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Lighting R&D Program:

Human Physiological Responses to Light R&D Meeting

October 2020

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DOE Lighting R&D Program, "Human Physiological Responses to Light R&D Meeting," October 2020.

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Comments

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1 Introduction

On September 8 & 10, 2020, twenty seven experts of lighting technology and human physiological responses to light gathered at the invitation of the Department of Energy (DOE) Lighting R&D Program to help identify critical research and development (R&D) topic areas in the field of human physiological responses to light. This small group discussion meeting is one forum for experts to provide technical input to the DOE Lighting R&D Program. The DOE Lighting R&D Program also collects inputs from stakeholders at the annual Lighting R&D Workshop, via a Lighting R&D Request for Information (RFI), and other means. The guidance provided by stakeholders in these various forums helps identify critical R&D areas which may be incorporated into DOE's technical roadmaps.

This year, for the first time, the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing the current state of physiological responses to light, knowledge gaps, and/or R&D opportunities to advance understanding of physiological responses to light. This was followed by a general discussion of the R&D challenges and barriers to implementation. Following these discussions, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop to be held February 1-4, 2021.

The meeting format provided an opportunity for lighting experts in the field of human physiological responses to light research to exchange ideas and explore collaborative research concepts. Participants included invited experts in lighting-relevant science and technology disciplines drawn from academia, National Laboratories, and industry. They included both DOE-Lighting R&D-funded researchers and non-DOE-funded researchers.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A of the report.

1.1 Key Conclusions

The meeting format encouraged each of the attendees to participate and present his/her perspectives on gaps in knowledge and critical R&D challenges. The discussions that followed the presentations offered a variety of valuable insights about the latest understanding of human physiological responses to light; however, there were some recurring themes that arose during these discussions regarding research areas that could advance understanding and practice in the topic of human physiological responses to light. These themes are as follows and are outlined in more detail in Section 2:

- Measurement and Characterization of Physiological Responses and Light Stimulus
- Lighting Design Guidance for Physiological Impacts
- Implementation and Impacts in Real World Settings

2 Critical R&D Topic Areas

2.1 Measurement and Characterization of Physiological Responses to Light Stimulus

In order to create evidence-based lighting designs for human health and wellbeing, quantification of the non-visual responses and a standard approach of reporting the properties of the lighting stimulus is essential. Participants agreed that a common framework for reporting lighting conditions and quantifying physiological responses is important to better understand the impact of lighting and to provide recommended threshold levels for lighting guidance. Many pointed to the international standard CIE S 026/E:2018[1], which defines spectral sensitivity functions, quantities and metrics that describe optical radiation stimulation for each of the five photoreceptor types that can contribute, via the intrinsically-photosensitive retinal ganglion cells (ipRGCs), to retina-mediated non-visual effects of light in humans. Another publication[2] was cited that recommended a set of minimum quantities to report (based on CIE S 026/E:2018) to describe the lighting stimuli. Participants agreed both of these recommended frameworks are a good start for characterizing light stimulus for physiological impacts and should be utilized by researchers.

This also led to a discussion about what are the right endpoints to measure for understanding and predicting human physiological responses (e.g. phase shifting, mood, alertness). There was a dialogue about how the current understanding of the spectral composition of light and its impact on human physiological responses is mainly limited to melatonin suppression, but there are multiple eye-mediated human non-visual physiological responses to light stimulus that should be considered. These include direct alerting effects, impacts on mood, circadian shifting as well as downstream health effects from these physiological responses. Various metrics being promoted for lighting design guidance, e.g. Circadian Stimulus (CS) or equivalent melanopic lux (EML) or melanopic equivalent daylight illuminance (melanopic EDI), are based on a primary role of melanopsin (melatonin suppression), which may not be the key factor for other non-image forming impacts of light. Participants agreed that it is vital to characterize and quantify the right endpoints so the standards for lighting being developed are the best suited to predict human wellbeing in the space and to prevent incorrect standards that set back our ability to improve lighting in built spaces.

While the CIE standards provide an important light characterization framework, it is important to be able to uniformly characterize realistic lighting stimuli experienced in the built environment and report it in a standardized way. Many meeting participants supported international standards as the best path to provide practical guidance for engaging physiological responses to light as part of lighting design guidance. While some participants expressed that it is too early to have a mature set of standards to implement in lighting for physiological responses, others expressed that we have adequate evidence to move forward. However, more R&D is needed to understand the non-visual physiological responses of interest and whether they can be directly measured or require a proxy measurement to develop guidance. Participants suggested to continue using melatonin suppression as a tool to unravel the physiology while also continuing to explore and understand all the other physiological responses to light.

