The experience of equivalent luminous colors at architectural scale

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ABSTRACT

Luminous color used in architectural settings impacts our perception of space and ambiance. With light emitting diode, solid state lighting technology the possibilities of customizing light spectra are manifold, and colored light can be mixed and matched using a variety of different spectral compositions. We conducted several experiments at architectural scale to explore whether stimuli closely matched for chromaticity and light level would produce recognizable differences in visual and visceral qualities.

Study 1 used qualitative research methods; during the experiment, participants were free to walk from one illuminated space to another to compare conditions close-up and from afar. Study 2 used quantitative research methods; participants were situated in a fixed viewing location and responded to a questionnaire that was designed based on the responses from Study 1. In Study 3 blood pressure was measured in response to all of the lighting conditions.

Overall, the results showed that subjects perceived differences in the visual qualities of the conditions. The results also showed significant differences in affective qualities and physiological responses between some of the conditions.

KEYWORDS

Full-field vision, Color perception, Architectural-scale experiment, Peripheral vision, Brightness perception, Metamers

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1. INTRODUCTION

The use of colored light in architectural design has increased significantly over the past two decades. Bold colors, for example, are frequently integrated into lighting for façades and public spaces, and subtle tunable solutions are being tested for retail (e.g., color rendering) and health care (e.g., circadian effects).

Perceptual experiments suggest that metameric color stimuli, stimuli with the same chromaticity coordinates but different spectral power distributions (Wyszecki and Stiles, 1982), at the same luminance, might not be identical in perceived brightness (Besenecker and Bullough, 2016) or saturation (Gerlach, 2003), especially when viewed in a full field-of- view including peripheral photoreceptive mechanisms. Most color metrics used in practice and application are based upon the central visual field of view (Boyce, 2003). In addition, light of different spectral compositions can vary in eliciting non-visual physiological responses (Choi et al., 2011; Lockley et al., 2006). The authors of this paper are interested in the architectural relevance of nominally metameric colors when experienced in large-scale conditions with a full- field of view including peripheral vision.

Lighting design for theater and music performance has developed a body of knowledge for the creation of sophisticated designs with colored light. In theaters and studios, seven-color light emitting diode (LED) systems are being used increasingly to replace traditional filtered tungsten sources. Three- or four-color LED sources, as used in many architectural color-changing fixtures, have been judged by design professionals as insufficient to produce the desired color range and quality for theatrical and other performance uses (Taylor, 2016). The transition from filtered tungsten sources to multi-emitter LED sources comes with the challenge to color match past projects that are being retrofitted (Schwendinger, 2016; Gerlach, 2016). It also comes with the opportunity to use metameric colors as a new design tool. The technology change also exposed shortcomings for the most common metrics used in industry to measure and match luminous color and light level. Practitioners and manufacturers observe limitations in matches made via color and luminance meters, and are often left with developing color and brightness matches by eye (Taylor, 2016; Gerlach, 2016).

In order to investigate the differences in the effects of large-scale colors matched for chromaticity and luminance, we designed dedicated experiments in the 15.25 m x 18.30 m x 10.65 m black box studio space of the Experimental Media and Performing Arts Center (EMPAC) at Rensselaer Polytechnic Institute (RPI). Semi-circular wall surfaces (denoted ‘tubicles’, 2.75 m diameter x 4.25 m height) were built and illuminated with nearly equivalent colors that were mixed using different methods: filtered tungsten, a three-color LED system, and a seven-color LED system, as well as a video projector. In addition, we closely matched the chromaticity of the colored light using paint pigments illuminated by white LED and tungsten light sources.

Using this ‘apparatus’, we conducted a series of studies with two hue groups, amber and cyan, using hybrid research methods (Besenecker and Krueger, 2015): a qualitative study (Study 1) with 17 participants, followed up by a quantitative protocol (Study 2) with 12 participants. The participants experienced the conditions at different vantage points using their full fields of vision. In addition, most of the participants (n=28) also participated in separate sessions (Study 3) dedicated to measure blood pressure in response to the lighting conditions.

2. STUDY APPROACH AND SET-UP

When viewing nominally equivalent colors with a full field of view, discrepancies in perceived brightness (Besenecker and Bullough, 2016) and saturation (Gerlach, 2003) have been observed. To explore the perceived differences of equivalent colors in architectural-scale spatial settings, we conducted a series of studies.

