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Published in:
Proceedings SPIE Human Vision and Electronic Imaging XIX, February 02, 2014 San Francisco, California, USA

DOI:
10.1117/12.2035373

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:

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Download date: 28. Oct. 2018
Effects of image size and interactivity in lighting visualization

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ABSTRACT

Rendered images of varied lighting conditions in a virtual environment have been shown to provide a perceptually accurate visual impression of those in a real environment, providing a valuable tool set for the development and communication of new lighting solutions. In order to further improve this tool set, an experiment was conducted to assess the impact of image size and viewing interactivity on perceptual accuracy. It was found that a high-quality TV-sized display outperforms a smaller laptop screen and a larger projected image on most measures, and that the expected value of the interactive panoramic format was masked by the fatigue of using it repeatedly.

Keywords: visualization, rendering, lighting, visual perception, interactivity, display

1. INTRODUCTION

In recent years, the efficiency, low cost, and flexibility of LED-based lighting has brought us far beyond simple, functional lighting, into an era where lighting can be creatively used in new ways, such as to accent architecture and space, to attract visual attention, and to convey affective characteristics such as atmosphere. In a similar timeframe, computer graphics tools have improved immensely in quality and speed. The lighting industry is poised to take advantage of advances in graphics, not only in an approximate way, but in a perceptually-accurate way, which can save significant money and time over the construction of physical prototypes. Computer graphics-based visualizations can now provide crucial visual previews of new lighting concepts for a variety of audiences: system manufacturers can rely on renderings while developing new luminaires and control systems, and designers and their clients can benefit from improved visual accuracy in the specification and design of new systems.

It is important in these cases to accurately and honestly illustrate the visual characteristics of a proposed lighting system. In our previous work, we introduced a novel approach of comparing the perceptual attributes of a virtual scene to those of an analogous real scene, and we have shown a good match between renderings, photographs, and the real scene [1]. The lighting in architectural environments is perceived by humans at many levels, including basic concepts of brightness and contrast, affective responses related to emotion and mood, and finally overall aesthetic quality or pleasantness. Perceived atmosphere, a response which refers to an affective evaluation of the environment and not necessarily an emotion or mood that is caused by the it, has been described in literature as a combination of four attributes: Coziness, which refers to cozy, warm, and pleasant; Liveliness, which is related to exciting and inspiring; Tenseness, which is related to tension and fear; and Detachment, which refers to businesslike and chilly or cold [2]. Atmosphere has been studied as both a response to an existing scene and as an inspiration to create a new scene which can be verified to convey the intended atmosphere [3].

When using computer graphics to create preview renderings of scenes with new concept lighting systems, a primary goal is an accurate perceptual experience: that the visual impression given by the rendering “matches” that of the real environment. With that in mind we focus on the perceptual attributes mentioned above and test if we can create and display virtual environments which convey the same attributes as a real-world example. Perceptual accuracy is affected by choices in all components of the rendering pipeline, illustrated in Figure 1: creating or capturing a scene, including the architectural environment’s geometry and material properties as well as all aspects of the lighting system; rendering, which includes both light-transport modeling as well as virtual photography and tonemapping; reproduction, meaning the medium such as a display or a print; and viewing, referring to who is viewing the image how and for what purpose.

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Much research has focused on the second block of the pipeline, which includes both the simulation of light transport and the virtual camera, whose primary purpose is the transformation of unconstrained scene intensity to an compressed intensity range that may be reproduced by a display. Villa et al. studied rendering engines for lighting simulations [4] as well as tonemapping operators used in the virtual camera [5]. Our previous studies looked at the effect of light transport renderer and tonemapping operator [6][7] and discussed the importance of further optimization of the tonemapping operator [1][8]. In all of our work, we put heavy emphasis on the comparison between real-world and virtual perceptual results, because that is where the proof lies that we have successfully made a visual preview of the real environment. We have demonstrated a high level of perceptual accuracy with our most advanced rendering pipeline choices, but of course we would like to understand what can push it closer to reality.

