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LUMINOUS COLOR IN ARCHITECTURE: EXPLORING METHODOLOGIES FOR DESIGN-RELEVANT RESEARCH

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ABSTRACT

This paper describes our process in conducting research toward better understanding of the experience and perception of luminous colors in architectural contexts. Our intention is to contribute to a body of knowledge useful for designers by introducing a designerly way of working into an otherwise academic research approach. Luminous color influences our perception of form, space, and ambiance. The use of such color in architectural design has increased significantly over the past two decades, and with the advent of light-emitting diodes (LEDs), this trend is rapidly accelerating. However, LEDs produce luminous color in a different manner than traditional lighting systems. Identical-appearing colors can have different spectral compositions. Current work in health and perception sciences demonstrates that these different spectra can have distinct physiological and neurological effects.

Current studies in different academic research fields into luminous color cannot be translated easily into a format relevant to architectural design. We therefore look to ways of studying the phenomenon using hybrid methods that would be consistent with design disciplines and goals. Efforts include structured experimental studies at a large scale to enable participants to experience different vantage points, peripheral perceptions, and free locomotion.

The objective is to listen to the phenomenon and let it guide the research. We are following a process and developing research methods that are at a scale and in contexts appropriate to architectural applications. Although we borrow qualitative and quantitative methods from other disciplines for our individual studies, the overall goal is to remain fluid and open, to go beyond such established methods, structuring the endeavor as much as possible as a design process. Our approach is less structured than laboratory research, but targeted to be more ecologically and architecturally valid.

Keywords:

Mixed method research, design-lead research, luminous color, peripheral perception

1. INTRODUCTION
1.1. Overview

The means of introducing color and light into architectural indoor and outdoor spaces is in transition. At the same time, an increased use of color in the built environment can be observed (Laganier and van der Pol 2011, Bahamon and Alvarez 2010, The Plan 2011). An individual's perception of a spatial environment is greatly influenced by the interplay of light and color. We intend to collect knowledge that helps designers understand the plethora of systems for illuminating and coloring surrounding environments.

In seeking background material for our research, we discovered that while in the first half of the 20th century there were architectural explorations into color for spatial design purposes (Braham 2002), current investigations into color generally occur in other disciplines. Even among research that exists, however, the different outlooks of designers and scientists contribute to a wide gulf in the reporting of results. Neither approach fully addresses the needs of our project. Designers produce physical objects or spatial environments to be used and experienced physically, while scientists produce a knowledge base to be used intellectually.

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Having worked in those realms and learned to use traditional methods of design practice and academic research, we argue that design methodology could inform an academic research endeavor, especially one intended to generate knowledge destined for design practice. Such an approach should be able to produce a knowledge base helpful to designers (as it was to be derived using similar processes). We are interested in the phenomenological changes that new technologies of color and light production present for design, and we believe that this topic lends itself to a hybrid research approach that explores new methodologies of investigation.

1.2. Methods of investigations

Our own educational and professional backgrounds are multidisciplinary, with experience in architectural and lighting design, and different academic research methods. Having worked within different academic and professional frameworks, we noticed that there is often no direct path for implementation in architectural design of the ideas and concepts that emerge from research in other academic research fields. Knowledge in such disciplines might cover topics related to architecture, but it is usually structured with different objectives. The bridging between disciplines is not as straightforward as one might think.

Scientific research methods tend to be consistent with a particular discipline's traditions, goals, and research questions. In perception science, research takes place in controlled laboratory environments, where researchers collect quantitative data using sensors, tests, and questionnaires. These data can then be statistically analyzed, evaluated, and interpreted (Field 2011). The objective is to control confounds as much as possible to investigate a specific, confirmable hypothesis, and be able to make statements about cause and effect of specific variables. Results are typically averaged across subjects and statistically tested to obtain mean values, and establish correlation and deviation. This results in values that are generalized across a larger population.

The obvious limitation of this approach is that people do not live and act in controlled laboratory environments, and that it is sometimes individual responses and exceptions that can be most informative. In fact, in some studies, results that are too far from mean values are discarded as erroneous. Thus, these studies can often temper individuality in a manner that is not consistent with the real world. These studies do not have ecological validity in the field. The individuals who occupy architectural environments are inherently complex, dynamic, and difficult to control. Simple cause-and-effect relationships are difficult to establish and might not be appropriate; multiple-causality dominates. In understanding such environments, the distribution of individual experiences is of interest, rather than an average one.

To address these problems, field research is often performed using qualitative methods rather than quantitative. Such techniques are often used for studies in the social sciences. Interviews, participant observations, and case studies are just three examples of the many possible qualitative approaches that might lead to new knowledge (Denzin and Lincoln 2003). Field research, however, is performed within the complexities of its context, and its validity has to be understood within that particular environment.

Another approach to address the issue of ecological validity can be found in the field of interactive arts installations (Candy and Edmonds 2011). These installations can be scaled and timed as needed for the research being performed. Qualitative methodologies can be adopted and developed for this research as such practice establishes itself. In a similar manner, some architectural designers start prototyping and testing their ideas by building temporary installations that can be experienced by the public (Minimaforms 2013). Research is performed using visitors and observers of the installations to learn about human behavior and technology-human interaction.

Design research, however, has not established a methodology of its own. Rather, it borrows methods from the disciplines described above: 1) quantitative procedures such as analyzing questionnaire data, and data collected from automated building systems or user logs; 2) qualitative procedures such as conducting and analyzing interviews with residents, and notes from observations in the field. Although systematic methodologies have been established in the traditional cultures of academic research that aim to produce and confirm repeatable insights, design practice and related research is targeted to produce new, often unique, solutions. Typically, the interests and objectives of the design disciplines are targeted at applications.