We built several semi-circular viewing chambers (tubicles) in a black-box studio and created seven nearly equivalent color conditions for amber and cyan respectively that were mixed using different methods. Figure 1 shows the spatial layout in the planning stages

The color conditions for the amber and cyan hue groups were created as follows (with the amber conditions mentioned first, the cyan conditions second):

1. AT or CT: a tungsten source with an amber or cyan color filter on white matte paint
2. ALED or CLED: an amber or cyan LED on white matte paint
3. ARG or CBG: a red + green LED mixture, or blue + green LED mixture on white matte paint
4. ARL or CIR: a red + lime LED mixture, or a red + indigo + cyan LED mixture on white matte paint
5. AP or CP: a digital light processing (DLP) projector red + green mixture, or blue + green mixture
6. APLED or CPLED: a white LED source on amber or cyan paint
7. APT or CPT: a tungsten source on amber or cyan paint

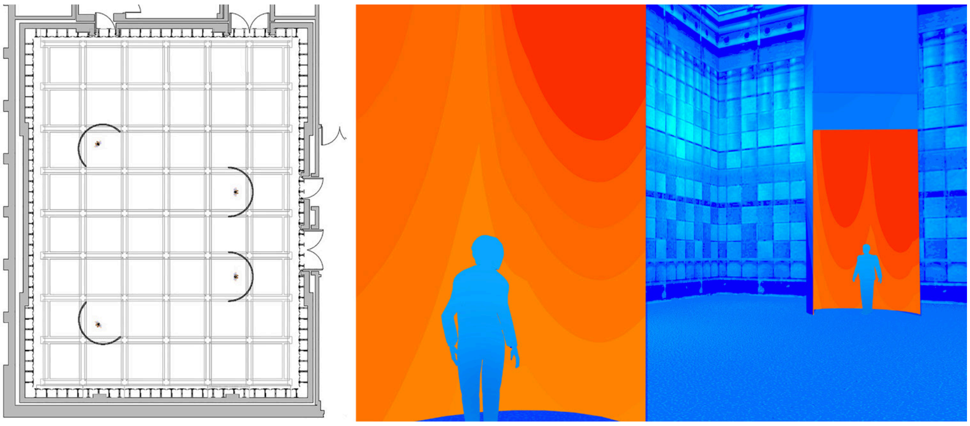

Figure 1 - Semi-circular viewing chambers (tubicles), size: 2.75 m diameter x 4.25 m height, in a 15.25 m x 18.30 m x 10.56 m black box studio space

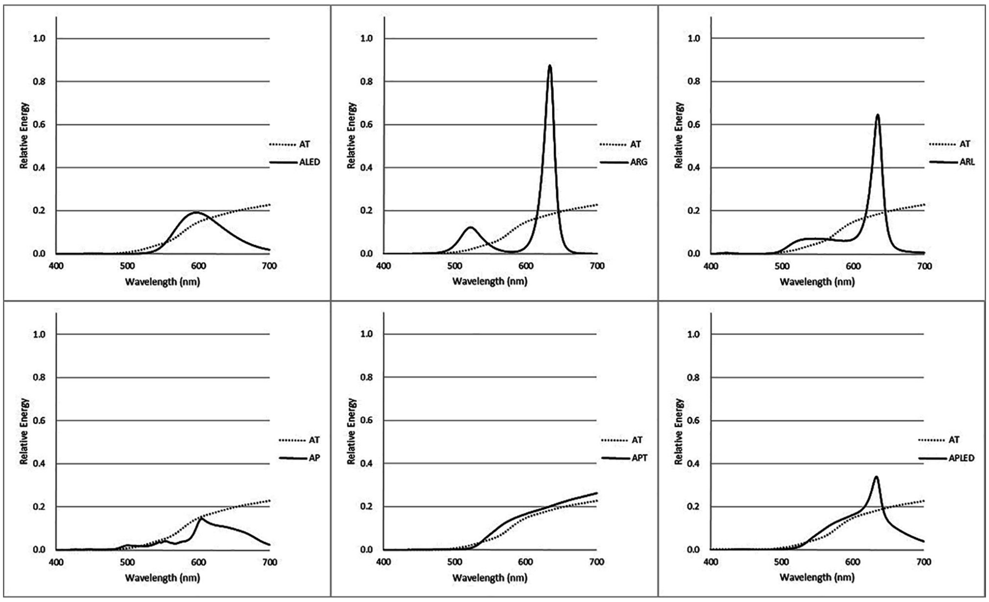

Figure 2 - Spectral power distributions of amber conditions 2-7 in relation to condition 1 (scaled for relative light level).

