Lighting in Flux

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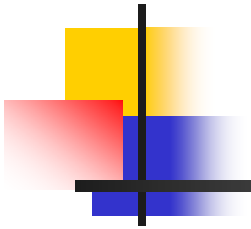
The Past

- For many decades, general lighting practice has been founded on:
  - Two objectives – good visual performance without discomfort
  - Two systems of measurement – photometry and colorimetry
  - Five criteria – Illuminance, illuminance uniformity, CCT, CRI , UGR
  - One location – the horizontal working plane

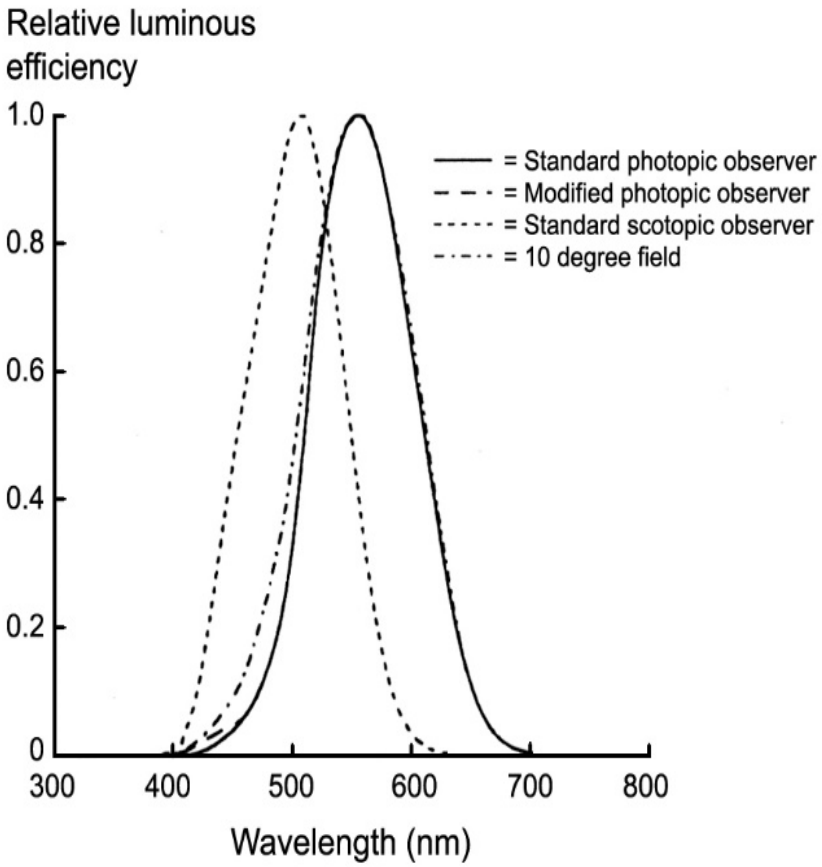


The Present

- Today, these foundations are all being questioned
- Some of the answers proposed to these questions are simple expansions, some are evolutionary, yet others are revolutionary
- As a result, lighting may soon be in a state of flux

The basis of photometry

- All photometry is based on the standard photopic observer, the V(λ) function
- It is this that converts radiometric quantities to photometric quantities



The V(λ) function is based on only two cone types

- The retina contains five photoreceptor types: three cone types, one rod type and some intrinsically photosensitive retinal ganglion cells
- These photoreceptors operate in different combinations for both visual and non-visual effects

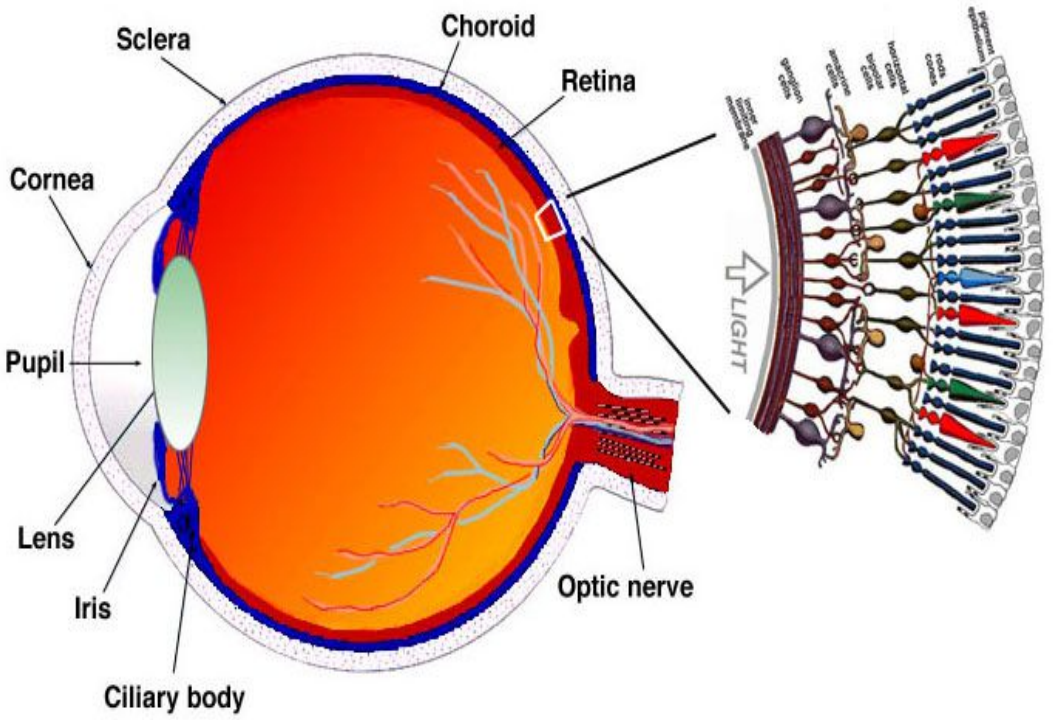
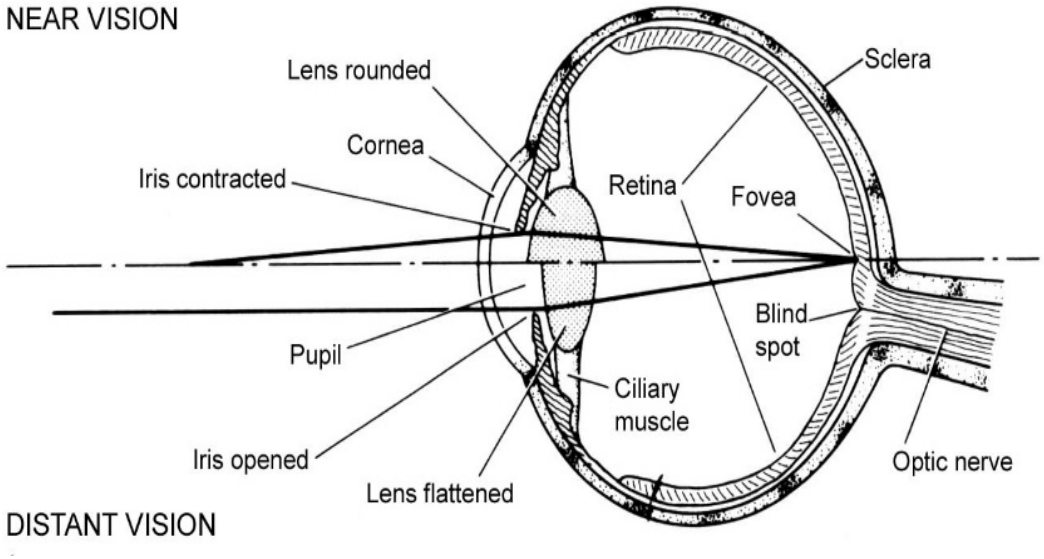


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

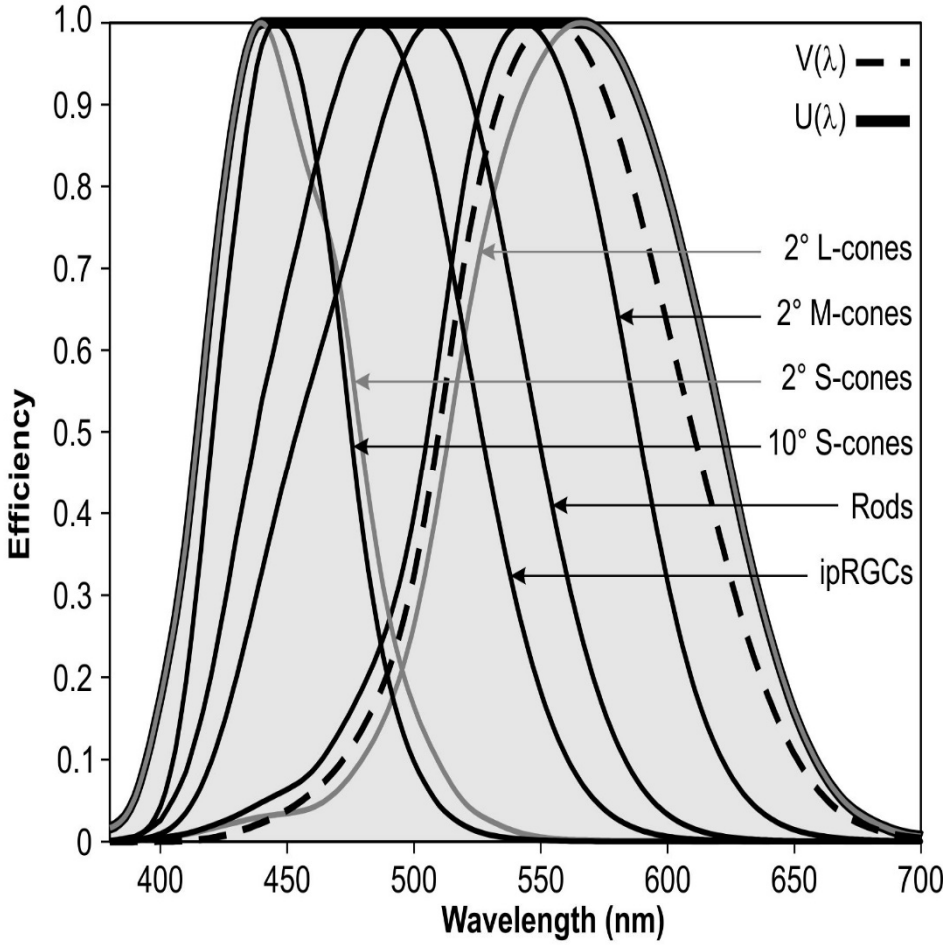
Photometry is biased towards the detection of detail

- Two cone types, the medium (M) and long (L) wavelength sensitive cones, dominate the fovea, which is devoted to seeing detail.



