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TUNING OPTICAL RADIATION FOR VISUAL AND NONVISUAL IMPACT

A Dissertation in
Architectural Engineering

by
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Abstract

Spectral tuning—the allocation of radiant energy emitted by a lamp—is a fundamental element of illuminating engineering. Proper placement of optical radiation allows for reduced energy consumption, increased brightness perception, and improved color rendition. It can also result in lamps that have a greater impact on nonvisual human functions such as circadian rhythms, sleep, mood, and cognition. For an architectural lighting system, careful consideration must be given to all of these areas; recent advancements in understanding nonvisual photoreception must be balanced with the traditional emphasis on visual quality and energy efficiency.

The three research projects described herein investigated spectral tuning by examining the effects of optical radiation or seeking ideal spectral power distributions. In all three cases, emphasis was placed on developing an architectural lighting system based on red, green, and blue (RGB) light emitting diodes (LEDs) that is capable of providing maximum stimulation to nonvisual systems while maintaining visual quality standards. In particular, the elderly were considered as a target population because they have an increased risk of developing disorders linked to illumination deficits. The three endeavors can be summarized as follows:

Light Therapy for Seniors in Long-term Care

**AIM:** To examine the effect of optical radiation on circadian rhythms, sleep, mood, and cognition for frail elderly in a long-term care environment.

**METHODOLOGY:** A double-blind, placebo-controlled clinical trial of light therapy was conducted using circadian-effective short-wavelength (blue) optical radiation to treat a sample of residents recruited for participation without bias for existing medical diagnoses.

**KEY FINDINGS:** Light therapy treatment improved cognitive functioning compared to placebo but no changes were detected in nighttime sleep statistics, reports of daytime sleepiness, circadian rhythms, or depression inventory parameters.

Perceived Brightness of Trichromatic Light Sources

**AIM:** To examine the effect of tuning optical radiation on brightness perception for younger (18-25 years of age) and older (50 years of age or older) observers.

**METHODOLOGY:** Participants made forced-choice evaluations of the brightness of a full factorial of stimulus pairs selected from two groups of four metameric stimuli. The large-field stimuli were created by systematically varying either the red or the blue primary of an RGB LED mixture.

**KEY FINDINGS:** Light stimuli of equal illuminance and chromaticity do not appear equally bright to either younger or older subjects. The rank-order of brightness is not predicted by any current model of human vision or theory of brightness perception including Scotopic to Photopic or Cirtopic to Photopic ratio theory, prime color theory, correlated color temperature, photometry, color quality metrics, linear brightness models, or color appearance models. Age may affect brightness perception when short-wavelength primaries are used, especially those with a peak wavelength shorter than 450 nm.

Optimizing RGB LED Mixtures

**AIM:** To investigate potential tradeoffs between luminous efficacy, nonvisual efficacy, and color quality of RGB LED mixtures when the peak wavelength and full with half maximum of the primaries are
varied. To identify mixtures suitable for architectural lighting which provide increased circadian stimulation.

**METHODOLOGY:** Software to calculate the properties of RGB LED mixtures matching the chromaticity of blackbody radiation was developed using Microsoft Excel and Visual Basic. Excel Solver was used to perform a series of optimization routines, identifying high-performing mixtures that were then compared to traditional lamps.

**KEY FINDINGS:** Trichromatic mixtures suitable for architectural interiors can outperform traditional lamps when luminous efficacy, nonvisual efficacy, and color quality are considered simultaneously. However, misplacement of radiant energy can result in poor performing trichromatic systems. When radiant energy is manipulated, tradeoffs may occur between luminous efficacy, nonvisual efficacy, and color quality.
# Table of Contents

1 INTRODUCTION ................................................................................................................. 1

2 BACKGROUND .................................................................................................................. 3
   THE HUMAN EYE—FUNDAMENTALS OF VISION................................................................. 3
      Rod Photoreceptors........................................................................................................... 3
      Cone Photoreceptors....................................................................................................... 4
   Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs) ......................................................... 5
   MODELS OF HUMAN VISION ................................................................................................. 7
      Color Vision ....................................................................................................................... 7
      Colorimetry ...................................................................................................................... 9
      Color Spaces .................................................................................................................. 13
   Additivity Failures ............................................................................................................. 13
   Prime Color Theory ........................................................................................................ 15
   Brightness Metrics .......................................................................................................... 20

CIRCADIAN RHYTHMS .......................................................................................................... 22
   Circadian Disorders ......................................................................................................... 22

CIRCADIAN EFFICACY OF OPTICAL RADIATION................................................................. 23
   Spectrum ........................................................................................................................... 23
   Duration and Intensity ....................................................................................................... 25
   Timing ............................................................................................................................... 26
   Photic History and Adaptation ......................................................................................... 27
   Location and Size ........................................................................................................... 27
   Daylight and the Importance of Circadian Lighting ......................................................... 27

CIRCADIAN DISRUPTION IN SENIORS: PREVALENCE, MEASUREMENT, AND CONSEQUENCES ............................................................. 28
   Depression ......................................................................................................................... 28
   Sleep Disorders ............................................................................................................... 29
   Cognitive Disorders ........................................................................................................ 30

TUNING OPTICAL RADIATION ......................................................................................... 30

3 LITERATURE REVIEW ..................................................................................................... 32
   LIGHT THERAPY ................................................................................................................ 32
      Mechanisms of Action .................................................................................................... 32
      Clinical Trials of Light Therapy ..................................................................................... 32
      Light Therapy for Seasonal Affective Disorder ............................................................... 33
      Light Therapy for Nonseasonal Depression ..................................................................... 33
      Light Therapy with Blue Light ....................................................................................... 34
   LIGHT THERAPY FOR SENIORS ....................................................................................... 34
      For Mood Disorders ...................................................................................................... 34
      For Sleep Disorders ..................................................................................................... 35
      For Cognitive Disorders ............................................................................................... 35
   SPATIAL BRIGHTNESS PERCEPTION .............................................................................. 36
ANALYSIS ........................................................................................................................................................ 74
LEDs versus Other Sources ..................................................................................................................................................... 76
Future Software Utility ..................................................................................................................................................... 79
Pathway to Circadian-Inspired Architectural Lighting Systems ......................................................................................... 80

7 CONCLUSIONS .......................................................................................................................................................... 81
Light Therapy for Seniors in Long-term Care .................................................................................................................. 81
Perceived Brightness of Trichromatic Light Sources ........................................................................................................ 81
Optimizing RGB LED Mixtures ......................................................................................................................................... 81

APPENDIX: M(\lambda) SPECTRAL DATA ......................................................................................................................... 83

REFERENCES .................................................................................................................................................................... 84
List of Figures

Figure 2-1  |  Normalized cone fundamentals derived from the color matching functions of
the CIE (1931, 1964, 2007), Judd (1951), Vos (1971, 1990), Smith (1975), Demarco (1992),
and Stockman (1993). Also shown are the photopigment sensitivities measured by Dartnall
et al. [1983]. ................................................................................................................................................... 4

Figure 2-2  |  Sensitivities of the five different photoreceptors found in the human eye and
six different visual efficiency functions recognized by the CIE. The spectral sensitivity
of melanopsin (M(λ), peaking at 480 nm) is distinctly different from the sensitivity of any of the
rod or cone photoreceptors. The 480 nm region corresponds to the area of greatest
discrepancy between the visual efficiency functions.................................................................................... 6

Figure 2-3  |  Opponent signals from the model of color vision by Hurvich and Jameson.
These functions (blue-yellow, red-green, and black-white) are linear transformations of color
matching functions........................................................................................................................................ 8

Figure 2-4  |  A schematic diagram of the vector model of color vision. Other dual-stage
theories have similar diagrams, but include different relationships between the
photoreceptor and neural stages.................................................................................................................. 9

Figure 2-5  |  Top: RGB color matching functions developed from different datasets. Bottom:
XYZ color matching functions. The peak of the functions remain in the prime color regions
(450, 530, and 610 nm) regardless of the primary set chosen. The functions of Thornton are
raw and unmodified, resulting in notable differences in the long wavelength region of the
blue and green functions. ............................................................................................................................ 11

Figure 2-6  |  Left: The ratio of measured power of the variable primary versus the measured
power of the two fixed primaries (denoted by the arrows). Right: The ratio of measured
power of the two fixed primaries versus the measured power of the variable primary. The
dashed lines have been added to demonstrate the limits of variation when the other two
primaries are fixed. [From: Thornton 1992a] ............................................................................................... 16

Figure 2-7  |  Top (A): Ratio of the measured power of the reference (broadband fluorescent)
versus the measured power of the trichromatic match for both prime (left) and anti-prime
sets (right). Values greater than one indicate greater brightness per watt than the reference.
The vertical dashed lines indicate the three different regions in which the variable primary
was changed while the other two primaries, denoted by arrows, remained fixed. The
distribution is distinctly bimodal. Bottom (B): Ratio of the computed luminance (CIE 1964
Standard Observer, V10(λ)) of the reference versus the luminance of the trichromatic match.
Values greater than one indicate that luminance underpredicts the brightness of the
trichromatic mixture. [From: Thornton 1992a] ........................................................................................... 17

Figure 2-8  |  Computed chromaticity (CIE 1964 Standard Observer, V10(λ)) of the reference
broadband fluorescent source (+) and matched trichromatic mixtures (denoted by
wavelength of variable primary mixed with two prime color primaries) for one observer. The
bowtie shape is common to different observers. [From: Thornton 1992a] ................................................ 18

Figure 2-9  |  Color Rendering Index (solid), Color Discrimination Index (long dashes), and
Color Preference Index (short dashes) as a function of the variable primary of a trichromatic
mixture equal in chromaticity to CIE Illuminant D65. The variable primary in each region
(divided by vertical dashed lines) is combined with a fixed primary from the other two regions. [From: Thornton 1992b]........................................................................................................................................................................19

Figure 2-10 | Rea et al.’s model of phototransduction by the human circadian system (CS) compared to experimental data from Brainard et al. [2001] and Thapan et al. [2001]. The blue curve is the sensitivity of the photopigment melanopsin, a key component of the model, which is found in intrinsically photosensitive retinal ganglion cells (ipRGCs). [Adapted From: Rea et al. 2005]..................................................................................................................................................24

Figure 2-11 | Spectral retinal illumination as a function of age. The differences are most pronounced in the short-wavelength region of the visible spectrum. [From: Turner & Mainster 2008].............................................................................................................................................25

Figure 4-1 | Top: The experiment room during treatment. Subjects were seated in two rows of tables that were fitted with continuous rows of lighting. During exposure, subjects participated in an activity such as bingo or reminiscence. Bottom: The exposure device. RGB LED architectural lighting products were used to provide either blue (treatment) or red (placebo) optical radiation. ..........................................................................................................................................................42

Figure 4-2 | Spectral power distributions of the treatment (blue) and placebo (red) stimuli. The treatment stimuli provided approximately 125 times more circadian stimulation according to the CS model. ........................................................................................................................................43

Figure 4-3 | Difference scores for the three index levels of the MicroCog Assessment of Cognitive Functioning. An increase (positive value) indicates an improvement. The asterisks indicate a significant treatment versus placebo effect at the $\alpha = 0.05$ level. ........................................................................................................................................45

Figure 4-4 | Difference scores for the Profile of Mood States (POMS) assessment. A decrease (negative value) indicates an improvement. The asterisks indicate a significant treatment versus placebo effect at the $\alpha = 0.05$ level. ........................................................................................................................................46

Figure 4-5 | Total counts per epoch, averaged over four days, for both treatment and placebo groups as measured with wrist actigraphy. Visually evaluated, these plots suggest the light exposure had no effect on circadian rhythms. ........................................................................................................................................47

Figure 5-1 | Top: Spectral power distributions for the blue series, with primaries at ###, 535, and 622 nm. Bottom: Spectral power distributions for the red series, with primaries at 448, 535 and ### nm. ........................................................................................................................................50

Figure 5-2 | Gamut areas enclosed by the primaries of the blue series (left) and red series (right), with the target chromaticity of the mixture shown by the star symbol on the blackbody locus. ........................................................................................................................................51

Figure 5-3 | The Light Replicator Dashboard used to control the Telelumen spectrally tunable luminaire. ........................................................................................................................................51

Figure 5-4 | Calibration of the viewing booth. The apertures for the illuminance meter and spectrometer used to calibrate the stimuli were located at the approximate location of the observers’ eyes........................................................................................................................................53

Figure 5-5 | Top: The Telelumen luminaire mounted above the viewing booth, out of the subjects’ view. Bottom: The viewing booth and the computer. During the experiment, the computer was situated behind the subject, out of view. ........................................................................................................................................55
Figure 5-6  |  Ranks (Ri) and results of the variance stable rank sums tests. Shaded, bold values represent comparisons that are significantly different at the $\alpha = 0.05$ level, which requires a difference in rank of at least 20.98. Comparisons with a rank difference of at least 25.42 are different with significance exceeding the $\alpha = 0.01$ level. 58

Figure 6-1  |  CS/w as a function of CCT for both a blackbody radiator and an RGB LED mixture. Both proposed models of rod inhibition are shown: model [a] predicts an instantaneous switch, whereas model [b] predicts gradual inhibition as rod saturation increases. 67

Figure 6-2  |  Maximum CS/w versus CCT with different constraints. Allowing the FWHM to vary between 10 and 40 nm, as opposed to being fixed at 30 nm, increases the maximum CS/w by less than 8%. Reducing the CRI constraint from 85 to 55 results in an increase in the maximum CS/w of up to 30%. 68

Figure 6-3  |  Top (A): Minimum (red) and maximum (blue) CDI possible for an RGB LED source with a given CRI and a CCT of 4100 K. Bottom (B): CRI versus CDI at various CCTs. Though the exact equation varies, the relationship is consistent across the range of CCTs found in architectural lighting. A higher CRI is more restrictive of the placement of energy, thus the range of CDI possibilities becomes smaller. This demonstrates the antagonistic relationship between the two color rendition metrics. 71