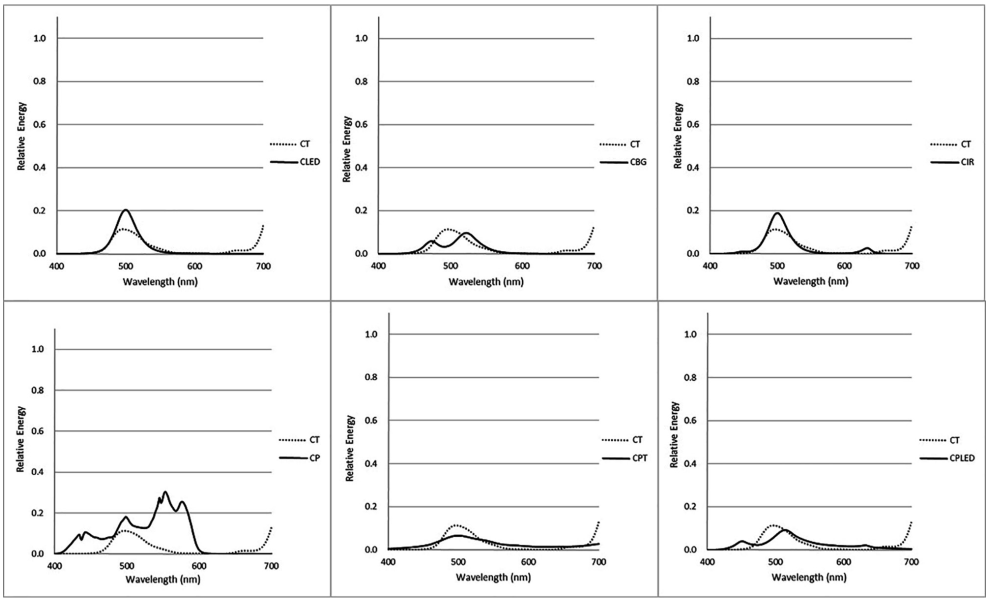

Figure 3 -Spectral power distributions of cyan conditions 2-7 in relation to condition 1 (scaled for relative light level).

Figure 2 (amber) and Figure 3 (cyan) show the different spectral power distributions (SPDs), scaled for relative light level, of conditions 2-7 in relation to condition 1 (filtered tungsten), which was used as a reference. Figure 4 shows the chromaticity coordinates for all conditions plotted on the 1964 CIE diagram for 10° vision. The CIE 1964 color space was chosen as the most commonly used one that includes data for peripheral vision and not only a 2° field of view (e.g. theatre lighting color filter manufacturers often communicate data that way). Due to the scale of the set-up and the equipment available, the conditions were not exact metamers; they did not match precisely in their chromaticity (see Figure 4). But these are the conditions that

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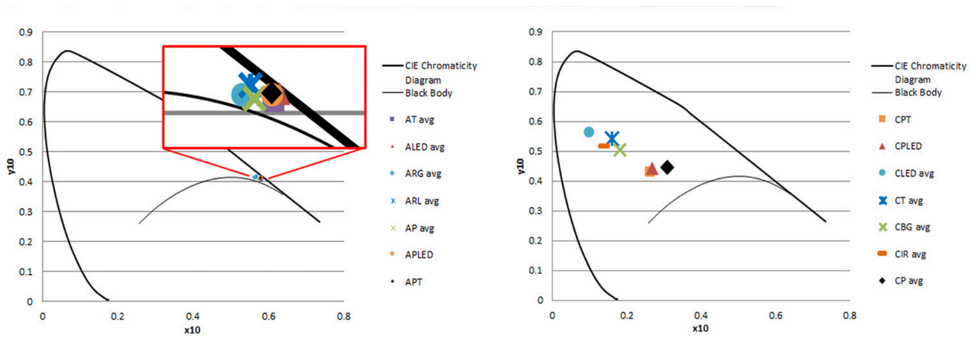


Figure 4 - Chromaticity coordinates (CIE 1964) for the amber (left) and cyan (right) conditions

are found in the field using currently available technologies and so have ecological validity for architecture and design.