2.2 Lighting Design Guidance for Physiological Impacts

Participants stressed the need for evidenced-based lighting design practices for human health and wellbeing. To date, the generally accepted guidance is more light during the day to support alertness and circadian rhythm (short wavelength/high melanopic EDI light), less light at night to facilitate sleep initiation (longer wavelengths/low melanopic EDI light), and darkness for sleeping. While these general guidelines are a good start, the big challenge is defining the threshold levels of the appropriate metrics for lighting design guidance,

[1] CIE (Commission Internationale de l'Eclairage). (2018) *CIE S 026:2018 CIE System for Metrology of ipRGC-influenced Light Responses*. Austria.

[2] M. Spitschan, O. Stefani, P. Blattner, C. Gronfier, S. W. Lockley, R. J. Lucas, "How to Report Light Exposure in Human Chronobiology and Sleep Research Experiments" *Clock & Sleep*, vol. 1, no. 3, 2019.

and determining if the currently used metrics of EML or CS are even the appropriate metrics to inform on the physiological responses of interest. Another challenge facing lighting designers implementing circadian lighting is the multiple metrics used in various building standards or design recommendations. The UL Design Guide 22480[3] for promoting circadian entrainment with light for day-active people uses the CS metric, which has two models – a warm light model and a cool light model; the WELL Building Standard[4] uses EML; the international standard CIE S 026:2018 recommends melanopic EDI (which is similar to EML). The current models of CS and EML agree in warm color temperature ranges only and diverge at 4000 K and cooler. Further R&D work and analysis is needed to confirm a model that is best at predicting empirically observed melatonin suppression, allowing for a unified model for circadian lighting that can further encourage adoption. This will also help in understanding the energy implication of circadian lighting since the different metrics require different lighting levels, especially as the current models (CS and EML) diverge at cooler color temperatures.

Another complication for defining lighting guidance is that simply defining threshold levels for a building design cannot fully impact the occupants' physiological responses since the full 24-hour cycle of light consumption dictates the responses. Participants stressed the need to consider 24-hour lighting profiles for augmenting or changing physiological responses and to consider the content of what the users are doing with their "light diet." Timing, light history, and location of the light delivery (optical distribution) all play a role. Individuals will also have variations in their personal physiological responses to light that will affect their personal light stimulus-response situation. There will not be a single solution that works for everyone so the guidance should focus on what is best for most and then supplement the lighting further for the population on the edges. Education and feedback to the users on how they are 'consuming' lighting is critical for overall population impact. More R&D is needed to understand how to navigate the 24-hour 'lighting diet' with more research on timing of lighting stimulus and light history, and how to account for the variation of lighting conditions that people move through in their workplaces and home environments to manage a total 24-hour lighting cycle. Ideally, the lighting system can be adapted to accommodate individuals on different circadian schedules. With a better understanding of how to manage a 24-hour lighting profile, better guidance can be provided to the design of circadian lighting for commercial buildings (which people occupy for 8-12 hours of their full 24-hour lighting diet) and the home environment.

It is vital to understand that guidelines will need to adapt and change as more of the science is clarified.

2.3 Implementation and Impacts in Real World Settings

Translational research is essential to understand and validate human physiological responses to light in real-world settings and situations instead of controlled lab-scale research. Participants discussed the challenges with moving forward in translational research. These challenges include characterizing physiological responses at scale, understanding the effects where there is a large interpersonal variability in the physiological responses to light, and accounting for the variation in 24-hour light profiles of real-world studies. More experiments must be performed in typical field conditions at scale with diverse populations, not just in controlled translational environments with specific subpopulations (such as nursing homes or hospitals). Studying lighting interventions for subpopulations should continue to be pursued, but not as a substitute for the large-scale general population studies.

