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Lighting Research Today: The More Things Change, the More They Stay the Same

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1. Introduction

Change. It is the one word that best characterizes the environment for lighting research, as well as for lighting technology, in recent years; and yet, beneath the change there is an enduring foundation upon which that research rests. A barrage of new technologies and tools for producing and measuring optical radiation has revolutionized the possibilities for creating and characterizing lighting systems and conditions, but understanding the application of these new technologies and tools builds on a legacy of established measurement methods and protocols. The discovery of a previously unknown photoreceptor has brought new excitement to lighting research and application, but this discovery exists within the context of a long history of applied psychological research in lighting.

When it comes to lighting research, and especially research on human factors and lighting, the current state-of-the-art seems accurately captured by a quotation attributed to French novelist Jean-Baptiste Alphonse Karr:

> "The more things change, the more they stay the same."

This special issue of *LEUKOS* is devoted to an exploration of lighting research methods. It was developed in parallel with an event sponsored by the CIE held at Aalborg University in Copenhagen in August 2018, the *CIE Expert Tutorial and Workshop on Research Methods for Human Factors in Lighting*. A collaboration between the CIE and the IES and the support of publisher Taylor & Francis has made every paper in this special issue freely available, in perpetuity, under an open access agreement. Everyone involved in this unprecedented collaboration recognizes the value and the importance of responding to the excitement and the challenge of the times with continued focus on high-quality research.

The topics presented and discussed at the CIE meeting and the content found in this special issue reflect the reality that, although the lighting industry and lighting research are experiencing dramatic changes, those changes occur against a background of longstanding traditions and practices. In a sense, the changes being experienced today are affecting the superstructure of lighting research, challenging the traditional tools and methods, altering the above-ground appearance of our research, while the foundations of that research remain both firmly in place and critically important.

Change attracts attention. It creates excitement, it generates "buzz," it engages new people. It inspires new discussions and new conferences and new journals. All of this can be very healthy and helpful.

But change can also bring about a loss of focus that can distract us in unhealthy ways. In the excitement and clamor over the latest and greatest new thing, we can lose sight of some of the rather stale old things that still matter. Those old things often comprise the foundation upon which the new things have been constructed; losing sight of them can make the underpinnings of the new things shaky indeed.

This special issue exemplifies how lighting research today is being profoundly affected by revolutionary changes in many ways, from the

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technologies that illuminate our built environments, to the technologies we use to present stimuli and measure responses, to the basic scientific understanding of how optical radiation is processed in the retina and brain and affects a variety of responses. In the midst of these changes, maintaining a focus and emphasis on some of the unchanging foundations of lighting research becomes even more critical for successful lighting research.

Because the more things change, the more they stay the same.

2. The more things change

The revolutionary changes affecting the lighting industry and related fields of research are perhaps most evident in lighting technology, where the rapid development and deployment of solid-state lighting (SSL) products and systems have completely transformed the commercial landscape. The ease with which the SSL technology platform allows for the spectrum, intensity, distribution, and timing of radiant energy to be controlled coincides with new scientific evidence about how those attributes affect the human response. This emerging evidence is completely changing our understanding of optical radiation's biological effects on humans (and other mammals). The collision of the changing lighting technology with our changing understanding of these effects creates new opportunities for more fully addressing health and well-being in the built environment.

2.1. Changes in our understanding of light, brain, and behavior

The discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) less than 20 years ago has led to an ongoing series of explorations documenting the connections of these photoreceptors to many parts of the brain. (Many of the papers in this issue provide summaries and citations to this research, but see also CIE 2004/2009, 2016, 2018.) Until these discoveries emerged, we assumed that information about radiant energy as sensed by the rod and cone photoreceptors was transmitted to the visual cortex and that that information then moved from the visual cortex to other parts of the brain. Now, our understanding has changed dramatically—we now know that, through the ipRGCs (which both sense radiant energy directly and receive input from the rod and cone photoreceptors), neural responses to radiant energy have direct connections to the suprachiasmatic nucleus of the hypothalamus, which controls circadian rhythms such as the production of melatonin. Neural pathways from the ipRGCs to other brain areas that influence mood and cognition have also been demonstrated. The ipRGCs also influence vision indirectly, by contributing to pupillary responses. Knowledge in this domain will become still more complex as we learn how subtypes of ipRGCs differ from one another.