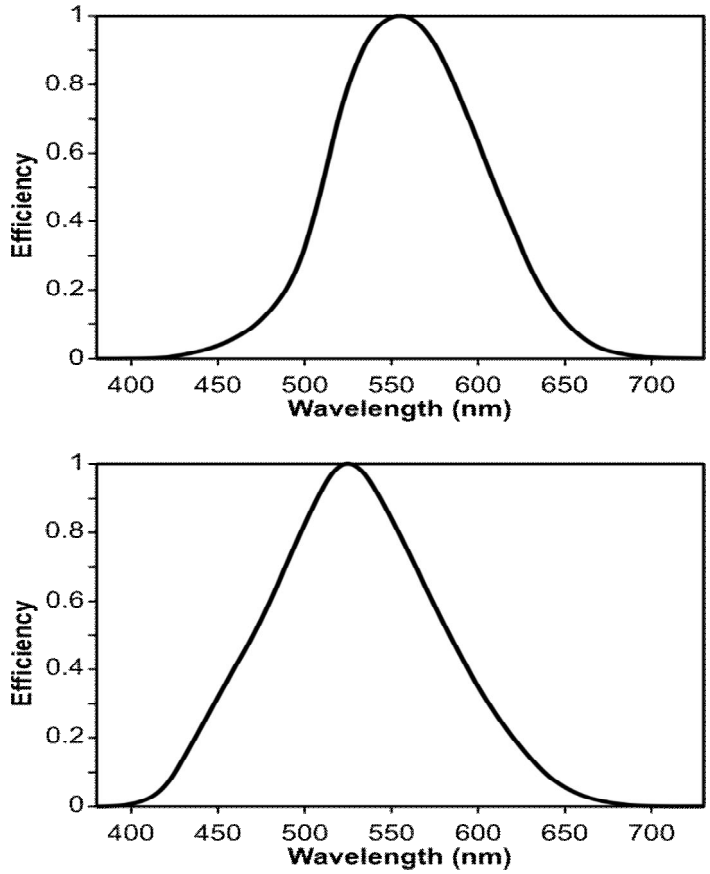
What is the spectral sensitivity of these photoreceptors?

- The spectral sensitivities of the five photoreceptor types in the retina are different
- Different combinations of photoreceptors are wired together in different ways to serve different effects
- This is why photometry does not accurately predict the perception of brightness, colour, off-axis visual performance or circadian stimulation.



Multiple spectral sensitivities

- Different spectral sensitivities can be created for any situation where photoreceptors other than the L and M cones are involved
- Upper figure is for foveal visual acuity
- Lower figure is for mesopic conditions and off-axis viewing

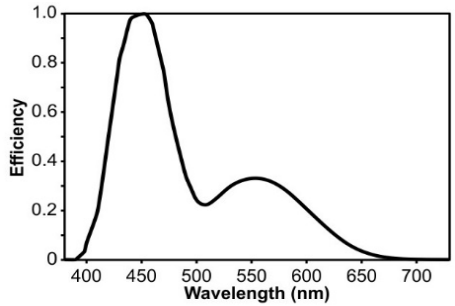


Multiple spectral sensitivities

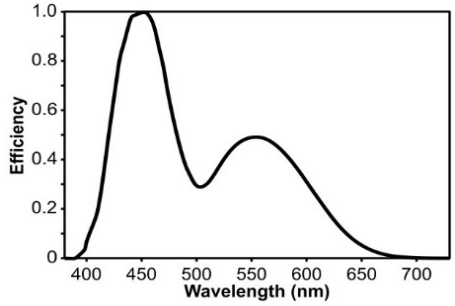
- Different spectral sensitivities can be created for any situation where photoreceptors other than the L and M Cones are involved

- These are for the perception of brightness in photopic, mesopic and scotopic conditions (Rea, 2013)

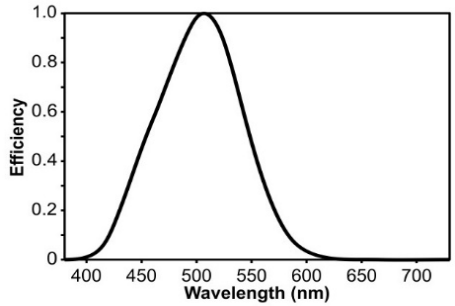
$V_{B3}(\lambda)$: above 25 lx



$V_{B2}(\lambda)$: between 1 and 25 lx

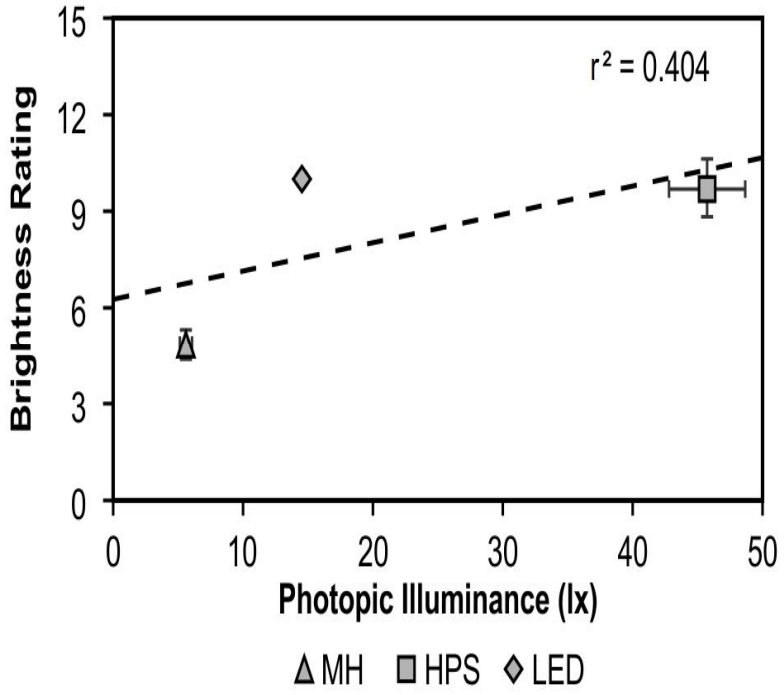


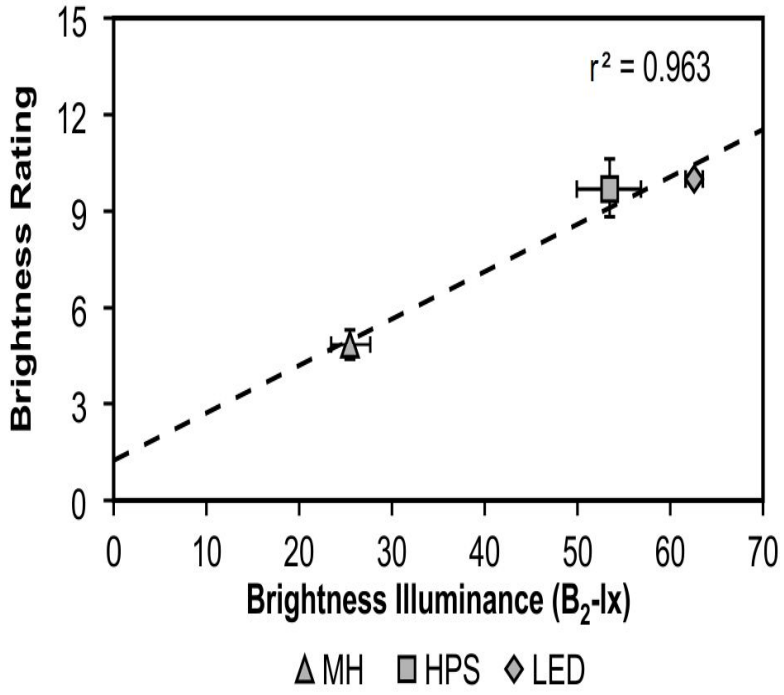
$V'(\lambda)$: below 1 lx



Multiple spectral sensitivities

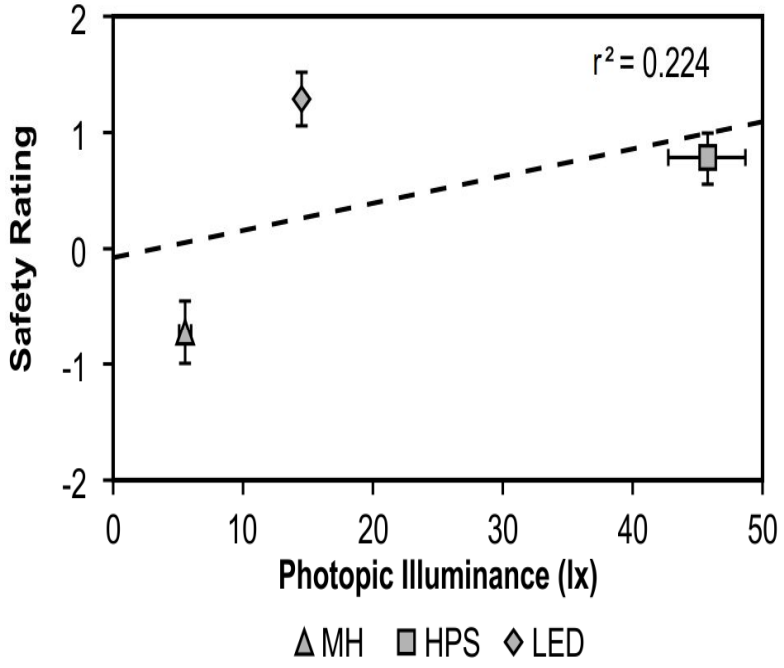
- Rea et al (2017) have demonstrated the value of using the appropriate spectral sensitivity in a field test of the lighting of a parking lot.

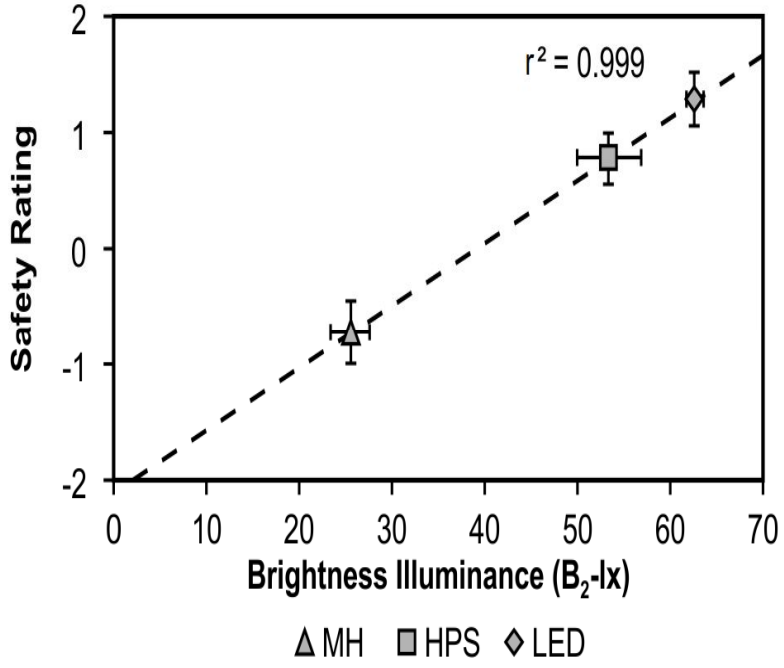




Multiple spectral sensitivities

- But is brightness really of interest? Rea et al (2017) also showed a similar pattern for the perception of safety in the parking lots

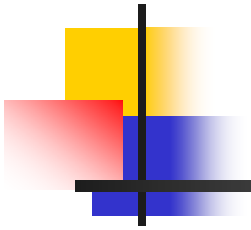




What are the alternatives?

