Beyond the Fraction:
Efficacy in Applied Lighting

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A **RATE** is a *ratio of unlike quantities*.

$$\frac{\textit{Miles}}{\textit{Gallon}} \qquad \frac{\textit{Gallons}}{\textit{Flush}} \qquad \frac{\textit{Points}}{\textit{Game}}$$

$$\frac{\textit{Dollars}}{\textit{Foot}^2} \qquad \frac{\textit{Words}}{\textit{Minute}} \qquad \frac{\textit{Watts}}{\textit{ft}^2}$$

$$\frac{\textit{Beats}}{\textit{Minute}} \qquad \frac{\textit{Miles}}{\textit{Hour}} \qquad \frac{g}{\textit{cm}^3}$$

Efficacy is a *ratio of unlike quantities* that represents a *rate of consumption*.

One side of the fraction (is intended to) represent a **BENEFIT**, the other a **COST**.

For example:

$$\frac{Miles}{Gallon}$$

$$\frac{Gallons}{Flush}$$

In practice, **Efficacy** and **Efficiency** are (usually) employed differently.

EQE = (Injection Efficiency) × (IQE) × (Extraction Efficiency)

$$\text{Injection Efficiency} = \frac{\textit{electrons injected into active region}}{\textit{electrons passing through device}}$$

$$\text{IQE} = \frac{\textit{radiative electron hole combinations}}{\textit{all electron hole combinations}}$$

$$\text{Extraction Efficiency} = \frac{\textit{photons that escape device}}{\textit{photons generated}}$$

If we frame the problem as **benefit/cost**, the *questions* are easy.

- **What are the benefit(s) of lighting?**
  [Corollary: What metrics define the benefits?]
- **What are the cost(s) of lighting?**
  [Corollary: What metrics define the costs?]

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Today, **benefit** per **cost** in applied lighting is largely defined as:

$$\frac{Lumens}{Watt}$$

With a few conceptual modifiers:

1. Which lumens?
2. Which watts?
3. In practice, color quality is not completely ignored.

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The ***lumen*** is a poor proxy for ***benefit***.

Experimental Context for V(λ)

- Field of View
- Methods
- Field Luminance

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Experimental Context for V(λ)

- **Field of View**
- Methods
- Field Luminance

2 deg. is about 0.01% of the total visual field that we see with both eyes.

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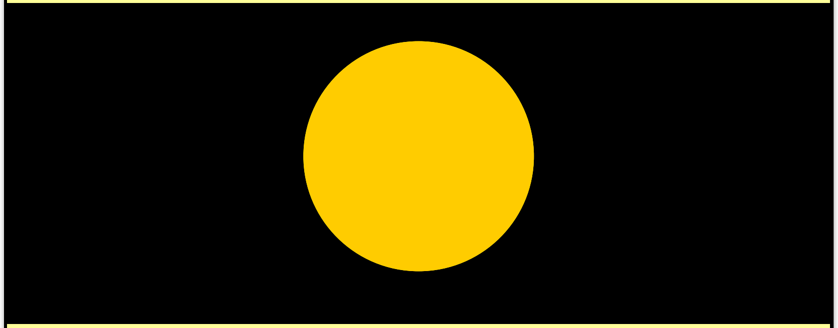
The ***lumen*** is a poor proxy for ***benefit***.

Experimental Context for V(λ)

- Field of View
- **Methods**
- Field Luminance

“visual equality” defined with **flicker photometry** and **step-by-step brightness matching**.



IMPORTANT: V(λ) based on visual comparisons of monochromatic stimuli.

The ***lumen*** is a poor proxy for ***benefit***.

Experimental Context for V(λ)

- Field of View
- Methods
- **Field Luminance**

Less than 10 cd/m^2. By comparison, interior building surfaces are more typically 50 – 200 cd/m^2.

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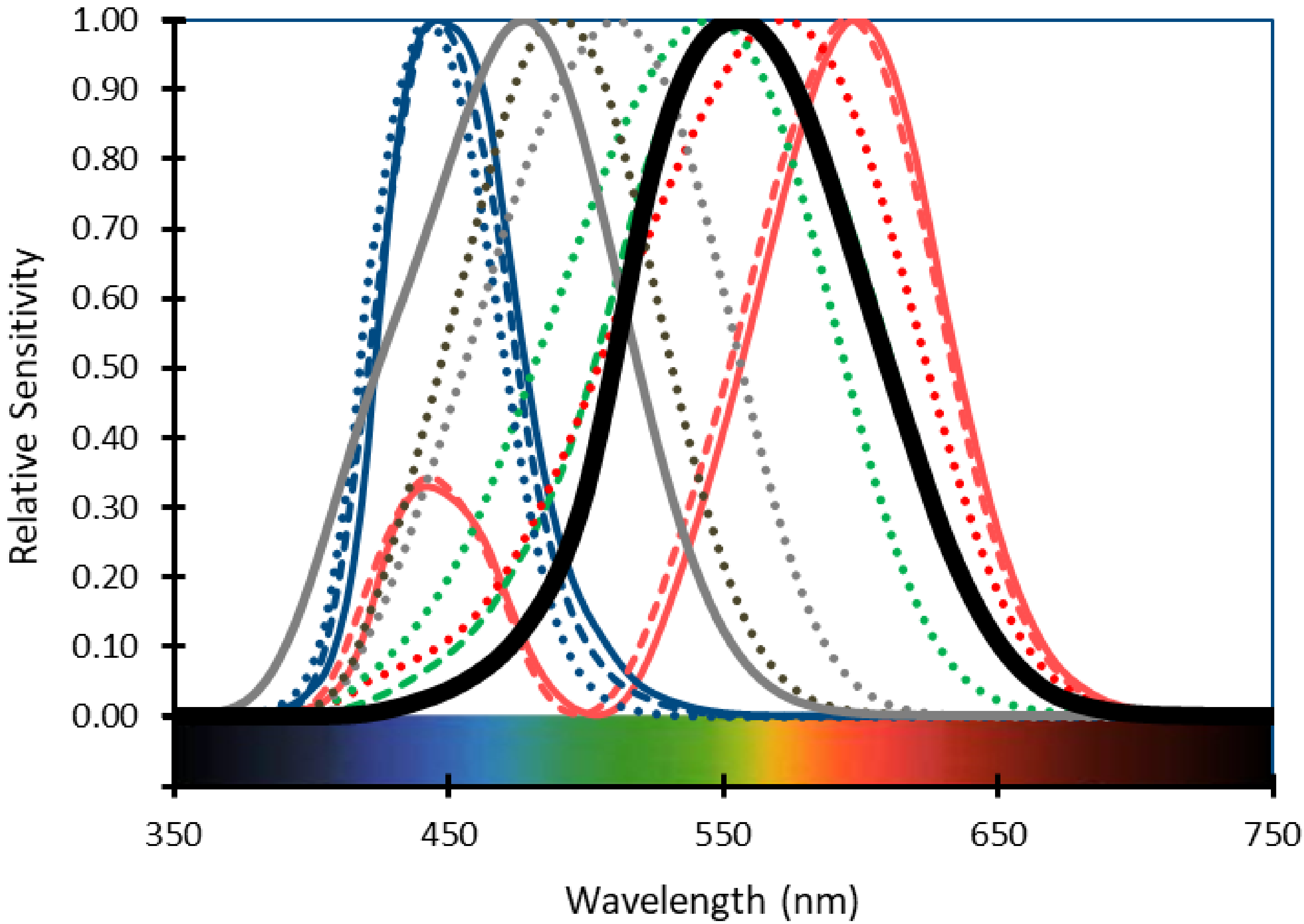
There are many other ways to characterize optical radiation.



