SDAR* Journal of Sustainable Design & Applied Research

Volume 6 | Issue 1 Article 2

2018

The Present and Future of Lighting Research

Peter Robert Boyce
Rensselaer Polytechnic Institute, New York, peter.robert.boyce@gmail.com

The present and future of lighting research

Professor PR Boyce PhD
peter.robert.boyce@gmail.com

Abstract

The aim of this paper is to consider where lighting research is today and what its future might be. There is little doubt that, today, lighting research is an active field. A brief review of the topics being studied reveals that they range from residual studies on visibility and visual discomfort, through attempts to identify the influence of lighting on factors beyond visibility such as mood and behaviour, to the whole new field of light and health. But activity alone is not enough to justify a future.

For lighting research to have a future it is necessary for it to be influential. To become influential, research needs to focus its attention on outcomes that matter to people and the elements of those outcomes on which lighting is known to have a major influence. Further, researchers will have to be determined to overcome the barriers to changing lighting practice. By doing this, lighting research may change the world for the better, to be an important topic, not an irrelevance.

Keywords

Lighting, research, future, technology, measurement, design, performance, health.

Glossary

Photopic vision

Occurs under daylight and conventional interior lighting. It is characterised by fine discrimination of detail and good colour vision.

Mesopic vision

Occurs under outdoor lighting at night. It is characterised by poor discrimination of detail and limited colour vision.

Scotopic vision

Occurs in the absence of any lighting. It is characterised by no discrimination of detail and no colour vision.

1. Introduction

In 2004 I published a paper entitled *Lighting research for interiors: the beginning of the end or the end of the beginning*[1]. It is always instructive for anyone attempting to predict the future to assess how accurate they were in the past, so the objective of this paper is to review what has happened since the publication of that paper and to consider where lighting research is likely to go in the future. The essential message from that paper was that to flourish, lighting research had to move beyond studies of the effects of lighting on visibility and visual discomfort. Specifically, it had to address questions about how lighting influences mood and behaviour through the "message" that lighting delivers to the perceptual system, as well as how lighting affects health and performance through what was then called the circadian system. Now it is more correctly called the non-image forming system. A move in that direction has certainly happened.

There are still papers published on specific visibility issues such as the seeing of trip hazards when walking on the streets at night[2], the ability to acquire information from traffic signs[3], and the marking of a work-zone on a motorway[4]. Likewise, there are still papers published on discomfort glare[5], [6] and, somewhat surprisingly, flicker[7], the latter being driven by the widespread introduction of LEDs with their very fast response times. Despite these, the last decade has seen a major shift in lighting research away from visibility and visual discomfort to work on perception and its consequences[8], [9], and to work on the use of lighting to ensure circadian stability[10] and improve work performance through increased alertness and cognitive function[11, 12]. From this it might be thought that lighting research is flourishing but I fear that it is not. Indeed, I rather suspect that the current state of lighting research might be compared to a fly in treacle, a lot of energy is being expended but it is not going anywhere. There are a number of reasons for this but, before getting to them, it is necessary to consider what the areas of active lighting research are currently.

2. The present

2.1 Technology

Lighting technology is always an active research area, although this is not always evident as little is published in the open literature until the resulting products are ready to market. Nonetheless, the dramatic growth in the adoption of solid-state lighting over the last decade is evidence enough that commercial research on light sources has certainly been active, so much so that academic papers are now appearing that offer ways to improve the colour properties of existing LEDs[13], limit the glare from LED luminaires[14], and provide better ways to estimate the life of LED luminaires[15]. By combining LEDs in different ways, a wide range of light spectra can be constructed. This has led to a resurgence of research on colour metrics[16-20]. Further, the light output of solid-state light sources is easy to adjust. This, combined with developments in information technology and wireless communication, has encouraged the development of control systems responsive to human activity and daylight availability[21], [22]. These developments offer the prospect of lighting ceasing to be a relatively inflexible building service and to it becoming a stimulating accompaniment to everyday life.

2.2 Measurement

Another area of lighting research where there have been significant developments is in the field of measurement. The most obvious changes have been the decrease in size and price of what, until recently, were very sophisticated measurement tools[23]. As a result, it is now quite common for luminance distributions to be measured using high dynamic range imaging[24], for spectral distributions to be measured using hand-held spectroradiometers[23], for what people are looking at to be identified using eye trackers[25], and for data on peoples' perceptions to be collected for virtual lighting installations using the internet[26]. Such tools allow measurements to be made that once were either impossible or impractical, and therefore open up new fields of study.