- Stay with V(λ) – accept that detection of detail is what matters for lighting
- Abandon photometry.
- Adopt the system of universal photometry proposed by Rea (2015)

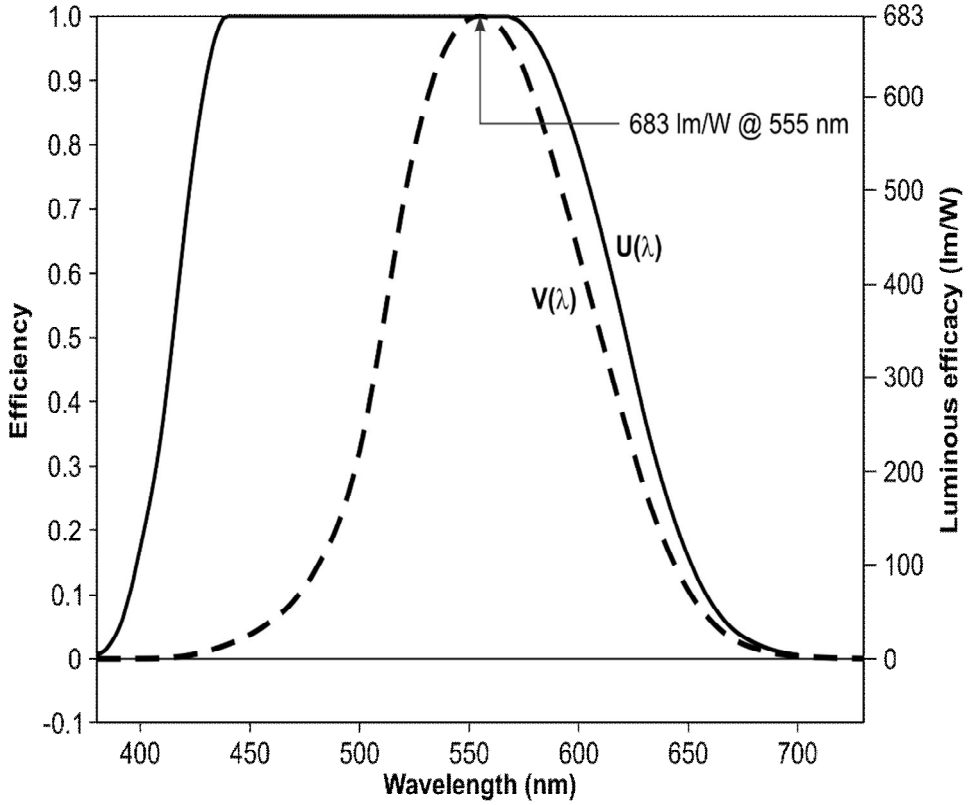
Abandon photometry



- Abandoning photometry and adopting radiometry within a fixed wavelength range is a radical but logical solution
- Light is an anomaly in the SI system of fundamental physical units. It is the only one that depends on a human response.
- If radiometry was to be used it would also be necessary to modify radiometric measurements with different spectral sensitivities for different effects.

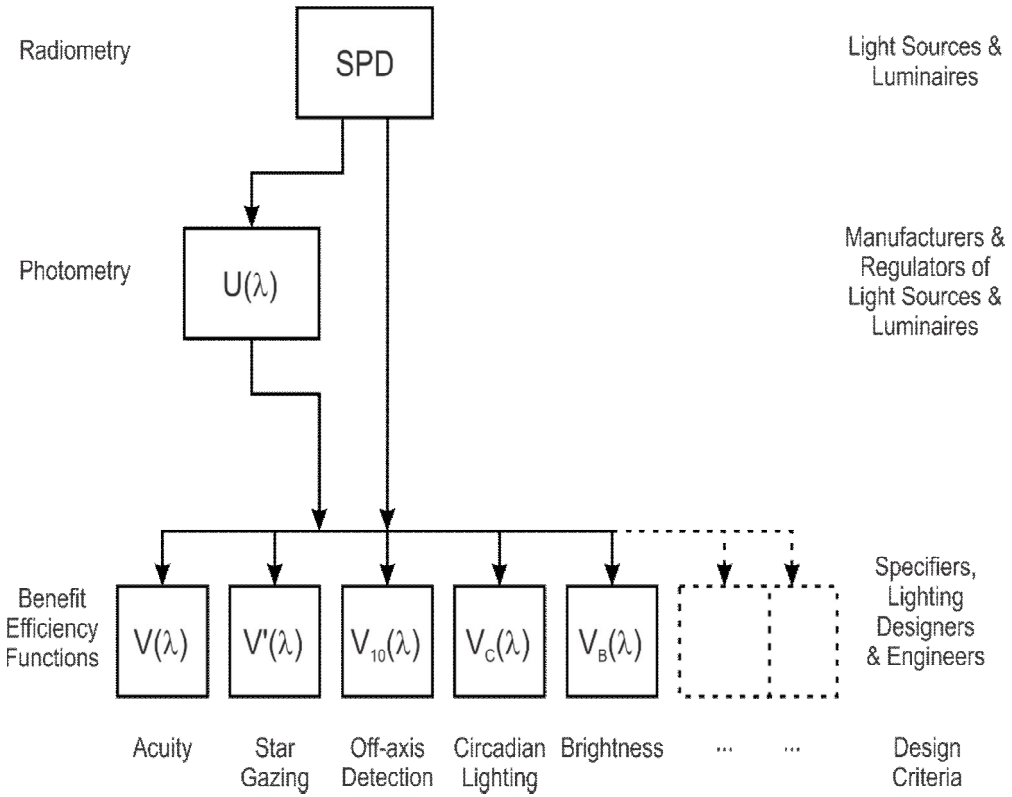
Universal photometry (Rea, 2015)

- The envelope of the Universal System encloses the spectral sensitivity of all photoreceptors but does not fit any specific perception or performance



How could you justify using universal photometry?

- If you, as a designer, are interested in one specific effect of light you cannot
- If you believe that lighting should be designed to fulfil multiple objectives you can



Expanding colorimetry

- Colorimetry is complex but the most widely used metrics for describing light source colour properties are the colour rendering index (CRI) and the correlated colour temperature (CCT)

Colour is multi-faceted

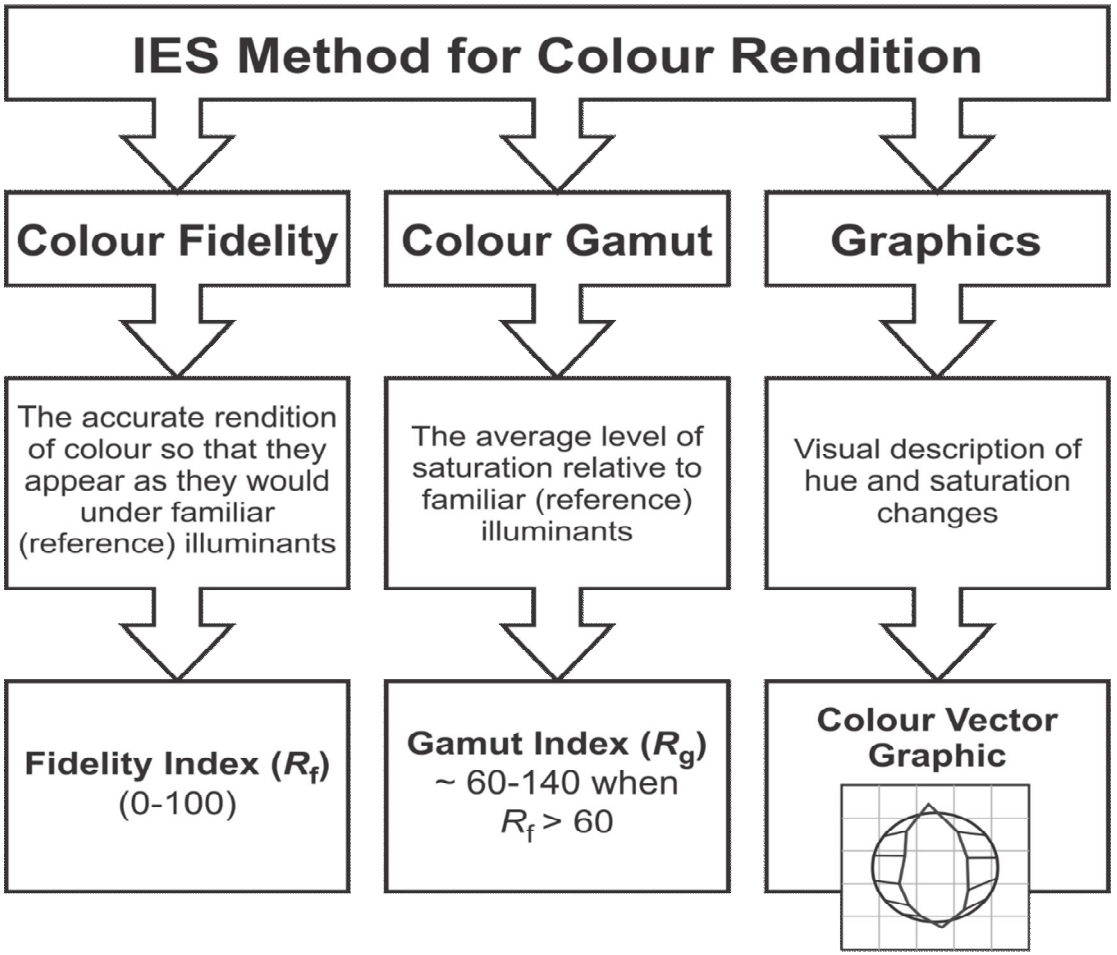
- The problem with CRI is that it used as a one-number indication of light source colour quality but there are several different facets to colour quality

- CRI essentially measures colour fidelity but in addition, attention should be paid to the naturalness, vividness and ultimately preference for a light source.

