International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

Achieving Good Lighting Quality with Integrative Lighting: Opportunities and Challenges

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NRC·CNRC

Gaithersburg, MD – CIE/USNC and CNC/CIE
11th Biennial Joint Meeting
October 2017

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Outline

- Introduction
- Opportunities & Challenges
  - Photobiological safety
  - Colour quality
  - Well-being
- Conclusions
  - Research quality and quantity
  - Future vision

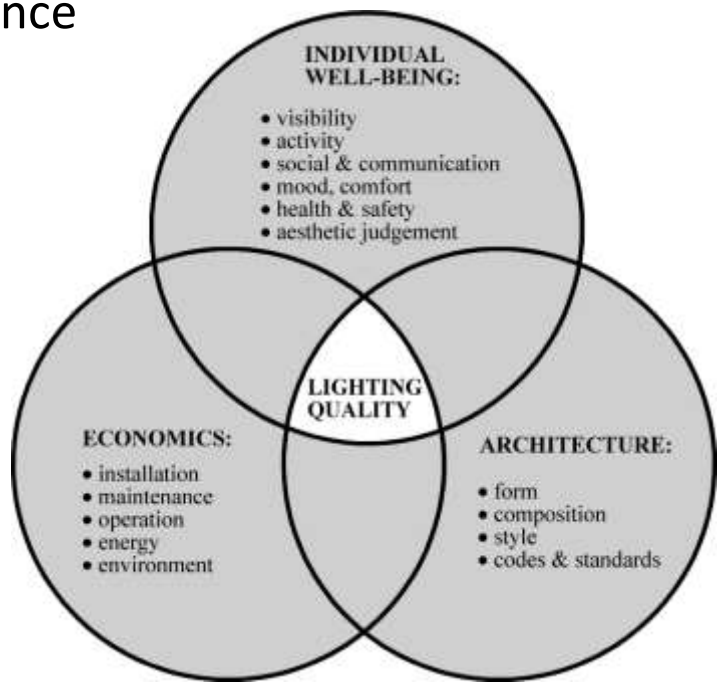
Introduction: Technology revolution

- General lighting LEDs improve upon fluorescents in lm/W
- Large reduction in lighting electricity possible from LED adoption
  - Additional savings from controls
- Smart glazing developments
  - PV integration
  - Glare control: thermo- & electrochromic, internal & external shades
- IoT integration, LiFi, sensors…

- **Building energy efficiency requirements**

Introduction: Definitions

- **lighting quality** [CIE DIS 017:2016]
  - degree of excellence to which the totality of lighting characteristics fulfils user needs and expectations or other applicable requirements
    - Note 1 to entry: The degree of excellence depends on the application area and covers individual end user well-being, safety and public security, architecture and lit environment



Introduction: Definitions

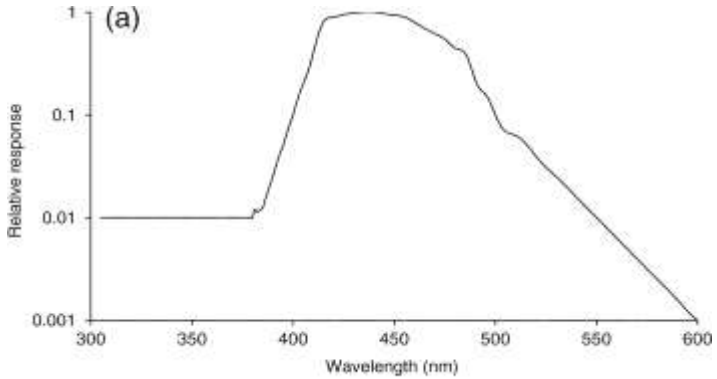
- **integrative lighting** [CIE DIS 017:2016, 17-29-030]
  - Lighting specifically designed to produce a beneficial physiological and/or psychological effect upon humans
    - Note 1 to entry: This includes both visual and non-visual effects.
    - Note 2 to entry: The term human centric lighting is used with a similar meaning.

- SO -- glare, color, sparkle, visual performance, flicker, and appearance all matter
- Good integrative lighting has many effects on viewers