Figure 6-4  |  Maximum CS/w versus CCT with different color rendition constraints (CRI, CDI) or a combination of constraints. 72

Figure 6-5  |  When maximizing CS/w, the peak wavelength for each primary becomes shorter as CCT increases. The peak wavelengths also vary based on the CRI constraint. 73

Figure 6-6  |  When maximizing CS/w, CDI increases as the value of the CRI constraint is increased and as CCT increases. 74

Figure 6-7  |  Properties of three different RGB LED mixtures, including circadian stimulation per watt of optical radiation (CS/w), luminous efficacy of radiation (LER), Color Rendering Index (CRI), and Color Discrimination Index (CDI). All three systems perform well. 76

Figure 6-8  |  Properties of seven different RGB LED mixtures, including circadian stimulation per watt of optical radiation (CS/w), luminous efficacy of radiation (LER), Color Rendering Index (CRI), and Color Discrimination Index (CDI). The choice of primaries has a dramatic impact on the performance of RGB LED mixtures. 77

Figure 6-9  |  Circadian stimulation per watt of optical radiation (CS/w), luminous efficacy of radiation (LER), Color Rendering Index (CRI), and Color Discrimination Index (CDI) of three RGB LED mixtures, the CIE F-Series, the CIE D-Series (5500 K, 6500 K, 7500 K) and blackbody radiation (4000 K, 5000 K). Except where the metric is defined by a reference source that is included, the RGB LED mixtures offer superior performance. 79
List of Tables

**Table 2-1** | Description and usage of the seven luminous efficiency functions recognized by the CIE. [From: CIE 1999] ................................................................................................................................................. 21

**Table 4-1** | Study Demographics. Subjects were divided into two groups, treatment and placebo. The groups were comparable in terms of age, gender, care type, cognitive ability, and mood disorders. ............................................................................................................................................. 41

**Table 5-1** | Peak wavelength, FWHM, and CIE 1931 chromaticity coordinates of the ten LEDs used as primaries............................................................................................................................................... 52

**Table 5-2** | Colorimetric, photometric, and other quantitative properties of the eight RGB LED mixtures ............................................................................................................................................... 53

**Table 5-3** | Results of the null condition trials. Shaded, bold values represent results that are statistically different from 50/50 at the $\alpha = 0.05$ level according to the Z test for proportions (normal approximation to binomial test) ................................................................................................................................................................. 56

**Table 5-4** | Results of the mixed condition trials, with each pairing representing a combination of both presentation orders. Shaded, bold values represent results that are statistically different from 50/50 at the $\alpha = 0.05$ level according to the Z test for proportions. Red, underlined values indicate combinations where the proportions for the younger and older groups were significantly different at the $\alpha = 0.05$ level. ............................................................................... 57

**Table 6-1** | Minimum, maximum, and average values of luminous efficacy of radiation (LER), Color Rendering Index (CRI), Color Discrimination Index (CDI), circadian stimulus (CS) and circadian stimulus per watt of optical radiation (CS/w) for three high-performing RGB LED mixtures. ............................................................................................................................................... 75

**Table 6-2** | CIE 1931 chromaticity coordinates, correlated color temperature (CCT), Color Rendering Index (CRI), Color Discrimination Index (CDI), circadian stimulus (CS), watts of optical radiation, luminous efficacy of radiation (LER) and circadian stimulus per watt of optical radiation (CS/w) for the CIE Standard Illuminants used as comparison standards........................................... 78
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/P</td>
<td>Circopic to Photopic Ratio</td>
</tr>
<tr>
<td>CAM</td>
<td>Color Appearance Model</td>
</tr>
<tr>
<td>CCT</td>
<td>Correlated Color Temperature</td>
</tr>
<tr>
<td>CDI</td>
<td>Color Discrimination Index</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de L’Eclairage</td>
</tr>
<tr>
<td>CMF</td>
<td>Color Matching Function</td>
</tr>
<tr>
<td>CRI</td>
<td>Color Rendering Index</td>
</tr>
<tr>
<td>CS</td>
<td>Circadian Stimulus</td>
</tr>
<tr>
<td>CS/w</td>
<td>Circadian Stimulus per Watt of Optical Radiation</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GDS</td>
<td>Geriatric Depression Scale</td>
</tr>
<tr>
<td>ipRGC</td>
<td>Intrinsically Photosensitive Retinal Ganglion Cell</td>
</tr>
<tr>
<td>L</td>
<td>Long-wavelength Sensitive Cone</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LER</td>
<td>Luminous Efficacy of Radiation</td>
</tr>
<tr>
<td>M</td>
<td>Medium-wavelength Sensitive Cone</td>
</tr>
<tr>
<td>RGB</td>
<td>Red, Green, Blue</td>
</tr>
<tr>
<td>RGC</td>
<td>Retinal Ganglion Cell</td>
</tr>
<tr>
<td>S</td>
<td>Short-wavelength Sensitive Cone</td>
</tr>
<tr>
<td>S/P</td>
<td>Scotopic to Photopic Ratio</td>
</tr>
<tr>
<td>SAD</td>
<td>Seasonal Affective Disorder</td>
</tr>
<tr>
<td>SCN</td>
<td>Suprachiasmatic Nucleus</td>
</tr>
<tr>
<td>SPD</td>
<td>Spectral Power Distribution</td>
</tr>
</tbody>
</table>
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1 Introduction

How much of beauty—of color as well as form—on which our eyes daily rest goes unperceived by us?

Henry David Thoreau, 1860

Though this prescient statement was not about the psychophysics of architectural lighting, it poses an important question. Human knowledge of vision has been increasing for centuries, but the last decade has ushered in a radical change. The recognition of the link between optical radiation and nonvisual biological processes challenges the very definition of “light,” which according to Merriam-Webster is something that makes vision possible. Today we know that radiant energy of wavelengths between 400 and 700 nm, the visible spectrum, is responsible for far more than making vision possible. In some ways, this energy does go unperceived, but it is not without impact.

Compared to many other technologies, architectural lighting is in its infancy; only in the past century has electric lighting become prevalent. Inconspicuously, humans have transitioned to a life lived indoors, inhabiting rooms illuminated by lamps optimized for luminous efficacy. Though the implications of such an evolution manifest themselves immediately, only with the dawn of the twenty-first century has society begun to comprehend that optical radiation not only provides for vision, but also has great bearing on human health.

The understanding of nonvisual photoreception, commonly called circadian photoreception, has built over the past decade and may eventually have a broad impact on architectural lighting design and lamp technologies. Existing illuminants are designed to specifications based on metrics that do not accurately capture the human response to optical radiation, whether it is brightness perception, color rendition, or other qualities of the luminous environment. Moreover, the proliferation of highly structured spectral power distributions (SPDs), brought on by the emergence of light emitting diodes (LEDs), has exacerbated the shortcomings of existing metrics.

Existing illuminants are not designed for maximum nonvisual effect per watt or maximum visual stimulation per watt. As both the characteristics of LEDs and their integration into a complete package improve, the ability to tune the spectral output of commercial lamps will progress. This improvement must be driven by research that better quantifies the psychophysical response to optical radiation. Better models of vision will allow lamp manufacturers to produce better products that increase circadian stimulation, elicit a greater perception of brightness, have improved color quality, and ideally do all these things simultaneously. In reality, these characteristics will require careful balancing.

Both visual and nonvisual impact must be optimized before efficacious illuminants intended to entrain human circadian rhythms and improve or maintain health can be used for general illumination. Light therapy has been effective for treating a variety of ailments, but employing lighting with similar characteristics and benefits in an architectural space is challenging because the therapeutic properties must be balanced with qualities that allow for an appropriate interior environment and energy efficiency. Using spectrally tuned architectural light sources could provide measurable benefit for populations at risk for conditions caused by poorly entrained circadian rhythms. One such population is seniors, who are particularly at risk for circadian disruption due to lifestyle, physiological, and environmental changes.
Properly tuning the spectral output of illuminants may help seniors to live healthier, more active lives and delay the need for higher-level care.

Properly tuned lamps with highly structured SPDs hold the promise of extending light therapy into architectural lighting. With the adaptable output of color-mixed LED systems, a 24-hour lighting scheme with variable potential for nonvisual stimulation is possible. Such a system has the potential to alleviate many of the conditions that now respond to light therapy treatment while maintaining an adequate visual environment and consuming less energy. To get to this point will require development in three areas:

1. Understanding the benefits, efficacy, and consequences of light therapy while documenting the broader implications of nonvisual photoreception.
2. Investigating the tradeoffs between nonvisual stimulation, brightness perception, color quality, and energy efficiency while building evidence for more accurate models of how humans process optical radiation.
3. Establishing models of optimized sources that target specific photosensitive systems or balance all the requirements of a healthy, energy-efficient, architectural lighting system.

Portions of these three areas were addressed with a series of research projects. The first was a clinical trial of light therapy for seniors in long-term care. The study examined the effect of tuned optical radiation on a sample of nursing home residents selected without prejudice for existing diagnoses using a battery of assessments for mood, sleep, circadian rhythms, and cognition. Second, a laboratory experiment examined the relationship between placement of short-wavelength or long-wavelength radiant energy and perceived brightness, seeking to provide insight into the effects of strong metamers and highlight challenges in source development that arise from the current system of colorimetry. Finally, in an effort to support development of illuminants for future circadian-inspired architectural lighting systems, a computer program was developed and calculations were performed to determine optimized red, green, blue (RGB) LED mixtures. Calculation parameters included metrics of luminous efficacy, nonvisual efficacy, and color quality to allow for an examination of the tradeoffs associated with tuning optical radiation.
2 Background

In order to tune the spectrum of illuminants for optimum benefit per watt, it is critical to understand the physical mechanisms of the human body that decipher electromagnetic radiation. Currently, much more is known about the phototransduction of visual information than nonvisual information, both of which are processed via the eye. However, the state of knowledge is changing rapidly.

The Human Eye—Fundamentals of Vision

Vision, the sense that allows for detection and interpretation of electromagnetic radiation, is the result of a complex composite of cells and neural pathways in both the eye and brain. The exact evolution of the primate visual system is speculative and the current understanding is far from complete, but the basic components that allow us to see the world are generally familiar. The fundamental components of the eye are presented in the following list. In addition, multiple muscles and fluids provide shape and structure.

- **Cornea**: The outermost layer of the eye, the cornea is the first and most powerful focusing element.
- **Pupil and Iris**: The iris, the colored part of the eye, is a muscle that expands and contracts to change the size of the pupil, the aperture that allows light to pass on to the retina. Change in pupil size alters our depth of field helps the eye adapt to various levels of brightness.
- **Lens**: The lens is another focusing element. Variable focusing, called accommodation, allows a sharp image to be formed on the retina. Yellowing and hardening of the lens over time is a significant factor causing changes in vision as people age.
- **Retina**: The retina is the back surface of the eye that contains photoreceptors as well as the supporting cells that combine and process signals before they are sent through the optic nerve to the brain.
- **Fovea**: The foveal pit is a small, 200 micron diameter region that lies at the center of the retina. It is unique because it has a concentration of cone photoreceptors that is much higher than in rest of the retina.

Photoreceptors are the elements of the eye that contain light sensitive pigments. Presently, the eye is known to contain three classes of photoreceptors: rods, cones, and intrinsically photosensitive retinal ganglion cells (ipRGCs). Each of these classes has different properties that allow visual and nonvisual systems to interpret light over a range of conditions and for multiple purposes. By having an array of photoreceptors with different capabilities, a greater amount of information can be passed on to the brain.

**Rod Photoreceptors**

Rods allow for night vision; they are the primary photoreceptors when luminance levels are less than 0.01 cd/m² [REA 2000]. The standard scotopic luminous efficiency function, V’(λ), describes the efficiency of radiant flux at stimulating the rod photoreceptors. This function has a peak wavelength at approximately 507 nm, relating to the spectral absorption properties of the photopigment rhodopsin, which the rods contain [REA 2000]. The distribution of rods on the retina is such that they are most heavily concentrated about 18° off-axis from the fovea, which contains no rod photoreceptors. While rods have the benefit of being extremely sensitive to the smallest quanta of light, they sacrifice the ability to distinguish between wavelengths, thus providing achromatic vision. Rod response is measurably
slower than cone response [MACLEOD 1972]. The signals from multiple rods converge on a single neuron, providing a low-resolution image that is best suited to detecting peripheral motion.

**CONE PHOTORECEPTORS**
Above 3.0 cd/m² rods are fully saturated and vision is dominated by the cones. This is called photopic vision. Humans with normal color vision have three types of cones, each with an opsin that peaks at a different wavelength. Through combination and interpretation of these three signals, humans are able to envision the world in color, despite the fact that the world itself is not inherently colored. The three types of cones, long-wavelength sensitive (L), medium-wavelength sensitive (M), and short-wavelength sensitive (S), are often erroneously referred to as red, green, and blue.

There are two ways of characterizing the peak sensitivity of cones: cone fundamentals derived from color matching functions (CMFs)—the numerical description of an observer’s response to chromatic stimuli—or through direct measurement of the sensitivity of the photopigments. When measured with microspectrophotometry, one of several methods for direct measurement, the three photopigments have peak sensitivities at approximately 430 nm, 530 nm, and 560 nm [DARTNALL ET AL. 1983], but other methods may result in slightly different peaks. Photopigment sensitivities are shown in Figure 2-1.

Cone fundamentals vary based on many factors including field size, match method, observer age, and chromatic adaptation. The peak wavelengths of cone fundamentals are approximately 440 nm, 545 nm, and 565 nm. While related to the sensitivity of the photopigments, cone fundamentals incorporate pre-retinal absorption and scattering of the lens, macula, and aqueous humors. They represent the sensitivity of the human visual system before light enters the eye [STOCKMAN & SHARPE 2007]. A variety of cone fundamentals, derived from multiple experiments using either a 2° or 10° field of view, are shown in Figure 2-1.