V(λ) and V'(λ)

LC, MC, Rods, Melanopic, SC

10 and 2 deg CMFs

NUMERATOR: Minimally, the **benefits of lighting (to people)** are visibility, color quality, psychological reinforcement, and circadian stimulation.

BENEFIT	COMMON METRIC	BETTER METRIC
• Visibility	→ V(λ)-based lumens	→ V(λ) or Mesopic
• Color Quality	→ CRI (CCT)	→ TM-30 (Chromaticity)
• Psychological Reinforcement	→ Hire a Lighting Designer	→ Hire a Lighting Designer
• Circadian Stimulus	→ CCT	→ CS, (Melanopic Lx)

While avoiding	COMMON METRIC	BETTER METRIC
• TLA (Flicker)	→ ?	→ IEEE 1789, NEMA 77
• Visual Discomfort	→ ?	→ UGR

<u>**DENOMINATOR**</u>: Using the ***watt*** as a proxy for ***cost*** is imperfect.

- Time *should* be considered, which implies efficacy characterization at the application level, rather than product level.
- Might it be better to account for the source of energy, for example by using CO_2 emissions?
- Should LCA be a part of a product's efficacy?

A family of efficacies could cover common situations.

The below are proposed only as a thought exercise!

$$\frac{Lumen\ Hours}{Lifetime\ Environmental\ Cost}$$

$$\frac{Lumens}{Ton\ CO_2}$$

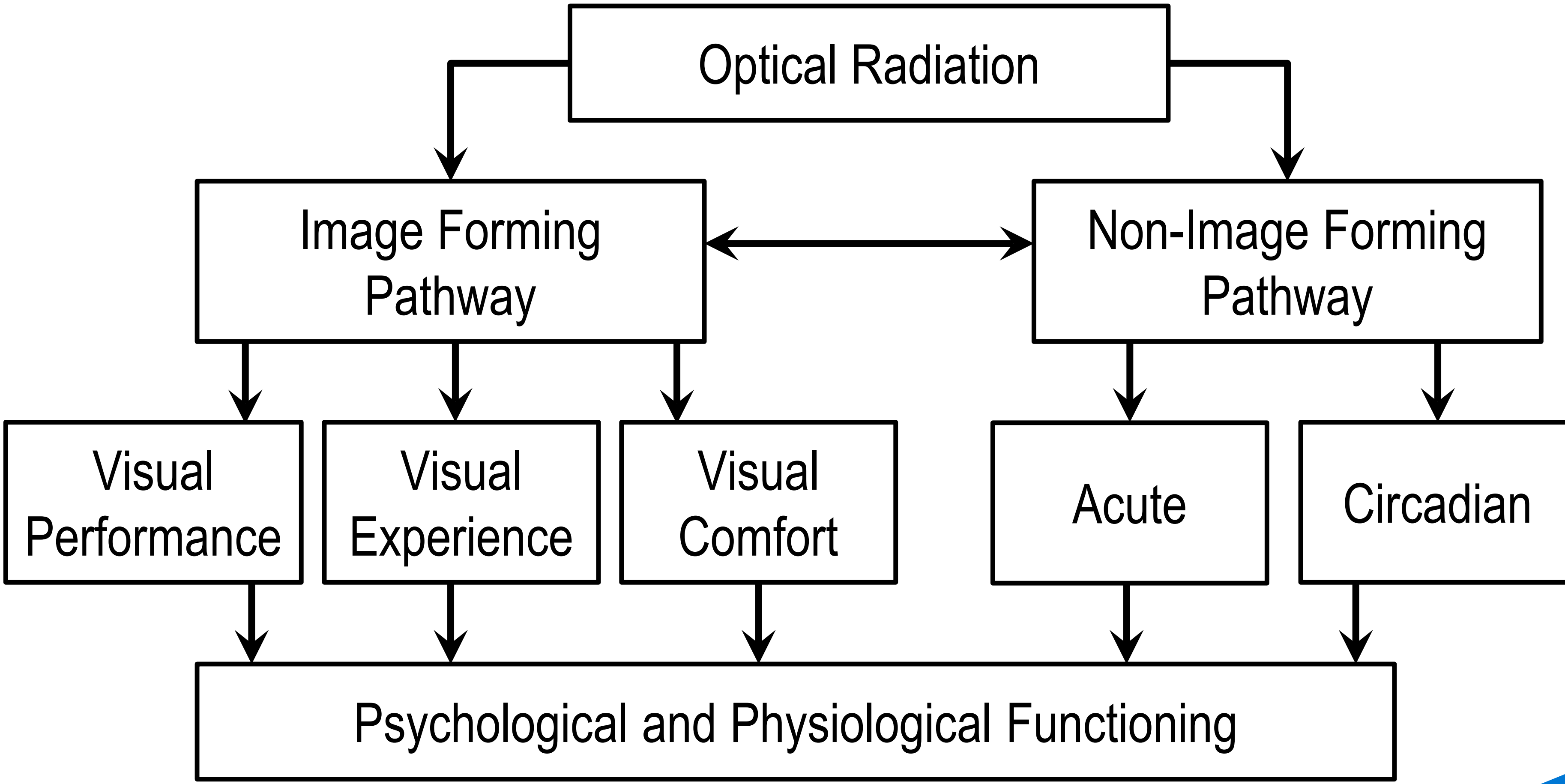
$$\frac{Circadian\ Stimulus}{Watt}$$

$$\frac{Lumens}{Dollar}$$

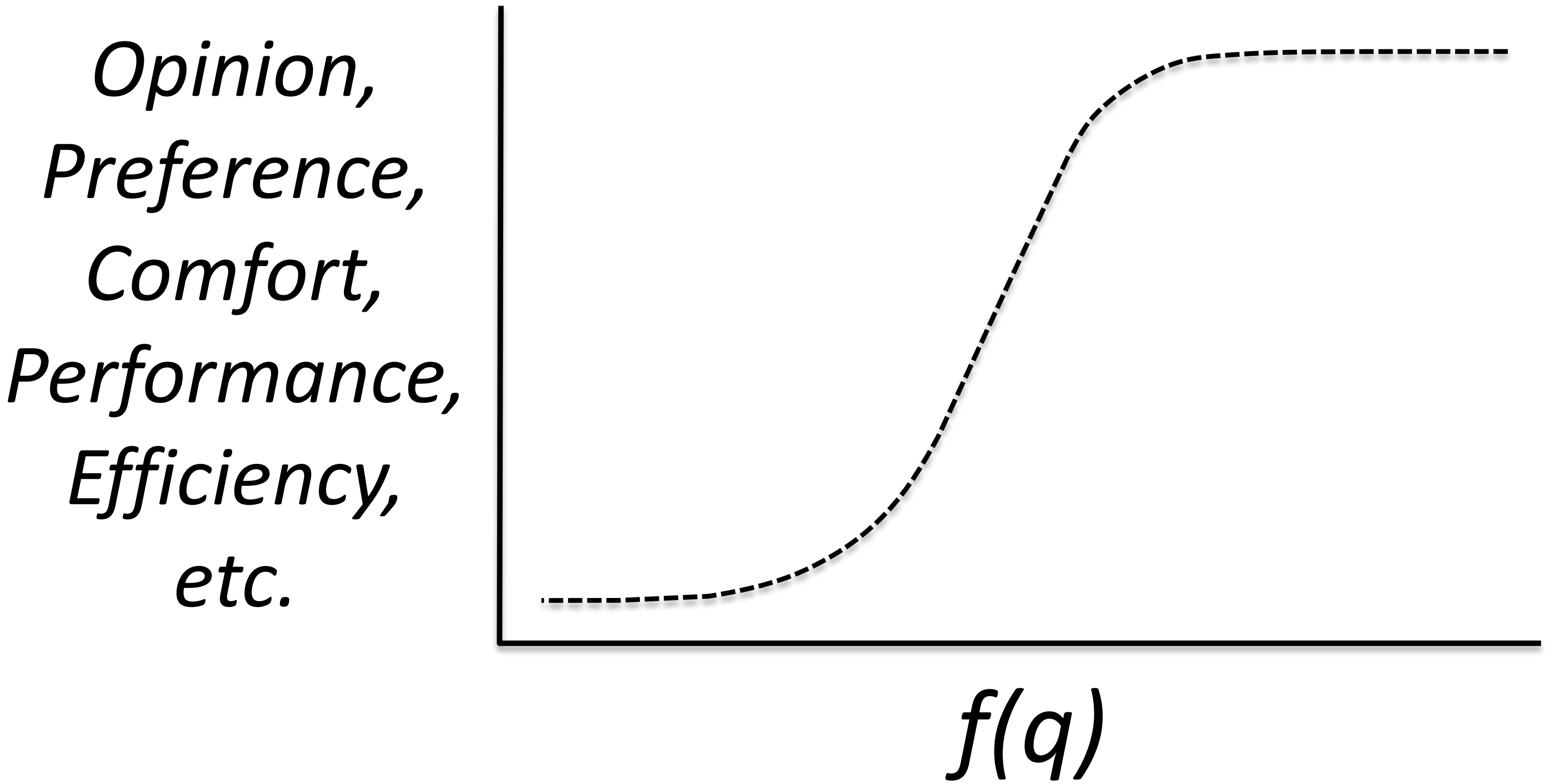
$$\frac{Color\ Quality}{Ton\ CO_2}$$

$$\frac{PAR}{Watt}$$

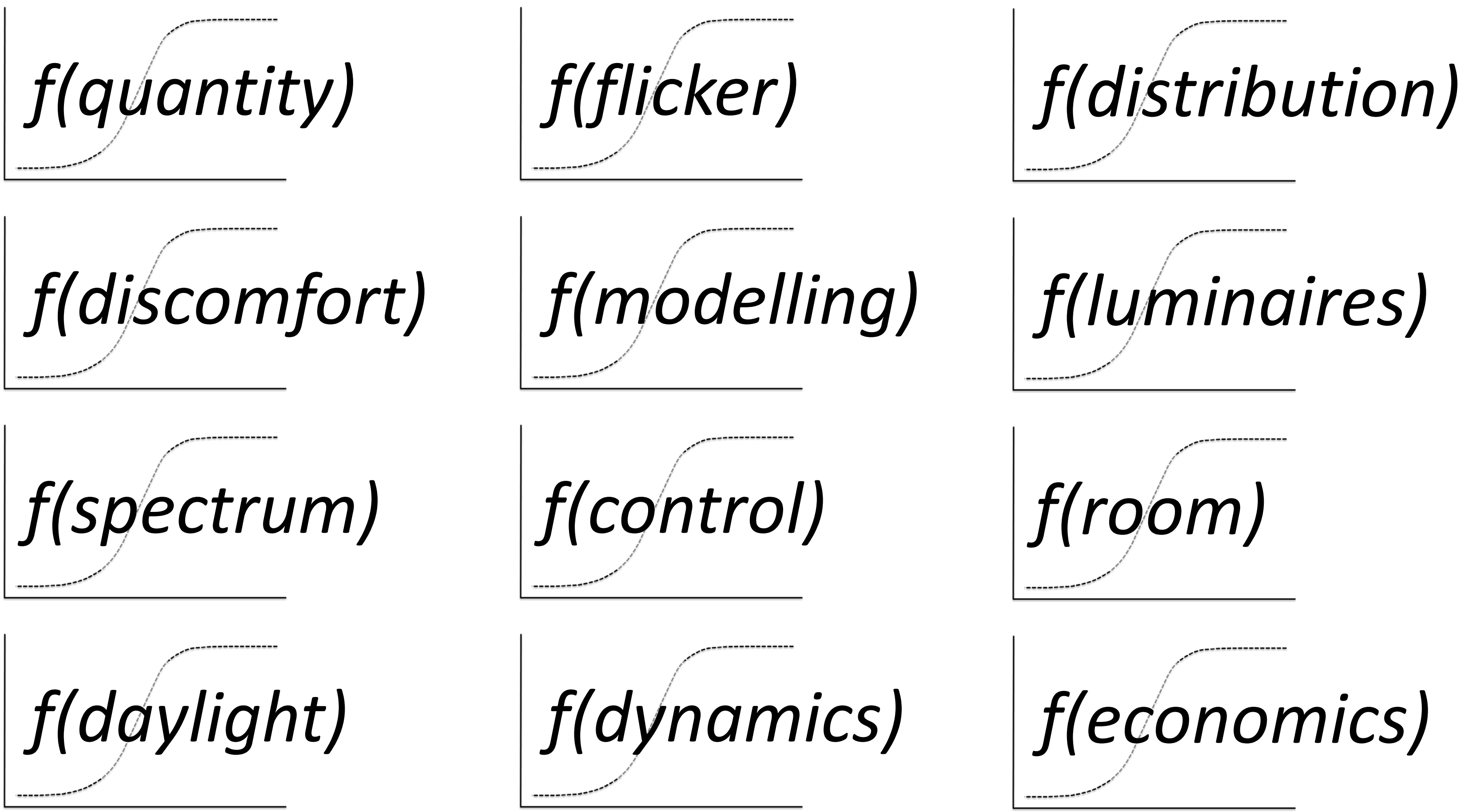
But, need to **move beyond a ratio** to consider the larger picture.