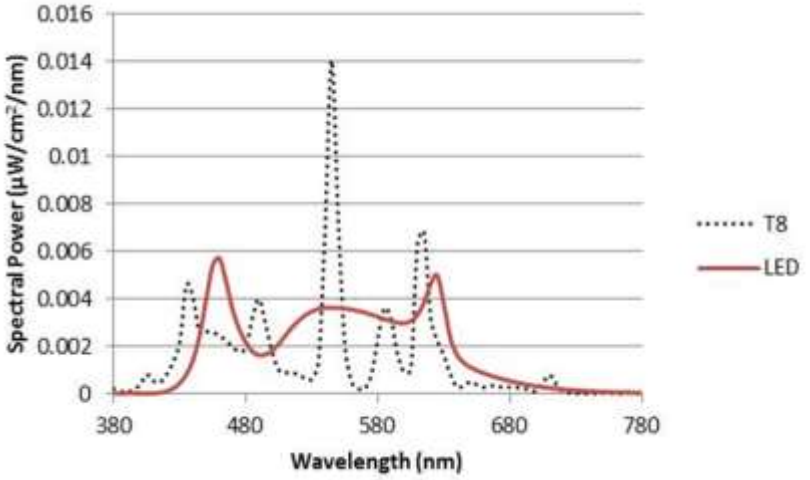
Introduction: Technology & knowledge

- The advent of LEDs revealed shortcomings in what we have always done, for example:
  - CIE General Colour Rendering Index (R_a)
    CIE 177:2007: Colour Rendering of White LED Light Sources
  - Glare from nonuniform sources, and other lighting quality issues
    CIE 205:2013: Review of Lighting Quality Measures for Interior Lighting with LED Lighting Systems
  - Metrology
    127:2007 (2nd edition): Measurement of LEDs

Challenge? Photobiological safety



Turnbull D J , Parisi A V Radiat Prot Dosimetry 2011;rpd.ncr251 © The Author 2011.



Measured at NRC. T8: 5700 K LED 5000 K

- The blue content in white light is not bad at normal interior levels.
- At 500 lx, nearly all of the tested LEDs fall into risk group 0 (no blue-light hazard even after 10000 s exposure)
- At 200 mm [20 cm], some LEDs fall into RG1 (blue-light risk after 100 s) or RG2 (blue-light risk within 0.25 s)
  - *But what is the likely exposure time at 20 cm?*

Challenge? Photobiological safety

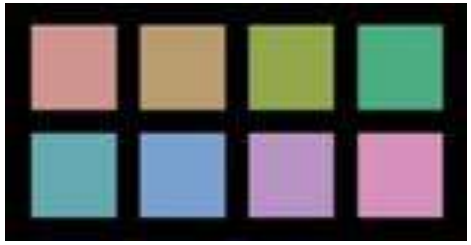
- O'Hagan, Khazova, & Price (2016) assessed light sources, display screens, & blue sky
  - None of the sources exceeded exposure limits – these include exposure times
- Revision of IEC 62471 / CIE S009 under way now
  - Likely to use time-weighted averaging for UV and blue light hazard
- Note that risks could be higher for devices used by children
  - probably best to avoid blue LEDs as indicators in toys

Opportunities – Photobiological safety

- Evidence gaps – topics for study, possible CIE work items:
  - Are there any effects of chronic exposure to optical radiation at levels just below the ICNIRP/ACGIH exposure limits?
  - Indirect effects of horticultural lighting on nutrition?
  - Clarifications sought concerning medical treatments using optical radiation (e.g., phototherapy for neonates, among others)

Challenges: Colour quality

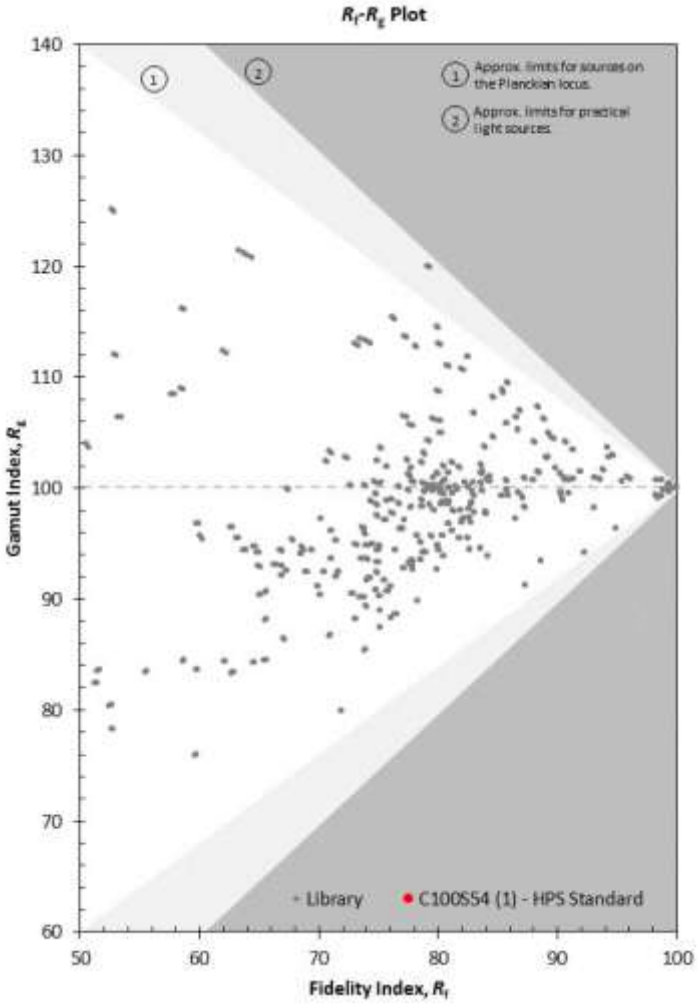
- Research from various labs showed need for both an indicator of light source accuracy of colour reproduction (colour fidelity) and
one more predictive of preference