The distribution of the three types of cones and their relative sensitivities is fundamental to understanding the intricacies of human vision, as well as the metrics that are used to quantify light. S

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**Figure 2-1** | Normalized cone fundamentals derived from the color matching functions of the CIE (1931, 1964, 2007), Judd (1951), Vos (1971, 1990), Smith (1975), Demarco (1992), and Stockman (1993). Also shown are the photopigment sensitivities measured by Dartnall et al. [1983].
cones can be identified because they have a slightly different geometry than L and M cones. S cones make up only 3-5% of the cones in the foveal pit, about 15% on the foveal slope—approximately 1° out from the foveal pit—and about 8% of the total cones elsewhere in the retina [AHNELT ET AL. 1987]. Because short wavelength energy becomes blurry due to the optics of the eye, the lower density of S cones is not detrimental [BERNS 2000].

L and M cones are densely packed into a regular hexagonal pattern, dominating the fovea and making up the majority of photoreceptors throughout the retina. Interestingly, the proportion of L and M cones appears to vary significantly among people with ‘normal’ color vision, ranging from 1.1:1 to 16.5:1 [HOFER ET AL. 2005]. Cones do not contribute to vision individually, but form receptive fields with their signals combined and modified by horizontal, bipolar, amacrine, and ganglion cells before being sent to the brain.

Between 0.01 cd/m² and 3.0 cd/m² both rods and cones function simultaneously in mesopic vision. The efficiency of the visual system in this range lies somewhere between scotopic and photopic, but it remains without a firm definition.

**INTRINSICALLY PHOTOSENSITIVE RETINAL GANGLION CELLS (ipRGCs)**

The third class of photoreceptors is ipRGCs. Although they were referenced by Barlow and Levick [1969], Berson and colleagues [2002] recently distinguished ipRGCs as the long-sought circadian photoreceptor, establishing a link between neurophysiology and circadian photobiology. As far back as the 1920s, Keeler [1928] observed mice lacking rods and cones that still exhibited some ‘visual’ function, such as pupillary reflex, and hypothesized a novel photoreceptor.

Between 1928 and 2002, a body of work was building that subsequently led to the classification and functional understanding of ipRGCs. In the 1980s and 1990s, light therapy manifested itself as a viable treatment for seasonal affective disorder (SAD), a disorder linked to poorly maintained circadian rhythms [ROSENTHAL ET AL. 1984]. Later, an action spectrum for melatonin suppression—melatonin is a key hormonal marker of circadian activity—was derived [BRAINARD ET AL. 2001; THAPAN ET AL. 2001]. This action spectrum, with peak sensitivity at approximately 460 nm, could not be attributed to the opsins found in rods or cones, as shown in Figure 2-2. Similarly, other properties of photo-entrainment such as response threshold and long term temporal integration did not match the previously known photoreceptors.

Research into the source of circadian photoreception led Provencio and colleagues [2000] to propose melanopsin, with peak sensitivity at 480 nm (see Appendix), as the responsible photopigment. It would take other research, however, to rule out other possible sources of circadian photosensitivity such as cryptochromes. Subsequent work identified melanopsin in a subset of retinal ganglion cells (RGCs), resulting in the ipRGC sub-classification [BERSON ET AL. 2002; HATTAR ET AL. 2002]. Key evidence supporting melanopsin as the photopigment in ipRGCs was found by Lucas and colleagues [2003], among others, when no photosensitivity was shown in ipRGCs with targeted deletion of the melanopsin gene. Recent research has further confirmed melanopsin as the photosensitive pigment and investigations into the phototransduction cascade are ongoing [BERSON 2007; HANNIBAL & FAHRENKRUG 2006; SHIRANI & ST. LOUIS 2009]. The 480 nm peak sensitivity of melanopsin does not perfectly match the action spectrum for melatonin suppression, which has a peak that is closer to 460 nm. However, a more complex set of signals is responsible for melatonin suppression and circadian entrainment.

Receiving input from the rods and cones via horizontal, bipolar, and amacrine cells, standard RGCs act as the last link between retinal processing and the brain. RGCs send an axon through the optic nerve to synapse in the brain. ipRGCs, estimated to make up 1-2% of the total RGC population, directly transduce photic stimulation into neural impulses which are sent to the suprachiasmatic nucleus (SCN), the brain’s
circadian pacemaker, via the retinohypothalamic tract [BERSON 2007]. ipRGCs are distributed throughout the retina, with a somewhat higher density in the superior and temporal quadrants, and have long dendrites that spread over a large area [HATTAR ET AL. 2002; HANNIBAL ET AL. 2002]. The response of ipRGCs to light stimuli is significantly different from that of rods and cones:  

- ipRGCs have a depolarizing response to light as opposed to the hyperpolarizing response seen in rods and cones. [BERSON ET AL. 2002; BERSON 2003]  
- ipRGCs have less sensitivity to light and slower kinetics, with response latencies up to one minute. [BERSON ET AL. 2002]  
- Though the response decays from an initial peak, ipRGCs are capable of a stable, sustained response to bright light that allows for accurate integration of stimulus energy over long periods. They are not responsive to short bursts of light. [BERSON 2003, 2007]  
- ipRGCs are larger than other RGCs and feature individually photosensitive dendrites forming an overlapping net on the retina. [PROVENCIO ET AL. 2002; BERSON 2003]  
- ipRGCs project to the SCN, the circadian pacemaker, and the olivary pretectal nucleus, which is responsible for pupillary light reflex.

The dendrites of ipRGCs maintain connections to bipolar and amacrine cells, receiving signals from rod and cone photoreceptors in addition to the intrinsic photosensitivity of melanopsin. Early work in discovering the circadian photosensitivity of ipRGCs relied on using mice lacking either rods and cones or melanopsin. In both cases, results suggest at least some nonvisual response is maintained, although the signal is stronger when melanopsin is maintained [BERSON 2003]. Additionally, the peak sensitivity of photo-entrainment shifts in mice lacking rods and cones [YOSHIMURA & EBIHARA 1996]. In humans, SCN neurons have been shown to exhibit a response that requires input from both ipRGCs and traditional
photoreceptors [DROUWER ET AL. 2007]. Thus, under normal conditions, the photo-entraining signal is a mixture of multiple and redundant signals, but most likely is dominated by the response of melanopsin in the ipRGCs [BERSON 2003; PANDA ET AL. 2002, 2003; REA ET AL. 2005]. Furthermore, in humans lacking an outer retina, ipRGCs allow some basic visual sensation of shorter wavelength light, specifically blue light at approximately 480 nm [ZAIDI ET AL. 2007].

In addition to their role in circadian entrainment, ipRGCs are the critical photoreceptor in human pupillary reflex [GAMLIN ET AL. 2007]. ipRGC axons project to the olivary pretectal nucleus, the portion of the brain responsible for controlling pupil size. The relationship can be observed by evaluating the pupil response of melanopsin knockout mice and triple knockout mice. Melanopsin knockout mice, or those without the melanopsin photopigment, show greatly diminished pupillary light reflexes whereas triple knockout mice, or those without melanopsin, rhodopsin, or the cone photopigments, show no pupillary reflex [LUCAS ET AL. 2003; HATTAR ET AL. 2003; PANDA ET AL. 2003].

It is understood that photoreceptors adapt both chromatically and achromatically. The independent input of L, M, and S cones allows for differential saturation and a changing white point. Rods and cones also produce an initial peak response that tapers under constant illumination. This desensitization, called light adaptation, increases the dynamic range of the visual system. A similar but opposite transition occurs in dark environments. Unlike rods and cones, ipRGCs developed to record and transmit absolute light levels over extended periods; however, ipRGCs still exhibit both light and dark adaptation [WONG ET AL. 2005]. This physiology is congruent with psychophysical observations that ipRGC response is not fixed [EVANS ET AL. 2007; FIGUEIRO ET AL. 2005; JASSER ET AL. 2006; SMITH ET AL. 2004].

Models of Human Vision

One important element of illuminating engineering is the development of improved lamps, such as those that elicit maximum brightness perception per watt. To do this it is essential to understand the psychophysical response to light stimuli that results in a given perception of brightness, where brightness is defined as an “attribute of a visual sensation according to which a given visual stimulus appears to be more or less intense...or...appears to emit more or less light” [WYSZECKI & STILES 1982]. The fact that input power does not correspond with perceived brightness was clear to early lighting researchers and remains imperative today.

Color Vision

The current dominant theory holds that color vision is the product of multiple stages of processing and is often referred to as dual process theory [BERNS 2000; PALMER 1999]. In the 1950s, Hurvich and Jameson formulated the opponent colors model, which is based on the sequential combination of two prior theories, trichromacy and opponent signals, which were previously thought to be incompatible [HURVICH AND JAMESON 1957, 1960; JAMESON AND HURVICH 1955A, 1955B, 1964]. Hurvich and Jameson were not the first to conceptualize multistage visual processing, but earlier work by von Kries, Schrödinger, Müller, Judd, and others was not widely accepted at the time and lacked experimental evidence [BERNS 2000].

Modern trichromatic theory was largely the work of Palmer, Young, and Helmholtz in the late 1700s and early 1800s, with predecessor concepts dating back to Aristotle. Trichromatic theory states that there are three types of photoreceptors, nominally red, green, and blue, and that the combination of their output produces all color perceptions. Trichromacy explains many of the basic phenomena of vision including the three dimensions of color space, that three primaries can match any color, the existence of metamers, and the varieties of color blindness. However, it could not explain all observations; thus, Hering developed opponent signal theory in the late 1800s and early 1900s. This theory explained paired color sensations, the existence of yellow, and color mixtures. Like Helmholtz and his contemporaries,
Hering’s theory utilized three primary mechanisms. Instead of three photoreceptors, however, Hering’s mechanisms were three opponent signals.

Seeing trichromacy and opponent signals as complementary rather than conflicting, Hurvich and Jameson attributed color vision to both processes. The three photoreceptors act as described by trichromacy, but their output becomes input into opponent channels, as shown in Figure 2-3. These opponent channels are black-white (achromatic), blue-yellow (chromatic), and red-green (chromatic). Subsequent physiological research has confirmed the existence of three types of photoreceptors with different peak absorptions. Furthermore, additional cells in the retina, such as bipolar, horizontal, amacrine and ganglion cells, establish the opponent channels, processing information from the photoreceptors before it is passed on to the brain. The exact combination of inputs and outputs from these cells has not reached consensus.

Zone theories merge multiple models of vision into a single, multistage process to better account for visual phenomena. While Hurvich and Jameson popularized the concept, earlier qualitative work by Müller led to a multistage model by Judd that included three stages: trichromatic cone receptors, intermediate coding, and final neural coding [WYSZECKI & STILES 1982]. Continued physical experimentation on both perception and neurology has led to many new, more-refined multistage models. Guth and colleagues built the vector model of color vision [GUTH & LODGE 1973, GUTH ET AL. 1980], shown schematically in Figure 2-4, in which neural signals are linear combinations of the cone fundamentals. Other models have built upon this conceptual framework, but introduced additional nonlinearity to the system to better account for additivity failures [YAGUCHI & IKEDA 1983; NAKANO ET AL. 1988].

Expanding and refining the vector model, Guth and colleagues [1991] have proposed CA90, which involves relationships of increased complexity. De Valois and De Valois [1993] have independently produced a multistage model of human color vision, including stages for cone photoreception, cone opponency, perceptual opponency, and color-selective complex cells. Both the Guth and De Valois

![Figure 2-3](image)

**Figure 2-3** | Opponent signals from the model of color vision by Hurvich and Jameson. These functions (blue-yellow, red-green, and black-white) are linear transformations of color matching functions.
models employ additional processing stages of the type theorized by Müller. Advanced understanding of the neurology of vision [NEUMANN ET AL. 1988; VALBERG & SEIM 2007] has helped to relate visual phenomena to physical mechanisms, although linking psychophysical and neural responses is difficult. There are many models not included in this brief review.

Today, complete color appearance models have integrated earlier vector models with additional functions to account for adaptation and other complex processes. By definition, a color appearance model attempts to mathematically represent color vision and predict various attributes such as brightness, colorfulness, hue, lightness, chroma, and saturation while employing a chromatic adaptation transformation. These models will be discussed in a subsequent section.

Recognizing, investigating, and understanding visual phenomena has played an important role in characterizing the visual system. The ability to detect subtle differences in perception will be instrumental to mapping the complex interconnections of both the physical and psychological components of vision. To date, no model can claim complete accuracy, though many offer valuable insight.

COLORIMETRY
Colorimetry is the science of quantifying and describing human color perception. Though color vision varies from individual to individual, the development and subsequent adoption of Standard Observers in the 1924 and 1931 by the Commission Internationale de L’Eclairage (CIE) established the foundation for the CIE system of colorimetry. Although it was not the first of its kind, the CIE system has become the international standard. The CIE system is not without flaw and has been the subject of numerous
experiments aimed at improving its accuracy. Oftentimes, however, practical progression is thwarted by the difficulty of changing standards that are relied upon by industry.

In 1924, the CIE adopted the Standard Photopic Observer, \( V(\lambda) \), an experimentally-derived visual efficiency function that weights the visible spectrum on a wavelength-by-wavelength basis on its ability to stimulate the achromatic channel of the human visual system. Because it was derived from experiments that used flicker photometry and a 2° field of view, \( V(\lambda) \) and its quantitative derivatives are technically only applicable for foveal vision. In practice, it is often misapplied to other situations.