Colour preference

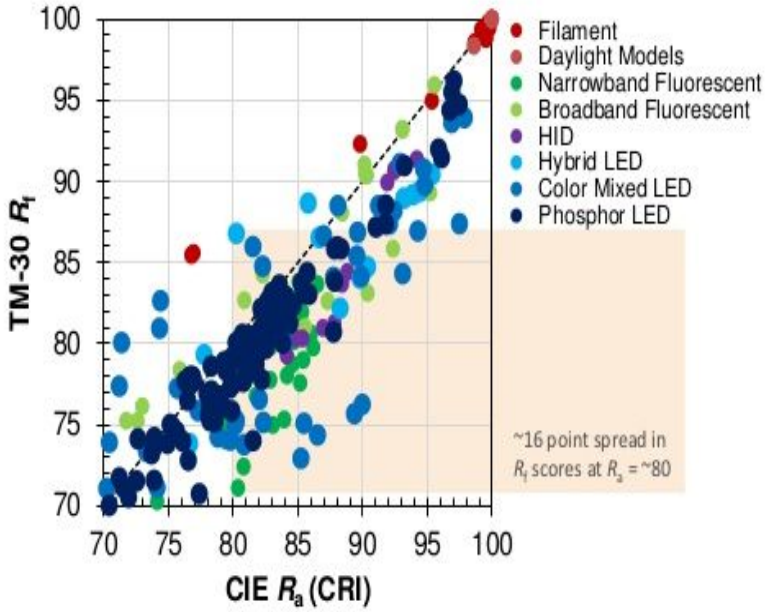
- Preference for light source colour involves more than colour fidelity.
- Teunissen et al (2017) have shown that colour saturation makes an important contribution to preference
- This implies that at least two metrics are required to specify light source colour quality

IESNA TM-30-15



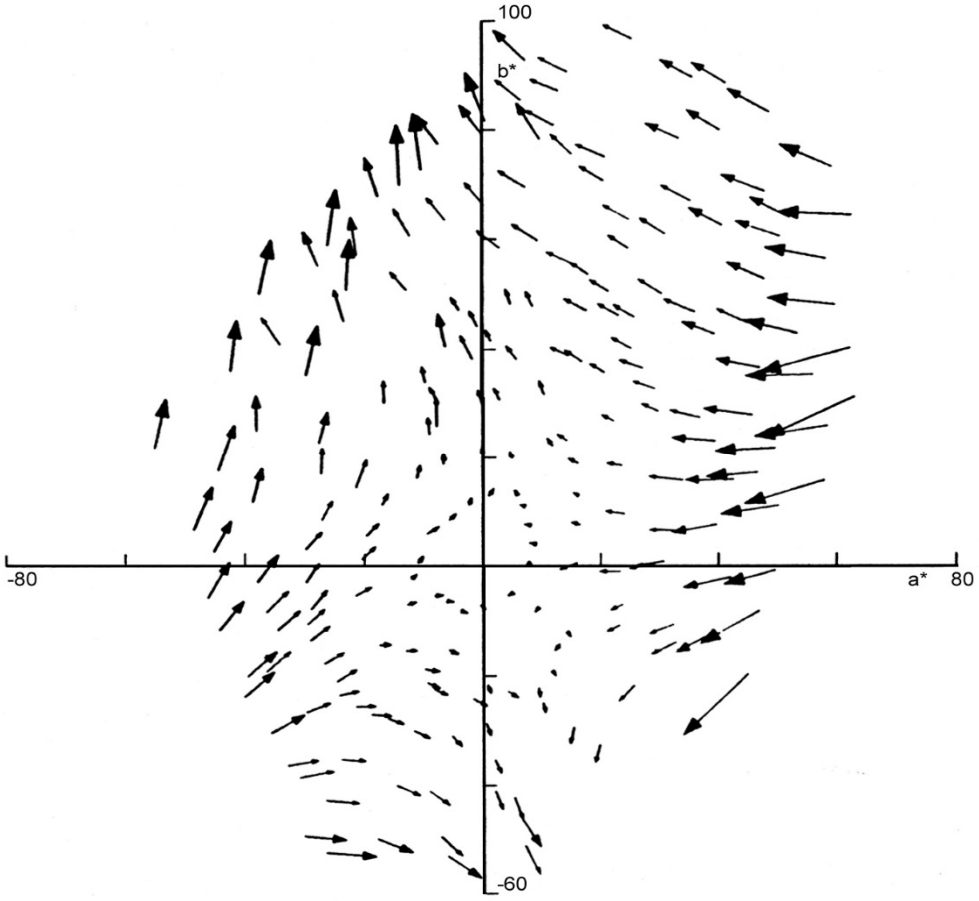
Will TM-30-15 or something like it be widely adopted?

- For that, there are three questions to be answered
- Will the CIE support it? The CIE has introduced its own improved colour fidelity index (CIE 224: 2017) and promises more metrics for preference
- How much difference does it make?
- Who wants it?



Numbers or graphics?

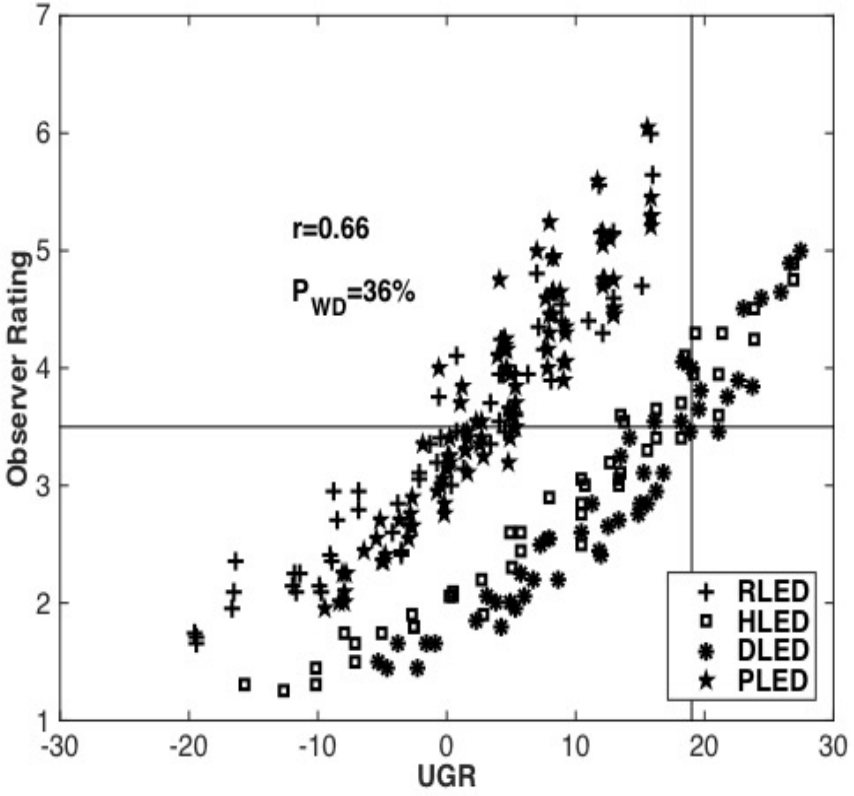
- I have always thought that a graphic display is the best approach to showing light source colour properties because all the information you need is there (see van Kemenade and van der Burgt, 1988).



Discomfort glare

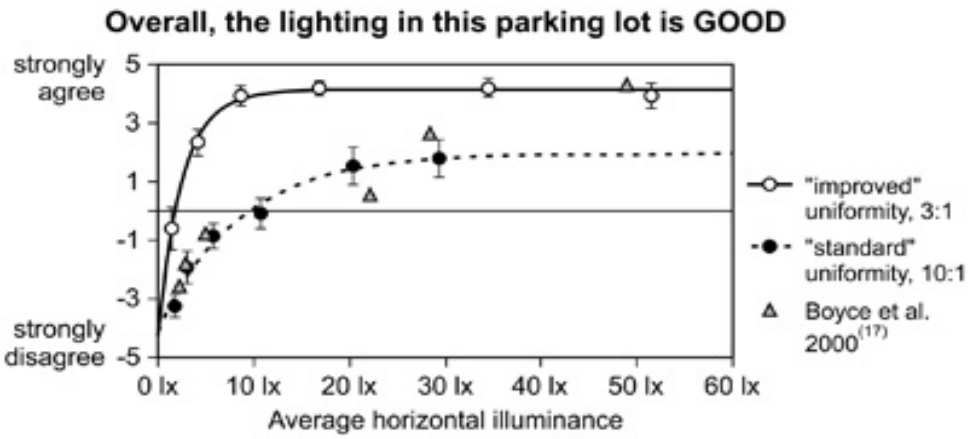
- The CIE unified glare rating (UGR) is widely used but has been shown to underestimate glare for non-uniform luminaires, typically those allowing a view of multiple bare LEDs

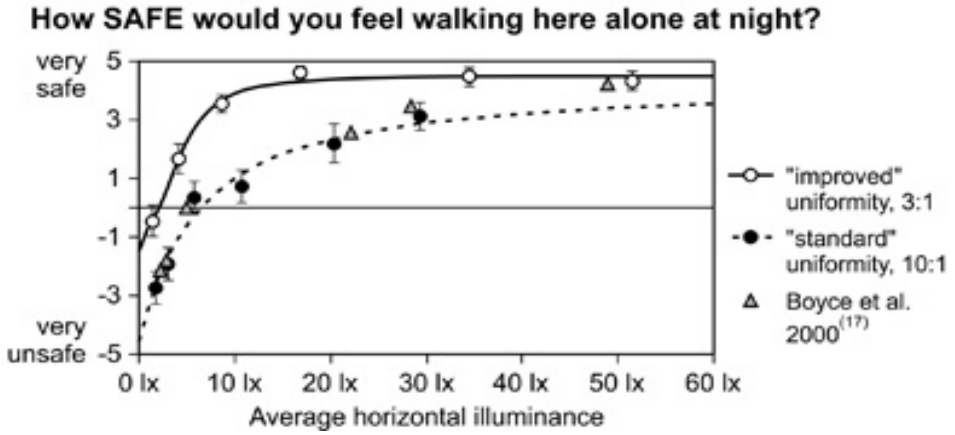
- Several modified versions of UGR have been proposed (Tashiro et al, 2015; Yang et al 2016; Scheir et al, 2016)



Illuminance uniformity

- There are no changes proposed for illuminance uniformity
- This is because it has rarely been studied, but when it has, it can have important effects (Narendran et al, 2016)

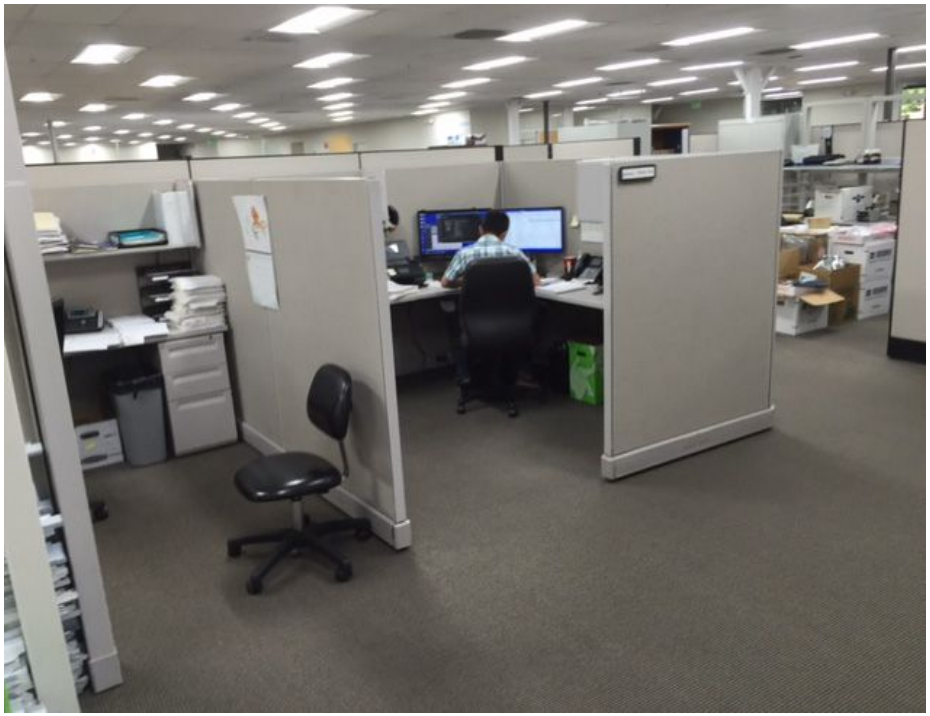




A flawed assumption

- It is often assumed that for efficient lighting light should be delivered to a horizontal working plane

- This assumption leads to regular arrays of luminaires



The nature of work

- This was appropriate when the objective was to ensure good visual performance and tasks were done on a desk or workbench.