While such measurements have been shown to be useful, the potentially most significant change in lighting measurements has had nothing to do with equipment. Rather, it has to do with the recognition that there are multiple spectral sensitivities operating in the retina, depending on what combination of the five types of photoreceptors present in the retina are active under different conditions, how their signals are connected, and the routes they take through the brain[27]. Despite this complexity, light as a physical quantity is still defined by applying the CIE Photopic Luminous Efficiency Function (Vλ) to the spectral power distribution. Every basic photometric quantity, luminous flux, luminous intensity, illuminance and luminance is defined using the Vλ function; yet Vλ represents only the outputs of the long- and medium-wavelength sensitive cones. When the main concern of people providing lighting was to ensure that people could see the detail they needed to see, Vλ was a reasonable way to measure light as it reflected the response of the fovea which is what we use when wishing to examine something closely. Although this is still an important aspect of lighting, other aspects of vision involving additional photoreceptors are now considered to be worth consideration, e.g., off-axis detection when driving, the perception of brightness and stimulation to the circadian system[27].

Although a number of alternative luminous efficiency functions for brightness perception and circadian stimulation have been proposed[27, 28], to date, Vλ and the scotopic equivalent (Vλ') – which reflects the activity of the rod photoreceptors – are the only ones recognised for photometric measurements. Until this limitation is admitted and a series of spectral sensitivities for different effects approved,it is unlikely that lighting will be able to achieve its full potential.

2.3 Design

Another area of active research interest is design. Using conventional experimental techniques and sophisticated statistics, different lighting designs have been shown to influence perceptions of spaces and products[29]. This has commercial significance but the most interesting research is more fundamental. Cuttle has argued the need to change the purpose of lighting of interiors in general[30]. He argues that basing interior lighting recommendations on visual performance can no longer be justified. With few exceptions, light is now inexpensive enough and illuminance recommendations are high enough to ensure good levels of visual performance, especially as visual tasks have become easier with the development of improved photocopiers and better (or ubiquitous use of) display screens. Even when they have not, there are other technologies available that can do the task better than a human using unaided vision.

Hence, he recommends that the purpose of interior lighting should be changed from ensuring adequate visibility so that tasks can be done quickly and easily, without discomfort or fatigue, to first lighting the space so that it is perceived as having adequate illumination, and then providing a hierarchy of light to suitably emphasise objects and surfaces of interest, including any tasks that require special lighting. This approach requires a different set of metrics and measurement procedures. Specifically, lighting recommendations would no longer be made in terms of illuminance on the task plane, usually assumed to be horizontal, but rather in terms of mean room surface exitance and task/ambient illuminance ratio. This approach is capable of being applied to a wide range of situations, from simple open interior spaces where there is no knowledge of what is to be done in the space, to a sculpture gallery where a great deal is known about what will go where and how it will be viewed. Essentially, this approach can be called a perception-based approach to lighting design[31]. In a way, it represents the change in how lighting is considered, from illumination engineering to environmental design.

2.4 Performance

While the fundamentals of how lighting and task characteristics affect visual performance are well established[32], there are still papers dealing with specific tasks, usually tasks where the stimulus is characterised by multiple contrasts and colours. For example, Fotios *et al* have been active in studying the ability to recognise intent from facial expression under street lighting[33], while Mundinger and Houser have shown that, contrary to popular belief, surgeons have no particular preference for the CCT of operating lights[34].

A more general trend in research related to performance has been the move away from simple visual tasks to looking at how stimulation of the non-image-forming system by light affects the performance of cognitive tasks and the intermediate condition of alertness[35]. This move started by looking at how alertness and cognitive performance could be enhanced during a night shift by the suppression of the hormone melatonin[36]. Then attention switched to what effects there are on alertness and cognitive task performance following light exposure during daytime[37]. While the cost and benefits of melatonin suppression for performance at night are well established, the same cannot be said for daytime exposure when melatonin concentration is at a minimum, although other hormones such as cortisol are certainly present and are influenced by exposure to light.