The more specific challenge with field studies is the impact of light does not result in a large change in behavior, but instead a subtler effect, thereby making it more difficult to track. Due to the subtler effects of light in the field, large data sets are needed to evaluate the impacts of lighting at the group level; but there are multiple competing factors involved in the outcomes being measured, consequently making the evaluation of the large data sets complicated. For example, a participant's sleep will be impacted by other factors than just

[3] UL (Underwriters Laboratories). (2020). *DG 24480, Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People*. Illinois.
[4] International WELL Building Institute. (2020). *WELL Building Standard v2*. New York.

the lighting they receive in a real-world setting. Because of this, it is necessary to study effects at the large group level since they may be unnoticeable at the individual level, but observed at scale, such as a productivity improvement for a large workforce in a building. This convolution of effects from varying interpersonal differences and individual choice differences in a 24-hour lighting cycle is challenging; part of effective translational studies is understanding how to deconvolute the effects. Some participants felt interventional studies with carefully controlled connected lighting systems could lead to clearer effects than big data.

Because of the complexity of field studies, participants felt that developing a consensus reference baseline for intervention studies would help clarify effects and allow various researchers to start from a same common baseline. This consensus baseline could be beneficial and allow the lighting system to be programmed with the baseline conditions before the interventions are applied. The participants suggested DOE can encourage and facilitate discussion groups to move towards development of a reference baseline for intervention studies.

Another point of discussion is the value of developing objective and easy to measure end points. Some examples of easy to measure outcomes include regularity of sleep, variability of sleep decreasing with lighting conditions, or variability with sleep timing. Collaborative field studies with lighting manufacturers and academic researchers are essential to develop the right lighting technology and sensors for the clinicians performing the study. Use of wearable sensors can measure many different things with one little patch (e.g. heart rate, activity level, sleep and wake cycles). Light sensors in mobile phones could measure the light exposure over a 24-hour lighting cycle and be leveraged in large-scale studies. Additionally, intervention studies can be used to work around the systematic error such as imperfect sensors or sensor location (e.g. wrist sensors when looking at effects of light reaching the eye). It is crucial to use the right measurement equipment, and understand its measurement accuracy, to quantify the desired outcome measures.

It is important to also consider the amount of light reaching the eye (retinal irradiance) to generate the physiological response. The distribution of the light in the room is a significant factor in delivering the lighting stimulus – not just overall light levels. We must move beyond just providing light from the ceiling and move to optical distributions that deliver the lighting stimulus more effectively to the eye. Care must be taken though since higher vertical luminance creates concerns about glare and acceptability of the lighting. Currently, it is a challenge for lighting practitioners to find lighting systems that allow for good optical distributions plus spectral optimization; often you are left with a tradeoff between optical distribution or spectral tuning. Researchers need improved lighting system functionality to carry out these translations studies; tunable optical distribution and spectral power distribution in lighting should be developed so they are widely accessible by translational researchers. Delivering the light for health and wellbeing requires a multi-criteria optimization to balance both visual and non-visual effects. Creating lighting systems that can change the spectral content, optical distribution, and light level will allow for the adjustment of lighting profiles when the scientific guidance becomes clearer. These types of systems can enable a nimble response to meet the latest understanding and provide value to the built environment in terms of optimizing physiological responses and energy usage.

3 Suggestions for the DOE Lighting R&D Workshop

The 2021 Lighting R&D Workshop, which is to be held February 1-4, 2021, offers another opportunity to continue the discussion on critical R&D challenges. Another goal of this R&D meeting was therefore to gather input and suggestions for suitable topics and speakers, and ideas for panel discussions. Participants suggested the following topics:

1. Daylighting implementation in building design
2. A path forward for lighting industry to implement practices addressing physiological impacts
3. Further studies in basic physiological and translational research
4. Discussion of a consensus baseline condition to include in lighting intervention studies

Appendix A: Participant Presentations

Mariana Figueiro, Rutgers University: Relative Light Sensitivities of Four Retinal Quadrants for Suppressing the Synthesis of Melatonin at Night

Mariana Figueiro, Director at the Institute for Healthy Aging and Chief the Division of Sleep and Circadian Medicine at Rutgers University, highlighted a study targeted at understanding the spatial distribution of circadian phototransduction circuits across the retina. The study varied the spatial distribution of light to learn about the retinal quadrant sensitivity, while keeping the amount and spectra of light entering the eye constant. The findings showed that greater melatonin suppression was observed for longer durations of light exposure. Additionally, the greatest melatonin suppression was associated with light exposure in the nasal quadrant, which was consistent with a few other referenced studies. These findings provide information about how to deliver light to the eye more effectively in the field; more specifically, lighting from the ceiling may not be the most effective way to deliver circadian-effective light. Lights placed to the left and to the right of the direction of gaze rather than directly above and below the gaze direction can be more effective. Splitting the circadian-effective light delivery into both locations (left and right of the gaze) may help reduce glare.