One branch of design research is interested in establishing insights into how designers work and confirm design as a third culture of knowledge production in addition to science and the humanities (Cross 2010). Design is a discipline that has its own processes. Although attempts have been made, it is uncommon that these processes are structured and taught in a prescriptive way. A creative design process consists of the iterative development and testing of ideas (e.g., through drawing and modelling) in which the nature of the problem is investigated. This arguably is itself a kind of research. However, much of this work is not directly pragmatic, in the sense that it is working toward a specific solution to a problem, but is instead epistemic (Kirsh and Maglio 1994). Its goal is to change the understanding of the designer. Designs typically go through multiple iterations to spur discovery in a nonlinear way but always with the design goal and objective in mind. The role of question finding is inextricably bound to the design process, and in many cases, the design solution is also simultaneously a definition of the problem itself (Rittel and Webber 1973). The questions and solutions coevolve. Any design solution is situated within that open process, answering some questions and at the same time posing new ones. Designers are typically interested in design manifestation, while scientists typically look to develop models that explain the mechanism of their particular interest. Thus, the designer's objective is creation and manifestation, and the objective of the scientist is explanation and confirmation. Instead of assuming a linear progression—from the confirmation and explanation of a phenomenon by scientific investigations to translation into a design solution—designers explore the phenomenon of interest by working in an iterative way toward a design solution, producing insights into the phenomenon itself along the way.

In the realm of arts and design, mastery and expertise are developed through practice. However, to produce creative works, it is necessary to be open to discovery and intuition. Johannes Itten (1888–1967) was an artist, researcher, and teacher who chose color as his field of study.

He explored color and subtractive color mixing in a structured way from within the art and design professions, and developed methods and practices to foster expertise in color for architecture, design, and art students. His work was heavily informed by his rigorous practice. However, it also reflected discoveries in perception science during his time. In the following quote, he explains the relationship, for him, of intuitive knowledge based on practice and experience, and of scientific knowledge based on research: “Doctrines and theories are best for the weaker moments. In moments of strength, problems are solved intuitively, as of themselves. Close study of the great master colorists has firmly convinced me that all of them possessed a science of color” (Itten 1973).

Ranulph Glanville (1946—2014), who was a researcher, educator, and practitioner in the field of cybernetics, design, and innovation, has also investigated the relationship between scientific research and the design process, observing “research to be a (restricted) design act, rather than design being inadequate research” (Glanville 1999). Both Itten and Glanville were practitioners and academic researchers, alluding to the ability of an iterative design process to produce a body of knowledge unattainable by a prescriptive, linear structure.

Working within a discipline that is design driven, and with backgrounds in both design production and scientific research, we set out to test ways to purposefully structure research in an iterative manner, with continuous tests, trials, and modifications as inherent in a design process. We intend to use Glanville’s insight to structure an investigation into the phenomenal properties of color relative to spectra and additive color mixing by moving from designerly ways of working to more structured or restricted methods as the question requires. The objective is to listen to the phenomenon and let it guide the research, becoming students of the phenomenon rather than its master, and to thus open ourselves to things that are new, unexpected, counter-intuitive, or surprising. We have been inspired by Glanville’s observations about design and science, and Itten’s way of working, and we use that inspiration as a basis to establish an approach to investigate the perception of equivalent colors produced by a range of lighting technologies.

We are following a process and developing research methods appropriate to the unfolding understanding of the phenomena in question at a scale and in contexts appropriate to architectural applications. Although we borrow qualitative and quantitative methods from other disciplines for our individual studies, the overall goal is to remain fluid and open, to go beyond such established methods, structuring the endeavor as much as possible as a design process.

For us, research methods are tactical. Our intention is to apprentice ourselves to the phenomena of interest and enlist others to help inform our understanding. As a result, our approach is less structured than laboratory research, but will be, we hope, more ecologically valid and open to discovery and creativity. This also includes, when designing a study for architectural validity, the creation of full-scale experimental environments. These environments thus allow participants to experience different vantages, peripheral perceptions, and free locomotion. Drawing from our background experiences, we propose to include designerly ways of working into a research inquiry that aims to produce knowledge targeted at designers.

1.3. Frameworks of investigations

Academic research is generally performed within certain frameworks, and often subject to the overall mission of institutions and agencies responsible for funding projects. Thus, researchers tend to interpret their research interests within the boundaries available. This provides certain constraints but also the opportunity to actively shape the research. Our own recent research curriculum moved through several phases. Some earlier background studies (Besenecker and Bullough 2014, Besenecker et al. 2015) were conducted in the tradition of lighting science perception studies as taught at the Lighting Research Center at Rensselaer Polytechnic Institute (RPI), an institution that educates on lighting to advance effective use of light. The project received funding from lighting manufacturers and lighting research foundations. The Lighting Research Center offered the perfect and necessary expertise, venue, and equipment to conduct such perception studies.

For more recent studies (Besenecker 2015), we were able to get funding from RPI’s School for Humanities, Arts and Social Sciences (HASS) through the HASS Fellowship. This fellowship funds research endeavors that don’t fit into more traditional science and/or art categories, for which support is often more readily available from other agencies. This presented the opportunity to experiment and aim to develop new approaches in architectural research. Architecture schools are professional education centers, but they have the opportunity to also act as academic research institutions. We are motivated by the idea and possibility to develop and establish discipline-relevant research methods that might differ from ones borrowed from other fields such as applied science, social science, and engineering.

Most recently, we were able to conduct an experimental study that was funded by the Jaffe Student Production Competition Grant and supported by equipment loans from the performance lighting manufacturer ETC and RPI’s Smart Lighting Engineering Research Center. The Jaffe grant is intended to support projects which take advantage of the infrastructure, resources, and expertise that the Experimental Media Performing Arts Center (EMPAC) has to offer. Our project was selected by an interdisciplinary committee that included members of different departments such as science, engineering and the arts. EMPACs performance spaces are controlled, large-scale environments that are set up for flexibility and access to high-tech media equipment. Moving our research, which was targeted to architectural investigations, into such an environment was a perfect fit.