The effect on lighting research of new discoveries about the ipRGCs and the physiological and behavioral processes they influence was a theme at the *CIE Expert Tutorial and Workshop* and continues in this special issue. At the CIE meeting, Yvonne de Kort (Technical University of Eindhoven) explored how this field of emerging science changes the theoretical constructs behind key lighting research questions. De Kort expanded on the CIE presentation in the initial paper in this issue, "Theoretical and Methodological Considerations When Planning Research on Human Factors in Lighting" (de Kort 2019). This paper demonstrates that although our understanding of the basic human visual effects of radiant energy—visual performance, visual experience, and visual comfort—remains the same, the new science on the circadian and acute effects of radiant energy as processed through the ipRGC pathways brings fundamental change to a holistic view of human perception, cognition, attention, emotion, and motivation.

2.2. Changes in how we present and measure the stimulus

The Copenhagen meeting also featured several in-depth discussions of the ways in which the changes in our understanding of how the eye–brain system detects and processes radiant energy affects what needs to be measured when conducting lighting research. Presentations by Myriam Aries on measuring the visual stimulus, Werner Osterhaus on assessing daylighting performance in real buildings, Peter Blattner on how to quantify photobiological and photochemical effects, and Martine Knoop on documentation of experiments all explored various topics related to this theme. Continuing that theme in this issue, Knoop and colleagues contributed a paper, "Methods to Describe and Measure Lighting Conditions in Experiments on Non-image-Forming Aspects" (Knoop et al. 2019), which explains why measurements of illuminance and correlated color temperature alone are not enough in today's changing lighting research landscape. Instead, the paper describes the need for both spectrally resolved and spatially resolved measurements, and it also presents several novel measurement strategies using cameras, scanners, and filters, along with new graphical techniques to represent data.

Those new measurement strategies highlight another changing area for lighting research: significant advancements in the technologies available for measuring light. Practical tools and techniques for fully characterizing the spectrum of light at a variety of eye locations and the distribution of luminances in the built environment have only recently become available. Today, imaging luminance measuring devices and high-dynamic-range imaging techniques have revolutionized researchers' abilities to more easily document important lighting attributes, so that the responses to light can be more carefully related to specific aspects of the lighting stimulus. These technologies and others were featured in the informal workshop sessions at the CIE meeting. In this issue, in addition to Knoop et al.'s discussion of these approaches, the growing use of wearable devices for lighting measurement is explored in the paper by Adamsson et al. (2018), "Comparison of Static and Ambulatory Measurements of Illuminance and Spectral Composition That Can Be Used for Assessing Light Exposure in Real Working Environments."

The adoption of new technology and approaches in lighting research includes how we can present the stimulus, as seen in several presentations at the CIE meeting on topics such as new ways to explore human behavior in full-scale models or in situ lighting installations and the use of calibrated photorealistic images as stimuli for lighting experiments. Perhaps the most dramatic presentation on this theme included a demonstration by Kynthia Chamilothori explaining the possibilities for using new immersive virtual reality technologies for lighting research. Chamilothori et al. (2019) provided detailed results from their research using this technique in their paper in this issue, "Adequacy of Immersive Virtual Reality for the Perception of Daylit Spaces: Comparison of Real and Virtual Environments." This paper describes how the new and still changing world of virtual reality allows lighting researchers to address an unchanging problem when studying daylight, where controlling the experimental conditions can be very difficult.

2.3. Changes in how we measure the response

Dramatic changes in technology for measuring lighting have been accompanied by exciting technological changes for documenting human responses, which some lighting researchers have begun to adopt. The growing interest in understanding how light affects different regions of the brain has occurred in parallel with advancements in techniques for measuring brain activity, such as functional magnetic resonance imaging. Improvements and miniaturization of prior generations of eye tracking devices has made documentation of that important response much more practical for lighting research, especially in realistic field conditions. Other changes in measuring human responses to light have not depended on new technologies but rather on lighting researchers learning and employing techniques from other fields that were previously little used in lighting research; measurement of physiological responses such as melatonin and cortisol levels is perhaps the most obvious example. These topics were all explored during the CIE workshop, with the acknowledgement that crossing disciplinary boundaries in this way is a significant challenge. The Call for Papers for this special issue did not elicit submissions, perhaps reflecting this reality.

In parallel with the expansion of measurement capabilities, the broader research community has been influenced by expansions in our awareness of researchers' ethical responsibilities to their research participants and toward their fellow researchers and the public. Changing conceptions of what constitutes acceptable behavior—for example, with respect to data privacy—equally fall into the concerns of technology developers. Jennifer Veitch described these considerations at the CIE meeting, providing a framework for ethical considerations drawn from psychology as a means to illuminate the principles. Veitch et al. (2019) touched on this in the special issue.