Celine Vetter, University of Colorado Boulder: Untitled

Celine Vetter, an Assistant Professor at the University of Colorado Boulder, examined how light during the day affects our health. Environmental light levels are a powerful modulator of the circadian system, which impacts many factors of our health including inflammation, oxidative stress, dysregulated glucose metabolism, insulin resistance, neuroendocrine dysregulation, and weight gain. We can fight cardiometabolic disease with circadian principles. Vetter continued by describing the gap in our understanding of light and the impact on populations. More research is needed to develop healthy 24-hour lighting profiles. Our light exposure is modifiable – and currently underused to improve health in the population. She finished by highlighting an example of how our light exposure changed with the COVID-19 pandemic; our average light exposure increased, sleep timing shifted later, and the sleep duration was longer. This highlights how many factors of how we live and move throughout the day affects our sleep patterns; analysis of a 24-hour "lighting diet" is important when considering translational research.

Timothy Brown, University of Manchester: Predicting Human Non-Visual Responses to Light

Timothy Brown, a Professor at the University of Manchester, discussed how to quantify and predict 'non-visual' responses to light. Ocular light exerts a range of physiological and behavioral (non-visual) effects via ipRGCs including circadian photoentrainment, neuroendocrine regulation, sleep, alertness, mood, etc. In addition to intrinsic (melanopsin-based) photosensitivity, ipRGCs act as a conduit for rod cone signals. The contributions potentially depend on duration, intensity, prior light exposure, and type of response. An interim solution has been to define a set of α-opic quantities that describes effective light intensity for each opsin; these are the new SI-compliant system (CIE S 026/E:2018 standard) scaled to provide Equivalent Daylight Intensities (EDI) in lux. Brown described how melanopic irradiance is a strong predictor of human non-visual responses to nocturnal light exposure and the spectral sensitivity of non-visual responses is well-approximated by melanopic EDI. Additionally, there is little evidence that melanopic EDI varies according to color. He expressed that the research shows strong support for using melanopic EDI as a guiding principle to control non-visual responses for integrative lighting applications. Brown finished by calling attention to remaining questions in the current understanding of human non-visual sensitivity:

- Is sensitivity under field conditions reduced compared to lab studies?
- What is the effect of prior light exposure?
- What explains the apparently large interindividual variation in sensitivity?
- Does the sensitivity of the daytime non-visual responses (e.g. alertness) differ?
- Are all methods of modulating melanopic EDI equivalent?

More research is required to understand these important questions.

John Hanifin, Thomas Jefferson University: Photic Regulation of Physiology in Humans: From Action Spectra to Defining Relevant Dose

John Hanifin, a Research Assistant Professor at Thomas Jefferson University, reviewed some of his groups' work with developing dose response curves for LED illumination sources and discussed the comparison of studies using both LED and fluorescent lighting sources using the CIE S 026/E:2018 standard metrics. He found that melanopic illuminance alone can sufficiently explain the various responses across these different test stimuli. Wavelength sensitivity is just one of the elements involved in light transduction. Other elements include conscious and reflex behavior, ocular media transmission, iris/pupil dilation, photoreceptor distribution, neural integration of time/space, and state of retinal adaptation. More studies and empirical testing of the various elements in lighting transduction are needed. The empirically generated data sets need to be quantified and discussed based on national and international standards.

Jaime Zeitzer, Stanford University: Human Physiologic Responses to Light

Jaime Zeitzer, Associate Professor at Standard University, began by considering the functional consequences that we care about for human health – circadian impact, alertness, mood, perceptual comfort, and more. He stated that our current understanding of the spectral composition of light and its impact on human physiological responses is mainly limited to melatonin suppression, which is not something most people care about. The various metrics being promoted by lighting implementation in buildings (e.g., CS, WELL, others) are based on a primary role of melanopsin (great for melatonin suppression) that may not be true for these other non-image forming aspects of light. Melatonin suppression requires a *sustained* activation by light, removal of light stimulus results in rapid reversion of melatonin to normal levels. Melanopic irradiance seems to fit the diversity of results from monochromatic stimuli very well and explain most of the variance. Though phase shifting is not the same as a melatonin suppression response. Most of the impact of continuous light exposure happens at the beginning of the light stimulus. Zeitzer finished by cautioning the development of lighting design standards for circadian lighting with incomplete data. Wide adoption of incorrect standards will set back our ability to improve lighting in built space by decades. It is imperative that we examine the endpoints in which we are actually interested in – melatonin suppression is not the right proxy. We must understand the impact of light spectrum on phenomena that are important from a public health perspective: phase shifting, mood, and alertness.