In 1931 the CIE adopted the 2° Standard Colorimetric Observer, characterized by the \( \bar{r}(\lambda) \), \( \bar{g}(\lambda) \), and \( \bar{b}(\lambda) \) CMFs. CMFs allow colored stimuli to be represented numerically by three tristimulus values, which represent the sensitivity of the visual system. The 1931 RGB CMFs are based on physically realizable primaries used in separate experiments by Wright and Guild [WRIGHT 1930; GUILD 1931; FAIRMAN ET AL. 1997; BROADBENT 2004]. In order to establish consistency with the Standard Photopic Observer and eliminate negative values, among other reasons, the RGB CMFs were transformed to \( \bar{x}(\lambda) \), \( \bar{y}(\lambda) \), \( \bar{z}(\lambda) \) using linear algebra and the XYZ tristimulus space was established. This process, predicated on Grassman’s laws, transformed the real primaries to imaginary ones so that \( \bar{y}(\lambda) \) became analogous to \( V(\lambda) \). Other manipulations were made, such as rounding \( \bar{z}(\lambda) \) to zero at long wavelengths, a move that has since been shown to be inappropriate [THORNTON 1999]. Both RGB and XYZ CMFs, derived from different experiments and through different transformations, are shown in Figure 2-5.

Colorimetry is reliant upon the trichromatic nature of human color vision, also known as the trichromatic generalization, as manifest in CMFs. Though it is commonly stated that trichromacy arises from the three cones, Thornton [1999] argues that trichromacy is in fact deeply rooted at the back end of perception. Of note is the fact that the peak sensitivities of CMFs, regardless of primary set used in their development, fall at approximately the same wavelength—450, 530, and 610 nm—which Thornton has coined the prime colors. It is notable that these peaks do not align with the cone fundamentals.

Due to the trichromatic nature of human color vision, the color of any light can be matched by a set of three independent primaries. This allows for metamerism, or the phenomenon in which spectrally different stimuli visually match to a given observer. Metamerism is fundamental to spectral tuning and the optimization of illuminants. It allows for the mixing of as few as two narrow-bandwidth primaries to create white light that is a visual match to a broadband source. The complexity lies in choosing the correct primaries to elicit maximum benefit per watt, considering many facets of illumination including brightness perception, color rendition, circadian phototransduction, and luminous efficacy. Furthermore, Commercialization requires consideration of practical realities such as quantum efficiency and other materials-based challenges.

Four distinct laws, known as Grassman’s Laws of Additive Color Mixing describe the linear combination of light stimuli. Generally, they are the symmetry law, transitivity law, proportionality law, and additivity law and can be combined and stated as: If \( A = B \) and \( C = D \), then \( kA = kB \) and \( A + C = B + D \) [WYSZECKI & STILES 1982]. Grassman’s laws are fundamental to colorimetry and are imperative to the validity of transformation of primaries, the process by which CMFs developed from a given set of primaries can be transformed to a different set. They can also be applied to brightness matching. Another fundamental element that governs the CIE colorimetry system is Abney’s Law, which states that the luminance of a compound stimulus is equal to the sum of the luminances of the individual parts. This can also be referred to as the additivity assumption. While luminance is additive by definition, brightness perception is not.
Figure 2-5 | Top: RGB color matching functions developed from different datasets. Bottom: XYZ color matching functions. The peak of the functions remain in the prime color regions (450, 530, and 610 nm) regardless of the primary set chosen. The functions of Thornton are raw and unmodified, resulting in notable differences in the long wavelength region of the blue and green functions.
The delicate, sometimes erroneous nature of CIE colorimetry has spurred continued development of CMFs, with the ultimate goal being a system that faithfully represents the human experience. Judd [1951] determined modified 2° XYZ CMFs that were subsequently updated by Vos [1978]. In both cases, the CMFs are more accurate in their representation of human vision, though they were never formally adopted by the CIE. Other subsequent modifications have been proposed by Smith and Pokorny [1975] as well as Stockman and colleagues [1993], among others. Through experimentation, Stiles and Burch [1955] generated a new set of RGB CMFs for a 2° field of view that has become the basis for more recent colorimetric data.

To help address the known confound of field size, data for color matching with a 10° field of view from Stiles and Burch [1959] and Speranskaya [1959] were combined and adopted as the CIE 1964 10° Standard Colorimetric Observer. It is defined by XYZ CMFs $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, and $\bar{z}_{10}(\lambda)$. Note that much like the 1931 Standard Observer, the 1964 Standard Observer is transformed to XYZ color space such that $\bar{y}_{10}(\lambda)$ is equivalent to $V_{10}(\lambda)$. The CIE recommends the use of the 1964 Standard Observer when field of view is greater than 4°. More recently, Thornton [1992a-c] collected new data for both 2° and 10° fields of view, using both the Maxwell and maximum saturation methods, and developed new RGB CMFs from different primary sets. Thornton’s work highlights the problematic nature of smoothing and manipulation that decreases the accuracy of the CIE CMFs. Large field CMFs have also been proposed and attempt to characterize perception at architectural scale [Hu & Houser 2005].

Though greatly improved, the newest CMFs proposed by Thornton [1997] still cannot perfectly predict metamerism. Thornton [1998] has advocated numerical-based optimization of CMFs in order to increase their prediction capabilities. Unfortunately, no matter how accurate a single set of CMFs, they will fail to represent individual variations in color vision because they are averages.

Cone fundamentals derived from both 2° and 10° CMFs and their modifications have been developed using several different linear transformations. Recently, the CIE has adopted new cone fundamentals for both 2° and 10° fields of view that are built upon the Stiles and Burch data, incorporate knowledge of pre-retinal pigment absorption, apply König’s hypothesis, and are intended to be physiologically meaningful [CIE 2006; Stockman & Sharpe 2007]. Work is ongoing to transform these cone fundamentals into XYZ-like CMFs with variations for age and field of view [Csuti & Schanda 2008].

The most recent addition to colorimetry is color appearance models (CAMs). The essential element of these models, and thus their relation to colorimetry, is the transformation of XYZ tristimulus values to cone responses, termed LMS or RGB depending on the model. These transformations can be either linear or nonlinear, though nonlinear transforms have less relation to the CIE system of colorimetry [Fairchild 2005]. Examples of these transformation models are those of Von Kreis, Nayatani, Guth, Fairchild, and the CIE. However, these chromatic adaptation models only predict matches under different viewing conditions, like those shown by Breneman [1987]. CAMs extend these models to predict absolute color appearance. In the book Color Appearance Models, Fairchild gives complete descriptions of several CAMs, including CIECAM02 as well as the Nayatani, Hunt, and RLAB models. How the recently adopted cone fundamentals are incorporated into CAMs remains to be seen.

Like chromaticity diagrams and color spaces, the inputs to CAMs are XYZ tristimulus values. One of the differences between the models is how this information is converted into cone sensitivities, but they are still reliant upon the ability of CMFs to predict metamerism. The importance of this cannot be understated. These models carry forward metameric mismatches and thus their application is limited. This is discussed further in subsequent sections.
COLOR SPACES
The prediction of color matches, color differences, and other properties of CMFs, as well as the graphical display of colorimetric quantities rely on tristimulus values, the vector representation of color stimuli in a three dimensional space. Tristimulus values epitomize the trichromatic nature of human vision. In basic terms, tristimulus values, with notation $X$, $Y$, and $Z$, are the amounts of each of three primaries necessary to match a given reference stimulus. They are calculated by integrating the product of the SPD of the stimulus and each of the CMFs. Chromaticity is a numerical, colorimetric quantification of color derived from the ratio of the tristimulus values. Chromaticity coordinates $x$, $y$, and $z$ are considered to represent the hue, chroma, and lightness of a stimulus for matching purposes and should not be used as an estimate of absolute visual appearance.

The visual display and mapping of chromaticity coordinates is another essential element of colorimetry. Through linear algebraic manipulation, the spacing of chromaticity coordinates in three-dimensional space, or a two dimensional projection called a chromaticity diagram, can be modified to better represent human perception. This is especially important when color difference is a concern.

The shape of chromaticity diagrams is reliant upon the primaries of the CMFs from which they are derived. The CIE system is based on the imaginary XYZ primaries and their associated tristimulus values. Thus, the XYZ color space is sometimes called the master color space of the CIE system. Nevertheless, it is possible to create a color space or chromaticity diagram based on any set of real or imaginary primaries.

The XYZ color space is commonly represented by the CIE 1931 chromaticity diagram, a two-dimensional projection of the three-dimensional space onto the x-y plane. Because chromaticity coordinates are a ratio of the three tristimulus values, their sum is always one. Thus, if the $x$ and $y$ coordinates are known, $z$ is also specified. The CIE 1931 chromaticity diagram is adequate in quantifying colors, but the spacing of the chromaticity coordinates does not match human perception. That is, two pairs of equal visual difference will not be equally spaced in the diagram. This shortcoming has been addressed with the adoption of new, more perceptually uniform spaces.

The CIE 1960 Uniform Chromaticity Scale uses a projection, obtained by weighting the tristimulus ratios, of the 1931 chromaticity diagram to create a more uniform space. This system was superseded by the 1976 system that further adjusted spacing by multiplying the $y$ coordinate by 50%. In 1976, the CIE also recognized CIELUV and CIELAB, two color spaces that add a third dimension to account for lightness in addition to hue and chroma. These spaces supersede the 1964 U*V*W* space.

It is worth repeating that chromaticity diagrams and color spaces are derived from CMFs via tristimulus values. All the spaces previously listed are mathematical representations of the 1931 XYZ color space. The use of different CMFs, such as the CIE 1964 10° CMFs, will result in variations to the diagrams including changes to the spectrum locus. It is thus implied that the accuracy of these representations, for color difference calculations or anything else, is limited by the ability of CMFs to accurately represent human perception.

ADDITIVITY FAILURES
Additivity, elucidated by Grassman’s Laws and Abney’s Law, is a fundamental assumption of CIE colorimetry. On many occasions, researchers have called into question the veracity of additivity [WYSZECKI & STILES 1982], providing evidence of its failure. Less conclusive are the impacts of additivity failures on CMFs and the transformation of primaries, the building blocks of colorimetry. Though evidence of consequential impact has been presented [THORNTON 1992A-C, 1997], recent work contests that both intra- and inter-observer variability are overriding factors [BRILL & ROBERTSON 2007, OLEARI & PAVESI 2008, ALFVIN & FAIRCHILD 1997]. It is likely that the same issue extends to the accuracy of CMFs in predicting
metamerism, as evidenced by the imperfection of any CMFs, even those mathematically optimized. Metameric mismatches can be attributed to many causes, including individual differences in pigmentation of both photoreceptors and transmissive elements of the eye, such as the macula and lens; participation of rod photoreceptors, or perhaps ipRGCs, though this is undocumented; the change in photosensor distribution across the retina, as manifest in field of view; photic history and adaptation condition; and cone saturation and other consequences of high luminance [WYSZECKI & STILES 1982].

Though its implication for colorimetry is obscure, additivity failure in photometry is well documented. Simply, luminance and brightness are not equivalent. Luminance, a derivative of the luminous efficiency function \( V(\lambda) \), is the product of flicker photometry. The flicker method negates the effect of spectral opponency, the root of additivity failure, whereas direct heterochromatic brightness matching and the threshold method, two other methods of photometry, do not [GUTH & LODGE 1973]. Independent research efforts have shown that either of these methods result in a visual efficiency function that is broader than \( V(\lambda) \), giving more weight to short- and long-wavelength energy. Alternative visual efficiency functions based on direct heterochromatic brightness matching [IKEDA & NAKANO 1986] have been adopted by the CIE.

In past research, additivity has been investigated as two somewhat distinct phenomena. Brightness to luminance ratios describe the condition where chromatic stimuli appear brighter with increased saturation [MACADAM 1950; CHAPANIS & HALSEY 1955; BURNS 1982; GUTH & LODGE 1973; WYSZECKI & STILES 1982]. This is also referred to as the Helmholtz-Kohlrausch effect. Multiple research methods can be used to derive these relationships, but one common method is for a series of monochromatic stimuli to be matched in brightness to a white reference. This can be done by either changing the luminance of the chromatic stimuli or reference white stimulus and have been named the Variable Chromatic Color method and Variable Achromatic Color method [NAYATANI 1997; NAYATANI & SOBAGAKI 2000]. One conclusion of the Helmholtz-Kohlrausch effect is that chromatic stimuli of short or long peak wavelength appear brighter than lights with peak wavelengths in the middle of the visible spectrum. Several researchers have developed chromaticity diagrams that display lines of equivalent brightness [GUTH & LODGE 1973; WYSZECKI & STILES 1982; NAYATANI 1997; NAYATANI & SOBAGAKI 2000].

Another approach to examining additivity failures is direct bichromatic brightness matching. In this method, two chromatic stimuli are matched to a broadband reference stimulus both independently and as a mixture. Though additivity predicts unity of luminances, the mixture will typically require either more or less luminance to appear at the same brightness as the reference with the combined luminance of the individual matches. Several major studies have developed comparable datasets to illustrate this effect [GUTH ET AL. 1969; YAGUCHI & IKEDA 1983; NAKANO ET AL. 1988]. When luminance underestimates perceived brightness, the pair is said to be superadditive (enhancement type), whereas when luminance overpredicts brightness, the pair is said to be subadditive (cancellation type). Subadditivity is typically seen between red and green stimuli, whereas superadditivity is typically seen for violet-blue and green-yellow stimuli. The root of these relationships lies in opponent color theory, but the contribution of chromatic channels to brightness perception, once thought to be solely a property of the achromatic channel, is now widely theorized. Like CMFs, additivity varies with individual as well as spatial and temporal features of the stimulus [NAKANO ET AL. 1988]. Although once predicted otherwise [GUTH ET AL. 1969], additivity has been shown to be independent of luminance [NAYATANI & SOBAGAKI 2000].

Nayatani has contended that B/L and additivity failure are in fact both elements of the Helmholtz-Kohlrausch effect. A model developed to predict the B/L effect [NAYATANI 1998] has also been shown to predict additivity failure associated with bichromatic brightness matching [NAYATANI & SOBAGAKI 2000], and has been integrated into the Nayatani color appearance model [FAIRCHILD 2005]. This model relies on
nonlinear principles, allowing more accurate prediction over linear vector models, such as those of Guth [GUTH & LODGE 1973; GUTH ET AL. 1980] which could not effectively model superadditivity.