The rapid change to SSL technology in the built environment has revealed underlying flaws in metrics related to human responses to radiant energy, which in some cases were developed decades ago in response to fluorescent lighting systems. At the workshop, for example, the need for a more fundamental approach to metrics related to glare and visual comfort were highlighted by several speakers, including Werner Osterhaus and Myriam Aries, and several of the presentations and posters of current research summarized new approaches in glare research. We have already seen the development and in some cases the adoption of new color rendering metrics; that topic is further extended by a paper in this issue that provides new insights about color discrimination. In that paper, "An Adjusted Error Score Calculation for the Farnsworth-Munsell 100 Hue Test," Esposito (2019) proposed changes to a color discrimination test that was first published in 1957, but that can produce known errors when considering the hue transpositions that can occur under today's light sources.

The final paper in this issue proposes changes in lighting research that are driven not by new technology but by new applications of an older way of thinking about the built environment. In that paper, Schielke (2019) argued that lighting research, design, and education have often been so focused on quantitative aspects such as efficiency and visibility that they have neglected the role of light as a form of visual communication in the built environment. In "The Language of Lighting: Applying Semiotics in the Evaluation of Lighting Design," the field of architectural semiotics is proposed as a new way to supplement the prevalent research strategies that focus on quantitative aspects of radiant energy while sometimes ignoring more qualitative effects.

2.4. Summary of changes in lighting research

Changes in the technologies that illuminate our buildings, changes in our basic understanding of how we detect and process that illumination, changes in presenting experimental lighting conditions and measuring the key aspects of those conditions, changes in measuring the human responses and the metrics used to characterize both the stimulus and the response—it sometimes seems that everything about lighting research has changed. But the more things change, the more they stay the same.

3. The more they stay the same

The technologies that we use to light the environment have changed, and our understanding of ocular neurophysiology has expanded dramatically. Some everyday activities have changed: Computers are no longer limited to static, vertical surfaces mostly viewed by seated people. We now use glossy tablets in any orientation and for many more hours per day than was common a few years ago. Underneath all of this shiny, attractive change, however, are many constants. The laws of physics have not changed, although we harness them in new ways to convert signals from raw electrical power to visible electromagnetic radiation reaching the eye. Human nature has not changed. People still need lighting to reveal the world around them, to see small details, to appreciate beautiful objects, and to communicate with others. The processes that ipRGCs influence are new to our understanding but not new to our experience: they were always present even though they were not part of our models of how the eye and brain work. Applied lighting research seeks now, as it has for the past century, to relate light and lighting conditions to receptors of those signals.

In nearly all fields, scientists aim to discern signal from noise. This fundamental characteristic has not changed. We continue to need to start our research projects with a clear definition of the signal that we wish to study. Much of the work of designing and carefully conducting research consists of identifying, excluding, and controlling sources of noise that can obscure the signal. Both the CIE tutorial and workshop presentations and the papers in this special issue demonstrate the continuing interplay between signal and noise.

3.1. The research process

Although we have new theories to test (de Kort 2019), the importance of developing sets of interrelated constructs that specify relationships between variables, through which we explain and predict phenomena, continues. A running theme through several workshop presentations was the message that, at its best, applied lighting research tests hypotheses that are tentative statements or propositions about these relations between variables and that through this process we establish support for our theories, both old and new.

Kevin Houser's presentation in Copenhagen exemplified this, describing the general research process as a search to relate X (independent or predictor variables) to Y (dependent or outcome variables) while controlling Z (extraneous variables that we want to exclude). His focus was primarily on the many ways in which we can describe our X, the light or lighting conditions that we study, whether we manipulate them (as in a laboratory experiment) or measure them (as in a field investigation). Myriam Aries also emphasized the importance of establishing a strong signal in research by clearly defining the stimulus variables and the lit environment in which it occurs and then taking steps to measure the stimuli with precision. Werner Osterhaus focused specifically on measuring daylight well in a field setting, which is a particularly challenging task even with the advanced devices available today. Peter Blattner provided the pure metrology perspective on lighting measurements, reminding us that physics meets physiology when radiometry becomes photometry and pointing ahead to the development of spectral sensitivity functions other than V_{λ}, through which we will be able to better understand the effects of our stimuli on the ipRGCs.