We proposed large-scale studies (further described below) that are not possible in different, more typical, university laboratory environments. The objective was to develop an architectural-scale, structured perception and design study that enabled participants to move through the spaces and use their whole body to interact with the installed setup.

Different research frameworks lend themselves to different specific research endeavors for which they are best suited. Actively moving the research through different institutional frameworks contributed to its developing agenda, and gave the opportunity for us as researchers to shape its direction. It also made it possible to develop hybrid methods that would not have been otherwise possible.

1.4. Luminous color as topic

The topic we chose for our investigations was color, more specifically luminous colors on white surfaces and white-light illuminated colored surfaces. The term 'color' cannot be defined easily; color 'happens' at the interplay of object, light spectrum, and the observer:

"Color is an event that only takes place through a network of exo-relations between the molecular endo-composition of the object, particular wavelengths of light, and a particular neurological structure in an organism. Take any of these elements away and color puffs out of existence. As such, color, as an exo-quality is a genuine agency of these three agencies being woven together. It is not the cup that is colored, but rather the entanglement of these agencies that produces color as an event." (Bryant 2011)

It is the entanglement identified by Bryant that makes color a rich but complex territory for investigation, drawing on diverse fields ranging from physics, physiology, and perceptual psychology to art and design. Each field sees color through its specific disciplinary lens. These various frameworks shape the kinds of research questions that are asked, the methods used in their interrogation, the kinds of data collected, and the types of analyses and interpretations. This shaping leads ultimately and inevitably to constraints on the nature of answers provided (Beer 2000).

Even today, there is little agreement on the "ontological status of color" (Beveridge 2000). That which is lumped under the term 'color' incorporates all, from Newton's theory of optics to Goethe's theory of color (Leshan and Margenau 1982). Each theory is documented and explored within its own discipline, with distinct research methods and objectives. Today, the discourses rarely overlap; the focuses and languages also differ widely.

We set out with the intent to produce structured, in-depth knowledge for design applications that considers the different kinds of light sources available that can be used to implement luminous color into spatial designs, and the kinds of phenomenal differences of spatial affects that might result. At the onset, we understood the complexities of this undertaking; it is our goal to develop research methodologies that reflect and are derived from these complexities.

This plethora of understandings of color, combined with the dearth of research into use of color as an architectural design medium, makes it a fitting topic for developing a hybrid research methodology.

2. PROJECT

2.1. Background research

Although there are varying motivations and knowledge bases that inform and drive research projects and their methods, we were not able to locate comprehensive, design-motivated research efforts. Furthermore, our area of interest, the qualities of luminous and illuminated colors in architecture, appears not yet to have been looked at beyond technological considerations. Without grounding knowledge from within the architectural profession, our investigation set out to be of a structured, exploratory nature, progressing through several phases and studies. Similar to a design process, our objective is to let discovery influence the direction of the research. This is to say that we are as interested in finding the right questions as we are in finding the right answers. The diverse methods that we employ are designed to educate us, and by extension the design disciplines, about the nature of the relationship between a given lighting technology and its effect.

To establish the research methods for this study, we started by drawing on literature from color science and perception studies (Stabell and Stabell 1982, Wyszecki and Stiles 1982, Fairchild 2013). We also sought insights from the architectural literature on color (De Heer 2009, Braham 2002, The Plan 2011 (Bahamon and Alvarez 2010), and examples of design-led approaches to generating knowledge applicable in design domains.

Although the scientific disciplines have a body of peer-reviewed publications and experts in the field that have published their research substantially, in the design disciplines, expertise is kept with individuals who only occasionally pass their knowledge on through writing. Designers are typically less concerned with publishing than their scientific counterparts—the product of a designer's work is the project. As a result, designers pass on their knowledge through oral teaching, either in an academic setting or through direct mentorship within design practices. Their works are more often analyzed, interpreted, and written about by others, but these generally focus on the objects designed rather than on the knowledge that informed them.

Although the available scientific literature does contain information relevant to the topic of color production in today's environments, we are interested in complementing these with the insights and experiences that professionals in design practice might offer to us. We are looking for knowledge in the field that might not have been recorded in archival publications. We set out to craft a multi-step study that aims to put us in touch with the knowledge that designers have. To access this knowledge, as a first step, we performed a series of interviews with color experts related to architectural scale design applications. Our objective was to use what we would learn from these interviews to inform an experimental study at an architectural scale that would provide us with direct feedback from designers, color experts, and the public.

Among the interviewees were two architectural artisan paint pigment consultants, the New York-based Donald Kaufman, who is renowned for bringing the first full spectrum paints on the high-end design market, and Katrin Trautwein, whose small and specialized Austria-based business has the exclusive license to produce paints from Le Corbusier's color palette. We also interviewed Robert Gerlach, the inventor of the first, and currently only, 7-color LED lighting system that can be found commercially available at present. In addition, we interviewed some designers. Clifton Taylor is a New York-based Broadway lighting designer who has worked his entire career professionally with colored light, and who teaches its use extensively. He is one of the first luminous color designers who embraces and experiments extensively with all lighting technologies, and teaches how to use different methods with different technologies to achieve the desired effects.

Leni Schwendinger has been described as a lighting urbanist since she illuminates the urban outdoors with the objective to improve pedestrian urban nighttime experience. She was one of the first to include colored light in her urban lighting toolbox at a time when the only other luminous color in the city came from advertisements. She recently joined the engineering design firm ARUP New York. The third lighting designer is considered the grandfather of lighting design, Howard Brandston, who has an educational background in theatre and architecture, and was among the first who established architectural lighting as a design practice.