Although the implications of additivity failure are notable, the theory can be difficult to accept. As MacAdam [1950] showed, it is clearly salient to human brightness perception:

_It is easy to show that the law of additivity, which necessarily applies to luminance because of its definition, does not apply to brightness. When a white mixture was kept unchanged in the comparison half of the field, and the red component of an equally bright white mixture was reduced in intensity, the resulting color was a bluish-green, very obviously brighter than the white. By merely removing red light from a white mixture, a brighter color was produced. The luminance as well as the energy content was obviously decreased, because the luminous red component was removed without any compensating increase of the other components. In order to obtain the resulting saturated color with brightness just equal to the white, it was also necessary to reduce the intensity of the green primary._

**Prime Color Theory**

It is well understood that vision is trichromatic, but this is often attributed to the three types of cones. It has been argued, most exhaustively by Thornton [1992A-C; 1997, 1998; THORNTON & FAIRMAN 1998], that the trichromatic nature of human vision lies not at the receptor stage, but rather at the back end of visual processing, the psychophysical. Dating back to at least Stiles and Crawford in 1933 [1933A], it has been shown both experimentally and analytically that the three peak sensitivities of the human visual system lie in the regions of 450, 530, and 610 nm, a triumvirate that Thornton has named the prime colors. It has also been demonstrated that energy in the intermediate regions, blue-green and yellow or 500 and 580 nm, is particularly detrimental to many aspects of vision, including color quality and brightness perception. Thornton has deemed these regions the anti-prime.

Thornton [1992B] provides an exhaustive review of early experiments that, while they did not all explicitly test prime color theory, demonstrate the trichromatic nature of perception that is fundamentally lost by the V(λ) function. Although there are dozens of articles, the works of MacAdam [1950, 1967] and Judd [1955, 1958] are particularly noteworthy. Thornton’s prime color theory was first developed in the 1970s and was described in a series of articles that show continued refinement of the theory [THORNTON 1971; 1972A; 1973A].

Prime color theory can be illustrated by considering a set of three chromatic stimuli, called primaries. If two primaries are held constant, the ratio of watts required in the third primary to those required in the sum of the other two primaries is minimized in the prime color region [THORNTON 1971] (Figure 2-6), and represent the regions of peak visual efficiency [THORNTON 1972A]. This relationship was first demonstrated analytically based on luminosity, and later experimentally with perceived brightness [THORNTON 1992A-C, 1997]. At the heart of this relationship are CMFs. Thornton has demonstrated that regardless of primary set, the peak of the three CMFs will always be in the prime color regions, within a 1-3 nm tolerance [THORNTON 1992A-C, 1999]. Also of critical importance is the fact that if the primaries are set to be prime colors, the peaks of the CMFs will all be equal in magnitude. These phenomena clearly demonstrate that the peak of the human visual system lies in the prime color regions.

As has previously been discussed, CMFs are at the heart of colorimetry. An important goal of color science is to establish CMFs that accurately weight the response of the human visual system. To date, this has not happened, as countless experiments have shown. In his six-part seminal work, _Toward a More Accurate and Extensible Colorimetry_, Thornton describes an extensive set of experiments undertaken to develop CMFs using three primary sets: prime color with primaries at 452, 533, and 607
nm, near-prime with primaries at 477, 558, and 638 nm, and anti-prime with peaks at 497, 579, and 653
nm. He used both the Maxwell method—matching three primaries to a white reference by varying one of
the primaries—and the maximum saturation method—matching two bichromatic stimuli. The matches
were carried out for both 1.3° and 10° fields of view and at high and low luminance levels of
approximately 30 cd/m² and 100 cd/m².

Thornton demonstrated that there is some difference between the 1931 or 1964 Standard Observers and
his modern CMFs [THORNTON 1999], as shown in Figure 2-5. The most notable difference is in the long-
wavelength tail of δ(λ). This function was modified and smoothed during development. However,
Thornton notes that these modifications are not responsible for brightness nonadditivity or metameric
mismatches. Rather, it appears that all CMFs are flawed. Thornton [1998] attempted to use optimization
techniques to reduce metameric mismatches with some success.

In the first experiment described in Toward a More Accurate and Extensible Colorimetry, Thornton
describes the visual matching of trichromatic sources to a reference white fluorescent lamplight, either
broadband or structured in nature. Using the Maxwell method, matches were made using prime, near-
prime, and anti-prime primary sets by varying one of the three primaries while holding the other two
fixed. Thirty total color and brightness matches were made by three observers using a different variable
primary for each. Several key relationships are shown in Figures 2-6 and 2-7. First, as previously
described, the peak power of the variable primary necessary for a match was always lowest at the prime
color. This is logical by the nature of CMFs and demonstrates the pure three-peaked response of the
human visual system. Second is the ratio of power for the broadband fluorescent reference stimulus to
the visually metameric trichromatic stimulus. Third is the ratio of computed luminance for the reference
stimulus compared to the trichromatic stimulus. These two relationships reveal that prime color stimuli
produce greater brightness per watt by up to 80% and greater brightness than is predicted by luminance
by approximately 20%. Simultaneously, it can be seen that energy in the anti-prime regions is very
detrimental, even if the other two primaries are in prime regions.

This dataset also illustrates the poor ability of either CIE Standard Observer, or any CMFs, to predict
accurately the chromaticity of strong metamers. The mismatch is particularly strong when at least one of
the primaries is in an anti-prime region, particularly the blue-green region between 480 and 500 nm (Figure 2-8). Prime color stimuli had less mismatch than anti-prime or bichromatic stimuli, where the difference in chromaticity of the reference and test stimuli were as great as 32 just noticeable differences or a $\Delta E^{ab}$ difference of 47. These mismatches were shown to be repeatable and in excess of individual variability. Demonstrating the practical impact of these mismatches, it was shown that a visual match could be made with a set of anti-prime primaries having a gamut not inclusive of the computed chromaticity of the reference. The metameric mismatches were not the result of rod intrusion [THORNTON & FAIRMAN 1998].

Additional work by Thornton [1992a] repeated the work of MacAdam to demonstrate the Helmholtz-Kohlrausch effect. Furthermore, using a cascade method of direct heterochromatic brightness matching, Thornton showed that perception of brightness varies in a trimodal manner, corroborating the much
earlier results of Stiles and Crawford [1933a]. While these findings were useful, the most profound concept to arise from this work was the fact that polychromatic stimuli of equal perceived color and equal luminance can elicit very different perceptions of brightness. In other words, brightness per lumen is not constant at constant chromaticity. Brightness and luminance do not appear to have a well-defined or easily modeled relationship for trichromatic sources.

In 1973, Thornton [1973a] proposed a brightness correlate similar to that of Guth and Lodge [1973]. Such correlates produce the equivalent of a three-peaked weighting function, although they cannot be used as such due to additivity failures. The correlates are derived from the three peaked response of CMFs such that they are a combination of the achromatic (additive) and chromatic (nonadditive) response predicted by opponent signals theory. Thornton demonstrated that the luminous efficiency function V(λ) can be modeled as a combination of only f*(λ) and g*(λ), the contributors to the achromatic channel of vision.

Thornton formulated an updated model in 1992, optimizing the coefficients based on experimental brightness matches. He found that, while it was not perfect in predicting perceived brightness of monochromatic, bichromatic, or trichromatic stimuli spaced throughout the color space, it reduced the discrepancy of luminance (40%) down to 10% [Thornton 1992c]. It is important to note that this model remains a linear model and cannot predict superadditivity as can be done with nonlinear models. The model predicted that between 93% and 96% of brightness perception of trichromatic stimuli was due to achromatic stimulation. However, earlier results showing luminance underpredicting brightness perception by 50% or more may suggest this is inaccurate.

Thornton has also observed the importance of prime colors in other ways. He demonstrated that metameric spectral reflectance distributions intersect in the prime color regions with remarkable
frequency [1973; 1993], a phenomenon that occurs regardless of the transformation primaries. This unique relationship again points to the importance of the prime color regions in human vision.

Prime color theory also has implications for color quality. Thornton [1971] showed that when two primaries of any three primary set matched to a reference white source were held constant, the variable third primary maximizes CRI when it is in a prime color region, 450, 540, or 610 nm. Although there is some variability (± 3 nm), this holds true regardless of the CCT of the reference source or the specific peak of the other two primaries. Color Discrimination Index (CDI) [THORNTON 1972b] holds a similar three peaked relationship, although the primaries are maximized at approximately 430, 525, and 650 nm [THORNTON 1992b]. These relationships, as well as the similar relationship for Color Preference Index [JUDD 1967] are shown in Figure 2-9, which also demonstrates the particularly harmful effect of energy in the anti-prime regions. It is important to note that these plots were developed by varying only one primary at a time. Thus, it is logical that color quality decreases as the peak wavelength of the variable primary becomes closer to one of the fixed primaries.

Simply, Thornton argues that prime color lights will elicit maximum brightness perception per watt [THORNTON 1999] while simultaneously offering pleasing color rendition. Though perceived brightness is nonadditive, Thornton has also shown that a polychromatic light comprised of prime color components will elicit a perception of brightness greater than predicted by luminance. Unfortunately, this relationship is not as simple as can be predicted by a simple linear combination of CMFs.

Figure 2-9  | Color Rendering Index (solid), Color Discrimination Index (long dashes), and Color Preference Index (short dashes) as a function of the variable primary of a trichromatic mixture equal in chromaticity to CIE Illuminant D65. The variable primary in each region (divided by vertical dashed lines) is combined with a fixed primary from the other two regions. [From: Thornton 1992b]
**Brightness Metrics**

Today, lamp output is maximized for lumens per watt even though it is well recognized that luminance does not equate to brightness perception. Furthermore, optimizing light sources for lumen output can have a detrimental effect on other attributes such as color rendition and preference. With the rise of LEDs in the architectural lighting marketplace, the presence of strong metameris and the associated visual mismatches of stimuli with equivalent tristimulus values will have a profound effect. Understanding the relationship between perception and spectral content of illuminants should be a foremost goal that will help to shape attitudes towards this technology in a positive manner.

\( V(\lambda) \) is inaccurate in representing the human response to illumination as it typically occurs in architectural environments [HOUSER 2001]. This relationship has been recognized since the 1930s, and has often been argued quite pointedly. In 1955, one of the creators of the 1931 standard observer, Judd, stated:

> It is worth pointing out the C.I.E... have come to regard its standard luminous efficiency function, on which all of photometry is based, as an arbitrary wavelength function adopted for its convenience and utility rather than because luminance so evaluated correlates with what the eye[s] see.

Judd argued that a new luminous efficiency function should be developed as a weighted mixture of the CMFs. This idea has been investigated in numerous experiments ever since, with many new metrics being proposed. It forms the basis for new luminous efficiency functions, linear and nonlinear brightness models, and color appearance models. To date, however, no function or model has gained prominence. Though they offer much increased prediction capabilities of visual phenomena, no single model can simply and accurately predict human perception. Thus, the misuse of \( V(\lambda) \)-based photometry continues unabated.

Most of the inapplicability of \( V(\lambda) \) stems from the way in which it was developed, a process that would likely be very different with increased technological capabilities [FAIRMAN ET AL. 1997; BROADBENT 2004]. Many researchers have sought to improve photometry by developing new luminous efficiency functions through alternative methods or by modifying the original function. Acknowledging these efforts, the CIE recognizes several alternative measures. These are described in a report by CIE committee TC1-30 [CIE 1999] and shown in Table 2-1 and Figure 2-2. The ensuing discussion highlights some of the important differences.

As RGB CMFs have been tweaked, their primaries can be transformed to the XYZ color space. This typically results in mismatches of the \( \tilde{y}(\lambda) \) function. One such example is the set of CMFs proposed by Vos [1978], which has been shown to produce better matches of both color and brightness [CSUTI & SCHANDA 2008]. Though its improvements were initially thought to be too minor to warrant change, in 1990 the CIE officially recognized \( V_m(\lambda) \), a modified luminous efficiency function that attempts to more faithfully characterize the visual response to short wavelength energy.

Recognizing the importance of field of view, \( V_{10}(\lambda) \) was adopted and recommended for use when field size is greater than 4°. This function is based largely on the work of Stiles and Burch [1959].

In recognizing the limitations of flicker photometry, direct heterochromatic brightness matching has been used on several occasions [STILES & CRAWFORD 1933A; GUTH ET AL. 1969; IKEDA & NAKANO 1986; THORNTON 1992A]. This method typically results in a broader visual efficiency function giving increased weight to short- and long-wavelength energy. In some cases a three peaked function results. The CIE officially recognizes the functions of Ikeda and Nakano [1986], which are derived for point, 2°, and 10° fields of view, as \( V_{b,p}(\lambda), V_{b,2}(\lambda), V_{b,10}(\lambda) \). Ikeda and Nakano also demonstrated the large variability in
individual visual efficiency functions. Thus, the average method used by all efficiency functions is unlikely to represent any individual accurately.

It is logical that improvements in understanding the processes of color vision have led to improvements in understanding brightness perception. The nonequivalence of luminance and brightness limits the utility of any spectral weighting function that distills the achromatic and chromatic responses of the trichromatic visual system into a single function. While no consensus model exists for brightness perception, the opponent colors model and other zone theories suggest that the human evaluation of brightness comes from a combination of the achromatic and two chromatic channels. The difference between a purely achromatic response, as is luminance, and human perception could be as great as 50% [THORNTON 1992A]. It is believed that the achromatic channel follows the additivity assumption, whereas the chromatic channels do not [HOUSER 2001].