We were interested in how people would evaluate the conditions and whether consistent patterns in their responses could be observed. We were particularly interested in the following questions:

- Are there consistent patterns in participants' comments on perceived differences among conditions?
- Are the differences consistent with or different from the metrics of chromaticity and luminance?
- Are there relationships between responses in different categories (e.g. visual and emotional or spatial qualities)?

3. PROCEDURES

Three studies were conducted.

3.1 STUDY 1

Study 1 was exploratory and qualitative. Seventeen color-normal (Ishihara, 1963) participants between the ages of 27 – 82 (mean 50 years) participated, ten males and seven females, with varying degrees of expertise in working with light and color. Nine of them work professionally with either light or color: seven as designers and two as photographers.

The participants were free to move around as desired; see Figure 5. Each participant was shown a timed sequence of 13 pairs of illuminated spaces, 2 minutes for each pair, with a 30 second break to reset adaptation of the eyes. They were asked to give any comments and comparisons in response to the color conditions.

Each participant conducted the study with both hue groups, amber and cyan, separately, one in the morning, one in the afternoon. The order of conditions and hue groups were varied for counterbalancing.

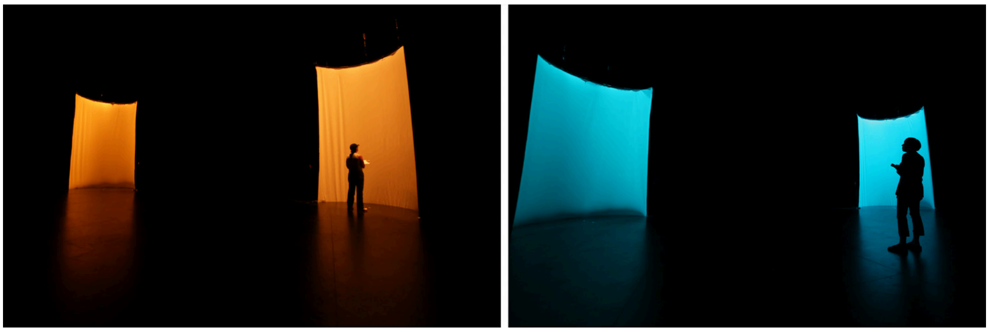


Figure 5 - Participants evaluating and comparing two amber conditions (left) and two cyan conditions (right)

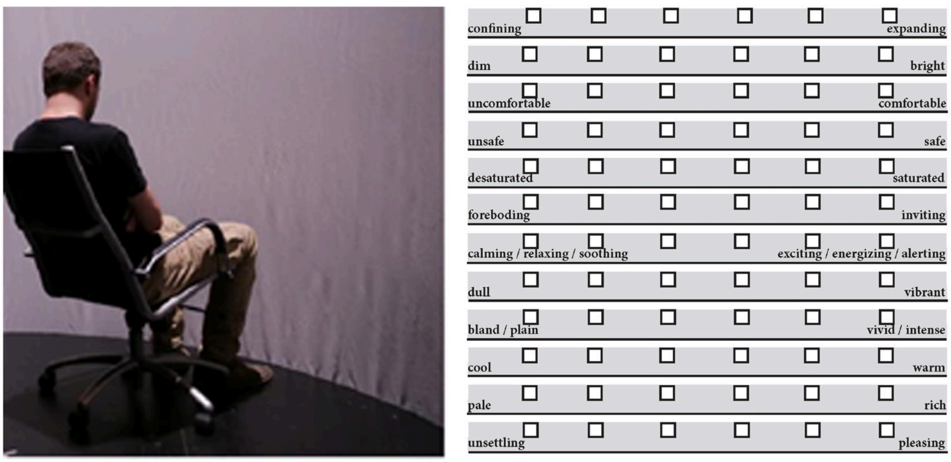


Figure 6 - Participant sitting in the tubicle (left) using a questionnaire (right).

All comments, whether written or spoken, were recorded, transcribed and coded into categories: visual qualities (brightness, saturation), emotional qualities (aversion, attraction), and spatial qualities. The results were graphed and produced ranking orders for the different conditions (e.g., bright to dim, saturated to unsaturated).

3.2 STUDY 2

Based on the terms used by the participants in Study 1 to describe the conditions, we conducted a follow-up study (Study 2) two months later using the same lighting conditions. Twelve color-normal (Ishihara, 1963) participants between the ages of 24 – 65 (mean 43 years), eight males and four females, sat in a fixed location (see Figure 6) and evaluated the conditions using a questionnaire. None of the participants had been part of Study 1. They had varying degrees of expertise in working with light and color. Six of them work professionally with either light or color: two as designers, four as scientific researchers.