These interviews were highly informative as background to guide our ongoing research. We learned that for aesthetically trained and color sensitive lighting design and paint consultant practitioners, LED lighting presents challenges in comparison to traditional broadband incandescent light (Kaufman 2015, Trautwein 2015, Taylor 2015, Schwendinger 2015, Brandston 2015). It behaves differently, and expectations and experiences accumulated through working with broadband light over the last decades do not necessarily hold for new technologies. When matching LED to incandescent light, light meters might give different readings, and cameras might render the color differently in a picture (Adelman and Broderick 2015, Taylor 2015). This insight has led us to be wary of technical instrumentation as an unqualified "objective" source of information about the perceived color and brightness of illuminated surfaces and spaces.

These perceived differences can be explained by the differences in the energy spectrum between the LED and the incandescent sources that will influence the color output of the light source, and the painted surfaces that the light might fall on (Fairchild 2013). Sophisticated, full-spectrum paint pigments, for example, might be specifically designed to look rich under changing daylight and incandescent light, however some LED sources might illuminate them with surprising and unexpected results (Trautwein 2015, Kaufman 2015). Compositions of LED spectra and paints can be adjusted. We could not find any published and structured investigation that looks into this subject in a way useful to designers.

Theatre and event lighting use colored light in sophisticated ways to illuminate objects, surfaces, and actors in a scene. This design skill is learned through a master-apprentice oral tradition, or direct fine-tuning on the stage (Taylor 2015, Simpson 2015). LED illumination is currently being introduced into theater and event settings due to its lower maintenance, heat production, and energy utilization, but the results, from an artistic and perceptual perspective, have been mixed. Color science and theory teaches that all colors can be mixed using three primary colors (Wyszecki and Stiles 1982). This assumption was first questioned in performance lighting where generally RGB lighting did not provide enough color flexibility to fulfill the needs of theater lighting designers (Gerlach 2003).

A study of RGB, LED-based theatre lighting (Gerlach 2003) established that this lighting had aesthetic shortcomings in terms of color saturation and preference agreement. As a result, 7-color LED fixtures have been developed for theatre, and are being continuously improved as LED technology expands. There is no perception metric, however, that can fully match human experience and aesthetic sense. The manufacturers creating these new systems use subjective evaluations by panels of people, including design professionals, to determine and establish ongoing improvements in the systems they are building (Gerlach 2015).

With a multi-color, LED system, designers now have the opportunity to compose equivalent colors with different spectral components and with different surface rendering properties. This adds color design control that did not exist before.

Architectural illumination increasingly uses colored lighting. However, in contrast to the 7-color theater lighting fixture, the fixtures used in architectural lighting applications typically are 3- or 4-color LED fixtures. The profession is just starting to develop an expertise in color design using these types of systems. As it does so, architects will find that the insights derived in the design field of theater lighting will be of value to them.

Based on the interview conversations with the lighting designers and the LED lighting manufacturer, we formed one main direction for our further inquiry:

- We sought to identify qualitative differences and resulting design opportunities of equivalent colors of lighting (i.e., luminous colors) that are mixed using different spectral light compositions.

Based on the conversation with the paint manufacturers and consultants, we extended that main direction to look additionally at color reflected from illuminated, painted surfaces.

- We also sought to identify qualitative differences and resulting design opportunities of equivalent colors, reflected from a surface, that are mixed using different spectral light and pigment compositions.

We subsequently started to plan further studies in a manner that would achieve architectural validity, with the direction above in mind.

In addition to the interviews, we also conducted a series of field observations and conversations with pedestrian visitors of urban nighttime environments. These were done in two different frameworks; one was a small field study during and after an urban light art festival in Eindhoven, Netherlands (Besenecker 2015), and the second was during a series of neighborhood community workshop activities about lighting improvements in Queens, NY with Leni Schwendinger.

These observations confirmed that colored light is a major component in contemporary outdoor light installations and everyday after-dark outdoor illumination, especially in the illumination of building façades. Color adds a sense of wonder and can help with orientation. Through illumination of vertical surfaces of buildings, objects, and plants, spaces often feel larger. The sense of space can be extended, which also can help with gaining overview and a sense of direction.

It became apparent in our observations that the scale and orientation of the illuminated surfaces and the surrounding environment were essentials components to shaping the pedestrians' experiences. Thus, for our investigations to be design relevant and architecturally valid, we considered it important to enable a changing relationship between the pedestrian participant and the color-illuminated, surrounding environment. We decided therefore to design our study to allow free movement of head, eyes, and body.

The performance center EMPAC offered the environment that made such studies possible (as described below). The size of the black box studio (60x55x30 feet) is large enough to build illuminated colored walls and spaces at architectural full scale that participants were able to experience up close or observe from farther away. At the same time, the environment could be regulated in terms of aural and visual cues for targeted investigations, making it into an architectural lab that is more controllable than an urban environment.

2.2. Laboratory perception studies

In addition to the interviews and observations mentioned above, our research has been informed by several prior investigations that were completed in the discipline of lighting and perception science at the Lighting Research Center in Troy, NY. This research helped with understanding some of the observations that designers and manufacturers described during our background interview, specifically:

- Light meters do not necessarily match what designers might see when comparing the brightness of different LED and incandescent sources, colored and white (Besenecker and Bullough 2014, Besenecker et al. 2015).
- Illumination nominally equivalent in color:
  - o can look different to some people (Fairchild 2013);
  - o can make surface colors look very different (Fairchild 2013);
  - o can create a different general feel or atmosphere for some people (Vandevalle et al. 2010).

The incandescent lamp has remained the 'gold standard' for quality lighting; nearly all lighting 'metrics' are based on this lamp. In the last two decades, however, LEDs have become increasingly capable sources of environmental illumination. With their flexibility, high efficiency, and economy, they are becoming the prevalent form of electric lighting. After a century of broadband incandescent light, we are changing to a world lit by solid-state devices. LEDs today have advanced to a point at which they are used for nearly every kind of illumination, projection, and display.