- A new metric for colour fidelity! $\mathbf{R_f}$
224:2017: CIE 2017 Colour Fidelity Index for accurate scientific use
- Based on IES TM-30:
  - 99 test colour samples
  - uniform colour space

Challenges: Colour quality

- IES TM-30 recommended a gamut metric, called R_g to capture the average deviation in object chroma
  - David, A., Fini, P. T., Houser, K. W., Ohno, Y., Royer, M. P., Smet, K. A. G., et al. (2015). Development of the IES method for evaluating the color rendition of light sources. *Optics Express, 23*(12), 15888-15906.
- Colour perception of a given target wavelength combination will depend on luminance, surround colours, observer adaptation and individual differences – i.e., on context

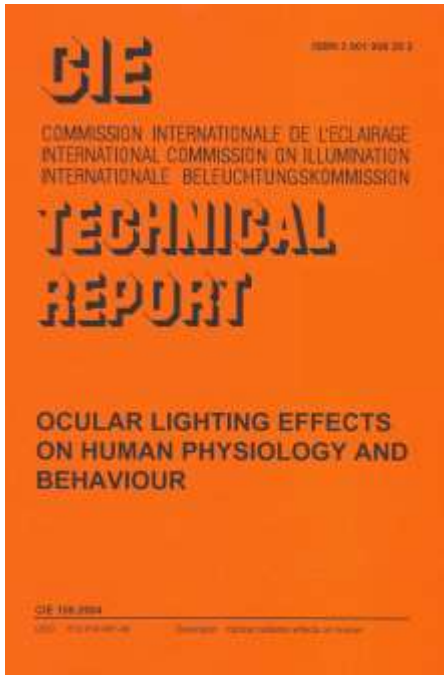


Opportunities: Light source colour & quality

- CIE Research Strategy identified many areas needing urgent research attention – 3 of 9 concern colour!
  - Colour Quality of Light Sources Related to Perception and Preference
  - Application of New CIE 2006 Colorimetry
  - Visual Appearance: Perception, Measurement and Metrics
- New! plans under way for a Research Forum to chart a way forward on light sources in context – approval expected in Jeju

Challenges: 5 Principles of Healthy Lighting

1. The daily light dose received by people in industrialized countries might be too low.
2. Healthy light is inextricably linked to healthy darkness.
3. Light for biological action should be rich in the regions of the spectrum to which the non-visual system is most sensitive.
4. The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.
5. The timing of light exposure influences the effects of the dose.



Challenges: How much light?

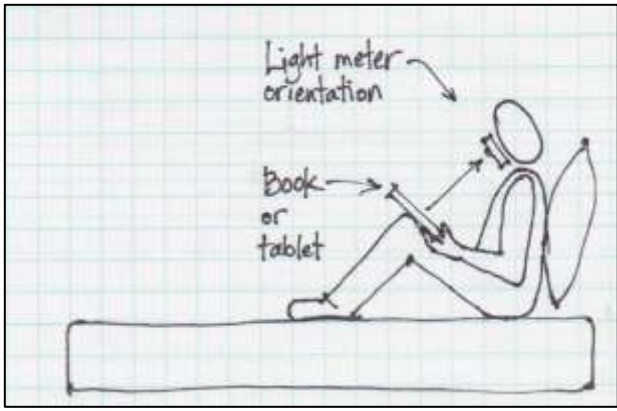
Average minutes per day while exposed to >1000 lx, by city and season.

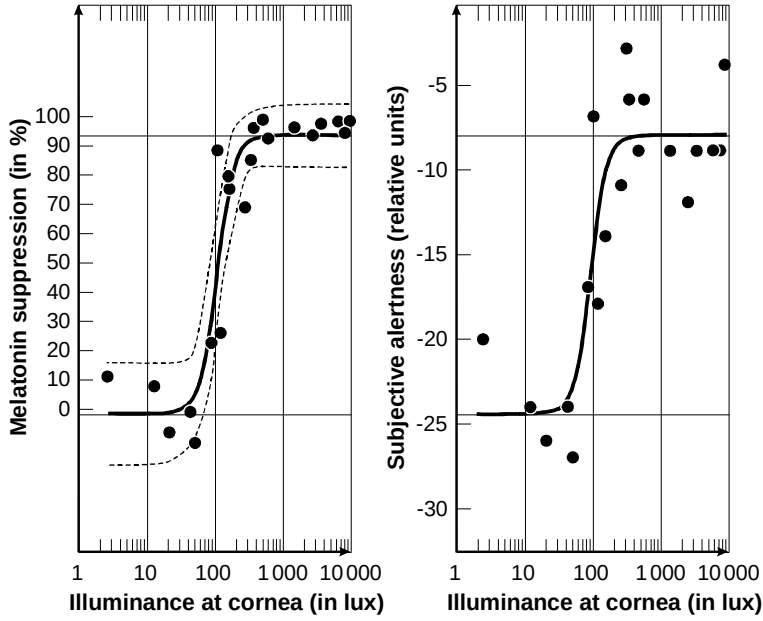
	Measurement location	Summer	Autumn	Winter	Spring
Bozeman, MT (46°N)	wrist		36		
Montreal, QC (45°N)	wrist	156		24	
Montreal, QC (45°N)	wrist	91		26	
Montreal, QC (45°N)	wrist				
Morning types		148			
Evening types		94			
Rochester, MN (44°N)	wrist	143		23	
San Diego, CA (33°N)	wrist	130		80	
Zurich, Switzerland (47°N)	spectacles				105

- Survey: monitored daily light exposure and administered questionnaires
  - Everyone had low overall exposure
  - Evidence that depressive people spent least time in bright light

Challenges: How much light?