There are a number of reasons why this is a difficult area to study. First, the impact of light exposure on the non-image-forming system depends on the retinal irradiance, the light spectrum, the timing of the exposure, the duration of exposure and the photic history of the individual. Usually, only one or two of these factors are considered in experiments. Second, the performance of cognitive tasks depends on many factors, lighting being just one of them. Third, there seem likely to be several different routes to the intermediate conditions such as alertness. For example, it has been shown that both short wavelength (blue) and long wavelength (red) light can increase alertness, but the non-image-forming system is only sensitive to short wavelength light[38]. This might be expected because compared to the visual system, the non-image-forming system is slow, insensitive and non-locating. From an evolutionary point of view, relying on such a system to alert you about danger is a recipe for extinction.

To summarise, while performance is still a topic of interest because of its relationship with productivity and wealth generation, research activities have generally moved on from the relative simplicity of the effect of light on visual performance to the more complex area of cognitive performance and the effects of light operating through the non-image-forming system. This is an interesting but difficult field of study and, as a result, there is no coherent understanding of the role of lighting at present.

2.5 Health

The ability of optical radiation to damage both eye and skin tissue has been appreciated for many years with the result that there exist standards and guidance about maximum levels of exposure to light[39]. The advent of phosphor-converted LEDs as a major light source with their peak emission in the short wavelength visible has resurrected interest in this field, particularly the blue light hazard[40]. Similarly, the fast response time of LEDs and their resulting sensitivity to any instability in the LED drivers has resurrected interest in flicker as a cause of migraines and illusions, resulting in more standards and guidance[41].

But one aspect of health, and its rather more nebulous companion well-being, that has generated a lot of research activity has been the effect of light on the non-image-forming system. It is well established that long-term and frequent disruption of the human circadian system is often associated with serious ill health[42]. This has resulted in efforts to discover how light can be used to limit circadian disruption[11]. Of course, one possibility would be to insist that everyone should sleep at night and be awake by day but this is seen as unrealistic in what has become a 24-hour society. For those who have to work at night, particularly those working rapidly-rotating shifts, schedules of exposure to light have been proposed to minimise circadian disruption while ensuring adequate performance[43].

For those who sleep at night and work during the day, there is considerable interest in ensuring enough light exposure to stabilise the circadian system. One way to do this is to go outside in the middle of the day but this may not always be possible, or effective, depending on the weather or the location. This has resulted in attempts to make lighting more effective in stimulating the non-image-forming system either by increasing the ingress of daylight into a building, by changing the spectrum of the electric lighting to provide more short-wavelength emission, or by increasing the illuminance provided at the eye by the electric lighting.

These have all been approaches aimed at the general population. However, there are some groups whose health is known to benefit from enhanced light exposure. One such group are those who suffer from seasonally-affective disorder. Exposure to bright light during periods of limited daylight has been shown to alleviate the symptoms of this condition[44]. Another group who have been shown to benefit from enhanced exposure to light at the right time are those who suffer from dementia[45]. Delivering light to the eyes of such people during the day is not easy using conventional lighting so a simple light table has been suggested[46]. There is little doubt that light and health has become a major area of research as it has the potential to improve the lives of many people.

3. The future

From the above it should be clear that lighting research has been very active. The question now becomes, what is its future? Before that question can be answered it is necessary to consider what determines its future. This is its value to society and that, in turn, depends on the reasons it was undertaken. Lighting research can have a number of different objectives. One is to develop a new product … a light source, a luminaire, or a control system that can be marketed and sold at a profit. Another is to gain new knowledge so as to explore a new concept or to develop a new model from which predictions about future uses can be made. Yet another is to change lighting practice so as to deliver the lighting that people desire in a sustainable and economic manner. How recent lighting research fits into this framework will now be considered, as will what is required from research to achieve these objectives.

3.1 New products

The history of lighting is a story of innovation. From incandescent to discharge to solid-state light sources, the story has been one of steady development interspersed with sudden and dramatic changes. The advent of solid-state lighting and the disruptive effects it is having on the lighting industry is only the latest of these changes. The brutal truth is that, whatever lighting equipment offers a good combination of luminous efficacy, appropriate light output, reasonable colour properties and a long life, all at an attractive price, that equipment will be widely adopted. Solid-state light sources are still being developed but the areas of research that seem most likely to be influential in the future are in the areas of artificial intelligence applied to lighting controls and 3D printing applied to luminaire design. It is not science fiction to believe that homes and workplaces equipped with lighting that has learnt the preferences of the occupants in different situations will soon be with us. But it is not enough to have a product that is new. Newness, itself, is of interest to only a few. What is essential for widespread adoption is that the product should offer something that was not possible before, something that makes a desirable outcome achievable in a convenient manner, at a reasonable price. Lighting research to achieve such products is ongoing. How successful it is will be for the market to decide.