In contrast to incandescent sources, these devices make light and render color very differently. While incandescent white light is a broadband source that uses color filtering or reflection methods to create a color sensation, LED technology utilizes emitters that produce light in various distinct color bands. These must then be mixed or transformed to create other colors or white light (Murdoch 1994, Schubert 2006).

Today's color mixing and calculation systems are based on averaged data; discrepancies due to physiological differences of specific individuals and training are however to be expected (Long and Fairchild 2014). This means that by narrowing the spectrum, as is happening in light/color technology today, individuals increasingly perceive differences in colors otherwise thought to be equivalent.

In addition, the currently most widely used set of color mixing metrics, called chromaticity, was developed in the early to mid-20th century (Wyszecki and Stiles 1982, Fairchild 2013). This color calculation system was based on perception experiments for the central 2° field-of-view, which is most sensitive to color, without taking into account peripheral vision. While we can distinguish millions of shades of colors, we have only three photoreceptors that are at the first level of collecting spectral information. This is what chromaticity is based on. A similar color event can be produced by lights having very different physical properties. Colors, including white, with the same nominal chromaticity, can be mixed in many different ways, using the three primaries: red, green, and blue (Wyszecki and Stiles 1982, Fairchild 2013). Itten acknowledged, "We cannot see component hues in a mixed color. The eye is not like a musical ear, which can single out any of the individual tones in a mixture" (Itten 1973).

Color perceived at large scale however includes peripheral vision with different photoreceptor mechanisms that also play a role in spatial orientation and brightness adaptation. Pallasmaa observed, "Focused vision makes us mere outside observers; …peripheral perception is the perspectival mode through which we grasp atmospheres" (Pallasmaa 2014). Peripheral perception is essential for the experience of architectural spaces and has to be included into studies that are applicable to architectural design. Although peripheral perception includes all the senses, our investigations start with including peripheral vision into architectural-scale color experiences. This is a first step toward learning more about how we experience spaces and atmospheres.

Prior work in perception research showed that colors that are defined to have equivalent chromaticities, and which are at the same measured light level, can nevertheless look different in brightness when mixed differently, and when viewed full field (Besenecker and Bullough 2014, Besenecker et al. 2015, Bullough 2015). This is partially because different spectral compositions can stimulate a recently discovered type of photoreceptor, the intrinsically photosensitive retinal ganglion cells (ipRGCs). This photoreceptor is located in the peripheral portion of the eye's receptive field, and is triggered only by light in a specific short wavelength range. In addition, work in light and health research shows that light that contains energy that triggers this group of receptors is likely to produce different non-visual effects on different individuals (LeGates et al. 2012, Lockley et al. 2006, Vandewalle et al. 2010).

These ipRGC receptors have been shown to signal information to areas in the brain that can influence visual effects such as brightness and non-visual effects such as mood, sleep, and alertness. It is, however, not a major contributor to color vision; color vision is facilitated mainly by a different group of photoreceptors (Stockman and Sharpe 1999, Stabell and Stabell 1982). Therefore, if equivalent, luminous colors are composed using different spectral compositions, some will trigger this receptor more than others will. We do not yet know if there might be differences in perceptual qualities in the illuminated spaces or the degree to which perceptually similar events could trigger emotionally or physiologically distinct responses.

Health and perception studies are typically done in controlled laboratory conditions using experimental protocols and statistical analysis, as mentioned above. Most laboratory color and light research uses light boxes and models that are typically small scale, focusing only on the eyes and the visual field needed to investigate a hypothesis. These studies typically do not include the whole body or the whole visual field, and do not facilitate an individual's movement through a space, and its associated eye motion, head motion, and locomotion—all of which would be part of a real-world, large-scale architectural experience.

2.3. Architectural scale perception study

Our field observations were exploratory and showed some impact of colored light in the urban environment, and our prior interviews acted as background information and suggested that luminous color is not yet sufficiently understood. Early perception studies that were conducted as part of our lighting science and perception investigations suggested there would be differences between different spectral compositions and lighting technologies. Unexpected and undesirable effects are produced when new light sources are used with the same assumptions as conventional lighting technologies.

Pallasmaa notes, "The all-encompassing and instantaneous perception of atmospheres calls for a specific manner of perception—unconscious and unfocused peripheral perception" (Pallasmaa, 2014). Our perception studies and interviews are in agreement, and suggest that the obsession and emphasis on the central (focused) field-of-view in color research has led to discrepancies between our actual visual and sensual experience and what we are "supposed to perceive." We deemed it essential therefore to include the peripheral into our studies, thus allowing a soft de-focusing of the senses.

Based on the above, we designed a study that would be more ecologically valid than a typical lab study, but more controlled than observations in the field, with the following research questions guiding the initial investigation.

When mixing a nominally equivalent color with different spectral light compositions and illuminating an architectural-scale, full-field immersive environment:

- Can people see and perceive the difference?;
- Will different conditions trigger different reactions and sensations ('atmospheres')?;
- Will there be agreement among individual participants, experts, and non-experts?

The intent was to create an experimental set-up that was closer in scale to an actual architectural experience, and to explore participants' reactions and comments to different architectural-scale color and light conditions.