- First, light at the eye matters:
- Relationships seem to saturate, at least when measured at night (as at right).
- For now, consider that <10 lx is dim for evening and >1000 lx for some of the day is desirable
- We still don't know what total daily dose would be desirable.





The left graph is re-drawn from Zeitzer et al. (2000). The right is redrawn from Cajochen et al. (2000). Both are © CIE, 2016 and used by permission.

CIE JTC 9: CIE system for metrology of ipRGC influenced light response

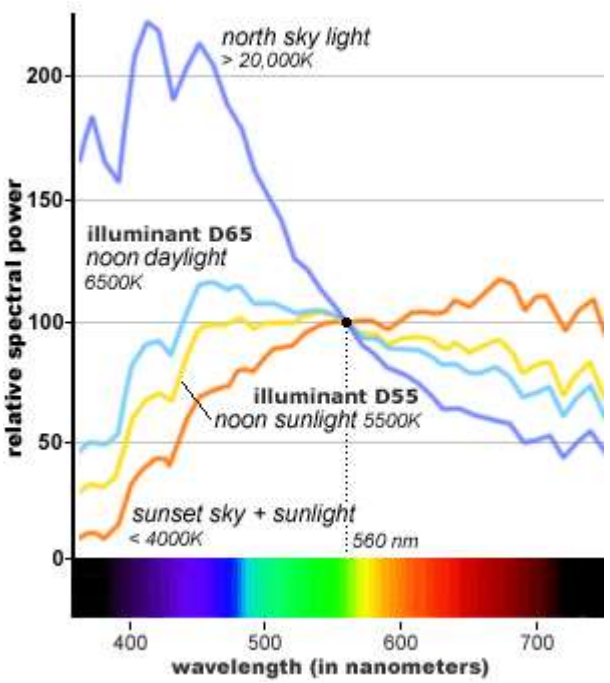
- International Standard -- will define spectral sensitivity functions, quantities and metrics to describe radiation for its ability to stimulate each of the five photoreceptor types...
- Definition of new quantities:

Response, α	α-opic spectral efficiency functions	α-opic irradiance, E_α (units)	α-opic equivalent illuminance (units)
Cyanolabe, sc	$s_{sc}(\lambda)$	E_{sc} (W·m^{-2})	$E_{v,sc}$ (lx)
Chlorolabe, mc	$s_{mc}(\lambda)$	E_{mc} (W·m^{-2})	$E_{v,mc}$ (lx)
Erythrolabe, lc	$s_{lc}(\lambda)$	E_{lc} (W·m^{-2})	$E_{v,lc}$ (lx)
Melanopic, mel	$s_{mel}(\lambda)$	E_{mel} (W·m^{-2})	$E_{v,mel}$ (lx)
Rhodopic, rh	$s_{rh}(\lambda)$	E_{rh} (W·m^{-2})	$E_{v,rh}$ (lx)

SI-units!