3.2 New knowledge

The search for new knowledge might be thought of as an academic exercise; certainly, generating new knowledge is the key to academic success. Yet new knowledge is also the key to new ideas and new products. Consider what has followed from the discovery of the intrinsically-photosensitive retinal ganglion cells and their link to the non-image-forming system. The consequences have ranged from a large number of studies exploring the effects of different light spectra, different radiant flux, different timing and different durations of exposure leading to a number of models of the impact on melatonin concentration, as well as a new way to represent circadian disruption. These, in turn, may lead to light sources weighted to provide a high level of circadian stimulation and lighting designed to

https://arrow.dit.ie/sdar/vol6/iss1/2
DOI: 10.21427/D7853J

provide both visibility and circadian stimulation. Before this can happen, there will need to be some consensus reached on the best way to quantify the circadian stimulation provided.

Unfortunately, outside of the field of circadian stimulation, there has been little by way of new concepts or models. It is true there is a new model for discomfort glare[47] but this is of little practical interest because discomfort glare is largely a non-problem today. Luminaire designers know how to minimise discomfort glare. A similar situation is evident for work on the calculation of mesopic luminances[48]. Luminances far into the mesopic region are rare. Most outdoor lighting standards recommend luminances in the low photopic or high mesopic range so the consequences of correcting for mesopic luminance are minimal. There have also been a few studies looking at the life-cycle costs of lighting[49], [50] but these have had little impact.

Where interest has been rising is in the psychological effects of lighting. Studies of learning in schools[51], recovery from medical operations[52] and perception of brand identity[29] have all demonstrated that the form of lighting used can have beneficial or detrimental effects on desirable outcomes. These effects tend to be probabilistic rather than certain and are associated with specific situations. Nevertheless, in the given situation they can be real enough and suggest that lighting has a consistent role to play in influencing behaviour. Yet other studies have been devoted to exploring the effect of lighting conditions on mood and behaviour[53-55]. Many of these studies can be considered to be proof of concept studies, i.e., they seek to establish that lighting does have an effect on the specific outcome and therefore should be considered when studying all the factors. Unfortunately, this is just the first step on what is likely to be a long and tortuous path to a full understanding resulting in a model capable of quantifying the role of lighting.

An example of such a development is the work of Veitch *et al*[56]. This reports two laboratory studies using simulated office spaces in which temporary office workers did a range of office tasks over a day. Two statistical analyses of the data revealed a series of links which demonstrated that people who perceived their office lighting to be of higher quality rated the office as more attractive, reported a more pleasant mood and showed greater feelings of health and well-being at the end of the day. Other studies have demonstrated that satisfaction with lighting contributes to greater environmental satisfaction, which in turn leads to greater job satisfaction, a factor that influences organisational commitment[57].

The defining feature of such models is that lighting is just one among many aspects of the situation that have to be considered when estimating the likelihood of the desired outcome, no matter whether it be mood, behaviour or cognitive task performance. Further, all three of these outcomes depend on the context. For example, if the context is a shop and the desired behaviour is for an item on show to be sold, there is no doubt that the way the item is lit has a role to play in making the item look attractive. The way the space is lit also has a role to play in bringing people into the shop and establishing the atmosphere they experience when inside. Unfortunately, the same could be said about the acoustic and thermal shop environment, the attitude of the shop staff and the price of the items on display, as well as the shopper's finances and recent experiences completely unrelated to a possible purchase of the item. Given this complex pattern of potential factors influencing the desired outcome, it is very difficult to establish a model that reliably quantifies the role of lighting in achieving the desired aim. At the very least it will require multi-disciplinary studies in a clearly-defined context, studies that are both expensive and time-consuming. It is unlikely that many such ambitious studies will ever be undertaken.