- But work today is different. Much is done on self-luminous screens and light levels are much higher than required for good visual performance

The Cuttle approach

- Cuttle (2010) has argued that illuminance on a horizontal plane is no longer how lighting should be judged

- It is the perceived adequacy of illumination that is important and that depends on the appearance of the whole space

Quantifying perceived adequacy of illumination

- The metric for quantifying perceived adequacy of illumination is the mean room surface exitance (MRSE).

- This is calculated as the first reflected flux divided by the weighted surface absorptance

MRSE	Subjective assessment
10	Lowest level for colour discrimination
30	Dim appearance
100	Lowest level for acceptably bright
300	Bright appearance
1000	Distinctly bright appearance

Implications of MRSE

- Adopting MRSE as the basis of lighting design rather than illuminance has some interesting implications
- Attention is directed to the lighting of the space not the task
- Indirect lighting becomes more efficient than direct lighting for providing a similar perception of brightness

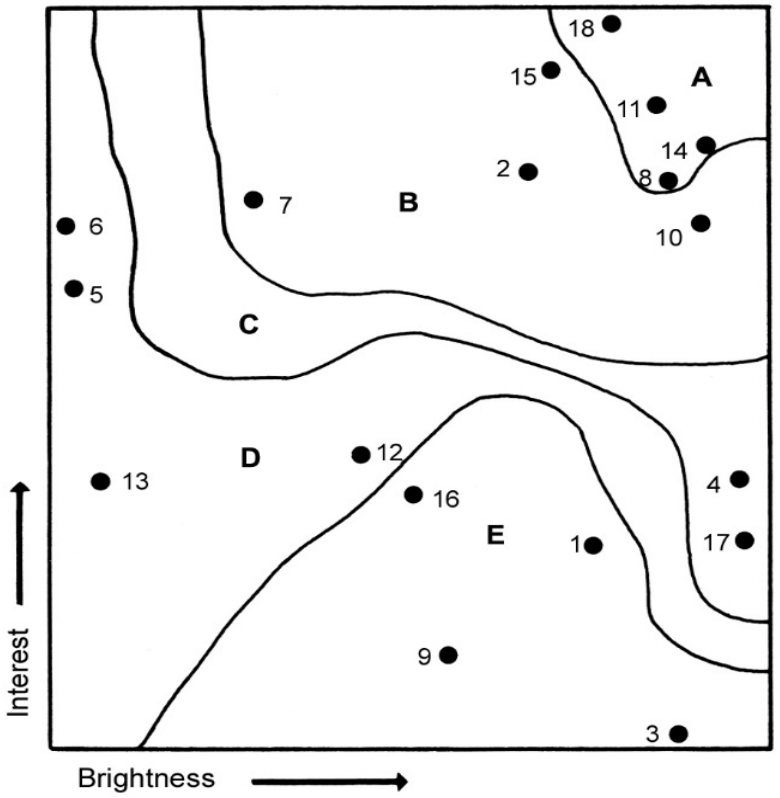
Lighting type	Required luminous flux
Down-lighting	86,000 lm
Wall-washing	38,000 lm
Up-lighting	23,000 lm

Implications of MRSE

- By concentrating on MRSE rather than illuminance on a horizontal working plane we risk moving from cave lighting to white box lighting

Implications of MRSE

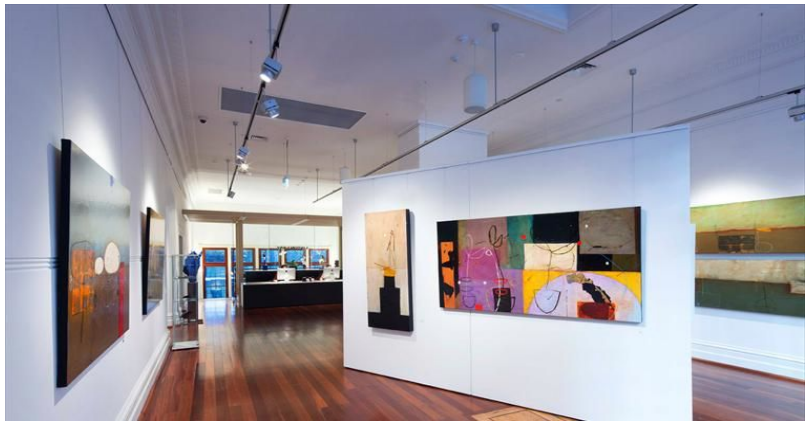
- A number of authors have shown that preferred lighting combines both brightness and interest (Flynn et al, 1973; Hawkes et al, 1979; Veitch and Newsham, 1998; Loe 2016)



Expanding MRSE to include TAIR

- To avoid the white box Cuttle (2013, 2015) has developed a design method allowing the designer to create a hierarchy of illumination using a metric, target / ambient illumination ratio (TAIR). This is the ratio of the sum of the direct and indirect illuminances on the target to the MRSE

- This is claimed to be how innovative lighting designers make decisions but it still allows for lighting the working plane if that is what is desired, but now it is a conscious decision not a reflex



Perceived difference in brightness	Target / ambient illumination ratio
Noticeable	1.5
Distinct	3.0
Strong	10.0
Emphatic	40.0

Lighting in flux?

- Clearly, the world of lighting is not short of ideas.

- If all these ideas were to be implemented, then lighting practice would definitely be in flux. So what should be done and what are the odds of anything being done?

Do you need to do anything?

- Most of the proposals discussed come from academics who may or may not have a good understanding of the real world

- Therefore, you can pick and choose from these proposals and may choose to do nothing

Evolutionary proposals 1

- Some proposals are evolutionary. One example is refining CRI to address colour fidelity

- This is very likely to be adopted now that CIE has its own improved colour fidelity index

Proposal	Odds on adoption
Better colour fidelity metric	1/5

Evolutionary proposals 2

- Proposals to introduce more ways to quantify and communicate the other effects of light spectra on the perception of colour are likely to be useful to some so their form should be carefully explored

- There is always a conflict between complex phenomena like colour and the simplicity required for widespread use. CRI is undoubtedly too simple. How far to expand it will depend on the user.

Proposal	Odds on adoption
Better colour fidelity metric	1 / 5
More colour metrics	1 / 2

Evolutionary proposals 3

- Proposals to revise UGR are unlikely to be adopted for two reasons:
- The solution lies in luminaire design by simply eliminating a direct view of bare LEDs
- If this is done then using the existing UGR formula is fine

Proposal	Odds on adoption
Better colour fidelity metric	1 / 5
More colour metrics	1 / 2
Refined UGR	10 / 1

Unopposed revolutionary proposals

- Cuttle's MRSE and TAIR design method is revolutionary and unopposed but may be ignored.

- It will be adopted if it can be shown to be easy to use and to produce superior lighting. For this to happen, software implementation is essential

Proposal	Odds on adoption
Better colour fidelity metric	1 / 5
More colour metrics	1 / 2
Refined UGR	10 / 1
Cuttle MRSE and TAIR method	3 / 1

Opposed revolutionary proposals

- Rea's universal photometry system is revolutionary and is likely to be opposed by powerful institutions.
- The problems it identifies are scientifically valid but is the universal photometry system the right answer. This question could take many years to resolve

Proposal	Odds on adoption
Better colour fidelity metric	1 / 5
More colour metrics	1 / 2
Refined UGR	10 / 1
Cuttle MRSE and TAIR method	3 / 1
Universal photometry	20 / 1

Pause for thought

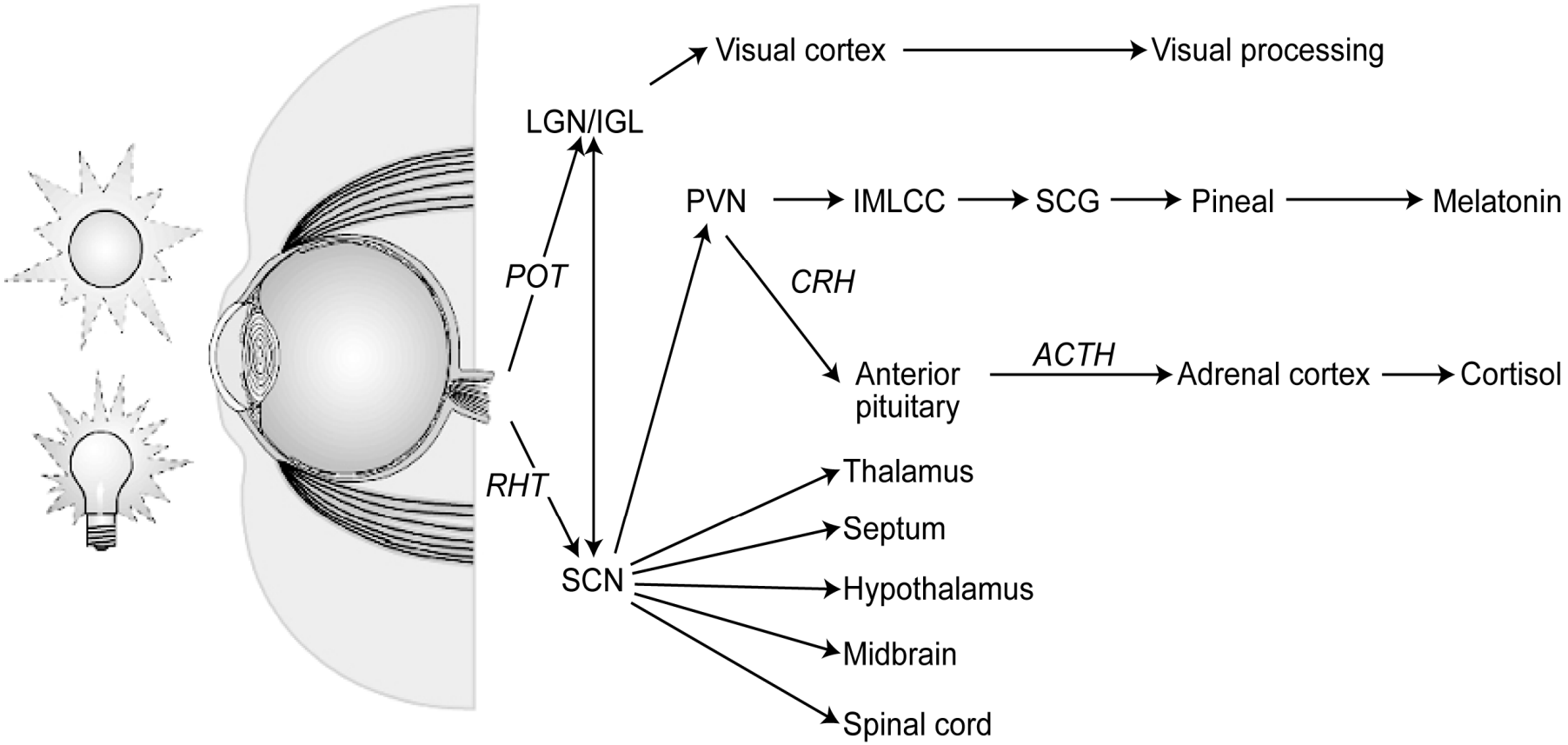
- By now it should be clear that the foundations of much lighting practice are being questioned. Why has this occurred now?