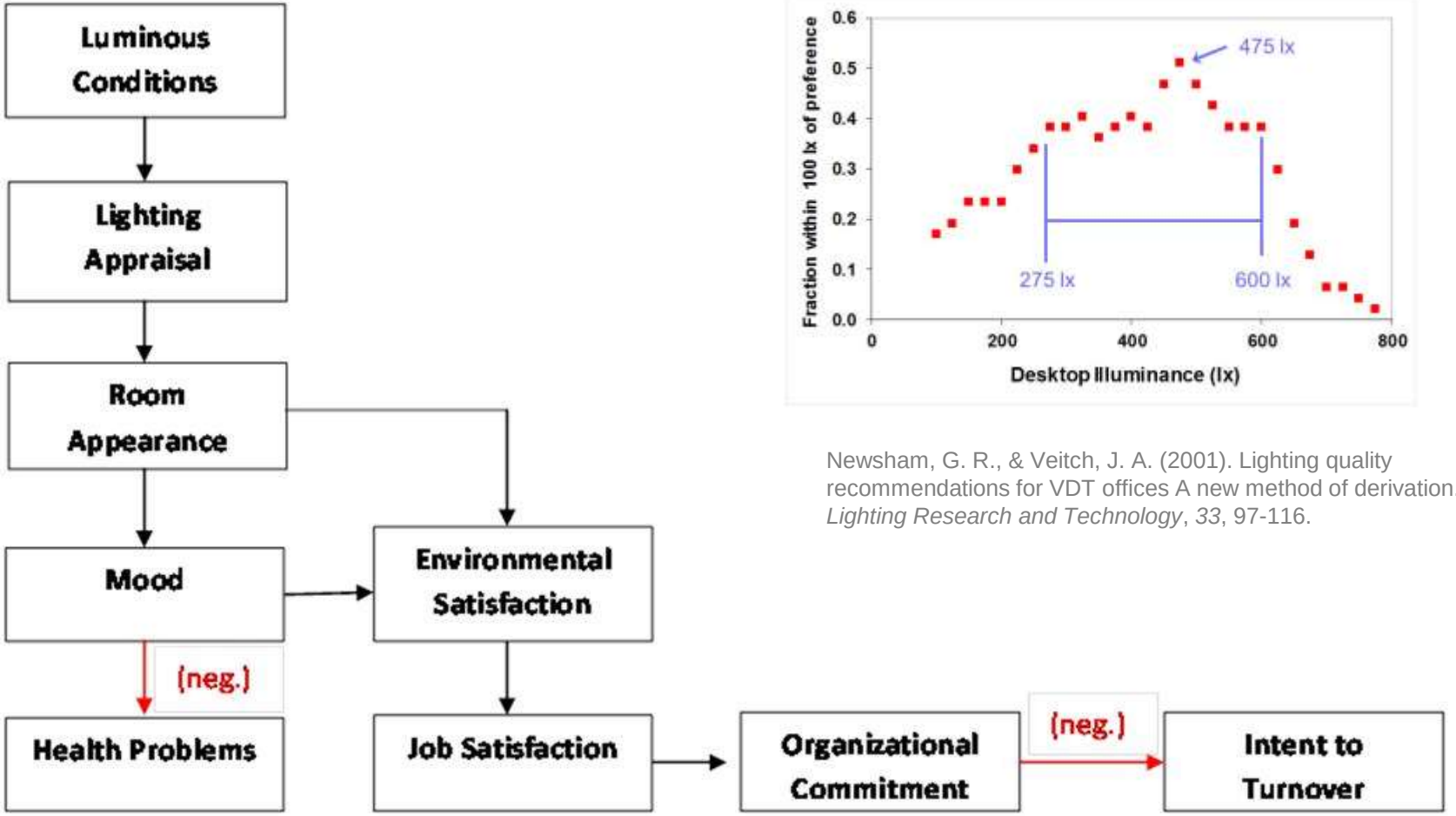
- For now, see TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013 – use the toolkit!

Challenge: Dynamic light?



- New technologies allow lots of cool effects!
- Should people follow a daily pattern that might be typical of millenia past?
  - Bright days from being outdoors
  - Light gets reddish and dim in the evening (sunset)
  - It's dark for a few hours before bed, with only firelight, moon and stars producing light
  - Sleep next to the fire in the dark with only glowing reddish embers
  - Dawn comes and light is again reddish as the sun is low on the horizon, then grows bluer and more intense

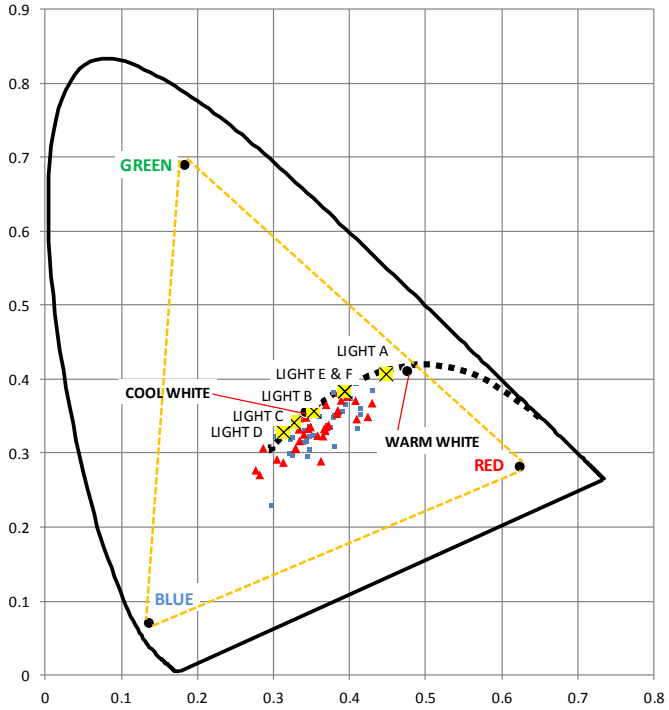
Challenge: Individual differences in preferences