The third and fourth blocks of the rendering pipeline include the display and viewing situation the viewer employs. Our previous studies were all conducted using static images on large (42-46 inch) televisions. In the present work, we want to know how perceptual accuracy is affected by screen size: either with a smaller, portable screen such as a laptop or tablet, or with a larger (nearly life-size) projected image. Additionally, expecting that a single, static image of a scene is perceived differently than a real room which may be visually explored by head and eye movements, we study the potential benefit of an interactive presentation mode that allows the observer to change the view direction to see details throughout the room rather than being constrained to a single overview image.

2. EXPERIMENTS

In this paper, three experiments are discussed: a baseline experiment, in which the perception of different lighting conditions was studied in a real environment; a pilot experiment, a virtual-environment study that explored the use of multiple views; and the main experiment of the paper, the virtual-environment experiment with variations in display size and interactivity whose perceptual results were compared with the baseline experiment.

2.1 Baseline experiment

The baseline experiment was conducted in a real environment in order to uncover ground truth lighting perception data over a range of lighting conditions. Full detail may be found in a previous paper [1]; here, a short summary is provided. The real environment employed was our Light Lab, which is an otherwise-typical office room with a flexible, computer-controlled lighting system installed. The locations of variable-color temperature fluorescent luminaires and halogen spot lights may been seen in Figure 2, and an overview of the lighting characteristics used in each of the 15 lighting conditions is given in Table 1.

In the experiment, 28 observers viewed all 15 lighting conditions in random order. They were asked to assess on a 7-point scale ten perceptual attributes regarding the atmosphere and light distribution in the room. The perceptual attributes were Overall Pleasantness, Overall Brightness, Overall diffuseness, Contrast, Uniformity, Shadow Visibility, Coziness, Liveliness, Tenseness, and Detachment (businesslike). This list of attributes was chosen to cover overall impressions, perceived atmosphere, and uniformity of light distribution. Mean opinion scores (MOS) for each lighting condition and perceptual attribute are shown in Figure 4. In this figure it is apparent that the lighting conditions effectively modulate all of the perceptual attributes being measured. The underlying effects of color, intensity, and light distribution on these attributes are not discussed here, but are the ground truth which we intend to match with our virtual presentations.
2.2 Pilot experiment

We had long hypothesized that a single view of a room gives the observer a more-constrained, less-complete “picture” of the situation than a freely-viewable real scene, and though we were well aware of various virtual reality systems which aim to immerse a viewer in a scene, the graphics quality of such systems is still lower than sufficient to physically accurately portray lighting systems. Thus we took a first look at an intermediate solution: using multiple static views of the room to see if they added value to perceptual accuracy. In an unpublished study involving a new lighting system in an office room (not the same as our Light Lab), we indeed found that providing observers access to multiple camera views gave a more accurate perceptual impression of the room than giving observers a single, wide-angle overview. Some of the images used are shown in Figure 3. The multiple-view results showed a better correlation with real-room results, and post-experiment discussions with observers confirmed that they appreciated the additional visual information the multiple views provided. We took this intermediate success as good evidence that an interactive, panoramic view would provide added perceptual value to our work.

Figure 3: Example images from a pilot study using a different office room. Assessments of the lighting quality were made using either the single large image (left) or a set of images showing the room, lighting configuration, and details of objects in the scene (4 examples shown at right).
Table 1: Overview of luminaire intensity and color settings for each lighting condition. Shaded regions distinguish categories: warm (conditions 1-4), cool (5-8), dimmed (9-12), and spots (13-15).

<table>
<thead>
<tr>
<th>Category</th>
<th>Condition</th>
<th>Color temp</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>Small sp.</th>
<th>Big sp.</th>
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<td>Full</td>
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<td></td>
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<tr>
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<td>2</td>
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<td></td>
<td>Full</td>
<td>Full</td>
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<tr>
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<td>2700K</td>
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<td>Full</td>
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<tr>
<td></td>
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<td>Full</td>
<td>Full</td>
<td></td>
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<td></td>
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<tr>
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<td>Full</td>
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<td>Half</td>
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<td>Half</td>
<td></td>
<td></td>
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<tr>
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<td>Min</td>
<td></td>
<td></td>
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<tr>
<td>spots</td>
<td>13</td>
<td>3000K</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Full</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>3000K</td>
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<td></td>
<td>Full</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>3000K</td>
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<td>Min</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Baseline results. Mean opinion scores (MOS) over all 28 observers for each lighting condition and each perceptual attribute in the real-room baseline experiment, shown with 95% confidence intervals. Shaded regions distinguish categories: warm (conditions 1-4), cool (5-8), dimmed (9-12), and spots (13-15).
2.3 Presentation mode experiment