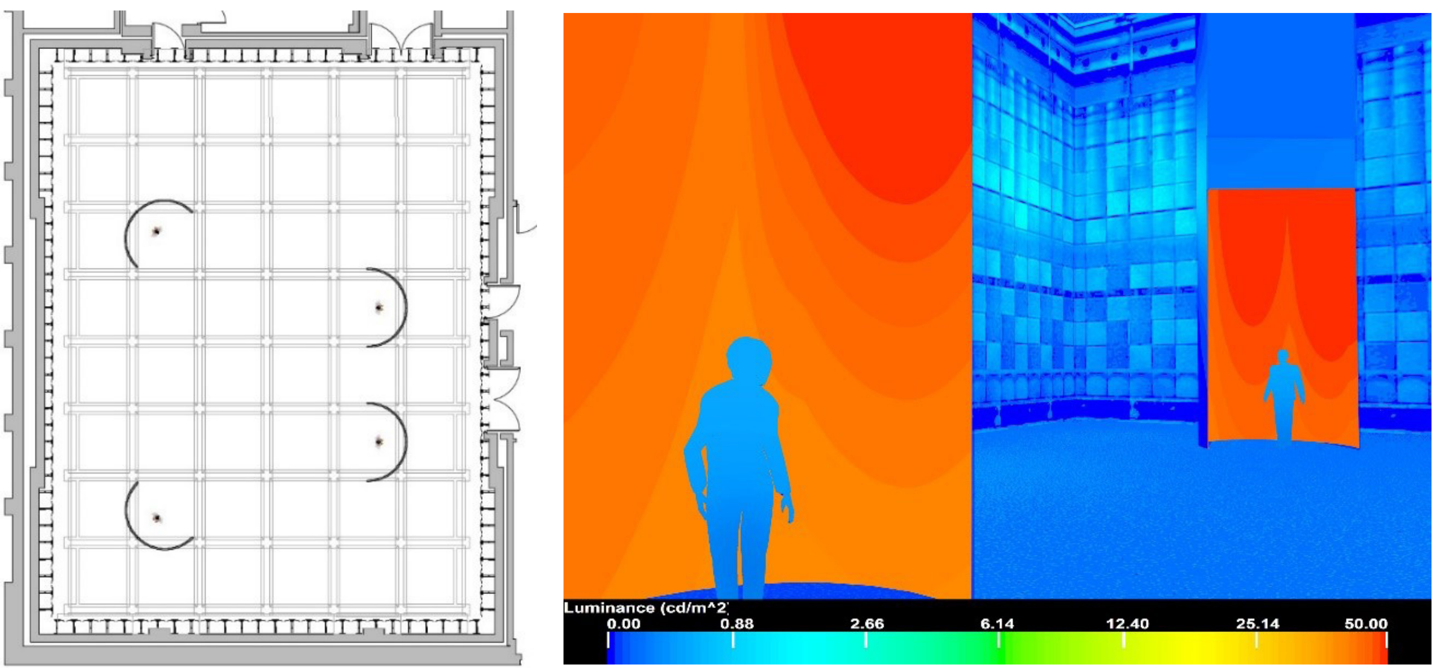

Figure 1: Layout diagram of the black-box space, with four semi-circular luminous color spaces (Left); light level and distribution simulation (Right)

The Jaffe Student Production Competition at EMPAC provided an opportunity to seek and receive support for such an investigation. Other venues like RPI's Collaborative Research Augmented Immersive Virtual Environment Laboratory (CRAIVE lab) also provided a place for architectural-scale, immersive studies.

Our study was set-up in the 60' (length) x 55' (width) x 30' (height) Studio 1 black box performance space at the Experimental Media Performing Arts Center (EMPAC) at Rensselaer Polytechnic Institute. The studio space is acoustically isolated, and the black finishes and ceiling grid enable full light control and prevent unwanted light and color reflections.

Figure 2: Photograph of the CRAIVE lab space at RPI during a mock-up

In this black-box space, we designed and conducted a controlled architectural-scale study that incorporated four open luminous color spaces with a semi-circular plan layout, 5' (length) x 9' (width) x 14' (height). These encompassing spaces could be entered by participants of the study, and the effects and appearances of the color could be described and compared from one space to the other.

To illuminate the walls of the semi-circular spaces, we created different colored lighting conditions to compare their aesthetics and effects on participants. The conditions were:

- Color filtered incandescent broadband lighting on white paint;
- Narrowband color LED lighting on white paint;
- Mixed-spectrum color LED lighting on white paint (3- and 7-color solution);
- Incandescent broadband white lighting on color paint;
- White LED lighting on color paint;
- Video projection on white paint.

The objective was to have participants evaluate nominally equivalent colors at the same level of illumination that were mixed and created using these different technologies and spectral compositions. Our prior research suggested that the participants might perceive distinct differences.

Two different color hue groups were designed for evaluation by the participants in two independent sessions: One hue group was amber-orange, the other cyan-blue/green. The colored light and paint conditions were carefully matched in advance, measured and documented using laboratory-grade spectroradiometer equipment that provided a level of detail not found in conventional light meters.

During the first exploratory and qualitative phase of the study, we had 17 participants between the ages of 30 and 80, with varying degrees of expertise in working with light and color. All were color-normal according to the Ishihara test for color blindness (Ishihara 1963). Nine worked professionally with either light or color.

Color and light are familiar to us from early childhood; they seem natural and we take them for granted. Many color preferences or color associations of different colors however vary depending on an individual's cultural or geographic origins (e.g., Asian versus European observers) or age group (e.g., adults versus children) (Taylor et al. 2013).

Relevant for our study of equivalent colors, investigations also show that training and experience generally changes and advances color discrimination (Özgen and Davies 2002, Neitz et al. 2002). In a more anecdotal account, lighting designer Howard Brandston mentions about his experience with students: "…most of the students who came to learn lighting had never first learned to see. Oh yes, their eyesight was normal, …. The students, in fact, were all suffering from a form of congenital achromatopsia, a total lack of any sense of color. … It was simply that no one had taught them to see." (Brandston 2008)

Many color perception studies do not take the participants' color experience into consideration. We decided for our study to have two groups of participants: 1) invited light and color expert observers and 2) participants from the public. This was done to be able to collect information from different observer groups, experts and non-experts, which average data cannot provide.

Our objective in soliciting subjects who have extensive knowledge of lighting and color was the realization that our own expertise and experience with color cannot be considered definitive. We invited color and lighting professionals to participate in the experimental protocol to receive responses from people trained and interested in color perception. After collecting their responses, we also discussed the study with them to get their feedback and comments. We are interested in developing a laboratory technique that is equivalent to our use of interviews with designers and color professionals in the start-up phase of the project.