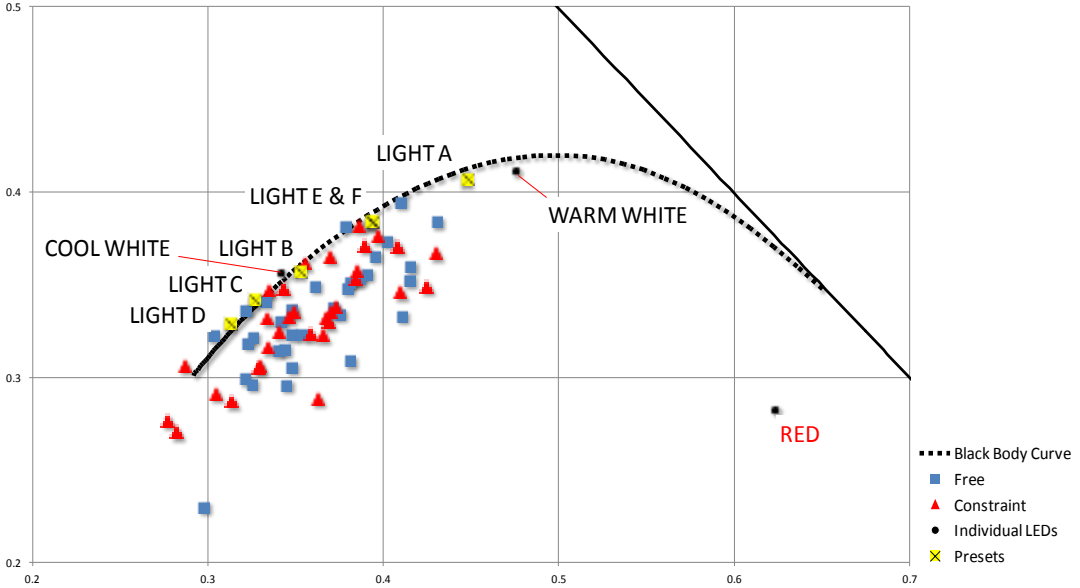


Newsham, G. R., & Veitch, J. A. (2001). Lighting quality recommendations for VDT offices A new method of derivation. *Lighting Research and Technology*, *33*, 97-116.

Veitch, J. A., Newsham, G. R., Mancini, S., & Arsenault, C. D. (2010). *Lighting and office renovation effects on employee and organizational well-being* (NRC-IRC Research Report RR-306). Ottawa, ON: NRC Institute for Research in Construction. Available at: http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?action=shwart&index=an&req=20374532&lang=en.

Individual differences: Tunable colour





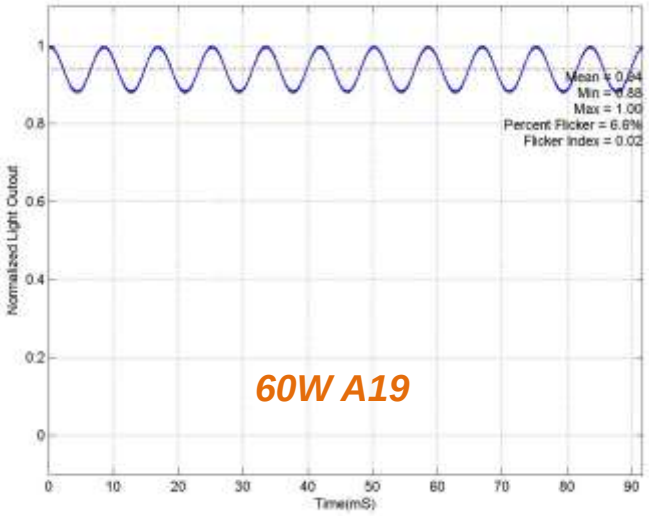
Measure	Condition	Median	Mean	SD	Min	Max
Ave E (lx)	Free	1042	992	391	109	1578
Ave E (lx)	Const.	540	517	50	320	553
CCT (K)	Free	4470	4747	2027	2832	14016
CCT (K)	Const.	4280	5013	2091	2726	11321
CRI	Free	87	82	16	29	95
CRI	Const.	83	82	11	55	96
CQS	Free	91	89	6	70	96
CQS	Const.	91	89	5	76	96
Δuv	Free	-0.0135	-0.0145	0.0109	-0.047	0.005
Δuv	Const.	-0.012	-0.0121	0.0094	-0.042	0.006

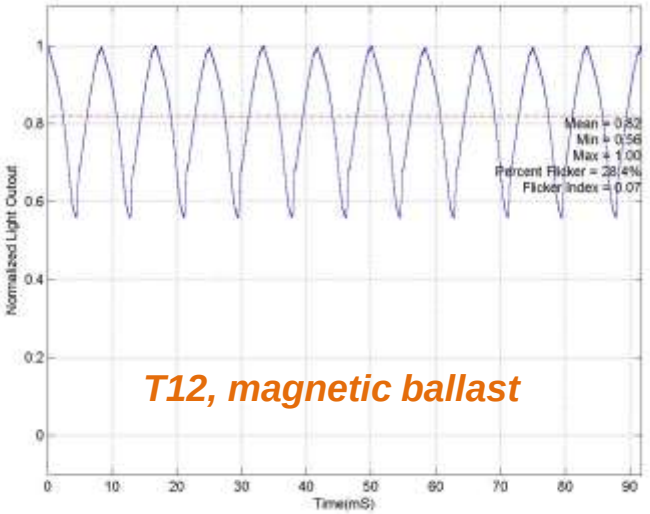
Dikel, E. E., Burns, G. J., Veitch, J. A., Mancini, S., & Newsham, G. R. (2014). Preferred chromaticity of color-tunable LED lighting. *Leukos, 10(2), 101-115.*