Our research track of proving the perceptual accuracy of visualizations of lighting systems with respect to a real scene was extended in a new experiment investigating the effect of image size and interactivity. Using the same scene as in previous experiments [1], a virtual scene created as a detailed 3D model of the Light Lab used in the baseline experiment, we showed the same series of 15 lighting conditions varying in spatial distribution, color temperature, and brightness. The six presentation modes (2 formats x 3 displays) were shown in a balanced incomplete block design to observers who rated the perceptual attributes of the lighting in each image.

Presentation modes

In total, six presentation modes were used: all combinations of two formats and three displays. The viewing formats were a static, wide-angle view of the whole room and a “panoramic” full-sphere view from a single viewpoint which was navigable in terms of view direction by the observer with a computer mouse. In general, it would be ideal to display an image with natural perspective, meaning the field-of-view of the display with a certain viewing distance matches that of the camera making the image. Doing so within the boundaries of a flat display means that a wider field-of-view (which is advantageous because it shows more of the scene) may only be achieved by shortening the viewing distance. However, this is practically limited by the pixel resolution of the display because at a close distance pixel structure becomes visible to the eye and may be a distraction from the images themselves. In our experiment, we circumvented this limitation in two different ways: in the static format, images were rendered with a virtual camera of 97 degrees field-of-view (width) and displayed with 54 degrees field-of-view. This is noticeably wider-angle than reality, but necessarily so in order to include enough of the luminaires and their effects in the scene in the limited angular size of a display. In the panoramic format, we matched the virtual camera to the display field of view (54 degrees width), a view which showed less of the scene at once but which could be explored in detail by the participants by changing the view direction interactively with a mouse.

![Experimental setup](image)

Figure 5: Experimental setup. This illustrative image shows the three displays (laptop, TV, projection) used to show renderings along with a second laptop used for the questionnaire. During the experiment itself, only one display was active at a time.

Both formats were viewed on three displays: a laptop screen, a 46” TV, and a projected image, as seen in Figure 5. The displays were each characterized photometrically in order to build an image transform to device-specific RGB to ensure accurate display of colors and tones. The laptop was a HP 8460p whose 14” LCD had 1366x768 pixel resolution and a peak white luminance of 217 cd/m², and the TV was a 46” NEC P462 LCD with 1920x1080 (Full-HD) pixel resolution and peak white luminance (as operated in the experiment at 50% backlight) of 278 cd/m². The projector was a 3-LCD Sanyo PLC-ZM5000L with 1920x1200 pixels, addressed at Full-HD resolution and configured to show a 138” image on a matte white wall with a peak white of 180 cd/m². To keep the visual angular widths constant between displays, viewing distances of approximately 33cm, 1m, and 3m, respectively, were used. This means that while the physical size of the display was varied, the visual angular size was held constant.
**Stimuli preparation**

Visualization images were made with our image rendering pipeline. A very detailed 3D model of the Light Lab with variations in lighting conditions was made in 3DS Max, rendered with Indigo Renderer, and tonemapped using Reinhard’s photographic tone reproduction algorithm [9]. These images included all improvements suggested and proven by our previous experiments, including material and geometry details and updated tonemapping parameters.

Renderings were made of each light condition in two versions: a single, static wide-angle view of the scene as if made with a normal camera, and a full-sphere panorama made with six 90-degree field-of-view cameras from the same viewpoint which was designed for interactive panoramic presentation on the faces of a cube. These are illustrated in Figure 6. Images were rendered with sufficient resolution for Full-HD (1920x1080) display. For the static wide-angle stimuli, this was simply the output resolution; for the panoramic stimuli, each 90-degree face of the cube was rendered with 3776x3776 pixels, so that when presented with 54 degrees field of view, there were just enough pixels to fill the Full-HD screen.