3.2 STUDY 3

Study 3 was conducted with participants of Study 1 and 2 in a separate session, sitting immersed in the condition as illustrated in Figure 7. There were twenty-eight participants, all between the ages of 24 – 79 (mean 46 years), with eighteen males and ten females. Blood pressure was measured using an arm cuff at the onset (base line) and for each condition (1.5 minutes of exposure). In between the conditions the participants were exposed to 30 seconds of darkness to reset adaptation

4. RESULTS

Study 1 produced a rich variety of comments, such as: *"Oh! That is very much more cheerful. I don't know why. It doesn't look that different, but it seems more cheerful. When you are in it, it feels more like it is difficult to balance. Try to stand on one leg. Hehehe. This is leathery. I could knit myself up in there though."*

Some comments revealed individual differences in perception and preference, depending on experience and personality. The below responses of two different participants to the same -exciting or upsetting- condition are an example:

Participant #16: "(Laugh) *Oh, wow, now that gets me excited. On the right. Oh my gosh. That's a happy color! Hah! Oh my lord. Nice contrast here."*

Participant #7: *"That's very bright and very light. Almost translucent. It's back to upsetting. A group that's upsetting. Unstringing. It makes me breathe hard."*

While individual differences could be observed, there were also reliable average patterns in the study results. For Studies 1 and 2, all results were organized in categories of visual qualities (brightness and saturation), emotional qualities (attraction), and spatial qualities (spaciousness). Results from both experimental sessions, Study 1 and Study 2, suggested that people consistently were aware of qualitative differences of the conditions for both hue groups, amber as well as cyan. This held true not only when observers were seated in one location and instructed to fill out a questionnaire (Study 2), but also when walking around comparing conditions from different locations (Study 1).

Differences in perceived brightness were distinct and significant, and the brightness perception results were predicted slightly better using a provisional scene brightness model (Besenecker and Bullough, 2015) than luminance, the industry standard.

Also, while differences in chromaticity were small, especially for the amber conditions, the differences in perceived saturation were relatively large.

Focusing on the three LED sources only (ALED, ARG, ARL (amber) or CLED, CBG, CIR (cyan)) suggests that the perceived visual differences in brightness and saturation between the narrowband LED condition (amber LED (ALED) or cyan LED (CLED) respectively) and the 3-color source LED condition (red+green LED (ARG) or green+blue LED (CBG) respectively) were reliable ($p<0.05$). However, the perceived differences in brightness and saturation between the 7-color source LED condition (red+lime LED (ARL) or red+indigo+cyan LED (CIR) respectively) and

Figure 7 - Participant sitting in the tubicle for blood pressure measurements, amber (left) and cyan (right).

the other two LED conditions (ALED and ARG, or CLED and CBG respectively) were not.

This suggests that when matching luminous colors in spatial environments, options beyond narrowband RGB sources can provide closer perceptual matches. In addition, these can also offer a variety in color rendering properties which might be useful for design applications (Taylor, 2016).

Further to exploring the differences between the luminous color conditions, the studies showed differences between luminous color and illuminated colored paint (illuminated color). The illuminated color conditions were evaluated as similar to the luminous color (colored light on white paint) when viewing them from farther away (Study 1), without being immersed or covering the full-field of view. The participants did not notice that it was not the light that was colored. From close- up, immersed in the condition (Study 1 and 2), there were, however, differences, as described in the quotes below:

Participant #10: *"Initially seems similar, but after looking at paper - seems almost grey / more dull and memory of other wall impact is more vivid".*

Participant #16: *"They both seem pretty similar, but the one on the right seems more saturated and luminous. And the one on the left, it feels more integrated with the fabric, and it appears less luminous. And… then when you get up close and it's the only thing around you it feels pretty saturated. Proximity changes some of the effect of the color. They're quite the similar hue, and now I do realize that that's actually painted."*