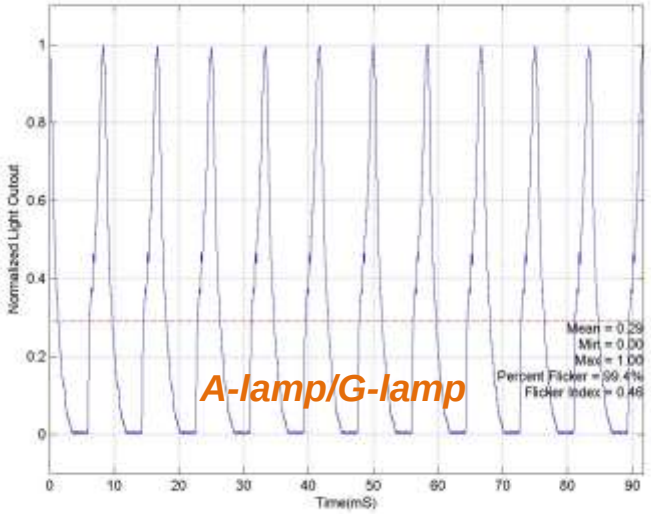
Opportunities: Lighting for well-being

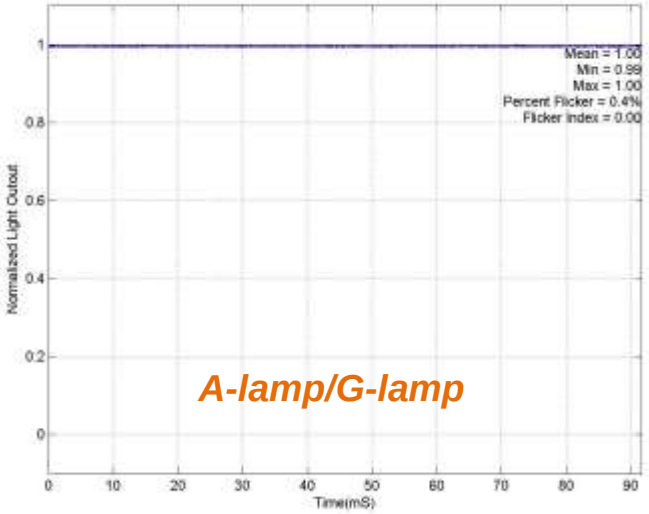
- CIE 218:2016: Research Roadmap for Healthful Interior Lighting Applications
- Research Strategy:
  - Recommendations for Healthful Lighting and Non-Visual Effects of Light
  - Support for Tailored Lighting Recommendations
  - Adaptive, Intelligent and Dynamic Lighting