Applied lighting research can encompass nearly any physiological or behavioral variable for the Y part of the equation, and most of these received no attention in Copenhagen because time did not permit it. The one exception was categorical rating scales, which are common tools for lighting researchers but not always well used. Steve Fotios presented his view of this topic at the CIE event and has also contributed a paper to this special issue (Fotios 2019) to provide guidance on good practice for the conduct of experiments that use this technique to elicit judgments from viewers about the conditions that they experience. His goal is to reduce experimental noise so that what remains is an interpretable X to Y relationship. Another way to tighten the focus on the intended signal is to measure the behavioral outcome with less noise. In this special issue, Allan et al. (2019) have reviewed existing scales for assessing general lighting quality and discomfort and have identified a gap: Applied lighting research needs more and better measurement tools, developed using established psychometric principles for demonstrating their validity and reliability.

Veitch noted in Copenhagen that research design is a balancing act. We want to reduce noise—which we may do by using tight experimental control to eliminate unwanted Z variables—but this can produce an environment that is unlikely to exist outside the laboratory. High internal validity often comes at the cost of low external validity. In this special issue, Veitch et al. (2019) have addressed all of these fundamental considerations in a cohesive manner, from specifying the research question, choosing and measuring X and Y variables, designing an experiment to control Z with an appropriate degree of representation of a real circumstance, to reporting with accuracy.

Providing strong evidence of our $X \rightarrow Y$ relationships is among the constants, but experimental control of the confounding Z conditions is not always possible, nor is it desirable. When the study outcome is a human response, there will be individual differences, and in general the relationships we report require a statistical analysis. Jim Uttley addressed this challenge both in Copenhagen and in this special issue (Uttley 2019). His aim in both presentations was to raise awareness of some of the fundamental issues, particularly the need for adequately large samples to have adequate statistical power to detect real effects. His review of a subset of lighting research, reported in this special issue, found that many of our studies have sample sizes too small to detect the effects that they seek. Among the remedies for this problem is to routinely report effect size statistics and to use this information to predetermine the necessary sample size as part of study design.

3.2. Reporting research

In this special issue, Veitch et al. (2019) included a checklist for the guidance of authors, in the hope that authors who address these points will achieve journal acceptance faster and to guide readers in applying critical judgment to what they read.

Writing well never goes out of style, and the same principles provide guidance for critical reading of others' work. This same point was addressed in the CIE event by both Martine Knoop and Peter Boyce. The body of knowledge gets stronger when work can be reliably repeated, but this requires documenting and reporting details in a systematic way. This good laboratory practice can seem tedious and slow in the face of exciting developments, but knowing what we have done speeds progress by preventing unnecessary repetition or information loss.

Boyce brought his inimitable wit and practicality to his advice, which came from his experience as an educator, author, and particularly as a journal editor. "Start with a question that is simple and straightforward and that provides evidence that you can use in practice." To write a good paper, follow his 4 Cs: *Cause* (have something to say to an audience that would benefit from hearing it), *clarity* (deliver that message clearly, with suitable support for any arguments or data for conclusions), *completeness* (include enough detail to permit replication, and place the work and conclusions in the context of existing knowledge), and *concision* (exclude extraneous details so that the message shines forth). Writing a good paper, Boyce said, is like telling a story: the reader needs to hear the essential message (the signal) without unnecessary embellishment (the noise).

4. Conclusion

In the closing plenary of the *CIE Expert Tutorial and Workshop on Research Methods for Human Factors in Lighting*, we were privileged to link the event and this special issue. Nearly 100 people, from very senior researchers to early stage graduate students, had gathered from around the world for the two days, and what they heard there, we hope, is also represented in these pages: just as lighting is both an art and a science, there is an art to conducting and reporting applied lighting research. The technologies that we use to deliver and control radiant energy are undergoing rapid change, as are the tools that we use to measure the radiant energy and the human responses to it. However, as Boyce observed in Copenhagen, our new technologies help us to overcome old limitations without changing the fundamental logic of the research process. We can change the stimulus in ways not previously imaginable, but to make best use of those new technologies we cannot lose sight of the unchanging fundamentals. Lighting quality exists in the balance of meeting needs, integrating with architectural elements, and addressing energy and environmental considerations. Understanding how lighting meets needs—whether of humans, animals, plants, or machines—requires the application of judgment and logic to discern the signal from the noise and ethical guidance on acceptable ways to do so. Participants came away from the two days excited and inspired, and we hope that readers of this issue will likewise take away the message that we have powerful new tools and knowledge at our disposal and a strong foundation of methods and logic upon which to build.

Because the more things change, the more they stay the same.

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