Given the difficulty of generating models of the effects of lighting on outcomes remote from visibility, does this mean that research in these areas is impossible? I think not, although what is possible will be less ambitious. Basically, what is proposed is to restrict study to whatever aspects of the desired outcome are primarily determined by lighting. In much the same way that visual performance has been separated from task performance by studying it using tasks where the non-visual components have been minimised, the suggested approach for the shop would be to study how lighting can be used to make the item to be sold most attractive, and how the ambient lighting affects people's perception of the atmosphere in the shop. The rationale for such an approach would be that the best identified lighting would be making as big a contribution to the desired outcome as it could, any failure to achieve the desired outcome being most likely due to some other non-lighting factor. It is this approach that has led to the studies on how lighting affects alertness described above, the assumption being that an alert individual will perform any task better than one who is sleepy. Such studies would certainly be less expensive and less difficult than attempting to identify the role of lighting among a host of competing factors and, thus, represent a practical way forward for studying such probabilistic outcomes as mood, behaviour and cognitive task performance.

3.3 Changing lighting practice

The overarching aim of many people involved in lighting research is to change lighting practice so as to deliver the lighting that people desire in a sustainable and economic manner. There are a number of ways to do this. One way is to produce a better product. The growth in the use of solid-state lighting has been driven by the fact that these light sources offer a higher luminous efficacy, a longer life and good colour properties, all at a reasonable price. Another example is the change in outdoor lighting where fully-shielded luminaires have been developed in response to the public concern about light pollution.

Another way is to use legislation to ban the use of specific products, usually energy inefficient products. This approach has been used for many years resulting in the removal of electromagnetic ballasts, incandescent lamps and, most recently, halogen lamps, from the market.

Yet another way is to change lighting standards or recommendations. This is effective because only the most self-confident lighting designers or electrical contractors are willing to ignore lighting standards and guidance because, to do so, would leave them open to litigation should the design prove to be unsatisfactory. Unfortunately, it is very difficult to get a standard changed even though most quantitative guidance on lighting is prepared by professional bodies. This is because most standards have a defensive screen of vested interests around them. A light source manufacturer who has designed a product range around existing colour metrics will not take kindly to a new metric, particularly if some existing products would be downgraded.

Similarly, lighting consultants who are familiar with daylight factor may not view having to learn a whole new method of daylight evaluation with much enthusiasm. Moreover, bodies that issue authoritative guidance may have difficulty changing the basis of that guidance if it means admitting that they have been wrong for many years.

Despite these defences, standards can be changed. To do this requires a good argument. Such an argument has to address a recognised problem, either a lighting problem or a policy issue related to lighting. Unfortunately, sustainability has not yet reached the critical mass necessary to cause a change in lighting standards. Given that a change in standards is necessary, what is required is a quantitative metric. Quantitative lighting metrics are what save the lighting world from anarchy. Without the lighting recommendations issued by authoritative bodies, and based on such metrics as illuminance on the working plane, illuminance uniformity, colour rendering index and unified glare rating, lighting practice would degenerate into a race to the bottom. Experience over many years has shown that qualitative advice issued by authoritative bodies has little impact. Then, the quantitative metric has to be easily understood, should make a significant difference, and has to be simple to implement in design and in practice. These are all requirements that the researcher should keep in mind if the aim is to change lighting practice.

Of all the research reviewed earlier, the quantitative metric most likely to change in the near future is the CIE Colour Rendering Index. An alternative and much more informative system for characterising light source colour properties has already been adopted as a standard in the USA and it is easy to understand[58]. The other attempt to change lighting practice, the removal of illuminances on the task plane as the basis of design and their replacement with the perception-based system of lighting design[30], [31], will take much longer, if ever, because it requires a compete reorientation of how lighting is designed, as well as a new set of metrics. Although it is claimed that the method developed simply follows the approach used by experienced lighting designers, it will require a lot of support for such a dramatic change in metrics to be accepted, as well as some assurance that the change will not lead to an increase in the amount of electricity used for lighting.

The wild card in this area is the effect of lighting on health. Very few people care about lighting *per se* but many care about their health. If it can be shown that exposure to light of a specific spectra and amount is necessary for the health of the whole population, then lighting standards will need to change. At the moment, lighting standards are concerned solely with ensuring visibility without discomfort. These objectives will remain but, if health becomes an additional objective, then lighting standards and lighting practice will have to change. At the moment, research is concentrated on the fundamentals of how light exposure influences the non-image-forming system. Research on application is rather limited and there is no agreement about how to quantify the stimulus delivered to the non-image-forming system so there is a long way to go before we can be sure about the effects of light exposure on human health. However, the potential for changing lighting practice is huge.