![Figure 6: Renderings used to construct stimuli. The single image (left) shows the static wide-angle view used for the static format, and the set of square images (right) are the faces of a cube which, when viewed from inside, provide a full panorama of the scene in the panoramic format.](image)

**Experimental procedure**

Each of 24 observers viewed images in four of the six presentation modes (2 formats x 3 displays) in a balanced incomplete block design. In this design we assured that every participant used both formats and all three displays, but not all possible combinations. Presentations were blocked, meaning that the participant viewed all 15 lighting conditions for a single format-display combination before moving to another presentation mode, and the order of presentation mode was counterbalanced over participants.

A laptop-based questionnaire was used by all observers in both virtual and real room experiments. For each lighting condition, observers assessed the scene according to perceptual attributes using the same questionnaire employed in the baseline experiment. After all stimuli were assessed, observers were asked to rate each format/display combination on five items related to presence and quality, each with seven levels with endpoints labeled: “I had a sense of being there – not at all/very much;” “the office space seems to be more like – images that I saw/somewhere I visited;” “Compared to real environments, I thought the lighting in the office looked – very artificial/very natural;” “For assessing the lighting in the office space the size of the image was – very poor/very good;” “For assessing the lighting in the office space the quality of the image was – very poor/very good.” Observers were then asked to rank the displays best to worst and formats better/worse with respect to which gave the clearest impression of the lighting in the office space. Finally, they were asked how easy to use was the panorama format.
3. RESULTS

The results of these experiments are explained in several steps. First, the results of the presentation mode experiment itself and the effects of image size and format on perceptual attributes are shown; there are some small effects here but it is not the focus of our analysis. Our core interest is in the perceptual accuracy of the presentation modes, and this is assessed mainly via comparisons between the presentation mode experiment and the baseline experiment, which we call indirect measures, and additionally through analysis of the post-experiment questionnaire on quality and immersion and the ranking on preference, which are direct measures.

Looking first at the observers’ ratings of the perceptual attributes within the presentation mode experiment, we performed several analyses using linear mixed models (LMM), which are appropriate for incomplete and mixed between-within subject designs [10]. Looking for the effects of format and display within the present experiment, separate LMMs were computed for each of the 10 attributes with three fixed factors (lighting condition, format, and display) and a random factor (observer) with both offset and gain parameters. In all cases lighting condition shows a significant effect, as expected. We found significant effects (p<0.05) of format for attributes Brightness, Contrast, Shadow Visibility, Liveliness, Tenseness, and Detachment; and significant effects of display for attributes Pleasantness, Brightness, Diffuseness, Contrast, Coziness, and Liveliness. These effects show that observers indeed perceived the room differently depending on the presentation.

Next, a between-subjects comparison with the baseline real room experiment results was performed to assess how accurately these different presentation styles convey the perceptual attributes of the real room. This is an indirect measure, a sort of meta-analysis across experiments. Separate LMMs were computed for each perceptual attribute with fixed factors of light condition and presentation mode (of which there were seven: six display/format combinations from the present experiment plus the real room data as if they were a unique display/format combination), with observer as a random factor. Main effects for the perceptual attributes are shown in Table 2, which shows differences in estimated marginal means between the real room and each presentation mode using the model. The differences have an average absolute delta mean of only 0.125 on 7 point scale – this overall high level of accuracy between the visualizations and the real room is the result of the success of our choices in 3D model, rendering, and tonemapping. The table shows a notable robustness to the presentation mode, with the only significant differences seen in Brightness, which is worse for the projector and in the panoramic TV presentation, Uniformity, which is worse with the laptop and in the static TV case, and Diffuseness, which is significant in the static laptop case. Thus, no presentation mode stands out as dramatically better or worse than the others in terms of overall perceptual accuracy.

Table 2: Differences in estimated marginal means (based on a 1-7 rating scale) between the real room and the visualization for the ten perceptual attributes (columns) and the 6 display/format combinations (rows). Significant differences are indicated by * (p<0.05) and ** (p<0.01).