In addition to the experts, we also recruited participants from the public to conduct the same protocol. As noted above, there is evidence that individual differences in color perception are highlighted when using narrow spectra, such as LEDs. Therefore, we are interested in the range and type of responses that come from expert professionals and representatives from the public who do not have prior exposure to color- and light-related questions.

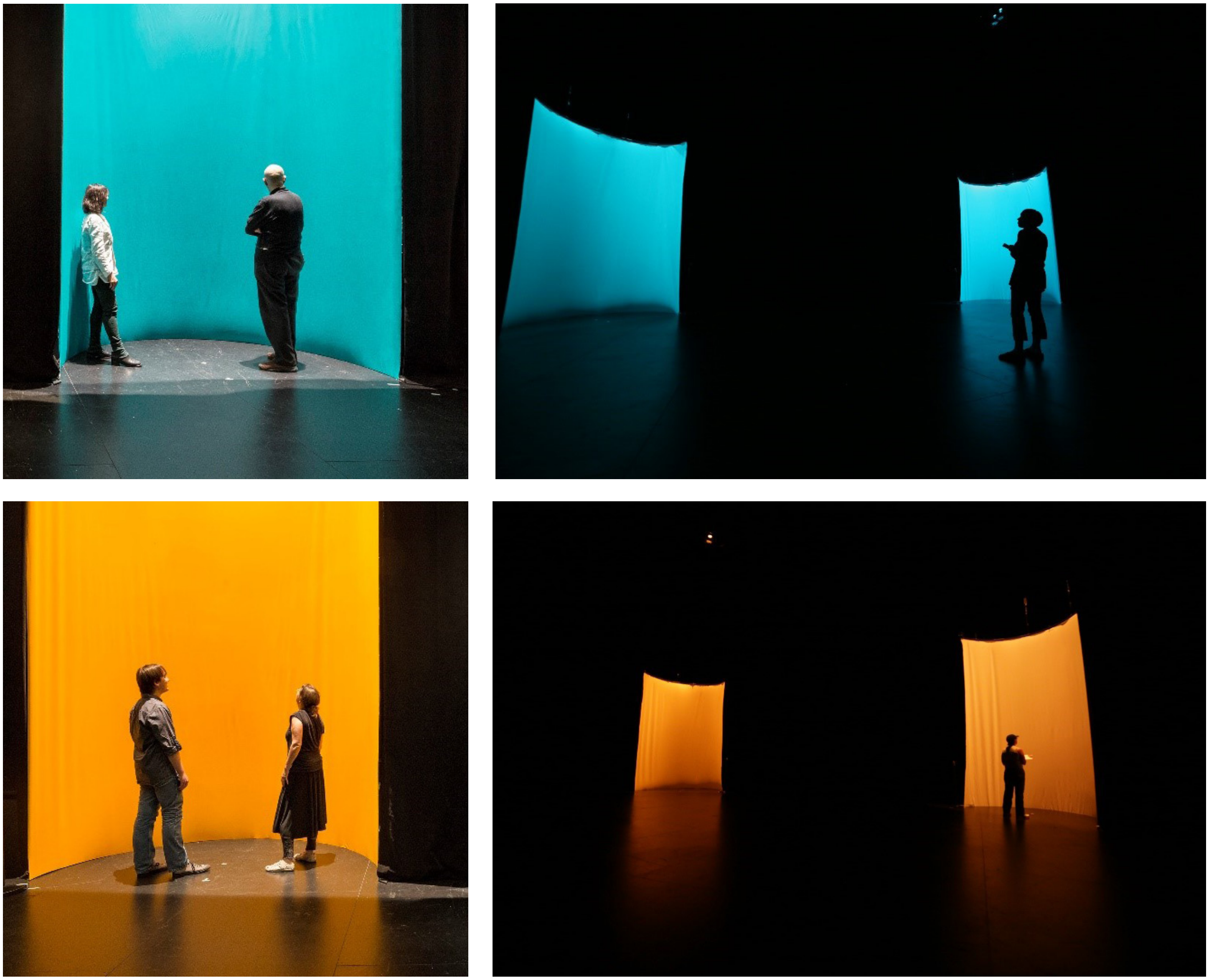

Figure 2: Evaluation sessions with cyan condition (top) and amber condition (bottom); conditions included color painted walls illuminated with white light (left), and white painted walls illuminated with different versions of colored light (right). (Photographs by Arch Photo and EMPAC)

The study was designed to receive subjective comments from each participant individually. Every participant watched the same introductory video that gave some vocabulary, definitions (e.g., saturation, brightness, and hue), and instructions, and each had a structured task to compare two illuminated colored spaces. They were asked to give comments and comparisons in response to the luminous color conditions both seen from afar (i.e., viewed from the center of the black box) and while being immersed in the luminous spaces. They were free to move around in the black box as needed.

Each participant was shown a timed sequence of multiple pairs of illuminated spaces for evaluation. To help with the analysis, we had a constant reference condition: one space was always illuminated by the color-filtered incandescent light. The specific space that was illuminated with this reference condition changed randomly from comparison to comparison to avoid location bias. The light sequences were varied between participants, and white light was shown between conditions to reset adaptation.

Although the environment and general protocol of the study were provided in a controlled, standardized structure, this study was designed to be exploratory. Participants were thus able to choose their movements and ways to comment on the comparisons. The participants were offered pens and note pads with pre-organized pages to make commenting on each comparison pair convenient, quick and easy. Most people appreciated the process of writing out their comments.

Throughout the study, we however discovered that several participants preferred to just give comments verbally or even through gestures (to be able to concentrate on their experience without having to translate their reactions onto paper). All movements, reactions, and spontaneous vocal comments during and right after any session were recorded with multiple cameras and microphones to capture this information, inform any written notes, and provide additional insights. In addition, the experimental protocols were followed by discussions with the participants, and thus the participants became partners, collaborators, and explorers whose feedback was collected in addition to their study responses.