- I believe there are three interconnected reasons
  - Increased understanding of the complexity of the visual and non-visual systems
  - The development of solid state lighting with its inherent flexibility
  - The need to find a more extensive justification for lighting to prevent it becoming a simple commodity

The non-visual system

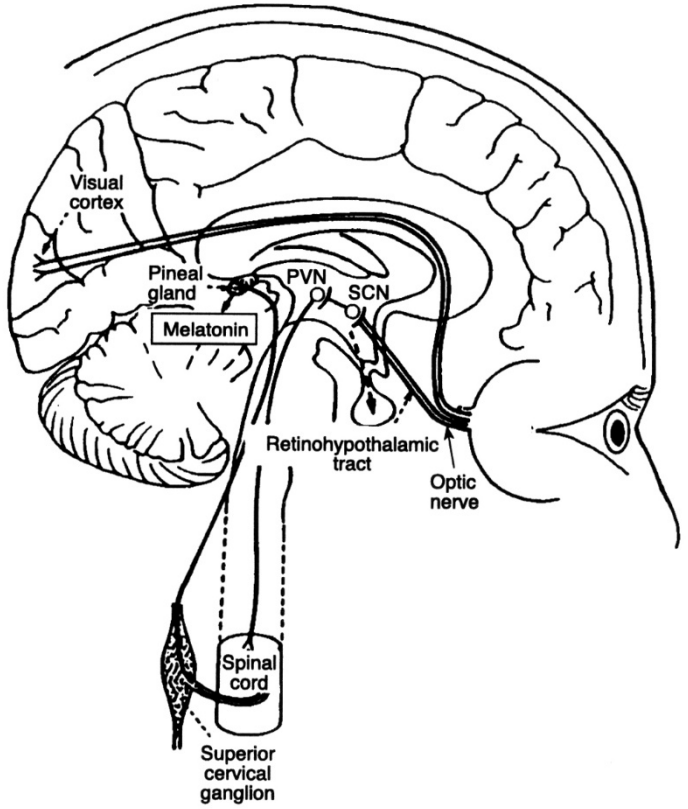
- Light falling on the retina sends signals to many parts of the brain other than the visual cortex
- These signals interact to produce many diverse effects
- The circadian response is the most extensively examined part of the non-visual system

The consequences of light stimulation



How are visual and non-visual signals different?

- Visual system responses are sensitive, fast, detailed and located
- Circadian system responses are insensitive, slow, crude and non-located
- But signals from the visual and non-visual systems are not separated but mingled.



What does the circadian system do?

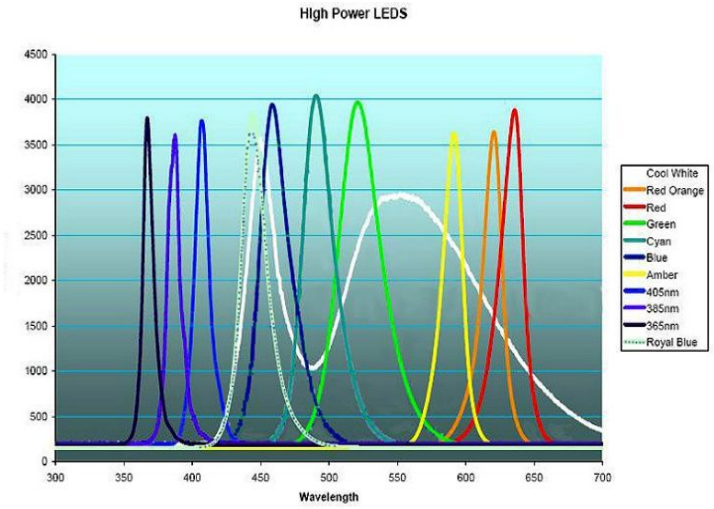
- The circadian system synchronizes all manner of physiological events over 24 hours, the most obvious being the sleep / wake cycle
- Alternate light / dark (day / night) periods are essential to entrain the circadian rhythm. In the long term, frequent disruption of the circadian system leads to poor health
- But our understanding of the circadian response is limited

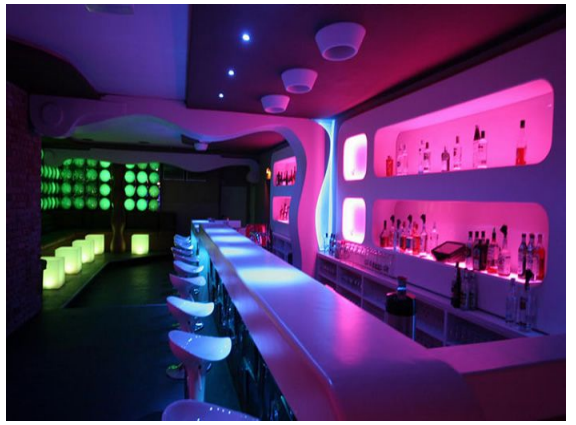
Is stimulating the circadian system useful ?

- It is certainly relevant for shift workers, those who cross time zones and those with damaged circadian systems
- Performance on cognitive tasks at night can be improved by suppressing melatonin
- Alertness in the morning can be improved by suppressing melatonin and increasing cortisol
- But is it relevant for those who are healthy and work by day and sleep at night?

Solid state lighting

- Lighting is in the middle of a major transition to solid state lighting
- Solid state lighting greatly enhances flexibility in spectrum
- Control system developments also enhance flexibility