Challenge: Temporal Light Modulation



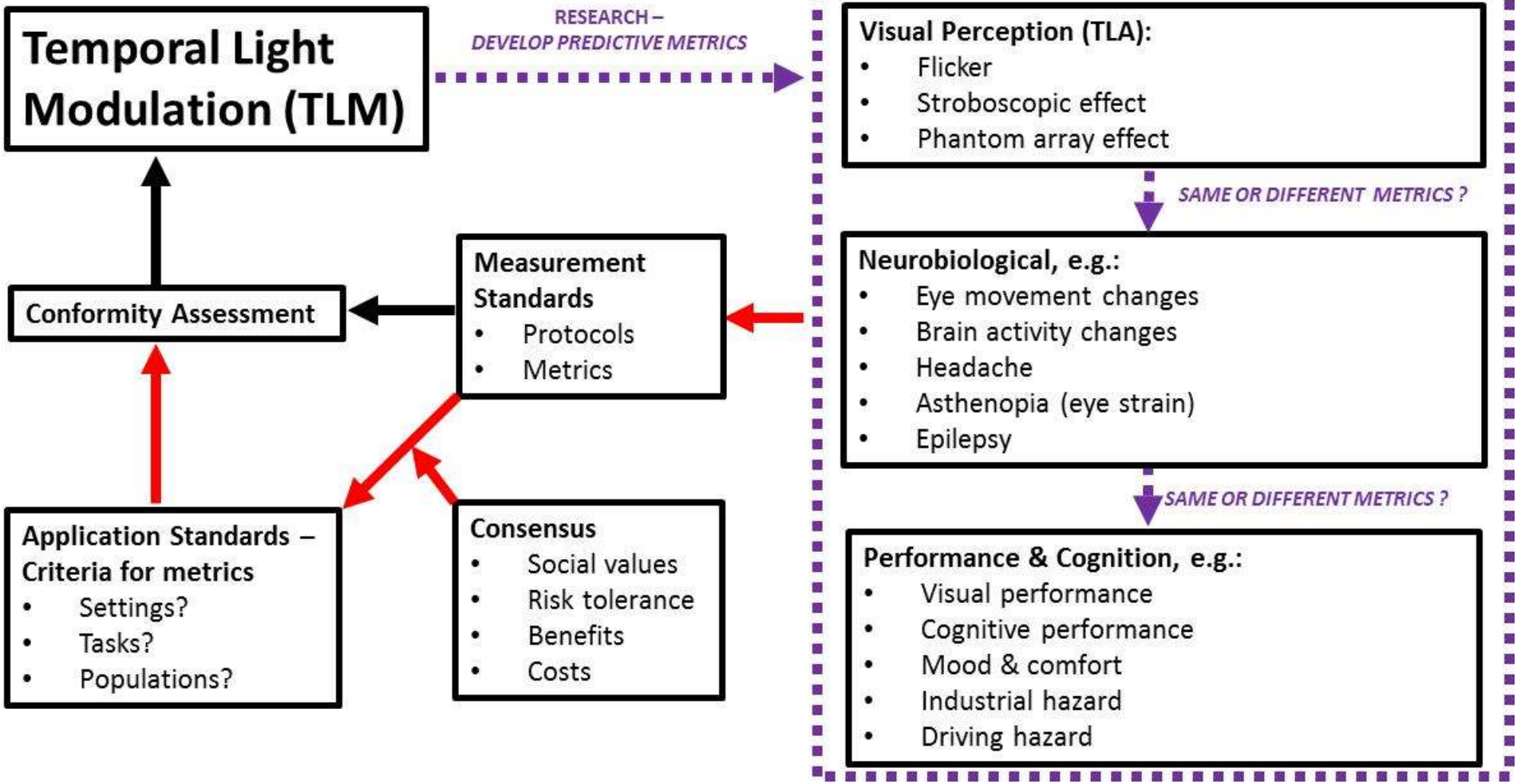






Source: M. Poplawski, PNNL

Summary of What's Needed (CIE TN 008:2017)



Opportunities: TLM knowledge gaps

- Phantom array – a metric to predict this
- Relationship between TLA phenomena and other cognitive & health effects
  - Can metrics that predict TLA also predict these other phenomena?
- Scaling up from short-term, small-scale viewing conditions to long-term, environmental viewing conditions

Opportunities: TLM and well-being

- Temporal Light Modulation:
  - TN 008:2017 Final Report CIE Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems
  - TN 006:2016 Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models
- Call for experts: CIE TC 2-89
- New – Research Forum planned!

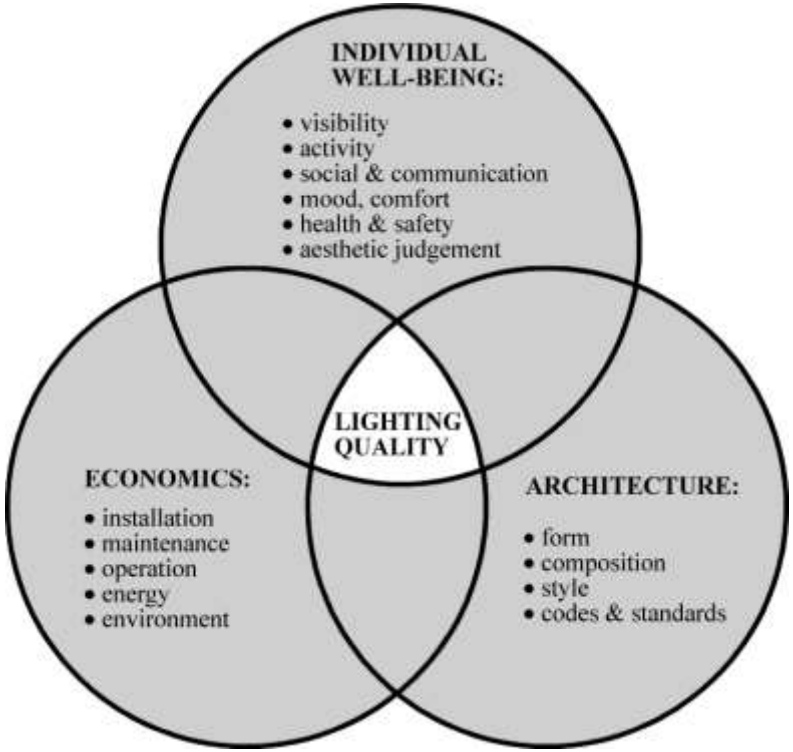
Conclusions

- We will succeed in meeting challenges when our research is of the highest calibre
  - CIE Expert Tutorial and Workshop on Research Methods for Human Factors in Lighting – Aug 13-14, 2018, Copenhagen, Denmark
  - LEUKOS Special Issue on Lighting Research Methods – Call for Papers

- CIE stands ready to engage with research funders to promote the work we need

Be ready for the future!

- When all the electric lighting is solid-state and controllable, energy efficiency takes care of itself and the designer can focus on the effects of the light on the occupants.



NRC Lighting Quality model.

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