Manuel Spitschan, University of Oxford: Physiological Responses to Parametric Changes in Light

Manuel Spitschan, a University Research Lecturer at the University of Oxford, considered several challenges of understanding physiological responses to parametric changes in light. One problem is that broadband and monochromatic light sources cannot distinguish between different photoreceptor contributions because of their overlapping spectral sensitivity. He found that the method of silent substitution (employs mixtures of ≥4 primary lights) can be used to stimulate different photoreceptor classes selectively. They have used this method to examine pupillary control. Another challenge is that parametric measurements of physiological responses to lighting conditions only go 'so far' in predicting real-world responses to light. Conjoint measurements of pupil size and spectrum can show how pupil size as a physiological indicator for the activation of light changes as a function of the 'real-world' spectra we encounter. Lastly, Spitschan discussed the challenge that there are no standard guidelines for reporting aspects of lighting in experiments. It is very difficult to compare studies in the literature unless they have very similar quantities that are reported. He co-authored a consensus article that proposes a set of minimum quantities to report based on the CIE S 026/E:2018 standard. He also encouraged reporting the spectrum as well to allow for meta-analysis and other data aggregation efforts in the future.

Satchin Panda, Salk Institute: Human ipRGCs

Satchin Panda, a Professor at Salk Institute, presented on ipRGC responses in the human retina. He highlighted some experiments his group performed exposing human retinas to pulses of light. Three different responses were observed: one has the characteristic of an acute on-response and is then sustained for a long time before it turns off (Type 1), another is less sensitive to light with a slow turn-on and turn-off (Type 2), and one more behavior (Type 3) is seen only in the presence of supplemental retinol. This Type 3 response is seen at high light intensity light, with a response that is higher compared to Type 1 and 2, and rapidly turns off. Numerically, Type 3 responses are more prevalent to Type 1 and 2 combined. Panda finished by recommending future research in the following areas: functional characterization of human ipRGCs under illumination conditions that represent human exposures; functional and morphological characterization of human ipRGCs and their distribution in the human retina; contribution of outer-retina photoreceptors to ipRGC function; and identifying factors that contribute to functional and morphological features of the ipRGC subtypes.

Sofia Axelrod, Rockefeller University: Sleep in Fruit Flies and Babies

Sofia Axelrod, a Research Associate at the Rockefeller University, presented on the molecular mechanisms and physiological importance of circadian rhythms and the downstream effects of what this core clock does in the body. Many processes are regulated by the circadian clock including sleep, metabolism, aging and disease. The blood-brain barrier (BBB) is not a static organ but instead exhibits circadian rhythmicity in its permeability. The BBB is more closed when we sleep and becomes more permeable when we are awake. This work was based with fruit flies but the preliminary results with mice show this may be true in mammals as well. There is an aging implication and shorter lifespans have more leaky BBB. Axelrod then moved to discuss how diet and eating at certain times of the day or night impact circadian rhythms and aging. Time restricted feeding (TRF) has shown to help with a variety of metabolic parameters (in fruit flies and humans). TRF has been found to impact aging; it prolongs a fruit flies' life spans and does it in a circadian-clock-dependent matter and is also light-dependent. TRF can halt the BBB deterioration process with aging.

Luc Schlangen, Eindhoven University of Technology, Director of CIE Division 6: Lighting for Sleep

Luc Schlangen, a Senior Researcher at the Intelligent Lighting Institute at Eindhoven University of Technology and Director of CIE Division 6, reviewed the impacts of lighting on physiology by discussing several studies. The first compared the different spectra of a conventional white LED and a full spectrum daylight LED light source (with higher melanopic lux). The results found that the daylight LED resulted in better visual comfort, increase of deep sleep, and no cognitive performance differences. Another study Schlangen mentioned showed that insufficient illuminance (during extended wakefulness) negatively impacts subsequent sleep intensity. He also reviewed brightness perception and melanopsin. A study found that a high melanopsin condition is perceived as brighter than a low melanopsin condition. Luminance and hue strongly drive brightness discrimination such that the melanopsin contribution can become hard to detect, though when there are minimal cone-dependent signals available, melanopsin can make a large contribution to brightness discrimination. Lastly, Schlangen encourage researchers to adopt the CIE S 026/E:2018 standard α-opic metrology in the exploration dose-response relationships (both non-visual/visual) and with light recommendations for non-visual responses.

