show that VS scores better on all items than the BF. On some items SP scores better than VS (‘Naturalness of skin tone’, ‘Energetic feeling’, and ‘Overall light quality’), while the VS scores better than SP on brightness, color tone, and items related to daylight experience. The daylight experience was measured with three items: “I think the room gives me the feeling that there is a ceiling window”; “I have the feeling that there is natural light from outside coming into the room”; and “I find the light in this room very natural”. Based on the results, we can conclude that the VS provides the best daylight experience of the three conditions that we tested. However, on several items including overall light quality the SP scored better. There are a few possible explanations for this. First, the SP provided much more light than VS and BF, including a large amount of indirect light reflected from the walls. The VS provided less indirect lighting via the wall due to the optical structure that creates the blue sky effect. As a result, people appreciated the light quality under the VS but did not appreciate the darker walls compared to the SP room. Furthermore, the light solutions were presented in an office setting and participants were provided with a reading task. The overall light quality has likely been evaluated with this specific context and task in mind. For other environments or tasks, other factors might determine experienced light quality.

To conclude, this paper presented a study to explore whether it is possible to create an electric light source that can provide an impression of daylight. The virtual skylight concept was presented that aimed to provide the impression of a blue sky view through the ceiling, combined with good quality white light in the room. The results of the user study showed that the virtual skylight can create a pleasant light experience that is closer to a daylight experience than standard electrical lighting and the tested alternative solution. One should realize the limitations of this study and that only three electric lighting solutions were compared. There might be other electric lighting systems that provide a similar or even better lighting experience than the VS. Also, the VS was not compared with a real skylight. This would be interesting for future research, although it still seems very difficult to come close to the real daylight experience. But all in all, this study shows first indications that the virtual skylight might become a viable alternative to traditional electric light sources and provide a more natural light experience indoors. In particular for applications where functional, aesthetic, and emotional lighting needs have to be fulfilled.

Acknowledgements

We would like to thank our colleagues from our laboratories in Shanghai and Eindhoven for their contributions to this study, as well as our participants.

References