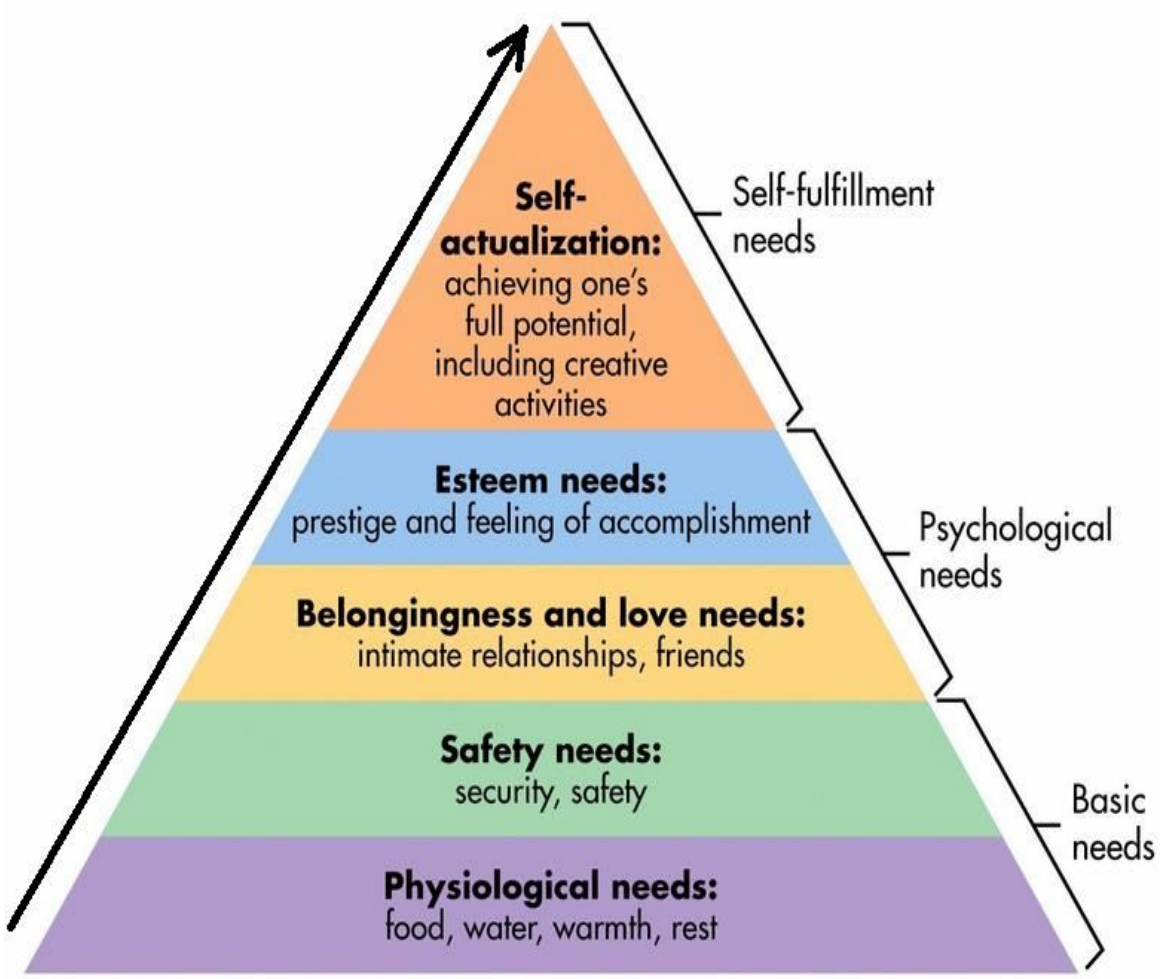


The need for new objectives

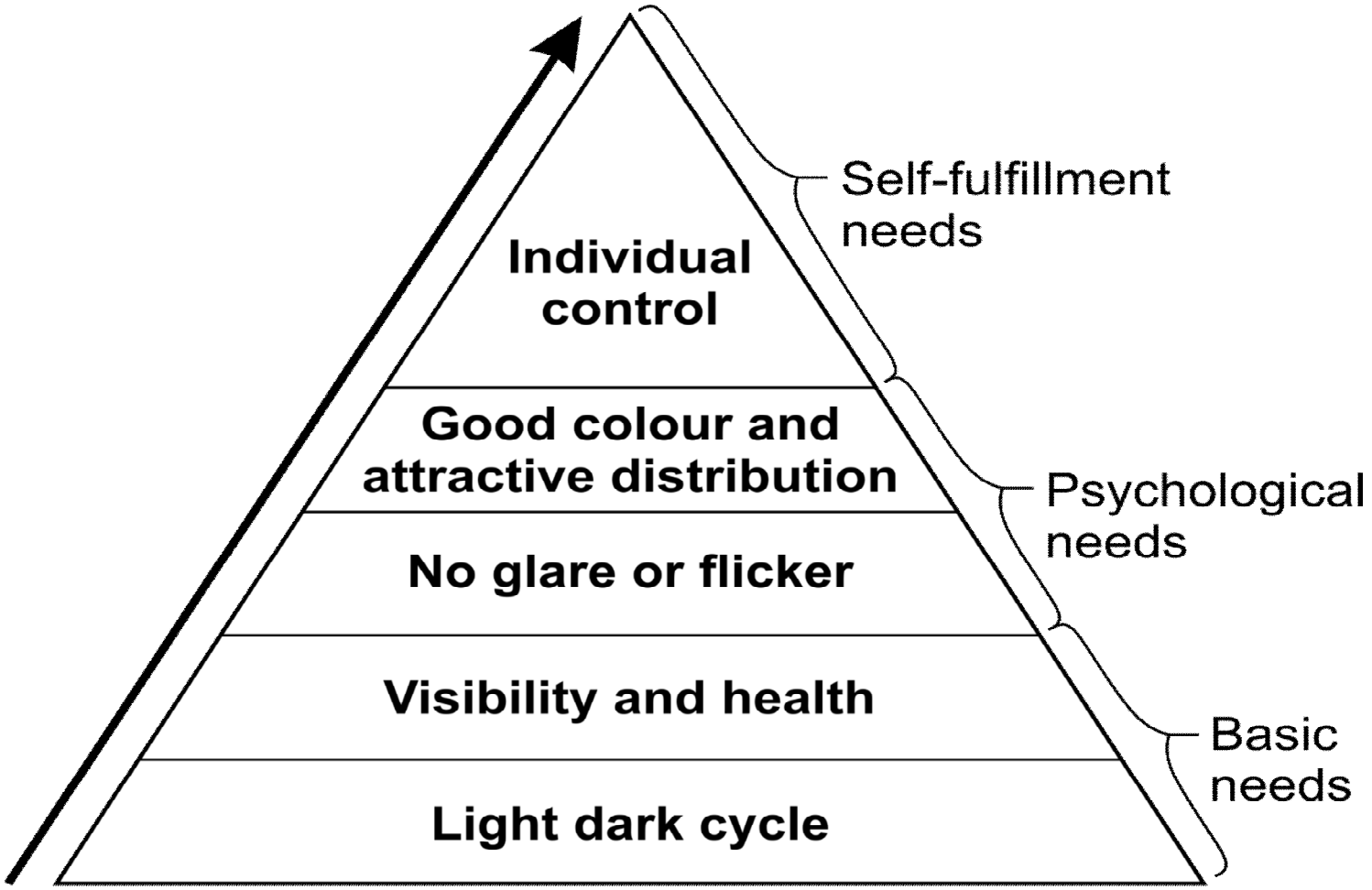
- As long as all lighting can achieve is limited to good visibility without discomfort and there exist well-established recommendations to achieve this, there is little to choose between lighting systems other than cost

- To encourage growth and technical innovation new objectives for lighting are required. What might they be?

Maslow's Hierarchy of Needs



Boyce's Hierarchy of Lighting Needs



Some new objectives for lighting

- New objectives for lighting can be found by moving up the hierarchy.
- Above visibility and health are the lighting conditions required for avoiding discomfort, creating an attractive appearance and meeting individuals' preferences.
- It is sometimes claimed that achieving these aims results in better cognitive performance, improved well-being and better moods, all of which come under the portmanteau term, human-centric lighting

Human-centric lighting - a definition

- Human-centric lighting is lighting devoted to enhancing human performance, comfort, health and well-being, individually or in some combination
- This means human-centric lighting has to consider the effects of light exposure on both visual and non-visual aspects of human physiology
- It is an approach to good quality lighting

Human-centric lighting

- The claimed effects of human-centric lighting can be considered on two dimensions: width and distance

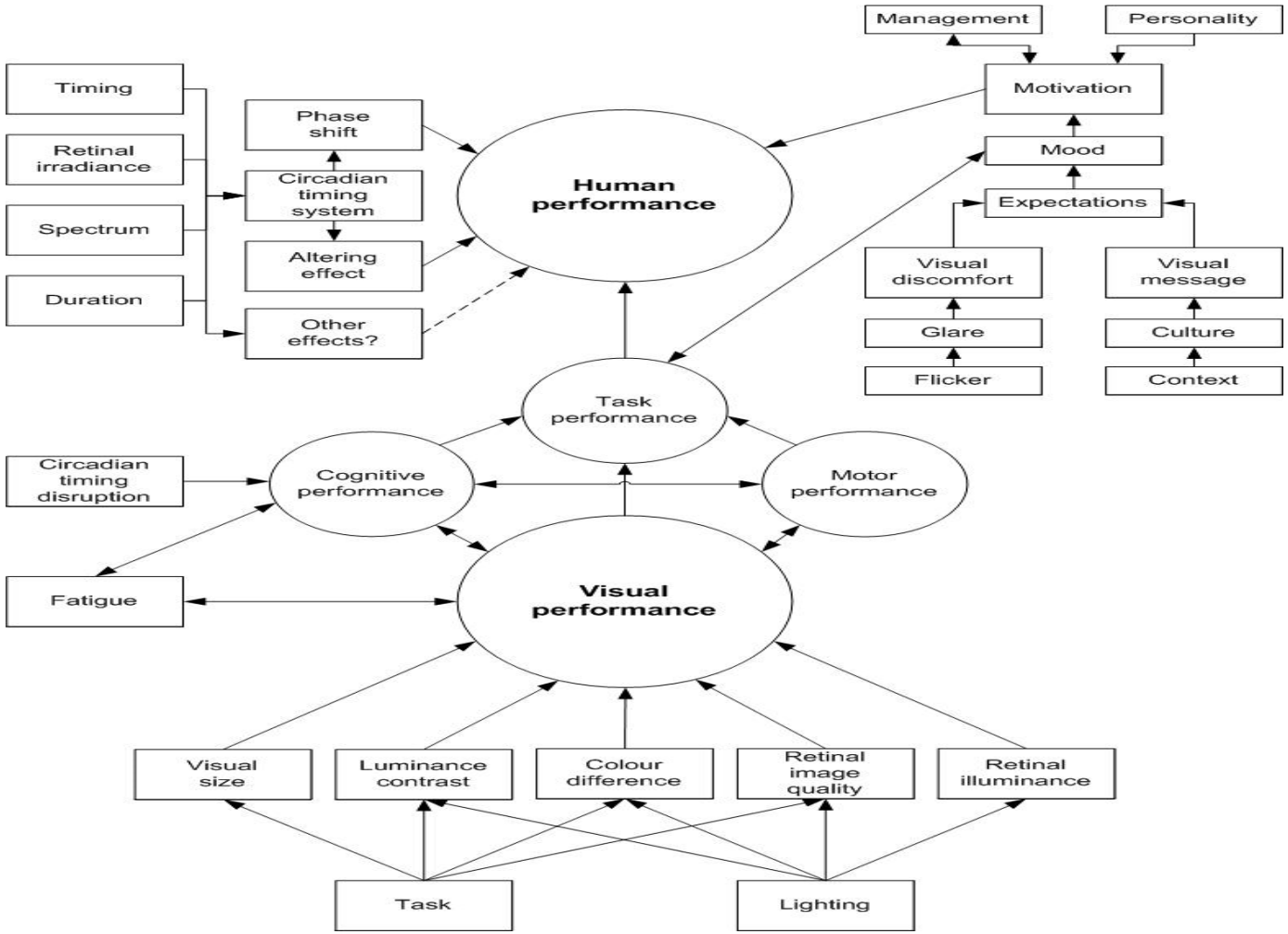
- Width because the claimed effects extend beyond visibility and visual discomfort to alertness, mood, motivation, health and well-being

- Distance because the claimed effects range from visibility into areas where lighting is only one of many influences, e.g., learning and sales.

So what's the problem?

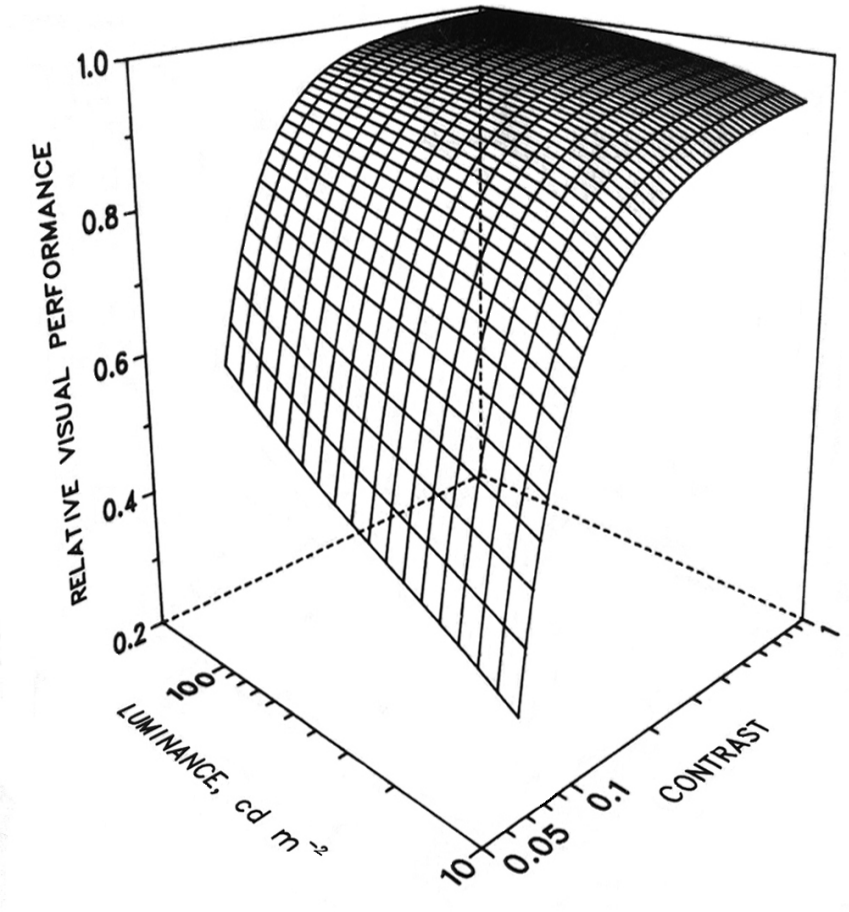
- The problem is that with new technology to sell, there is a temptation to make claims that cannot be upheld
- Such claims lend support to the view that human-centric lighting is nothing but a commercial bandwagon
- But there are also reasons for thinking of it as a breakthrough because it recognizes both the visual and the non-visual effects of light

How does light affect us?



Light and visual performance

- This is well understood.
- There is a replicated, predictive model showing the effects of the amount of light on visual performance for foveal tasks , e.g. reading (Rea and Ouellette, 1991; Eklund et al, 2000)



Light and visual discomfort

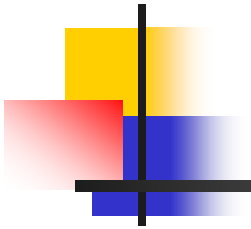
- This is well understood
- However, visual discomfort caused by glare and flicker can still be a problem with LEDs but this is on the point of being solved

Light, mood and atmosphere

- This is where we enter the realm of human-centric lighting
- Every lighting installation does two things. It makes things visible and sends a message
- Both can influence the atmosphere of a space

But can it change mood?