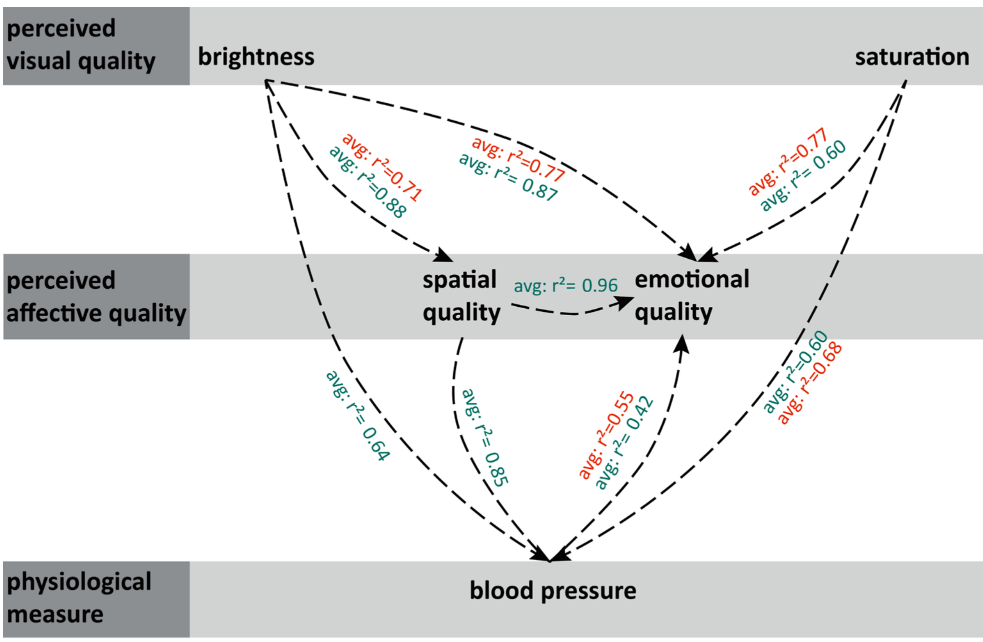
The illuminated color retained saturation, while the luminous color conditions desaturated (likely due to chromatic adaptation (Fairchild, 2013)). This was especially apparent in the results for the cyan hue group, because chromaticity predicted that the cyan paint condition would look less saturated than the cyan light conditions, which was not the case when being immersed.

The above observation suggests that with the increasing use of colored light in architectural environments, more detailed perception studies into full-field chromatic adaptation would be useful to inform the appropriate use of colored light and colored paint in design applications.

One of our objectives was to learn about possible relationships between the perceptions of visual, emotional and spatial qualities, and, as well, physiological measures (blood pressure). Therefore, after coding all results into such categories and creating interval rankings, we correlated the results. The statistically significant correlations ($p<0.05$) are summarized in Figure 8.

As Figure 8 shows, for this set of experiments, the perception of brightness was correlated with perceived spatial and emotional qualities for both hue groups, amber and cyan. For example, brighter looking conditions seemed preferred and appeared more spacious than dimmer looking ones. For the cyan condition brightness perception was also correlated with blood pressure (higher brightness was correlated with lower blood pressure).

The correlations also suggested that for the amber conditions a higher perceived saturation was evaluated as more attractive and preferred (emotional quality). For the cyan conditions, however, the correlation was reversed: a less saturated appearance was preferred. Perceived saturation was also correlated with blood pressure for both hue groups: higher perceived



Note: Dashed lines and arrows show reliable correlations.

Figure 8 - Correlation between the participant responses (coded into categories) for amber and cyan.

saturation coincided with a higher blood pressure.
In addition, blood pressure was correlated with emotional quality (preference) for both, amber and cyan. For the cyan conditions, blood pressure was also correlated with how spacious a condition appeared. Perceiving a cyan condition as more spaciousness coincided with a lower blood pressure and was correlated to higher preference (emotional quality).

5. SUMMARY

For cyan and amber conditions that were matched closely for chromaticity and luminance, participants reported (reliable average trend); these differences were larger than predicted by the industry metrics in common use (luminance, chromaticity). Participants also reported differences between the nominally similar conditions in emotional (preference) and spatial qualities (reliable average trend). In addition, there were correlations between visual qualities, spatial, emotional qualities and measured blood pressure.
This confirms observations from field practice that the metrics and tools currently used to visually match luminous colors do not provide satisfying perceptual matches when used for large-scale set-ups.
Furthermore, the results suggest that participants can pick up subtle differences and evaluate nearly equivalent colors differently depending on spectral composition. This could inform design practice when choosing the technologies and tools to implement color into spatial designs.
In addition to the average patterns, transcribed qualitative responses and associations substantiated the average trends while also adding information about individual variations between the different participants.

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CONFLICT OF INTEREST

The authors state that no actual or potential conflicts of interest exist including financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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