<table>
<thead>
<tr>
<th>Display</th>
<th>Format</th>
<th>Pleasantness</th>
<th>Brightness</th>
<th>Diffuseness</th>
<th>Contrast</th>
<th>Uniformity</th>
<th>Shadow Visibility</th>
<th>Coziness</th>
<th>Liveliness</th>
<th>Tenseness</th>
<th>Detachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop</td>
<td>Static</td>
<td>-.09</td>
<td>-.13</td>
<td>.36**</td>
<td>-.07</td>
<td>.43**</td>
<td>-.05</td>
<td>.04</td>
<td>.05</td>
<td>.13</td>
<td>-.05</td>
</tr>
<tr>
<td>Laptop</td>
<td>Panorama</td>
<td>.10</td>
<td>-.22</td>
<td>.30</td>
<td>-.11</td>
<td>.42**</td>
<td>.11</td>
<td>.04</td>
<td>.00</td>
<td>-.25</td>
<td>-.03</td>
</tr>
<tr>
<td>TV</td>
<td>Static</td>
<td>-.06</td>
<td>-.13</td>
<td>.18</td>
<td>-.14</td>
<td>.36*</td>
<td>-.22</td>
<td>.07</td>
<td>.05</td>
<td>.15</td>
<td>-.16</td>
</tr>
<tr>
<td>TV</td>
<td>Panorama</td>
<td>-.14</td>
<td>-.39**</td>
<td>.15</td>
<td>.04</td>
<td>.29</td>
<td>.13</td>
<td>-.06</td>
<td>-.19</td>
<td>-.01</td>
<td>-.07</td>
</tr>
<tr>
<td>Projector</td>
<td>Static</td>
<td>.12</td>
<td>-.27*</td>
<td>.05</td>
<td>.12</td>
<td>.27</td>
<td>-.03</td>
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<td>.07</td>
<td>.11</td>
<td>-.09</td>
<td>.00</td>
</tr>
</tbody>
</table>

Though the analysis included presentation mode as a fixed factor rather than display and format separately, it is worth looking at the results in a different way to try to uncover where differences arise. Figure 7 shows the baseline real room results along with the present experiment’s results split on format (static and panoramic). Overall both formats perform quite similarly to the baseline, however where disparities are present, the difference between formats is generally smaller than the difference between either format and the real room data. The biggest differences are seen in Brightness, where
in lighting conditions 9-12 (the dimmed conditions) the results of both formats are significantly higher than the results from the real room, with panoramic performing somewhat worse. A few other lighting conditions for some attributes also show differences, such as the dimmed conditions for Pleasantness and Liveliness. We prepared a similar figure with the baseline results along with all three displays, but it is not included in this paper because the displays consistently matched each other and the differences between them as a group and the baseline follow the trends seen in Figure 7.

![Figure 7: Mean opinion scores (MOS) for each lighting condition and each perceptual attribute of the baseline experiment (solid) compared with virtual experiment split on format: static (line) and panoramic (open). Shaded regions distinguish categories: warm (conditions 1-4), cool (5-8), dimmed (9-12), and spots (13-15).](image)

An analysis of the post-experiment questionnaire can relate direct impressions to the above indirect measures. For the five questions regarding presence and quality, LMMs were computed for each question with display and format as fixed factors and observer as a random factor. Display was found to be significant for all questions, while format and interaction effects were found not significant. Plots showing the effect of display and format are shown in Figure 8, where the markers refer to the five questions. In the left plot it is clear that all the questions show a peak for the TV and lower values for the laptop and projection. The right plot shows the lack of effect of format.

The rank order results clearly showed a preference for the TV. Treating the rankings as paired-comparison data and applying Montag’s method [11] resulted in z-scores of 0, 1.5, and 0.98, for laptop, TV, and projector, respectively, with all pairwise differences significant at the 95% level. For format, the paired-comparison result was 15 of 24 in favor of the static format, which is just not significant. The final question on the ease of use of the panoramic format showed an average value of 5.5 out of 7. Thus, all the post-experiment questions point toward a preference for the TV among the three displays and no preference for format.
We began this study with the expectation that screen size and interactive view direction would affect the perceptual accuracy of visualizations of lighting conditions. In our indirect measures, a between-observer comparison of our virtual presentations of a rendered environment with a real environment, the differences among the presentation modes are smaller than the overall difference between virtual and real. However, much of these differences are found in the attribute of Brightness, which throughout our research is consistently difficult to convey. Setting aside Brightness, both large-size projection and interactive viewing show an advantage.