The three opponent signals can be mathematically manipulated in linear or nonlinear fashion to produce a measure of brightness perception. There are many examples of this type of model, some of which have been discussed previously, which all follow the same basic form [HOUSER 2001]:

\[
\beta = (|aX + bY + cZ|^p + |dX + eY + fZ|^p + |gX + hY + iZ|^p)^{1/p} \\
\]

In this formula, tristimulus values are modified by an exponent and multiplied by nine coefficients that vary based on the empirical derivation of different researchers. Models of this form have been shown to
predict brightness perception better than V(λ) since they account for both the achromatic and chromatic components, though they are still imperfect [THORNTON 1992c]. The addition of nonlinear terms in these models and nonlinear transformations from tristimulus values to cone responses can result in improved accuracy [NAKANO ET AL. 1988; FAIRCHILD 2005]. CAMs typically employ some form of this function to compute a brightness correlate. The inherent flaw in this model, however, is the reliance upon tristimulus values. Thornton has definitively shown that no set of CMFs can eliminate metameric mismatches [1992A-C; 1998B]. In other words, no matter what currently available system is used to define perception numerically, there will always be a difference in colorimetric and perceptual appearance. This confound is investigated in chapter six of this dissertation, where eight numerically equivalent illuminants were found to elicit statistically significant differences in brightness perception. Not even the most current forms of brightness metrics can account for this discrepancy.

As knowledge of the stages of visual processing continues to develop, the form of brightness correlates is almost certain to change. However, a final, perfectly accurate model of human vision may never be achieved.

Circadian Rhythms

Just as plants grow towards sunlight, light sends critical information to the human body that cues many internal functions. The complex system that receives and interprets photic cues developed under the regular patterns of natural daylight. With the development of electric lighting, humans now spend much of their time indoors where they do not always receive the photic stimulation required to entrain circadian rhythms.

Circadian rhythms are related to homeostasis and regulation of many important physiological and functional capacities including sleep-wake patterns, activity levels, arousal, appetite, hormone secretion, body temperature cycles, cardiovascular function, mood and emotions, cognition and memory, and some specific cell functions. Circadian rhythms, however, are not synchronous with a 24-hour clock—they are generally found to be slightly longer [CZEISLER ET AL. 1999; MIDDLETON ET AL. 1996] and require entrainment from an external stimulus, typically light, called a zeitgeber. Recent advances in understanding the physiology of the eye, previously discussed, clearly demonstrate the importance of light by establishing the interface between illumination and the brain.

Three recognizable markers of human circadian rhythms are core body temperature, cortisol, and melatonin, though there are undoubtedly more. Of these, melatonin is most often used as a measurement tool in scientific applications since it can be easily measured in saliva, blood, or other body fluids [MIRICK & DAVIS 2008]. Levels of melatonin, or the ‘sleep hormone,’ are highest during the night, peaking between 2:00 and 4:00 AM, and decrease in the morning [REITER 1993; BRZEZINSKI 1997]. Conversely, cortisol levels rise in the morning and are high during the day. The ability of light to suppress melatonin was reported as early as 1975 [WURTMAN 1975] and more specifically in 1980 when Lewy and colleagues showed that nocturnal exposure to light could return melatonin to daytime levels.

CIRCADIAN DISORDERS

While the full range of consequences of disrupted circadian rhythms is not completely understood or documented, disruption may be linked to cardiovascular, respiratory, endocrine, rheumatological, psychiatric, and neurological diseases [KLERMAN 2005]. Light therapy is a general term that refers to using light as a nonpharmacological intervention for these disorders, most often mood, cognitive, and sleep disorders. The precise link between the circadian-entraining effects of light stimuli and health benefits, such as antidepressant effects or improved cognition, is still being investigated. However, in investigating this link, many of the properties of circadian phototransduction have been established.
Circadian Efficacy of Optical Radiation

The relationship between light and human biological systems has been actively examined for decades. Developments by illuminating engineers, medical doctors, and others will undoubtedly lead to improvements in the efficacy of light therapy. This tuning is likely to occur over time as individual aspects of circadian light are examined.

Many studies that have examined properties of circadian light have relied on nocturnal melatonin suppression. This experimental method has been used since at least 1980 and although it cannot be related directly to the daytime effect of light treatment for various ailments, it does indicate the relative ability of different lighting conditions to affect the human circadian system. Such protocols typically are performed in a laboratory environment where light exposure before and during the stimulus period can be carefully monitored. As the quantity and quality of daytime light therapy trials increases, the properties of circadian light that provide maximum benefit will be better understood.

SPECTRUM

Brainard and colleagues [2001] and Thapan and colleagues [2001] both identified the action spectrum for light to suppress melatonin in humans as having peak sensitivity between 460 and 480 nm. Subsequently, researchers identified ipRGCs as the key link between light stimuli and circadian entrainment [HATTAR ET AL. 2002; BERSON ET AL. 2002]. It is apparent that many previous light therapy trials were not using illuminants with high circadian efficacy.

While ipRGCs are a key element in the nonvisual neurological pathway and function in the absence of other photoreceptors [CZEISLER ET AL. 1995; KLERMAN ET AL. 2002; ZAIDI ET AL. 2007], the response of the circadian system is not solely reliant on ipRGCs. Rather, research by Rea and colleagues [2005] led to the development of a model for phototransduction by the circadian system that accounts for the complex relationship between rods, cones, and ipRGCs that all send information to the SCN. This is similar to models of visual efficiency that combine inputs from multiple photoreceptors.

Rea and colleagues’ model, called CS for circadian stimulus, utilizes previous research on the spectral sensitivity of the circadian system while also considering complex interrelationships such as spectral opponency. For example, in two sources having the same irradiance at 436 nm, the source with no other radiant energy has a greater ability to suppress melatonin [FIGUEIRO 2005]. Spectrally opponent retinal neurons are believed to be responsible for this subadditivity [FIGUEIRO 2008]. While Rea’s model of phototransduction by the human circadian system accounts for spectrum in a very detailed manner, it does not attempt to include other important stimulus characteristics such as spatial distribution or pre-exposure photic history.

CS is the instantaneous circadian stimulus and can be multiplied by time to generate a dose-response. CS weights irradiance based on the sensitivity of the human circadian system and therefore carries units of circadian weighted W/m². However, CS cannot be considered an action spectrum because additivity is not obeyed—radiant energy weighted by the CS function cannot be summed to predict response because quantity of energy is an element of the function. Figure 2-10 shows both experimental data and the response of the circadian system to monochromatic light at each wavelength predicted by the CS model.

The concept of a spectral response for circadian stimulation existed long before 2001. The teams led by Brainard, Oren, and Lee all investigated the effect of different light spectra, but did not systematically develop a spectral response model [BRAINARD ET AL. 1990; OREN ET AL. 1991; LEE ET AL. 1997]. Since 2001, several light therapy trials have utilized efficacious blue light with conclusive results. For example, over the same duration and with the same photon density, monochromatic light at 555 nm produced only half...
of the phase-shifting effect of monochromatic light at 460 nm [LOCKLEY ET AL. 2003]. Similarly, short-wavelength, 470 nm light was most effective at producing a phase advance in melatonin cycles compared to light at 497, 525, 595, and 660 nm wavelengths [WRIGHT ET AL. 2004]. The same trends can also be seen by measuring alertness, thermoregulation, and heart rate [CAJOCHEN ET AL. 2005]. Because circadian phototransduction is spectrum-dependent, V(\lambda)-based metrics, such as illuminance and luminance, are not sufficient for characterizing circadian light without additional information.

The CS model was shown to predict accurately the results from earlier studies and continued research offers additional confirmation. Kozaki and colleagues [2008] measured melatonin suppression by lamps providing 200 lux at varying correlated color temperatures (dim, 2300 K, 3000 K, 5000 K) for 1.5 hours of exposure beginning at midnight. The 5000 K lamp was most effective, the 3000 K lamp had some effect, and the 2300 K and dim lamps had no effect. The importance of SPD in dosing is even clearer when comparing a blue LED to a 3000 K rare earth fluorescent lamp. The blue LED provides more than 30 times more circadian stimulation than the fluorescent lamp [REA 2006].

As the visual system ages, reduced pupillary response and yellowing lenses mean less optical radiation, especially circadian-effective short-wavelength radiation, reaches the retina. People in their 80’s and 90’s maintain only 10% of the circadian photoreception of a 10-year-old (Figure 2-11) [TURNER & MAINSTER 2008]. Considering this decline is particularly important because the reduction in transmission is not uniform across the spectrum. In order to investigate the impact of this changing physiology, CS-age was calculated by using the curves in Figure 2-11 to multiply the measured or calculated input to the eye, which is not weighted. However, this can only serve as an approximation because efficiency functions already consider the transmissive elements of the eye based on the experimental methods used in their development.
**DURATION AND INTENSITY**

In early trials, a light therapy dose was typically described by duration (hours) and illuminance (lux), or lux-hours. Clinical trials of nominally white light have used stimuli ranging from 2,000 to 10,000 lux with durations from 30 minutes to several hours. While many studies have reported using 10,000 lux of white light, the actual delivery of this large quantity of light at the eye is rarely verified or documented. Individuals may receive a very different dose that is inversely proportional to the square of the distance between the source and the eye. Furthermore, such high intensities may cause squinting or discomfort, which can reduce retinal exposure. Because of the spectral response of the circadian system, a true measure of dose must also include SPD. Since few studies documented the SPD of the lamp or the actual stimulation at the eye, it is difficult to compare, validate, or synthesize results. Nonetheless, many of the outcomes from previous research can be translated to current knowledge and assist in the development of new trials. Recent blue light trials have used much lower illuminance levels, less than 500 lux, since the blue light has a much higher CS value.

Aoki and colleagues [1998] examined the relationship between salivary melatonin suppression and both intensity and duration, finding a linear inverse relationship between the minimum light intensity needed to suppress melatonin and the duration of exposure. Curves were also calculated for mean percent of melatonin suppression as a function of dose (lux-hours). A cool-white full-spectrum fluorescent lamp was used and intensity was varied by altering the distance between the stimulus and observer. Lower intensity light still suppressed melatonin, but at a lower rate. Thus, dim light over long periods of time is not a good placebo. Similarly, McIntyre and colleagues [1989] found the maximum suppression of melatonin following 1 hour of light at midnight was 71%, 67%, 44%, 38%, and 16% with intensities of 3000, 1000, 500, 350, and 200 lux, respectively. These studies also show a maximum achievable suppression rate of approximately 1.5% per minute, with a plateau being reached between 30 and 60 minutes.
Cajochen and colleagues [2000] and Zeitzer and colleagues [2000] examined the dose-response relationship using melatonin measures, subjective measures of alertness, and electroencephalographic (EEG) recordings during the early biological night. While having only half the alerting effect of light at 9100 lux, light at 100 lux still had a significant effect on circadian rhythms. A logistic dose-response curve was reported. Another study examined subjects in temporal isolation experiencing 12-hour light-dark cycles of 200 lux or 1000 lux broad spectrum white light, finding that 200 lux was not sufficient to maintain circadian phase while 1000 lux was sufficient and produced a significant overall phase advance [MIDDLETON ET AL. 2002].

With increased knowledge of the spectral response of the circadian system, Figueiro and colleagues [2006] measured nocturnal melatonin suppression under 4100 K and 8000 K fluorescent lamps at 30, 100, 300 and 1000 lux at the eye, seeking validation of the CS model. The model proved accurate in ordering the capability of the two spectra, but the rate of nocturnal melatonin suppression cannot be predicted by the magnitude of the stimulus alone. Corroborating the work of McIntyre and colleagues [1989], Figueiro and colleagues found the maximum melatonin suppression after 30 minutes of exposure to be approximately 45-50%, or 1.5% per minute.

The relationship between dose and circadian regulation cannot be modeled in a simplistic fashion, in part because it relies on specific human response. For example, melatonin suppression at 1000 lux was found to be lower than predicted after 30 minutes of exposure, with researchers noting that some subjects found this intensity to be uncomfortable, leading to squinting and reducing the amount of light entering the eye [FIGUEIRO ET AL. 2006]. While the work of Aoki, McIntyre, Cajochen, Middleton and others all used white light with little consideration for SPD, it illustrates that duration must be considered along with spectrum and intensity. While it may suppress melatonin at a slower rate, lower intensity light still has an effect. It is important to note, however, that dose relationships have only been investigated for specific circadian parameters. The dose necessary for light to have an antidepressant effect or improve cognition remains unknown.

**TIMING**

Timing of light therapy is an easily identifiable source of variability, though its effect on circadian phototransduction is less defined. Based on the time of application of the light therapy treatment, the circadian cycle of the subject will be either phase-advanced or phase-delayed. Treatment at the end of the circadian night, or early morning, will result in a phase advance—a forward movement in the cyclic pattern of circadian activity—while treatment in the evening or early night will result in a phase delay [JEWETT ET AL. 1997]. Advances are greater with earlier treatment and delays are greater with later treatment [TERMAN ET AL. 2001]. Phase shifts do not vary between men and women, or older and younger subjects [KRIPKE ET AL. 2007]. Furthermore, clock time and circadian time are asynchronous and each individual has a different circadian time. Thus, providing bright light therapy at a specific clock time will not have the same effect on all patients. In lieu of developing a specific melatonin profile for each individual, morningness-eveningness score may be used as a proxy [TERMAN & TERMAN 2005].

One study has shown marginal correlation between the size of phase advance and the antidepressant effect of light therapy for SAD [TERMAN ET AL. 2001]. However, in numerous clinical trials morning light treatment has been shown to have a significantly greater antidepressant effect in treatment of SAD [EASTMAN ET AL. 1998; LEWY ET AL. 1998; TERMAN ET AL. 1998; TERMAN ET AL. 2001]. Ideally, light therapy should be tailored to an individual’s circadian rhythms. Since many seniors experience a phase-advanced cycle, evening light may be a better treatment [STEPNOWSKY & ANCOLI-ISRAEL 2008]. However, only one study of seniors included an evening light treatment group with seniors, with no benefit over placebo being found regardless of time [LOVING ET AL. 2005].
Another alternative to short-duration light therapy sessions is an architectural intervention. These systems are designed to provide higher levels of illumination in the daytime living environment. Several studies have shown a positive effect from this type of treatment [RIEMERSMA-VAN DER LEK 2008; HICKMAN ET AL. 2007; VAN HOOF ET AL. 2009].