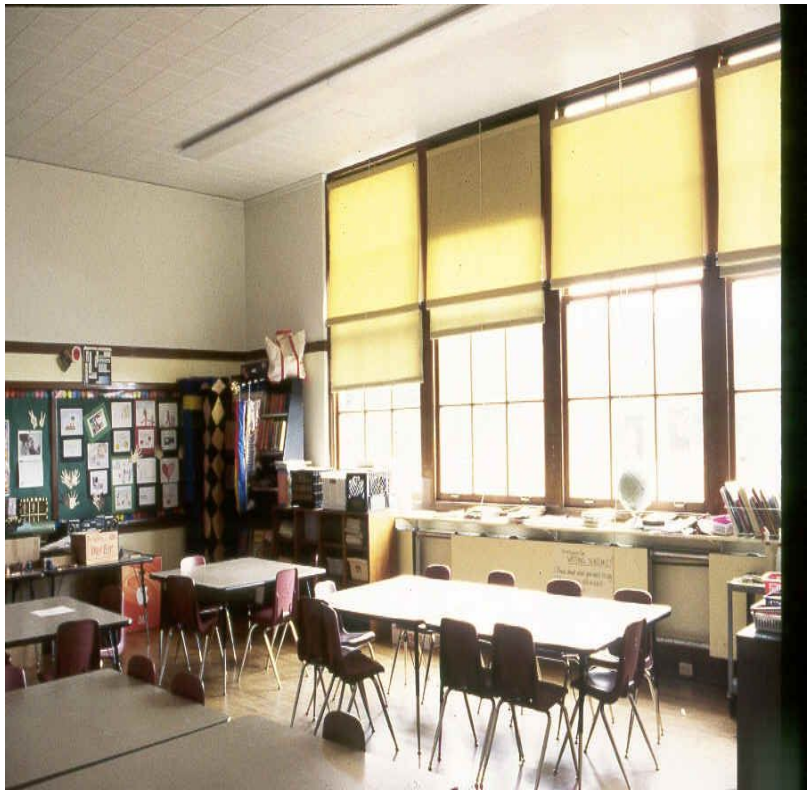
And what about motivation?



- Whether or not lighting will change mood depends on context, circumstances and personality
- The same applies to motivation
- This is because like mood, motivation is subject to many influences, lighting being just one
- So, these more remote effects are possible but not certain

An example and a warning

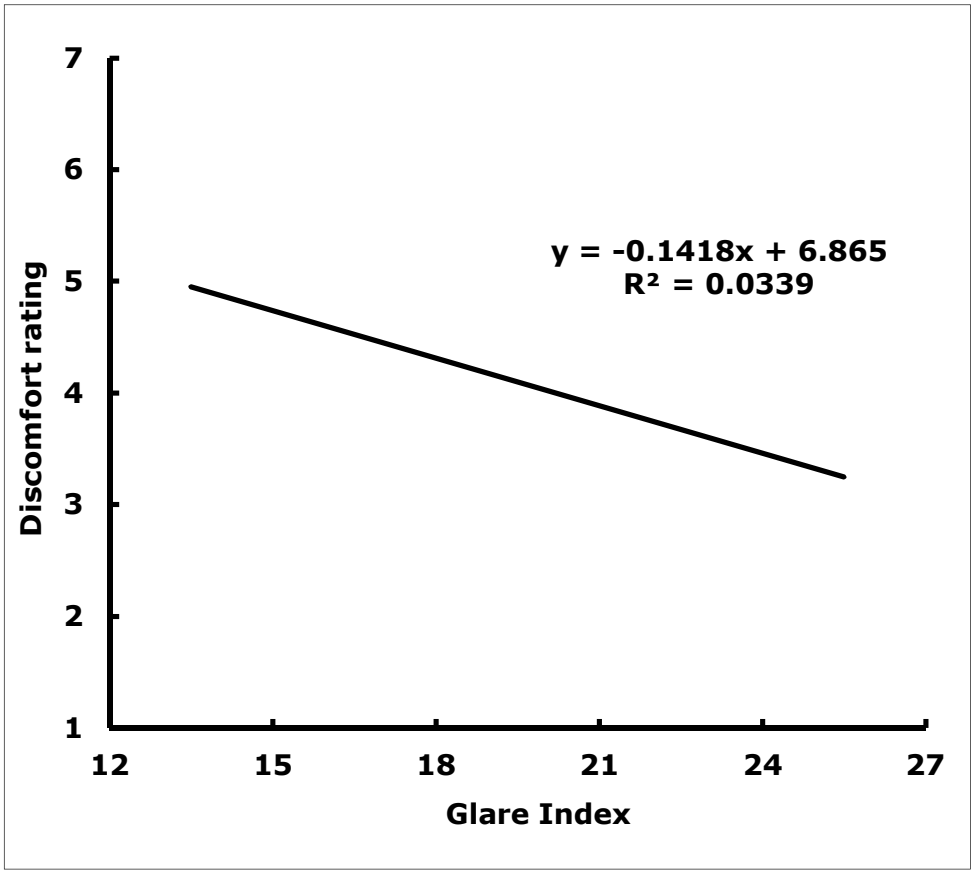
- In California an attempt has been made to show that the presence of daylight in a classroom improves learning
- It is claimed that good daylighting can increase end of year test scores for reading and maths by a significant amount
- Is this true?



Is it statistically significant?

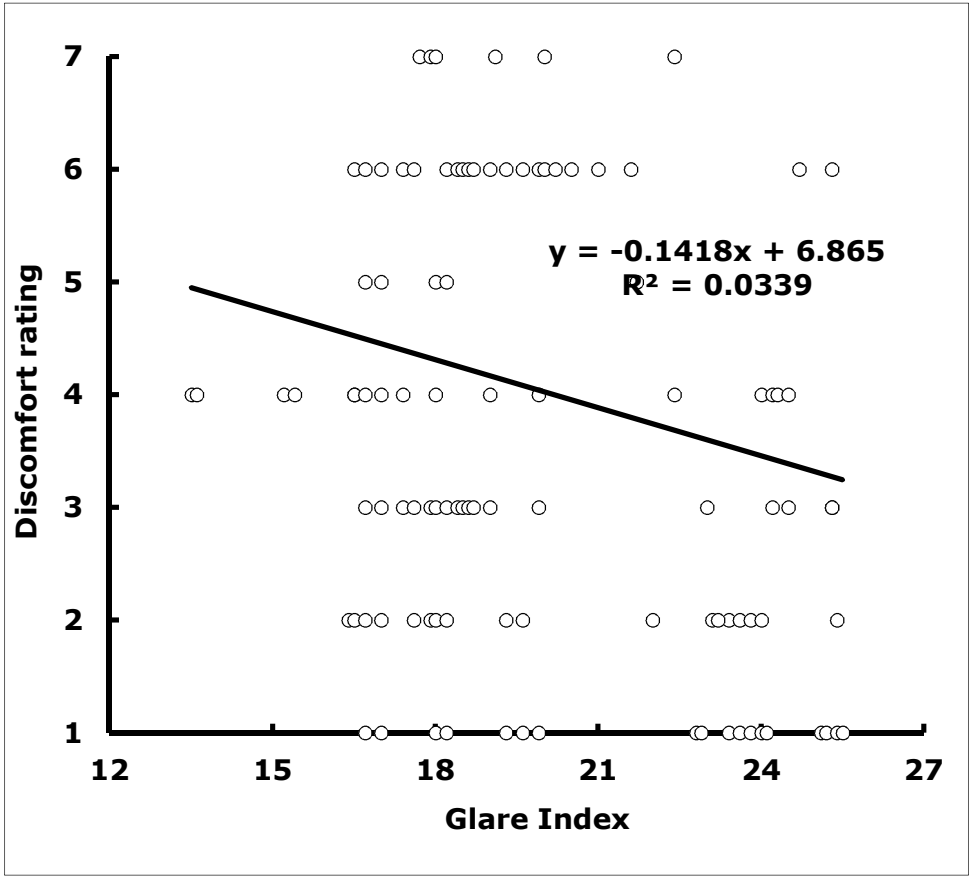
- Yes, the multiple linear regression between daylighting conditions and test scores was statistically significant ($p<0.01$)

- This is a necessary but not sufficient finding for acceptance



What is the effect size?

- The effect size is small (<1%) meaning that the effect of daylight explains very little of the variance in the test scores
- This means that although the effect is real, it is tiny.



What is the mechanism?

- This is not clear
- It could be that more windows provide more daylight and hence stimulate both the visual and non-visual systems to a greater extent
- It could be nothing to do with daylight. Windows provide a view out and it may be what is seen through the windows that matters
- It may be that better teachers get better classrooms with more windows

Has it been replicated? Are there any converging measures?

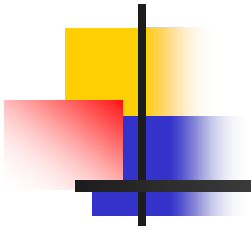
- No. An attempt to replicate these findings in another school district failed to show a statistically significant effect.
- This is to be expected given the very small effect size
- There are no converging measures such as fewer absences, quieter classrooms, less disruption etc.

What to do?

- Claims about the benefits of human-centric lighting are likely to be with us for some time as there is a lot of commercial interest.

- The following list of questions is offered as a means of assessment of such claims .

Human-centric lighting: Seven critical questions



- Is the effect statistically significant and at what level?
- What is the effect size?
- What is the proposed mechanism?
- Has the effect been replicated?
- Under what circumstances should the effect occur?
- To whom does the effect apply?
- Is there any supporting evidence using other measures?

Some consequences of flux

- Lighting is in flux but in what areas, who will be affected and for how long?
- Light source and control technology are continuously evolving. This affects everybody involved in lighting
- This has happened before, will happen again and everyone will be affected

Some consequences

- New colour fidelity metrics and discomfort glare metrics will make a lot of work for manufacturers for a short time but have little impact on designers

- Other new colour metrics will have a bigger and longer impact on both manufacturers and designers

Some consequences

- Changing the basis of lighting recommendations from performance to perception as suggested by Cuttle will have a major impact on those who prepare lighting recommendations and those who use them for a long time

- Cuttle's design approach may not affect how experienced designers work but should improve the work of basic designers

Some consequences

- Abandoning photometry or adopting universal photometry will affect everyone involved in lighting; manufacturers, regulators, specifiers and designers, for ever

- This is because the whole system of quantification of light and lighting will change

Some consequences

- If the objectives of human-centric lighting become widely accepted, much more transparency will be called for from designers if confusion and chicanery are to be avoided

More generally

- If some of these proposals are adopted, then two more general trends become evident
- Lighting practice will become more complex because there will be more lighting objectives and criteria to choose from
- The effects of lighting will become matters of probability rather than certainty. This has always been the case for task performance but it applies even more strongly to the objectives of human-centric lighting

We live in interesting times

Acknowledgements

- It is a pleasure to acknowledge the contributions of Mark Rea and Kit Cuttle to many of the thoughts expressed in this lecture.

- They have been an endless source of stimulation and argument for which I am very grateful. However, I should make it clear that while they might agree with some of what I have said, they certainly would not agree with all of it