We were able to observe and record a range of reactions and feedback during the sessions that will inform an upcoming installation to test possible implementations into the design of spatial environments. The installation will further explore the possibility of designing environments that stimulate peripheral perceptions and spatial awareness by making use of transitioning specially designed luminous colors that look equivalent to our central field of vision (but that elicit differences in the periphery).

In addition to the subjective evaluation study described above, we recorded EEG and heart rate/blood pressure data in response to the different lighting conditions, and performed some perception tests with the peripheral field-of-view. These recordings were obtained in separate sessions to prevent the recording devices and necessary posture restrictions from affecting qualitative results. The data will be analyzed quantitatively to evaluate if consistent patterns and correlations can be observed; the results will be subject of a subsequent paper.

In summary, this qualitative study was purposefully designed to structure the stimulus, direct the participants' attention, and provide a framework consistent with the questions we set out to investigate. However, other variables were left open. Although participants were asked to respond to and comment on the conditions, they were free in their movements, behaviors, and mode of responding (e.g. written notes, verbal commenting, or/and gestures).

3. CONCLUSION

Light and color metrics currently applied in design incorporate neither peripheral vision nor the free movement of an individual. Both of these are important to human perception and architecture. Many designers and engineers are unaware of this and might obtain unexpected and undesired results by using those metrics. Those who are aware of these limitations do not generally have a more relevant source of information on which to draw.

Our purpose in conducting the studies described in this paper was to inform design activity and inform and inspire further research, especially in more ecologically valid contexts. To design the conditions in our study, we used technologies that are typical in architectural settings to create color metamers composed of pigments, filtered broadband light, and narrow-spectra LED sources.

We developed large-scale, color installations distributed in a black space, and encouraged participants to execute both immersive viewing and free movement within and among them. The stimuli experienced were like those found in architectural contexts—large painted surfaces with brush texture and small irregularities that cause shadowing. We observed and recorded participants' locomotion, gestures, expressions, and behaviors with the intent of finding both commonalities that might exist and the range of responses that would occur. We believe that design practitioners will find both the commonalities and differences interesting.

The procedures were developed to collect data in a structured way to be compared and analyzed with statistical methods, but we also built in mechanisms to collect 'soft' information that enable us to understand the phenomenon in new ways and become aware of things that others might perceive that we do not, and observe responses that others might have that differ from our own. A preliminary and far-from-comprehensive look at the resulting data allows several initial observations to be made:

For colors that are considered equivalent when viewed with the central field of vision, certain aesthetic differences (e.g., brightness, hue, and saturation) were described consistently across participants when observed without restricting the visual field. We argue, with Pallasmaa, that peripheral vision is very important to architectural perception, and so this finding is of interest to designers.

After-effect colors, visible in the breaks between color conditions, varied from condition to condition, even when the color conditions viewed were nominally equivalent. After-effect color could depend on spectral composition. This finding asks for a range of more controlled follow-up experiments for confirmation, and to explore its effect on perceptions over time. Adaptation of the eye persists and influences the perception of colors over its duration. In architectural settings, movement from one space to another might be accompanied by this adaptation and after-effect, shifting color perceptions.

We recorded the behavior of each individual in response to the color conditions. The variation in responses was sometimes marked. For example, one participant who was a professional dance performer had very strong consistent emotional reactions when entering particular illuminated color spaces (e.g., crying and laughing). While the performer was immediately compelled to enter certain spaces and avoid others, another participant, who was a professional photographer, generally preferred to stay back, viewing and comparing the conditions from afar. The latter participant provided responses that were very analytical, clear comments on the aesthetic qualities of the conditions. While these responses were logically correlated with life experiences, we have no basis on which to predict similar responses from other dancers or photographers. What is of more interest is to be sensitive to this degree of individual variation and react with certain skepticism to descriptions of color qualities that are inherently 'calming' or 'invigorating,' or that are said to prescribe human behavior by their presence.

Most participants did not detect a difference between white light on colored paint and colored light on white paint, especially when viewing both conditions from the middle of the room and looking at the spaces side-by-side. This surprised us. However, at that point, the participant would not be immersed in the lighting condition. When the participant moved closer to the wall and became immersed in one light and one color condition after the other, the differences became more apparent. This was particularly true for those participants with a professional understanding of color, and especially in terms of the saturation and vibrancy of the color. Saturation and vibrancy seemed to fade with proximity for the colored light, but less so for the colored paint. This effect might have to do with the light falling onto the subject in the immersive condition. In this case, the hand plays a visual role as an index over which change of illumination can be registered.

Color and light can be customized purposefully to influence the experience of an environment. In architectural spaces, people move around. Vantage points, visual fields, illumination of the surroundings, visual adaptations, and contrast of adjacent areas change constantly and play crucial parts in how we perceive an environment. Our study enabled us to collect valuable information that we currently organize and structure to explore connections and design possibilities. Our objective is to gain expertise and clarity about the subject useful for application, and contribute to an understanding of light spectra and color production for human experience in architectural spaces. Such knowledge could enable more sophisticated use of the technologies available, and enable informed design decisions.

Our next step, in addition to organizing and structuring the information received into matrices and summarizing the results in dedicated publications, will be to integrate selected findings into an installation to explore validity in the field of architectural design further.

In this paper, we propose a research approach that includes "designerly ways of working" in addition to traditional academic research methods to produce knowledge that is useful for architectural design. Although our study contains elements of traditional academic research methods that help answer the research questions we posed at the onset, the built-in exploratory mechanisms enable us to learn from 'soft' and unexpected information. The study fosters awareness of individual subjective responses in comparison to patterns that are consistent among participants. This provides information and clues useful for a wider understanding. We feel that given the nature of the phenomena we are studying, the kind of hybrid research approach described here will give us the useful, design-centered results that we seek.

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