The exact effect of morning, evening, or full-day light therapy cannot be easily measured in a highly controlled laboratory experiment. Additionally, the effect can be examined through a variety of outcome measures. Considering individual differences and specific subpopulations that may have a different circadian phase, one specific ideal time may not exist. The lack of understanding of the specific link between melatonin suppression and measurable health benefits further complicates the choice of exposure time.

PHOTIC HISTORY AND ADAPTATION

Past studies have noted changes in the sensitivity of circadian phototransduction, a result that is not surprising since it has been demonstrated that ipRGCs, as well as rods and cones, experience adaptation. Jasser and colleagues [2006] compared nocturnal melatonin suppression in two groups: one completely dark-adapted and the other adapted to 18 lux of white light. Those adapted to dim light experienced less melatonin suppression. Another study confirmed that in mice, dim light is not a zeitgeber but found it to alter circadian rhythms significantly [EVANS ET AL. 2007].

These results indicate that photic history and adaptation condition are important variables in clinical trials of light therapy, even though they have rarely been considered. This behavior may also relate to the variable efficacy of light therapy based on time of treatment, as the adapting condition for morning versus evening treatment would likely be different. More effort is needed in this area to determine the precise effect that adaptation has on the other properties of circadian light.

LOCATION AND SIZE

The suppression of nocturnal melatonin in humans is dependent on the exposure area on the human retina. Some research indicates inferior (lower half) retinal light exposure is more effective at suppressing melatonin than superior (upper half) retinal light exposure [GLICKMAN ET AL. 2003]. One plausible explanation for this is that the human eye has developed in response to natural daylight, which has greater exposure on the inferior retina. This finding tacitly implies that a relationship between source area, luminance, and melatonin suppression should exist. However, another study found that melatonin suppression by light exposing the central and peripheral portions of the retina did not differ [ADLER ET AL. 1992]. This latter result is supported by more recent findings that the density of ipRGCs is somewhat higher in the superior and temporal quadrants of the retina [HATTAR ET AL. 2002; HANNIBAL ET AL. 2002]. However, circadian phototransduction is not solely a function of ipRGCs. Thus, the conclusions of Glickman and colleagues are still plausible, but further investigation is warranted.

DAYLIGHT AND THE IMPORTANCE OF CIRCADIAN LIGHTING

Not unexpectedly, daylight is an outstanding circadian source. It is of high intensity, it exhibits regular patterns, during most of the day it has a spectrum with a high level of optical radiation in the shorter wavelengths, and it is economical and sustainable. In fact, CIE Standard Illuminant D65 has a dominant wavelength of approximately 477 nm, well aligned with the peak sensitivity of ipRGCs and within the peak region for phototransduction by the circadian system.

The human body developed under daylight and when daylight exposure is lacking, disorders linked to circadian disruption are more prevalent. This can occur in less-mobile populations, in areas far from the equator, for night-shift workers, or in poorly designed buildings. The latter could be managed by
designing better buildings, but this does not account for the stock of existing buildings. Light therapy is, essentially, an attempt to replicate the effects of normal exposure to daylight.

As the amount of carefully documented data increases, a more precise dose-response function may be developed that considers the many properties of circadian light. However, the enormous variation in human physiology will likely prelude the development of one single ideal light therapy regimen. It is clear though that spectrally targeted light does not require the very high illuminance once thought necessary for circadian entrainment. Other studies have shown the effect of relatively low levels of illumination over a long duration. For some populations, such as seniors in long-term care, full-day architectural lighting solutions may provide a meaningful entraining effect, acting as a prophylactic measure to prevent ailments associated with circadian disruption. Such solutions may better replicate the daily patterns of daylight that entrain circadian rhythms in healthy, mobile individuals.

Circadian Disruption in Seniors: Prevalence, Measurement, and Consequences

Physiological, environmental, and lifestyle changes in seniors, especially those in long-term care, can have a profound effect on circadian function, often leading to a decrease in functional capacities and quality of life. Degeneration of the SCN [HOFMAN & SWAAB 2006], a decrease in transmission of light through the lens [TURNER & MAINSTER 2008], and reduced exposure to lower levels of environmental illumination [SOCHAT ET AL. 2000; MISHIMA ET AL. 2001; CAMPBELL ET AL. 1988] can act in parallel with changes in melatonin secretion [DEUSCHLE ET AL. 1997, TOUITOU 2001, MISHIMA ET AL. 2001] and circadian rhythms [HOFMAN & SWAAB 2006; MONK 2005] to cause sleep disorders and daytime deficits [STEPNOWSKY & ANCOLI-ISRAEL 2008; ANCOLI-ISRAEL & COOKE 2005; ANCOLI-ISRAEL & AYALON 2006; OHAYON 2002; VAN SOMEREN 2000] as well as depression [ZARIT & ZARIT 2007; KESSLER ET AL. 2003; BLAZER 2002] in a significant percentage of seniors. The conditions are not exclusive, as research suggests that about 20% of insomnia patients have depression whereas 90% of depressed patients report sleep problems [STEPNOWSKY & ANCOLI-ISRAEL 2008]. Forty percent of insomnia patients have co-morbid psychiatric disorder, and the odds of a future diagnosis of major depression are much higher for those with a diagnosis of insomnia [FORD & KAMEROW 1989; ROBERTS ET AL. 2000]. Moreover, both sleep and mood disorders are more prevalent in residents of long-term care [ZARIT & ZARIT 2007; MIDDLEKOOP ET AL. 1994] and are a significant factor in the evaluation of whether a person requires institutionalization [POLLACK & PERLICK 1991]. Unfortunately, features of depression may overlap with medical illness among seniors and can lead to misdiagnosis and lack of treatment, regardless of care setting, severity of illness, or level of dependency [MURPHY & CAMPBELL 1996; WARNER 1998].

Degeneration of the SCN and disturbed circadian rhythms are also associated with dementia [FORBES ET AL. 2009; HOFMAN & SWAAB 2006], a condition that affects about 5% of the population by age 75, but upwards of 30% by age 85 [ZARIT & ZARIT 2007]. Research indicates that exposure to light stimuli can help restore SCN activity [LUCASSEN ET AL. 1995; VAN SOMEREN 2000], which raises the possibility that certain light exposure may have a therapeutic effect for not only circadian rhythms but other associated diseases. With the combination of ailments affecting seniors, especially those in long-term care, research into the prevention and amelioration of circadian-linked disorders is a high priority. While these ailments are subsequently discussed individually, it is critical to understand that they are interconnected with each other and with circadian disruption. A tremendous benefit of light therapy is its ability to improve simultaneously many of the ailments that plague aging adults.

DEPRESSION

Unfortunately, depression among seniors is often under-diagnosed and adequate treatment is not guaranteed [ZARIT & ZARIT 2007]. Depression is not singularly defined, but can refer to a range of symptoms or various distinct syndromes, such as manic depression in bipolar disorder, major depressive
disorder (MDD), dysthyemic disorder, or adjustment disorder. Further complicating the issue is depression associated with medicine or illness. All of this makes quantifying the efficacy of light therapy for mood disorders more challenging.

When considering light therapy interventions, depression is typically divided into two categories: seasonal and nonseasonal. Seasonal affective disorder (SAD) prompted the genesis of bright light therapy and has driven developments in understanding the physiology of circadian rhythms. SAD is typically characterized by major depressive episodes that commence in the fall and remit spontaneously in the spring. Nonseasonal depression is a much broader category, but in the context of light therapy, MDD is commonly considered.

Many scales exist for quantifying depression in research applications. These scales are typically severity measures and do not necessarily form the basis for a medical diagnosis or distinguish between depression subtypes. For nonseasonal cases, the Geriatric Depression Scale (GDS) or Hamilton Depression Rating Scale (HDRS) are often employed. Other scales that have been used in research applications involving light therapy include the Montgomery-Asberg Depression Rating Scale (MADRS), the Adjective Mood Scale (AMS), the Depression Scale (D-S), and the Beck Depression Inventory (BDI) [TuuInaInen et al. 2004]. For seasonal depression, the Structured Interview for the Hamilton Depression Rating Scale—Seasonal Affective Disorder Version (SIGH-SAD) is commonly utilized. In reality, no single scale or diagnostic criteria can perfectly capture and quantify the complexities of depression.

The prevalence of depression in seniors must be discussed categorically as it is difficult to produce a single number. Contrary to common stereotype, the highest 12-month prevalence of MDD in the community is not amongst seniors, but rather in the youngest (18-29) age block [Kessler et al. 2003]. Seniors have the lowest prevalence at between 1% and 5% [Kessler et al. 2003; Blazer 2002]. Another 2% are diagnosed with dysthymia, while another 10% to 25% of seniors exhibit clinically significant depressive symptoms, sometimes called minor depression [Zarit & Zarit 2007; Blazer 2002]. The exact reason why a smaller percentage of seniors are diagnosed with MDD is not known. One factor, among many others, may be that the diagnostic criteria are largely based on younger populations and the elderly may have a different presentation of symptoms.

When discussing the prevalence of depression in seniors, it is important to consider the subpopulations in medical facilities and long-term care environments. The prevalence of MDD for seniors in hospitals has been found to be between 6% and 44% with an average of 12% [Zarit & Zarit 2007]. Another 18% to 26% of hospital patients have some other form of depressive diagnosis. Similarly, 16% of residents in long-term care facilities met criteria for MDD and another 16% had significant depressive symptoms [Zarit & Zarit 2007]. The numbers for these subpopulations are notably higher than the general senior population. Thus, special attention and investigation into depression in these populations is warranted. Without regular diagnosis, depression in the elderly remains a significant health risk regardless of the reported prevalence.

Sleep Disorders
Changes in sleep architecture are a normal part of human aging; however, these changes often progress to more severe sleep disturbances and disorders. Difficulty sleeping is reported by 20% to 70% of all seniors [Stepnowsky & Ancoli-Israel 2008; Ancoli-Israel & Cooke 2005; Ancoli-Israel & Ayalon 2006; Ohayon 2002; Van Someren 2000]. Besides negative daytime consequences, sleep disorders increase the risk of mortality due to common causes such as heart disease, stroke, cancer, and suicide, although insomnia itself does not increase mortality risk [Kripke et al. 2002]. While not all forms of insomnia are related to circadian rhythms, they do play a key role in the sleep cycle [Van Someren 2000]. While seniors
may spend more time in bed, both quality and quantity of sleep decrease while daytime sleepiness increases [OHAYON 2002].

Though sleep disturbances in older adults may be caused by illness, medication, or other conditions, there is no doubt in the link to circadian rhythms. Melatonin differences between young and old subjects have been examined and a review suggests a decrease in peak plasma melatonin with age [TOUITOU 2001]. While the trend is apparent, this finding is not universal. It is not clear whether environmental conditions cause changes in melatonin or if changes in melatonin lead to lifestyle changes. Either way, it is important to note that circadian changes are an important part of senior physiology and sleep patterns.

In a laboratory, sleep can be measured with medical equipment such as an electroencephalogram (EEG), but in clinical trials less invasive measures are necessary. Numerical scales such as the Stanford Sleepiness Scale or the Epworth Sleepiness Scale are designed to measure daytime sleepiness. The Pittsburgh Sleep Quality Index is designed for use in clinical settings as a measure of sleep quality and a tool for diagnosing sleep disturbances. Numerical scales are often used in combination with daily sleep logs or sleep journals.

Both daytime and nighttime sleep can be measured using actigraphy, or the recording of motor activity with an actimetry sensor. The devices, oftentimes similar to a wristwatch, continually record movement data for days or weeks at a time. Once collected, the data can be analyzed with computer software. Actigraphy is an accepted method for measuring sleep quality [SADEH & ACEBO 2002] and has been used in many light therapy trials, including some involving seniors [ALESSI ET AL. 2005; DOWLING ET AL. 2008; FETVEIT ET AL. 2004; FETVEIT & BJORN 2003]. Actigraphy is more common in research applications than for making clinical diagnoses, although its prevalence is growing. Standard practice parameters have been developed [MORGENTHALER ET AL. 2007].

COGNITIVE DISORDERS

Estimates on the prevalence of dementia vary, but one review suggests it affects about 5% of the population by age 75, but upwards of 30% by age 85 [ZARIT & ZARIT 2007], although numerical estimates can be difficult due to the insidious onset and slow progression. Dementia is most notably associated with cognitive impairment, but depression, behavioral issues, agitation, and sleep disturbances are problematic symptoms for both the elderly and caregivers [FORBES ET AL. 2004]. Dementia is associated with degeneration of the SCN, potentially exacerbating normal age-related changes in circadian rhythms [FORBES ET AL. 2004].

Dementia is a category of diseases with varying causes and symptoms. The most frequent cause of dementia is Alzheimer’s Disease, but other types include frontotemporal and vascular dementias as well as Lewy Body dementia. It is also possible to experience multiple types of dementia at the same time. While all dementias involve cognitive deterioration associated with changes in the brain, the exact symptoms vary by type. Like depression, dementia is clinically diagnosed using DSM IV criteria. However, several screening assessments are commonly used in research applications including the MicroCog Assessment of Cognitive Functioning, Mini-Mental State Examination (MMSE), and Geriatric Mental State Schedule (GMS), among many others.

Tuning Optical Radiation

Lighting designers, illuminating engineers, and lamp manufacturers have the ability to affect humans in many ways, both visual and nonvisual, by choosing or designing lamps with different SPDs. As commercially available LEDs continue to improve, the opportunity to take advantage of their unique characteristics will also expand. In order to create sources with the greatest visual and nonvisual impact,
it is critical to understand the human psychophysical response to illumination. While this knowledge has grown tremendously in the past few decades, improvements can still be made to models of visual and nonvisual photoreception.
3 Literature Review

Light Therapy
Light therapy was first described and tested as an intervention for SAD by Rosenthal and colleagues in 1984. It was implemented as a direct attempt to address the hypothesis that SAD is caused by the shortened photoperiod that occurs in winter months. Rosenthal and others were able to speculate on the human physiological response, or the depressive effects of melatonin, and target the new therapy at suppressing melatonin. While many of the factors required to optimize light therapy were yet to be researched, it quickly became an area of interest to many scientists who began to expand research applications to nonseasonal depression, mood disorders, dementia, sleep disorders, jet lag, eating disorders, and other behavioral syndromes [GOLDEN ET AL. 2005; TERMAN 2007]. After a quarter century of clinical trials and development, much more is known about the efficacy of light therapy and the mechanisms by which it works [SHIRANI & ST. LOUIS 2009]. However, recent reviews indicate that many early trials were too short in duration or lacked rigorous experimental designs [TUUNAINEN ET AL. 2004; GOLDEN ET AL. 2005; EVEN ET AL. 2008]. Work to optimize circadian illuminants is ongoing and will be instrumental in improving the efficacy of treatment, along with clarifying the mechanisms by which light can improve sleep, mood, cognition, and other disorders [TERMAN & TERMAN 2005].