We maintain an opinion that physical intensity differences in a reproduction such as on a TV are discounted in some way by observers, perhaps because people are more likely to interpret a dark image as a poor photo of a normal room rather than a good photo of a dark room. We took a look at exactly which lighting conditions perform worst, which tend to be the “dimmed” conditions (9-12) and the darkest spot image (15), and found an interesting trend in the Brightness data: the difference in Brightness between full-brightness and dimmed conditions was larger (and more like the real room) for the static format than for the panoramic format. However, there was no consistent trend among the other attributes. Regardless of presentation, additional research is warranted on how visualizations affect brightness perception in general and on unusual, for example dimmed, lighting conditions.

It is interesting which responses to lighting are most accurately conveyed. The four atmosphere attributes are consistently rated the same in all virtual presentation modes as in the real environment, as is Pleasantness. Some of the more basic attributes, Brightness and Uniformity, are predicted less accurately overall. Yet, Contrast and Diffuseness, which in many experiments correlate well with Uniformity, are predicted consistently accurately.

For the direct measures regarding quality, immersion, and preference, the effect of display size is a consistent peak for TV. This could perhaps be completely explained by image quality: the TV is visibly better in brightness and dynamic range than both other displays and better in resolution than the laptop display. Format provides a very weak effect in all post-experiment measures, which is somewhat of a surprise. In informal discussion with observers after the experiment, many mentioned that the extra work required to navigate the panoramic format became tiring. Perhaps, then, if observers tired of exploring the panoramic images, they missed the extra information which they contained and in fact saw a more constrained view of the scene. This could relate back to the brightness differences where the panoramic format performed worse than static: we could imagine that the limited view of the back wall of the Light Lab (where the panoramic mode shows the starting view for each lighting condition) did not show as great a difference in intensity/brightness as would be seen in the room overall. If observers didn’t take the time to explore the scene for each lighting condition, this might explain the overestimation of brightness in the few unusually dim ones.

4. DISCUSSION
In the present experiment observers were asked to explore tens of panoramic stimuli – in a more reasonable and practical use case, exploring one or two scene variations could be much less tiring and may show more added value. A fatigue effect might be seen in the perceptual attribute data as well: looking solely via a visual interpretation of our data, we see a trend that the real room attribute ratings, given in a single experimental session of 15 lighting conditions, are generally more extreme than the virtual ratings, which were given in a longer experiment of 15 lighting conditions times 4 presentation modes. If the observers indeed become fatigued by repeated assessments of similar scenes, then their mean results may trend toward the middle. It is always tempting in the construction of these experiments to include many within-observer stimuli, and while we always strive to keep the experiment length under 40 minutes, that limit may already be too liberal for the small differences we are studying.

5. CONCLUSIONS

In this experiment we assessed the impact of display size and interactivity on the perceptual accuracy of visualizations of lighting in an indoor environment. We can conclude that a high-quality, well-calibrated TV-sized display performs best overall in conveying the perceptual attributes of lighting systems in an indoor scene, especially knowing that Brightness is consistently a difficult attribute to convey accurately in virtual environments. Based on preference and observers’ opinions about which is better for assessing lighting, the TV outranks the other displays, which also correlates with its higher image quality. However, because all of the virtual presentation modes give a good impression of the real world, choosing to use a laptop (e.g., for convenience and portability) or a projector (e.g., for a large audience) does not risk losing perceptual accuracy for most attributes. We can also conclude that an interactive display format which allows the observer to look around the virtual scene shows some minor value in conveying the perceptual attributes of the scene, but is not preferred in a significant way, despite being found easy to use. The expected added value of a panoramic format may be found in normal use cases of one or two scenes, but is too fatiguing for a long series of scenes as presented in this experiment.

REFERENCES