David Sliney, Independent Consulting Medical Physicist: Retinal Exposure– the Spatial Aspect Visual Field-of-View

David Sliney, an Independent Consulting Medical Physicist, considered what the best metric is to estimate the light exposure of ipRGCs. Metrics such as horizontal or vertical illuminance in lux or even horizontal or vertical "melanopic lux" alone are inappropriate to characterize what light (and spectrum) is really falling on the retina – and on the ipRGCs. Retinal irradiance and illuminated retinal region are the appropriate metrics to characterize the stimulus reaching the eye. Sliney also mentioned how eye lid position depends on scene brightness, which limits the field of view (FOV) and impacts what position of the eye receives the light stimulus. The inferior versus superior retinal illumination varies greatly; the inferior retina is 'in the dark.' Regardless of ambient light levels, the macula is always exposed. The area of the pupil aperture determines the total light entering the eye, but there is a wide individual variability. He finished with keys to remember: measurement of overhead artificial lighting luminaires is not highly related to retinal illumination; vertical illuminance is a metric that is really only relevant to light boxes within direct FOV; and the reflectance of natural or built materials in the lower FOV dominates retinal illumination.

Jennifer Veitch, National Research Council of Canada: CIE Research Priorities for Healthful Lighting

Jennifer Veitch, the Principal Research Officer at National Research Council of Canada and CIE Vice President Technical, presented several CIE research priorities for healthful lighting – myopia, daily lighting diets, and temporal light modulation effects. Myopia is increasing worldwide, but especially in east Asia, and light exposure could be one influence. Research is required to close the gap in understanding and needs both fundamental and applied components. More research is also needed in learning what pattern of daily light and dark exposure best supports wellbeing. In addition to circadian regulation, we need to learn what other physiological and psychological processes are influenced by ocular light detection. Our lighting recommendations need to consider interpersonal diversity – not everyone is the same. There must be tailored lighting recommendations, so researched must expand beyond healthy young adults working in white-collar jobs during the day. To enable better understanding of the 24-hour "lighting diet", measurement issues relating to ecological light exposure devices must be improved. Measurement devices must be small, have expanded spectral range, good responsivity, ability for data storage, easily worn, and easily calibrated. Veitch finished by discussing temporal light modulations (TLM), which include visual perceptions such temporal light artefacts, flicker, stroboscopic effect, phantom array. These TLMs can lead to cognitive and neurobehavioral which impacts eye movement (saccade) disruption, visual performance, clerical work performance, and brain activity. Also, health effects can include epilepsy, headache, eyestrain, and discomfort. Understanding and eliminating TLMs is a critical part of lighting for health and wellbeing.

Kevin Houser, Oregon State University: Neurological Metamerism, Field Studies, and Daylighting

Kevin Houser, a Professor at Oregon State University, discussed how light is a complex stimulus that can be manipulated to affect people. Visual comfort, performance, and experience are important to consider in addition to the non-visual pathways. Uncertainty increases between stimulus and response as the signal moves from the physical stimulus to the eye and through the neural pathways. While light is potent, it must be kept in context since other factors such as age, climate, diet, disease, exercise, and genetics, among other factors play a role as well. Houser listed several R&D needs to advance understanding of physiological responses to optical radiation beyond the photopigments. These include: research to support understanding of neurological metamerism; field studies for the general population of healthy, day-working individuals; and advancing the understanding and use of daylight for supporting physiology.

Erin Flynn-Evans, NASA Ames Research Center: Efficacy of Experimental Lighting for Enhancing Alertness and Performance Among Airline Pilots

Erin Flynn-Evans, the Director of the Fatigue Countermeasure Laboratory at NASA Ames Research Center, described the findings from a study evaluating the use of lighting for enhancing alertness and performance among airline pilots. Short haul airline pilots often have early-start work shifts that begin before sunrise. Relative to mid-day starts, the early-starts result in shorter sleep duration, reduced performance, and reduced alertness. The study investigated exposure to 20 minutes of blue-enriched light upon waking before early starts to help shift circadian phase, facilitate improved sleep, alertness, and performance outcomes. The results showed that the bedtime, wake time, sleep duration, and sleep quality were the same for the lighting intervention and placebo during the early starts. Additionally, there were not differences in the performance tests between the intervention or the placebo during the early starts, but the baseline mid-day starts were better than either of the early-start results. Some phase shifting was observed for the lighting intervention during the early start, but it did not improve sleep, performance, or alertness.