4. Conclusion

This paper has addressed the current state of lighting research and its future prospects. From the brief review of current research topics, it should be evident that lighting research is indeed active. What is not so clear is whether or not all that activity will lead to any improvements in lighting practice as it affects the bulk of the population. After writing this paper, I have to conclude that the answer is a definite maybe. New technology is waiting to be introduced. Some of this technology has the potential to allow people to choose the form of lighting they like, and to vary it as they desire. The market will decide if such technology is worth having.

There is also a lot of new knowledge on the effects of lighting being produced. A lot of this has to do with lighting's impact on the non-image-forming system and the consequences for health. There have also been some attempts to explore the impact of lighting on remote effects beyond visibility such as mood, behaviour and cognitive task performance. Much of this is of doubtful value because these remote effects are determined by many factors other than lighting. If the aim is to demonstrate the benefits of lighting other than visibility, it is necessary to focus attention on those aspects of the desired outcome that can be strongly linked to light exposure.

As for attempts to change lighting practice, new colour metrics seem certain to be adopted soon, but expecting to completely reorient the purpose of lighting away from task visibility to lighting the space seems unlikely to succeed unless it can be demonstrated that it would make a significant difference to people's satisfaction with lighting without imposing additional costs. One research area where this is not so is the impact of light exposure on human health. If it can be shown that lighting can have a significant impact on human health, then both lighting standards and lighting practice will have to change, regardless of the cost. This is the research area that is most likely to drive major changes in lighting practice.

In conclusion, in my earlier paper[1] I said that for lighting research to flourish it had to move beyond studies of the effects of lighting on visibility and visual discomfort to studies of how lighting influences mood and behaviour. These studies should be done through the "message" that lighting delivers to the perceptual system and health and performance through the effect light has on the non-image-forming system. That has certainly happened. But although lighting research is flourishing, it is not necessarily influential. To become influential, it needs to focus its attention on outcomes that matter to people and the elements of those outcomes on which lighting is known to have a major influence.

Further, researchers will have to be determined to overcome the barriers to changing lighting practice. By doing this, lighting research will be seen to change the world for the better, to be an important topic, not an irrelevance.