Illuminating engineering (lighting design) is a **multi-criterion problem** with interactions.



Consider the below as **indirect measures of lighting quality**. What is their functional relationships to opinions of lighting quality?



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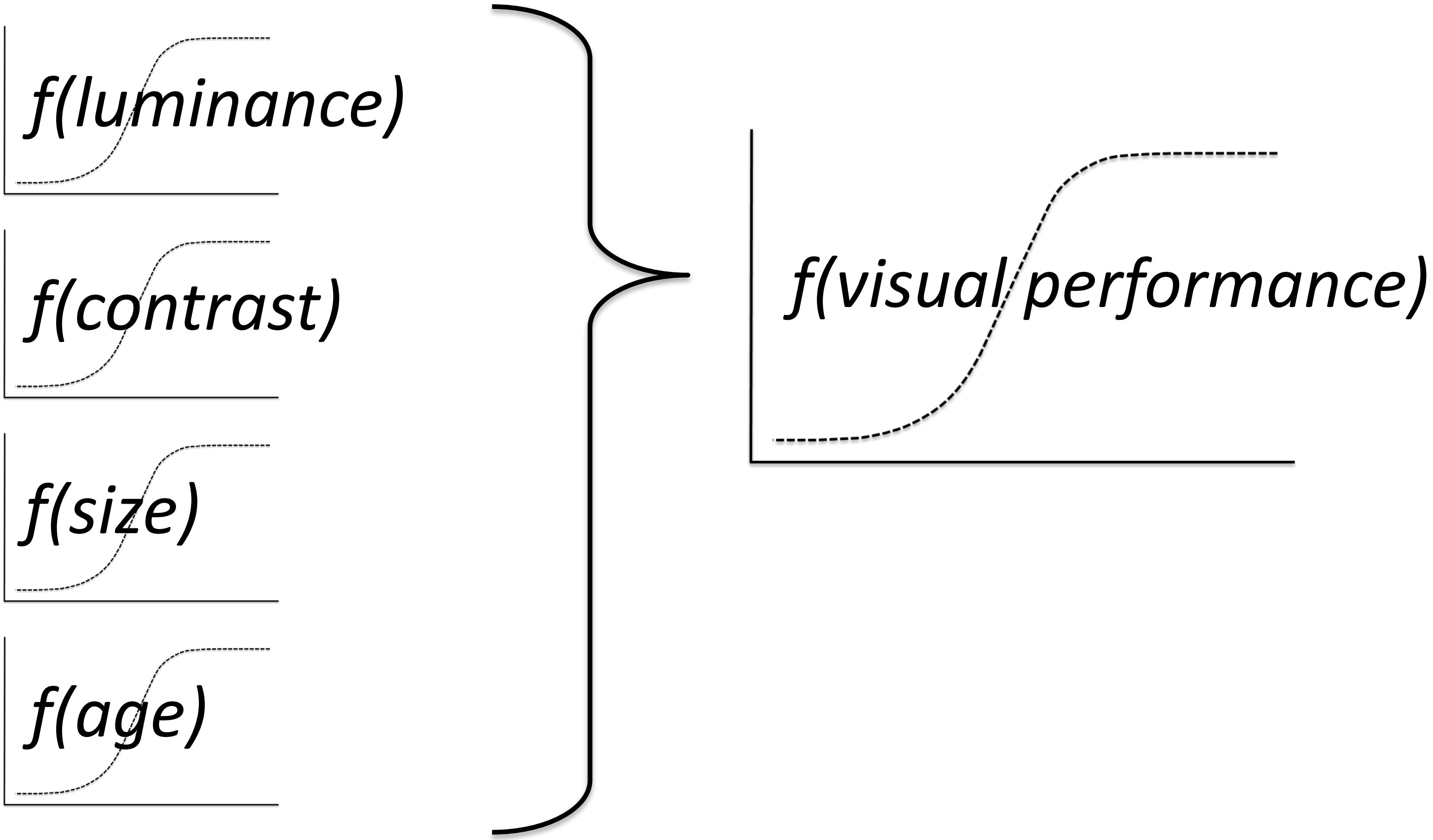
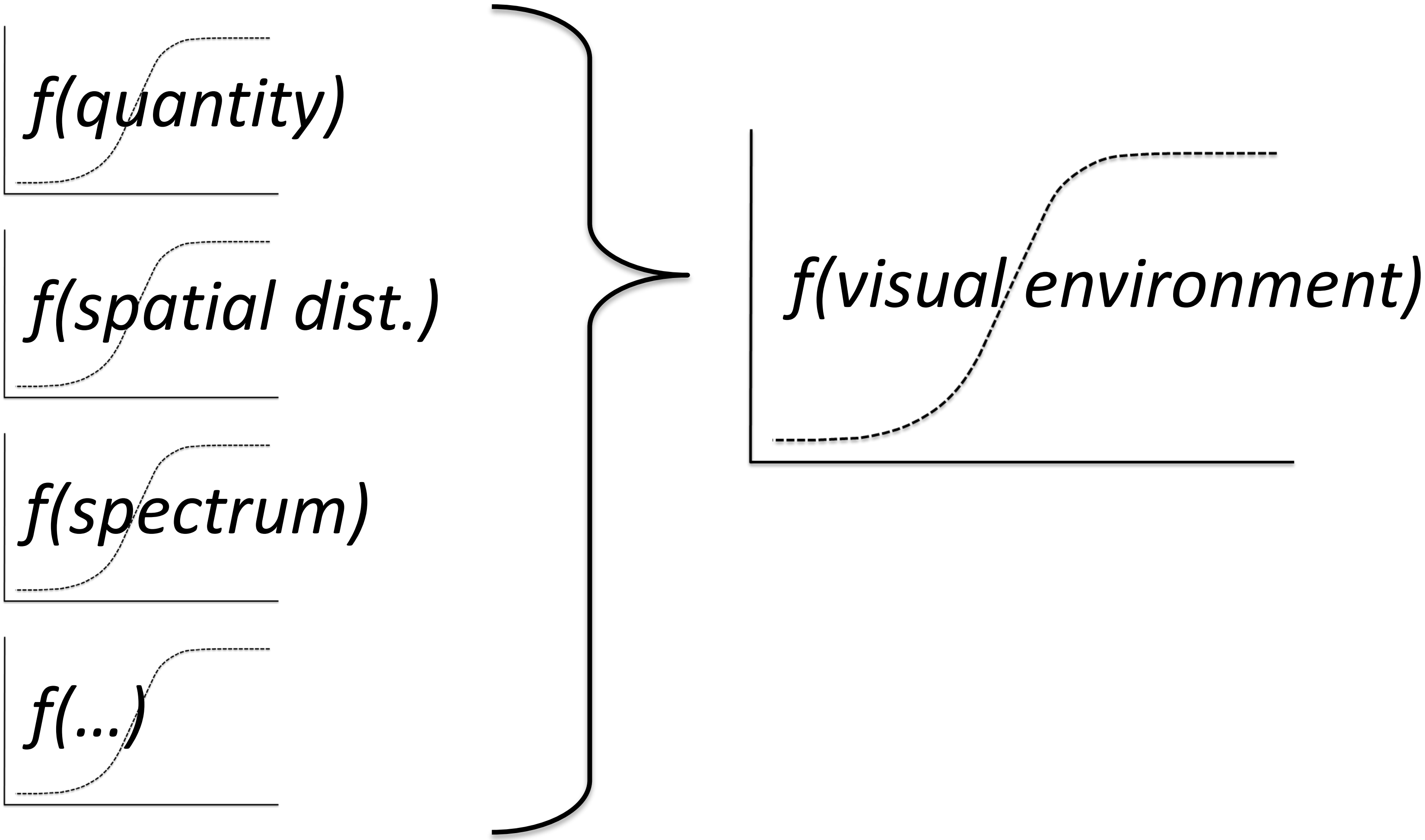
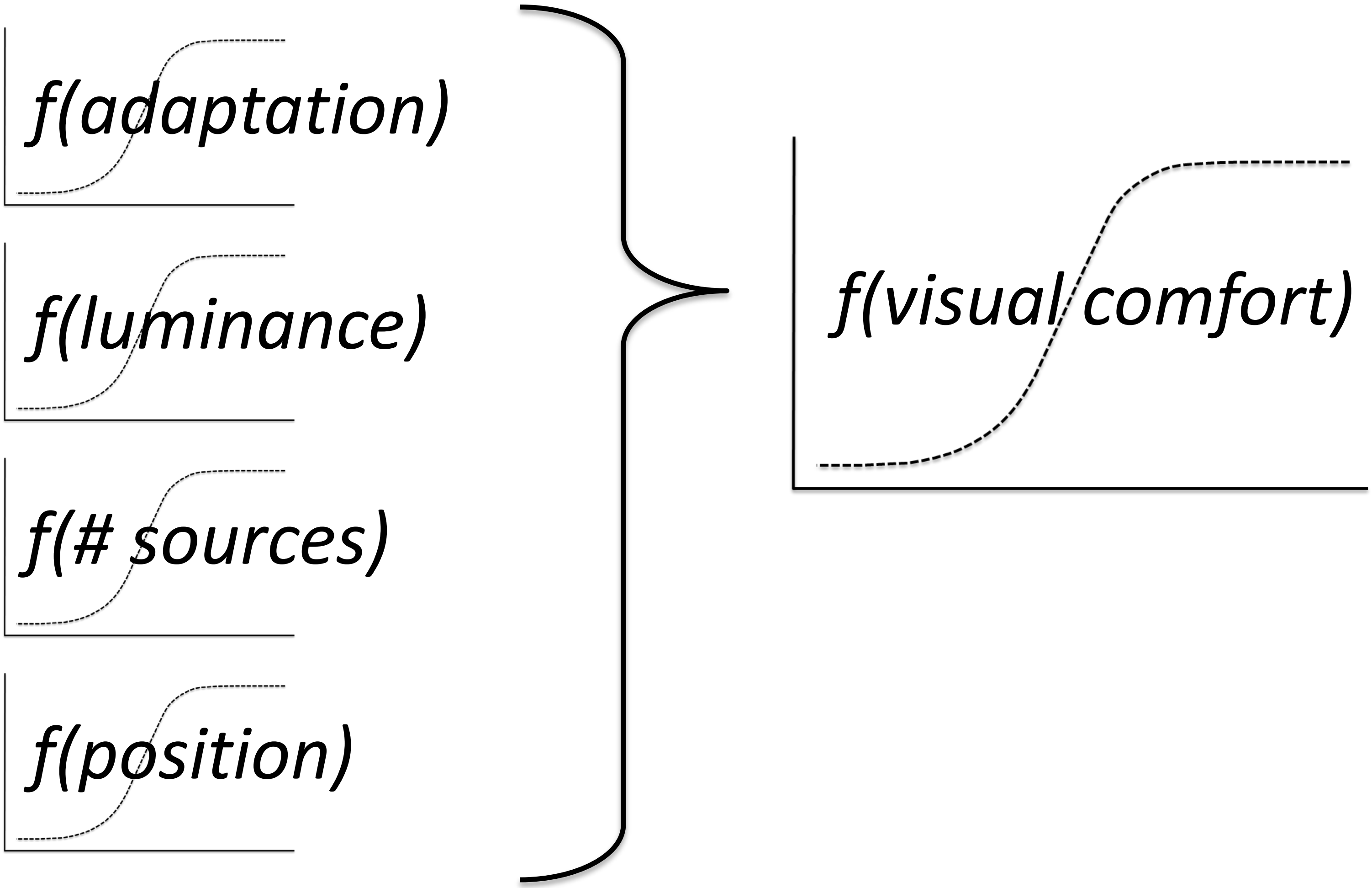
Visual performance is a function of:



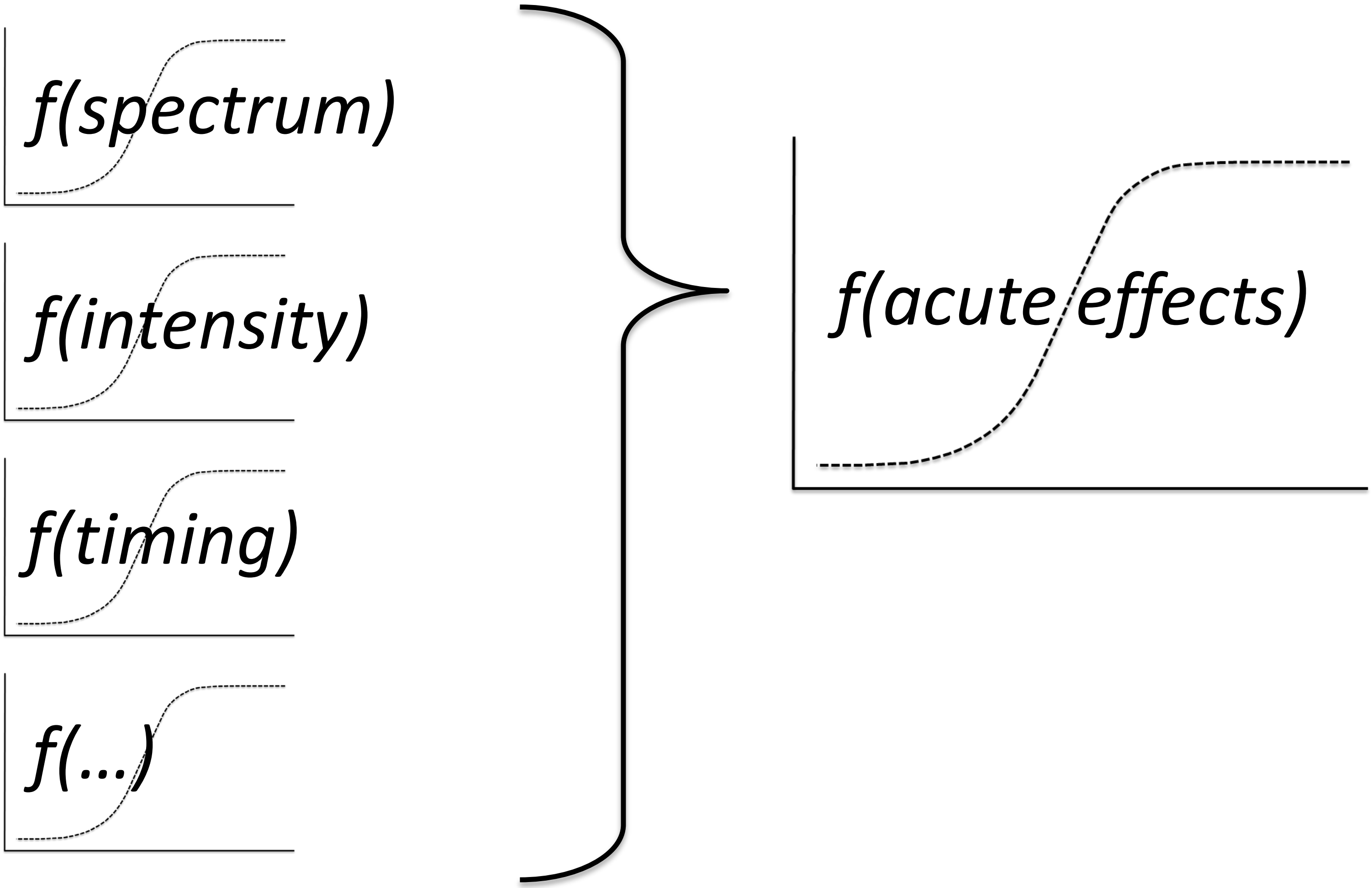
Visual environment is a function of:



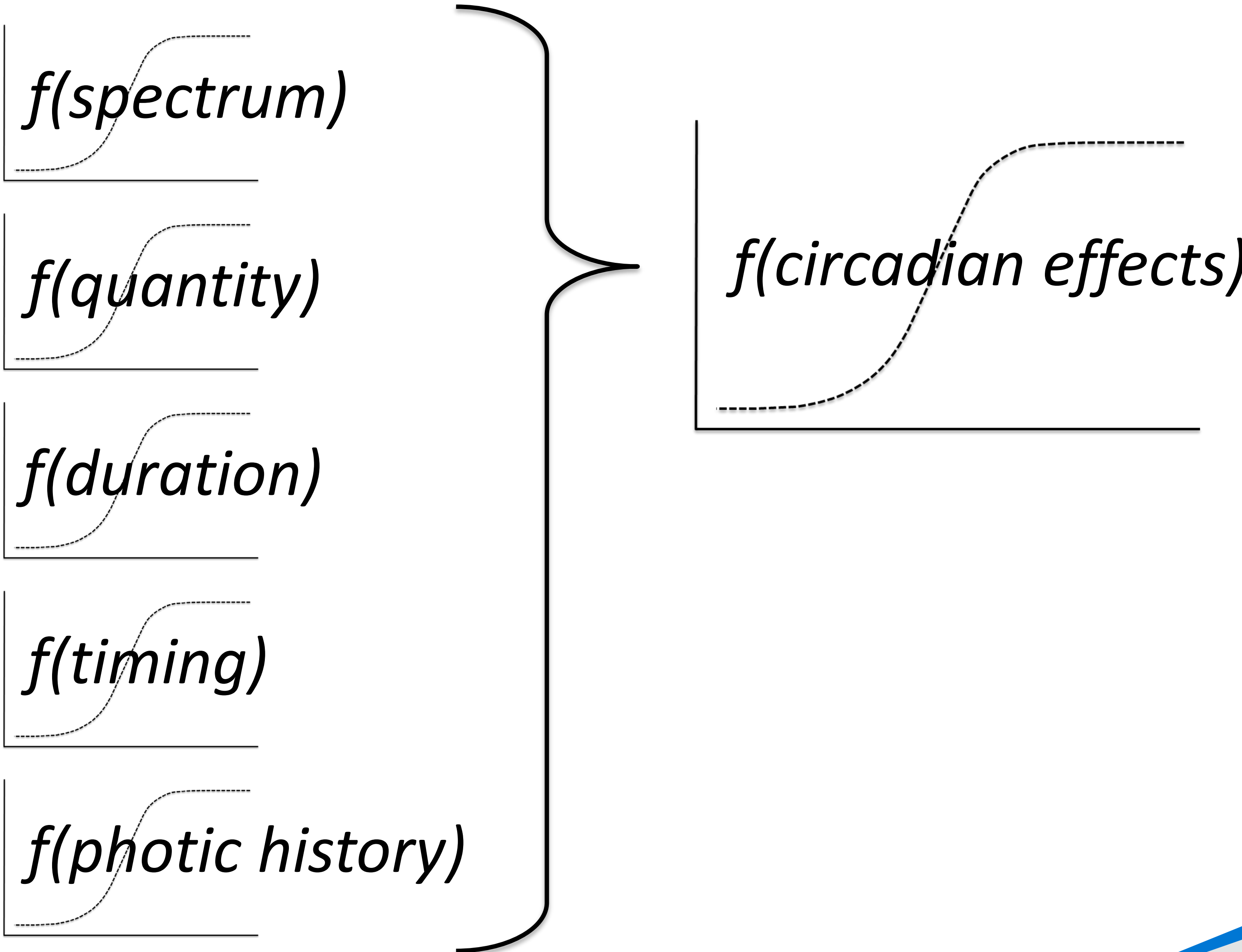
Visual comfort is a function of:



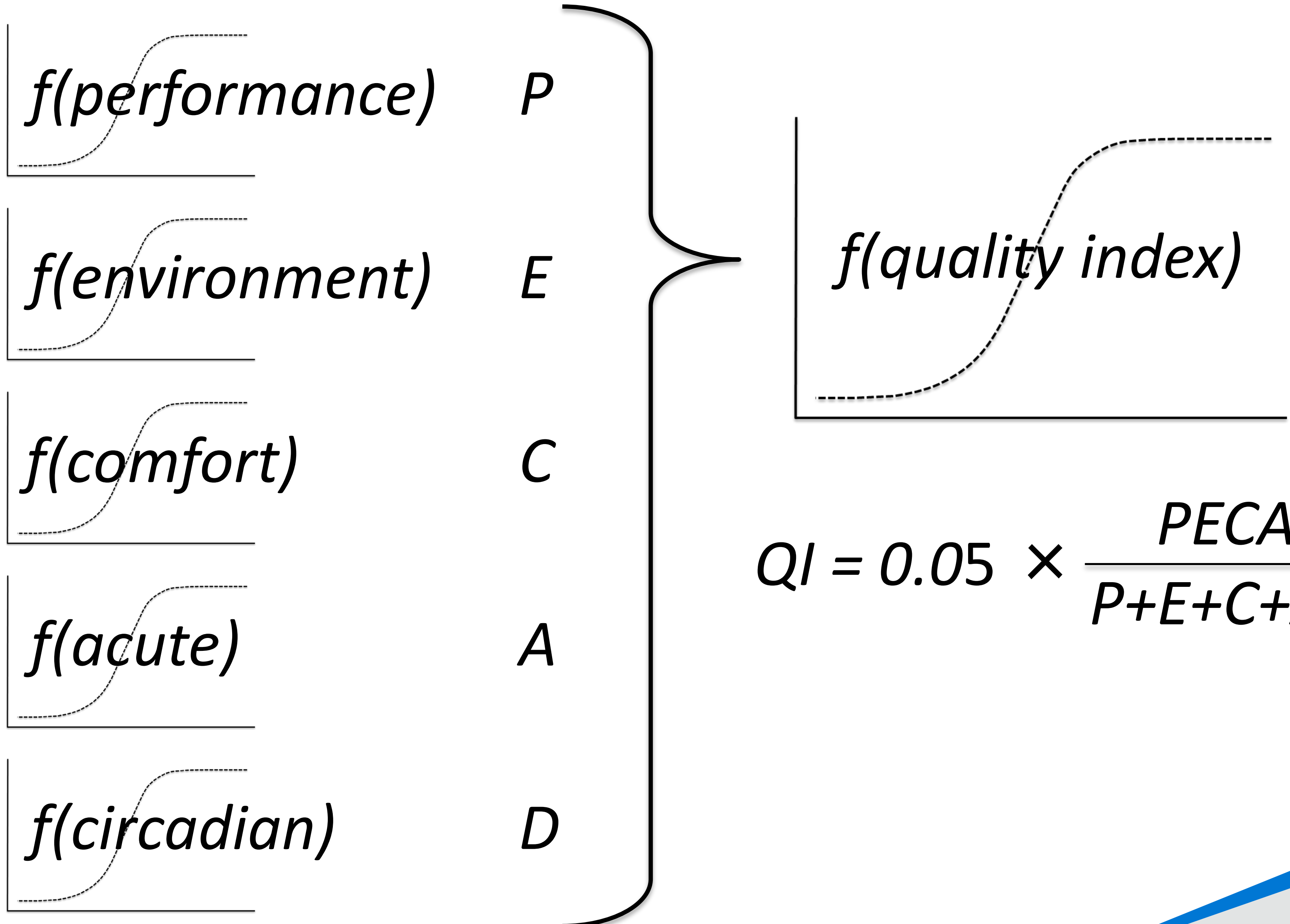
Acute effects are a function of:



Circadian effects are a function of:

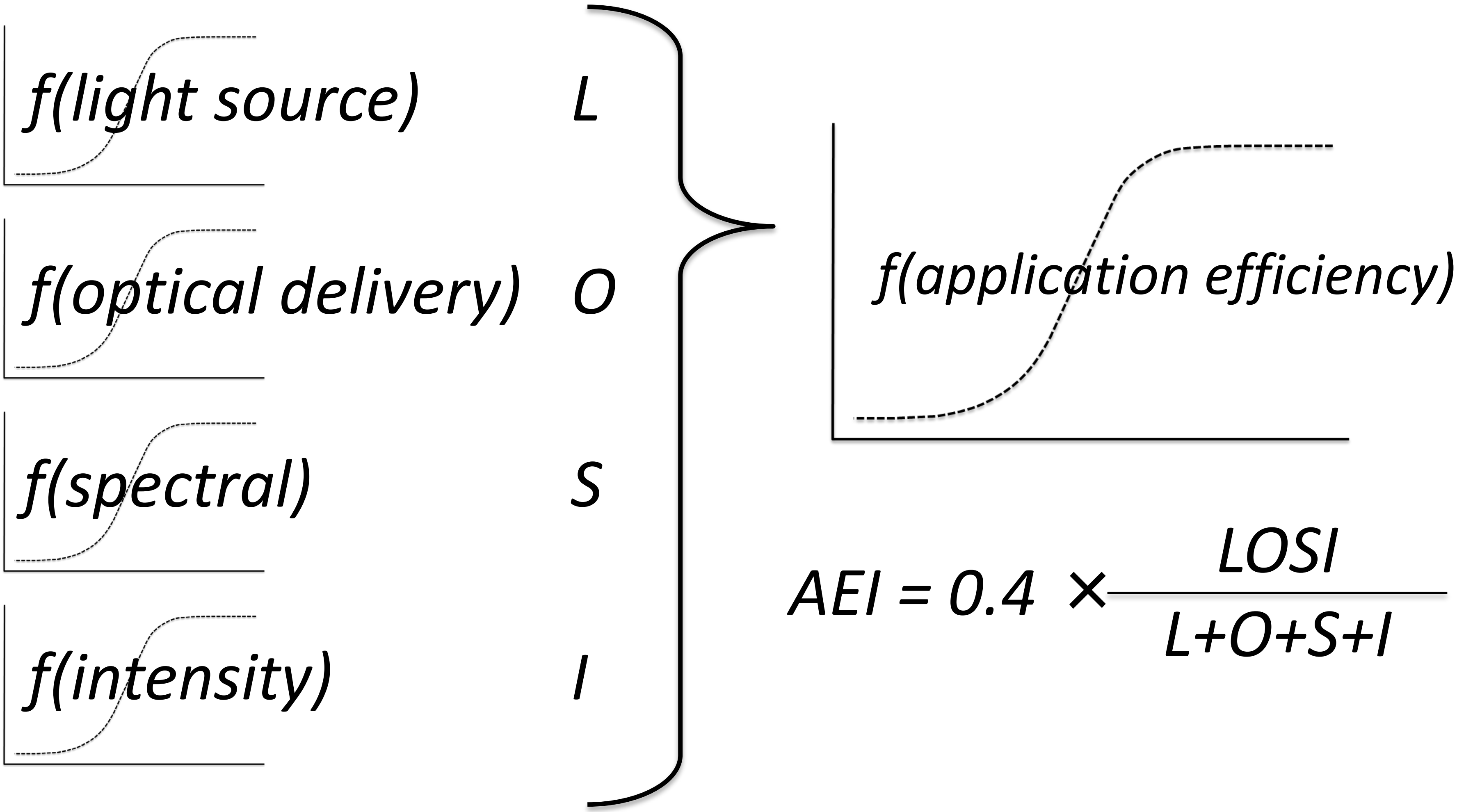


Combine for a composite **Quality Index** (QI).



$$QI = 0.05 \times \frac{PECAD}{P+E+C+A+D}$$

Combine for an **Application Efficiency Index** (AEI).



$$AEI = 0.4 \times \frac{LOSI}{L+O+S+I}$$

When lighting for **people**, the benefit should be defined by **human needs** And the costs should be defined by the **detrimental effects on our planet.**

Sources of ideas and inspiration:

- Bean AR, Bell RI. 1992. The CSP index: A practical measure of office lighting quality as perceived by the office worker. Light Res Technol. 24(4):215-225.
- de Kort YAW. Veitch JA. 2014. From blind spot into the spotlight: Introduction to the special issue 'Light, lighting, and human behaviour'. J Environ Psych. 39:1-4.
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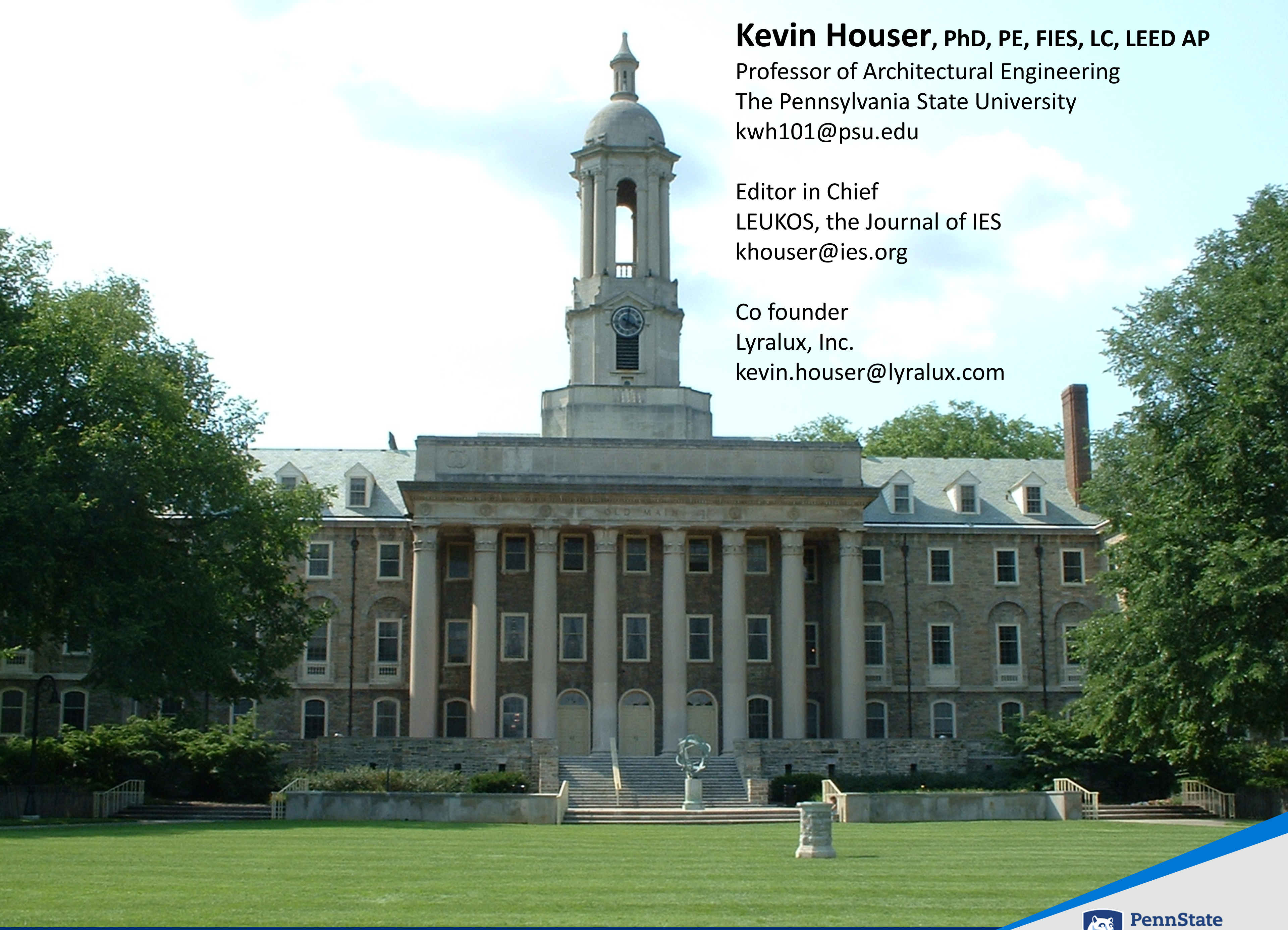
- Rea MS. 2012. Value metrics for better lighting. Bellingham (WA): SPIE Press. 122 p.
- Veitch JA, Newsham GR. 1998. Determinants of lighting quality I: State of the science. J Illum Eng Soc. 27(1):92-106.



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