John Sammarco, National Institute for Occupational Safety and Health: Underground Mine Field Study to Reduce Circadian Disruption

John Sammarco, the Principal Research Engineer at the National Institute for Occupational Safety and Health, examined an underground mine field study aimed at reducing circadian disruption in miners. Underground miners are especially vulnerable to circadian disruption and fatigue since they work in darkness with a noisy environment, heat, and physically demanding and repetitive tasks. The study targeted reducing circadian disruption via pre-shift lighting interventions with light emitting glasses worn for 30-40 minutes before starting a shift. The field study challenges the team encountered include the mine's need for any benefit to be implemented afterwards, thereby limiting the interventions to commercial products. Also, the pre-shift intervention time is limited to only 30-40 minutes. The dynamic mining environment also poses challenges including a lighting intervention "dosage" that can vary greatly in mine, and the balancing of the visual and non-visual needs. Sammarco finished by listing a number of areas that have gaps in understanding. More work is needed to understand: how much circadian disruption is "safe" for a person; what the relative contribution of health issues are from circadian disruption verses workplace hazards or lifestyles choices; how to improve alertness without melatonin suppression and increased health risks; and how to address visual performance, circadian entrainment, and worker acceptance. More consensus is also needed on what is the right metric to characterize the non-visual stimulus – CS, EML, or something else. There is also the need for more industry & academia partnerships to carry out these studies.

Robert Soler, BIOS Lighting: Current Models and Recommendations

Robert Soler, the Vice President of Research at BIOS Lighting, discussed current models and recommendations for circadian lighting in buildings. The leading models are equivalent melanopic lux (EML) and Circadian Stimulus (CS). CS has two models in one: a warm model with a peak sensitivity of 485nm, and a cool model with a peak sensitivity at 465nm, and a sub-additivity that is known to exist in color vision. EML is adopted by the WELL Building Standard – a voluntary performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing, through air, water, nourishment, light, fitness, comfort, and mind. Additionally, a third metric is melanopic EDI from the CIE S 026/E:2018 standard, which is similar to EML. A high melanopic EDI during the day is usually supportive for alertness, the circadian rhythm, and a good night's sleep. A low melanopic EDI in the evening and at night facilitates sleep initiation and consolidation. Soler went on to illustrate how the CS cool model lead to prohibitively high light level requirements at 4000 K, 5000 K and 6500 K, which is impeding industry adoption. He continued by describing a new study where the CS models were analyzed for how well they predict observed melatonin suppression. It was found that the CS warm model was better at predicting the melatonin suppression observed in this unpublished pilot study. He finished by stressing that the field needs to get this science down to a unified model to encourage adoption. Current available models only agree in warm color temperatures, and the disagreement at colder color temperatures slows adoption of circadian lighting. Because of the potential for tremendous energy savings, Soler advised that it is in the best interest of DOE to support studies that clarify the efficacy of the models in current use and development.

Andrea Wilkerson, Pacific Northwest National Laboratory: Energy Impacts

Andrea Wilkerson, a Senior Lighting Research Engineer at Pacific Northwest National Laboratory (PNNL), spoke about the energy implications of circadian lighting. She discussed studies using simulations to explore the circadian metrics in a lighting design as a function of room layout, view direction, and varying specular reflectance of the room wall and furniture colors. She found that the spectral reflectance of the objects in the room need to be taken into account when designing for circadian lighting since many absorb the short wavelength light which impacts the melanopic EML with view direction. Wilkerson continued by discussing installations of tunable lighting at health facilities. It is important for researchers working in realistic settings to make sure the lighting system is working as expected since the interventions may not run as designed because occupants may change the settings. Focus areas for future PNNL studies include: access to outcomes data (is the host organization willing and able to provide access to patient / user outcomes data?); controls data (can the use of controls be easily recorded so we know how people on the site are using the lighting?); innovation (is there some aspect of the lighting system and application that is particularly innovative and worth documenting?); and partnerships (is there a firm commitment from the host organization?). Lastly, she stated that the future PNNL projects evaluating office lighting will consider more factors including environmental factors (air quality, thermal comfort), workplace factors, personal factors, and how lighting plays a role considering the full environment.

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