https://arrow.dit.ie/sdar/vol6/iss1/2
DOI: 10.21427/D7853J

References

1. Boyce PR. Lighting research for interiors: the beginning of the end or the end of the beginning. *Lighting Research and Technology* 2004; 36: 283-294.
2. Fotios S, Uttley J. Illuminance required to detect a pavement obstacle of critical size. *Lighting Research and Technology* 2018; 50: 390-404.
3. Schnell T, Yekhshatyan L, Daiker R. Effect of luminance and text size on information acquisition time from traffic signs. *Transportation Research Record* 2009; 2122: 52-62.
4. Rea MS, Bullough JD, Radestsky LC, Skinner NP, Bierman A. Toward the development of standards for yellow flashing lighting in work zones. *Lighting Research and Technology* 2018; 50: 552-570.
5. Yang Y, Luo MR, Huang WJ. Assessing glare. Part 3: Glare sources having different colours. *Lighting Research and Technology* 2018; 50: 596-615.
6. Yang Y, Luo MR, Huang WJ. Assessing glare. Part 4: Generic models predicting discomfort glare of light emitting diodes. *Lighting Research and Technology* 2018; 50: 739-756.
7. Roberts JE, Wilkins AJ. Flicker can be perceived during saccades at frequencies in excess of 1 kHz. *Lighting Research and Technology* 2013; 45: 124-132.
8. Yang B, Fotios S. Lighting and recognition of emotion conveyed by facial expression. *Lighting Research and Technology* 2015; 47: 964-975.
9. Cui Z, Hao L, Xu J. Lighting of a cardiac intensive care unit: Emotional and visual effects on patients and nurses. *Lighting Research and Technology* 2018; 50: 701-715.
10. Miller D, Figueiro MG, Bierman A, Schernhammer E, Rea MS. Ecological measurements of light exposure, activity and circadian disruption. *Lighting Research and Technology* 2010; 42: 271-284.
11. Figueiro MG, Nagare R, Price LLA. Non-visual effects of light: How to use light to promote circadian entrainment and elicit alertness. *Lighting Research and Technology* 2018; 50: 38-62.
12. Rea MS, Figueiro MG. Light as a circadian stimulus for architectural lighting. *Lighting Research and Technology* 2018; 50: 497-510.
13. Zhou Z, Wang H, Zhang J, Su J, Ge P. LED chip-on-board package with high colour rendering index and high luminous efficacy. *Lighting Research and Technology* 2018; 50: 482-488.
14. Tashiro T, Kawanobe S, Kimura-Minoda T, Kohko S, Ishikawa T, Ayama M. Discomfort glare for white LED light sources with different spatial arrangements. *Lighting Research and Technology* 2015; 47: 316-337.
15. Zhang JP, Bai YF, Zhang X, Chen Wl, Li WB, Cheng GL, Chen X. An optimized model for lifetime prediction of LED-based light bars using luminance degradation method. *Lighting Research and Technology* 2018; 50: 316-325.
16. Luo MR, Cui G, Georgoula M. Colour difference evaluation for white light sources. *Lighting Research and Technology* 2015; 47: 360-369.
17. Wei M, Houser KW, David A, Krames MR. Colour gamut size and shape influence colour preference. *Lighting Research and Technology* 2017; 49: 992-1014.
18. Ma S, Wei M, Liang J, Wang B, Chen Y, Pointer M, Luo MR. Evaluation of whiteness metrics. *Lighting Research and Technology* 2018; 50: 429-445.
19. Ohno Y. Pratical use and calculation of CCT and Duv. *Leukos* 2014; 10: 47-55.
20. Dikel EE, Burns GJ, Veitch JA, Mancinci S, Newsham GR. Preferred chromaticity of color-tunable LED lighting. *Leukos* 2014; 10: 101-115.
21. Wen Y-J, Agogino AM. Control of wireless-networked lighting in open-plan offices. *Lighting Research and Technology* 2011; 43: 235-248.
22. Caicedo D, Li S, Pandharipande A. Smart lighting control with workspace and ceiling sensors. *Lighting Research and Technology* 2017; 49: 446-460
23. Bergen T, Young R. Fifty years of development of light measurement instrumentation. *Lighting Research and Technology* 2018: 50; 141-153.
24. Cai H, Chung TM. Improving the quality of high dynamic range images. *Lighting Research and Technology* 2010; 43: 87-102.
25. Fotios S, Uttley J, Cheal C, Hara N. Using eye-tracking to identify pedestrians' critical visual tasks. Part 1: Dual task approach. *Lighting Research and Technology* 2015; 47: 133-148.
26. Villa C, Labayrade R. Validation of an online protocol for assessing the luminous environment. *Lighting Research and Technology* 2013; 45: 401-420.
27. Rea MS. *Value Metrics for Better Lighting*. Bellingham,WA: SPIE Press, 2013.
28. Rea MS. The lumen seen in a new light: Making distinction between light, lighting and neuroscience. *Lighting Research and Technology* 2015; 47: 259-280.
29. Schiekle T. Light and corporate identity: Using lighting for corporate communication. *Lighting Research and Technology* 2010; 42: 285-295.
30. Cuttle C. A new direction for general lighting practice. *Lighting Research and Technology* 2013; 45: 22-39.
31. Cuttle C. *Lighting Design: A Perception-based Approach.* Abingdon, UK: Routledge, 2015.
32. Rea MS, Ouellette MJ. Relative visual performance: A basis for application. *Lighting Research and Technology* 1991; 23: 133-144.
33. Fotios S, Yang B, Cheal C. Effects of outdoor lighting on judgements of emotion and gaze direction. *Lighting Research and Technology* 2015; 47: 301-315.
34. Mundinger JJ, Houser KW. Adjustable correlated colour temperature for surgical lighting. *Lighting Research and Technology*. First published 24 November 2017. DOI: 1477153517742682.
35. Ye M, Zheng SQ, Wang ML, Ronnier Luo M. The effect of dynamic correlated colour temperature changes on alertness and performance. *Lighting Research and Technology*. First published 14 February 2018. DOI: 1477153518755617.
36. Eastman CI. Circadian rhythms and bright light recommendations for shift work. *Work Stress* 1990; 4: 245-260.
37. Figueiro MG, Kalsher M, Steverson BC, Heerwagen J, Kampschroer K, Rea MS. Circadian effective light and is impact on alertness in office workers. *Lighting Research and Technology*. First published 9 January 2018. DOI: 1477 153517750006.
38. Figueiro MG, Bierman A, Plitnick B, Rea MS. Preliminary evidence that both blue and red light can induce alertness at night. *BMC Neuroscience* 2009; 10:105.
39. Commission Internationale de l'Eclairage. S009 *Photobiological Safety of Lamps and Lamp Systems*. Vienna: CIE, 2002.
40. Bullough JD. The blue light hazard: A review. *Journal of the Illuminating Engineering Society* 2000; 29: 6-14.
41. IEEE Standards association. IEEE Standard 1789-2015 *IEEE Recommended Practices for Modulating Current in High Brightness LEDs for Mitigating Health risks to Viewers*. Piscataway, NJ: IEEE Standards Association, 2015.
42. Knutsson A. Health disorders of shift workers. *Occupational Medicine (London)* 2003; 53: 103-108.
43. Smith MR, Fogg LF, Eastman CI. A compromise circadian phase positon for permanent night work improves mood, fatigue and performance. *Sleep* 2009; 32: 1481-1489.

44. Golden RN, Gaynes BN, Ekstrom RD, Hamer RM, Jacobsen RM, Suppes T, Wisner KL, Nemeroff CB. The efficacy of light therapy in the treatment of mood disorders: A review and meta-analysis of the evidence. *American Journal of Psychiatry* 2005; 162: 656-662.

45. Forbes D, Blake CM, Thiessen EJ, Peacock S, Hawranik P. Light therapy for improving cognition, activities of daily living, sleep, challenging behaviour and psychiatric disturbances in dementia. *The Cochrane Database of Systematic Reviews* 2014; 2: CD003946.

46. Figueiro MG, Plitnick B, Rea MS. Research Note: A self-luminous light table for persons with Alzheimer's disease. *Lighting Research and Technology* 2016; 48: 253-259.

47. Scheir GH, Donners M, Geerdinck LM, Vissenberg MCJM, Hanselaser P, Ryckaert WR. A psychophysical model for visual discomfort based on receptive fields. *Lighting Research and Technology* 2018; 50; 205-217.

48. Uchida T, Ohno Y. Defining the visual adaptation field for mesopic photometry: Effect of surrounding source position on peripheral adaptation. *Lighting Research and Technology 2017*; 49: 763-773.

49. Principi P, Fioretti R. A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED) – a case study. *Journal of Cleaner Production* 2014; 83: 96-107.

50. Takhamo L, Halonen L. Life cycle assessment of road lighting luminaires – comparison of light-emitting diode and high-pressure sodium technologies. *Journal of Cleaner Production* 2015; 93: 234-242.

51. Sleegers BE, Moolenaar NM, Galetzka M, Pruyn A, Sarroukh BE, van der Zanden BM. Lighting affects students' concentration positively: Findings from three Dutch studies. *Lighting Research and Technology* 2013; 45: 159-175.

52. Joarder A. Price, A. Impact of daylight illumination on reducing patient length of stay in hospitals after CABG surgery. *Lighting Research and Technology* 2013; 45, 435-449.

53. Boyce PR, Veitch JA, Newsham GR, Jones CC, Heerwagen J, Myer M, Hunter CM. Lighting quality and office work: Two field simulation experiments. *Lighting Research and Technology* 2006; 38: 191-223.

54. Hubalek S, Brink M, Schierz, C. Office workers' daily exposure to light and its influence on sleep quality and mood. *Lighting Research and Technology* 2010; 42: 33-50.

55. Johansson M, Rosen M, Kuller R. Individual factors influencing the assessment of the outdoor lighting of an urban footpath *Lighting Research and Technology* 2011; 43: 31-43.

56. Veitch JA, Newsham G.R, Boyce PR, Jones CC. Lighting appraisal, well-being and performance in open-plan offices: A linked mechanism approach. *Lighting Research and Technology* 2008; 40: 133-151.

57. Wells MM. Office clutter or meaningful personal displays: the role of office personalization in employee and organizational well-being, *Journal of Environmental Psychology* 2000; 20: 239-255.

58. Illuminating Engineering Society of North America. IES TM-30-18 *IES Method for Evaluating Light Source Color Rendition* New York: IESNA, 2018.

https://arrow.dit.ie/sdar/vol6/iss1/2
DOI: 10.21427/D7853J