Mechanisms of Action
While it is generally accepted that a stable circadian rhythm is useful for maintaining good sleep-wake patterns and disruption of rhythms has physiological consequences, the exact etiology of light and its effect on mood and cognition remains hypothetical. Light has been unequivocally linked to melatonin suppression and circadian rhythms [MIRICK & DAVIS 2008], but this does not show a causal relationship between lack of light stimuli, circadian rhythms, sleep, and depression or cognition.

The hypotheses linking light and SAD can generally be separated into two groups: changes in melatonin cycles and phase shifting. The photon-counting hypothesis [HEBERT ET AL. 2002] and the amplitude hypothesis both suggest that seasonal abnormalities or exaggerations in melatonin rhythms may cause SAD. The basis of the phase-shift hypothesis is that later dawn in winter months creates a desynchronization between natural circadian rhythms and external cues, like a clock, that set the sleep-wake cycle [LEWY ET AL. 2006]. This theory is supported by the greater efficacy of morning light therapy. However, one cannot ignore the fact that evening therapy has also shown some effect. It is possible that SAD patients are comprised of both phase-delay and phase-advance patients.

Linking circadian rhythms to the biology of nonseasonal mood disorders is currently difficult, but hypothetical explanations do exist. Serotonin, norepinephrine, and dopamine are all major neurotransmitters that have a circadian rhythm [MCCLUNG 2007]. The circadian control of these neurotransmitters, their relation to the SCN, and their role in mood disorders is still unresolved, but further research is warranted.

Degeneration of the SCN is associated with dementia [FORBES ET AL. 2004; HOFMAN & SWAAB 2006] and light stimuli may help restore SCN activity [LUCASSEN ET AL. 1995; VAN SOMEREN 2000]. This indicates a potential link between ipRGC phototransduction and cognitive decline. However, like other hypotheses direct confirmation is pending.

Clinical Trials of Light Therapy
While countless experiments have been conducted in an attempt to determine the efficacy of light therapy for treating various ailments, quality experiments that follow proper design protocols are limited. In a review of light therapy for depression, Golden and colleagues [2005] were able to include in
a meta-analysis only 20 of the 173 studies identified. Much of the early work on light therapy did not involve randomized, controlled trials and oftentimes the number of subjects was very small. Additionally, placebo control and patient blinding is difficult since light therapy is inherently visual. Thus, it is not easy to ensure that expectations are the same among treatment and control groups. Combined with these inherent difficulties, a lack of standard procedures and doses has resulted in less than conclusive results from a rather large body of trials. Golden notes: “...the limitations in much of the literature on light therapy research may have created the unsubstantiated impression that the treatment itself has limitations in terms of its efficacy.” Despite the inconsistencies, several recent reviews conclude that light therapy is efficacious and the effect is similar to or greater than that of pharmacological treatments [Kripke 1998; Golden et al. 2005; Terman & Terman 2005; Even et al. 2008].

**Light Therapy for Seasonal Affective Disorder**

When Rosenthal reported net benefits—defined as treatment reduction in depression scale minus placebo reduction—of 52% within one week of treatment, many researchers jumped to investigate light therapy [Rosenthal et al. 1984; Kripke 1998]. While many studies found a positive effect, few were able to report such dramatic success, perhaps due to the issues of placebo and expectation controls. In 1989, Terman and colleagues compiled a cross-center analysis of 332 patients from 29 data sets and 14 research groups, finding that morning bright light treatment resulted in a 53% remission rate for SAD, significantly higher than that for dim light control groups or for evening or midday treatment. However, much of the data included in this work were excluded in later reviews because they did not meet the inclusion criteria—for example, control groups were not used or placebos were not adequate.

In more recent work, Terman and colleagues [1998] and Eastman and colleagues [1998] reported remission rates of 54% and 55% respectively—defined as an improvement of at least 50% on the SIGH-SAD with a post-treatment score of less than eight—in trials employing rigorous controls with placebos. A review, which includes both the Eastman and Terman studies, found eight studies targeting SAD to meet the inclusion criteria and found a positive effect in all cases. The effect size ranged from 0.09 to 2.11 with an average of 0.84 (p<0.0001) [Golden et al. 2005]. Golden reports that this effect size is equivalent to those in most antidepressant pharmacotherapy trials. One recent study directly compared light therapy to fluoxetine, finding nearly identical positive effects [Lam et al. 2006]. Light therapy, however, showed earlier response onset with fewer side effects. Another recent trial showed light therapy in combination with cognitive-behavioral therapy might have even greater effects [Rohan et al. 2007].

In general, it is now widely accepted that light therapy should be considered as a treatment for SAD. It is an effective, nonpharmacological solution with few, if any, side effects and a fast onset.

**Light Therapy for Nonseasonal Depression**

Review papers documenting clinical trials of light therapy for nonseasonal depression report similar, though somewhat less dramatic, results compared to trials examining light therapy for SAD. Kripke [1998] reports on six studies that found the net benefit of light therapy compared to placebo for MDD and bipolar to be between 12% and 35%. Five of the six studies lasted only one week, with the remaining study lasting four weeks. However, the percent improvement is equal to or better than drugs evaluated over a much longer period. Kripke concludes: “...There is now a preponderance of relatively consistent evidence that bright light treatment produces statistically significant net reductions in mood symptoms...” Terman and Terman [2005] note that trials have achieved as high as a 64% reduction in depression scale ratings after three weeks of treatment. Although only reporting on three nonseasonal depression studies, Golden reports an effect size of 0.53 (p<0.003) for treatment of nonseasonal depression [Golden et al. 2005].
In perhaps the most comprehensive review on light therapy for nonseasonal depression, Tuunainen, Kripke and Endo reviewed 45 studies. Including only 20 of these 45 in the final analysis, the authors note the lack of quality in the available reports, a similar conclusion to those found in other reviews. However, the authors do conclude that the benefit of light therapy for nonseasonal depression is “modest though promising,” despite the inherent limitations of light therapy clinical trials. The authors note that additional rigorous studies are necessary, especially for specific subpopulations such as seniors [TUUNAINEN ET AL. 2004]. Another meta-analysis found that 15 of 62 reports were sufficiently rigorous to include [EVEN ET AL. 2007]. The conclusions were similar: light therapy should be considered, but more research is necessary. As a matter of good research practice, future light therapy studies should utilize an appropriate and effective placebo, have a large enough sample, attempt to examine a homogenous group, and ensure blinding to limit bias.

LIGHT THERAPY WITH BLUE LIGHT
Two recent studies have examined the use of narrow-band blue light for treatment of SAD. One provided 45 minutes of exposure in the morning for three weeks in an outpatient setting, comparing 398 lux of blue light (created using an LED with a peak wavelength of 468 nm) with dim red light (created using an LED with a peak wavelength of 654 nm) [GLICKMAN ET AL. 2006]. SIGH-SAD scores for those receiving blue light treatment were significantly lower than those receiving red light treatment and were comparable to previous studies using bright white light. Another compared bright blue light at 176 lux with a 470 nm peak wavelength to bright red light at 201 lux with a 650 nm peak wavelength in a double-blind parallel in-home trial [STRONG ET AL. 2009]. Subjects were diagnosed with both the DSM-IV and SIGH-SAD systems. Those receiving blue light had a significantly greater reduction in SIGH-SAD scores, with efficacy similar to treatment with white light.

Light Therapy for Seniors
FOR MOOD DISORDERS
Relatively few studies have investigated light therapy as a treatment for depressed seniors. In perhaps the first trial of light therapy for depressed seniors, Sumaya and colleagues [2001] treated ten institutionalized patients who had moderate to high GDS scores but were not diagnosed with MDD. Each subject received five days of treatment, five days of placebo, and five days of control, with a weeklong washout period of no treatment in between each condition. Treatment consisted of 10,000 lux of white light for 30 minutes, whereas the placebo group was exposed to 300 lux of white light for 30 minutes and the control group received no light treatment. Although the experimental design was unorthodox, the results indicate the treatment was effective with the average GDS score reduced in the treatment group from 15 to 11 (p<0.01) with 50% of participants no longer scoring in the depressed range while the placebo and control had no significant effect.

Another study examined subjects who were hospitalized in Taiwan and diagnosed with MDD [TSAI ET AL. 2004]. Light therapy was administered for 50 minutes, in the morning, for five days, at 5000 lux of white light. A control group did not receive any treatment. The results indicate that GDS scores were significantly reduced for the treatment group but not for the control group. However, a larger study that provided home based treatment at 10000 lux, for one hour per day, over five weeks versus control at 10 lux, both divided amongst three groups for morning, afternoon and evening treatment, found no significant difference between the bright light and control treatments [LOVING ET AL. 2005]. Both groups showed a clinically significant 16% overall improvement. This study employed the HDRS, GDS, and SIGH-SAD scales.

In the most recent study on light therapy for depressed seniors, researchers conducted a randomized controlled trial of 89 subjects 60 years or older diagnosed with MDD [LIEVERSE ET AL. 2008, 2011]. Subjects
were recruited from psychiatric outpatient clinics, databases of general practitioners, and nursing homes. The therapy lasted three weeks, with one hour of treatment per day anchored to the subject’s habitual wake time. Compliance was monitored with multiple systems. The authors carefully considered the placebo, sample size, and the illuminant. Blue light at approximately 7500 lux was created by filtering white light, whereas red light at approximately 50 lux was used for the placebo. The primary outcome measure was HADRS-17 depression ratings, which demonstrated a 7% improvement (p = 0.03) between baseline and the end of treatment and a 21% improvement (p=0.01) compared to baseline for measurements taken three weeks after treatment ended. Significant improvements were also recorded for sleep efficiency, melatonin levels, and cortisol levels, suggesting the antidepressant mechanism was related to the enhancement of circadian functioning. Notably, patients already being treated with antidepressant medications did not respond differently.

The combined results of these studies indicate that light therapy has potential as an intervention for depressed seniors. Because of the complex conditions of subpopulations of seniors, more studies should be conducted to confirm these findings. As a target group, depressed seniors seem to be a prime target for light therapy, but the aging eye and physiological changes may mean that light therapy will require different parameters to be effective.

**FOR SLEEP DISORDERS**

Sleep parameters have been measured in a number of trials, for both demented and non-demented seniors. While many have reported some level of improvement, others have reported no significant effect [Kim et al. 2003]. The effect of light therapy for sleep disorders in seniors is rarely considered outside of larger studies examining other conditions. No studies met the inclusion criteria of a 2002 review [Montgomery & Dennis 2002]. An earlier review of several preliminary studies [Campbell et al. 1995] strongly supported light therapy for sleep problems in older adults. However, other studies [Suhner et al. 2002; Alessi et al. 2005] have found no impact of light therapy on nighttime sleep measures, despite significant changes to circadian rhythms or daytime sleep measures.

While morning light therapy has become the predominant choice, individualized timing may be more effective at improving sleep, especially in a mixed population of demented and non-demented seniors. Advanced sleep phase syndrome is common among the elderly [Stepnowski & Ancoli-Israel 2008; Campbell et al. 1995], but sleep patterns can be very fragmented in people with dementia [Ancoli-Israel & Cooke 2005]. One study found no difference between morning, midday, and evening light when it was scheduled based on the needs of each individual, based on phase-typing prior to the experiment [Loving et al. 2005]. Another alternative is providing full day bright light, a method that has shown a positive effect in at least one study [Riemersma-van der Leck et al. 2008], but no effect in another [Hickman et al. 2007]. A variable 24-hour lighting scheme may produce good results and has been recommended [Figueiro et al. 2008].

**FOR COGNITIVE DISORDERS**

Many clinical trials have investigated the effects of light therapy on elderly subjects with dementia [Forbes et al. 2004], with outcome measures including a range of sleep, behavior, mood, and cognitive measures. Like other reviews, Forbes and colleagues found few studies worthy of inclusion in a meta-analysis. In general, results were mixed.

At least three studies have examined the impact of light therapy on cognition directly. Yamadera and colleagues [2000] found that light therapy improved Mini Mental State Examination (MMSE) scores in patients with questionable and mild dementia diagnoses while simultaneously improving daytime and nighttime sleep measures. A control group was not used. Later, the same group of researchers found similar effects from administration of melatonin, potentially implicating improved sleep as a mechanism
of cognitive improvement [ASAYAMA ET AL. 2003]. Graf and colleagues [2001] also found that light therapy significantly improved MMSE scores versus dim light placebo. Although the authors also found significant changes in core body temperature rhythm, they attributed the cognitive gains to mechanisms beyond circadian rhythms. In the most comprehensive study to include cognition as an outcome measure, Riemersma-van der Lek and colleagues [2008] found significant improvement in MMSE scores, and the intervention prevented decline over the long duration of the study. Light also improved some non-cognitive measures. The same study also investigated melatonin both independently and in conjunction with light therapy, finding it to have some beneficial effects but also an adverse effect on mood.

Spatial Brightness Perception
The effect of lamp SPD on brightness perception is an important element of illuminating engineering and architectural lighting. Past research has shown that a relationship between lamp properties and brightness perception exists, although the relationship is not well defined [FOTIOS 2001A]. Spatial brightness perception in architectural interiors is inherently tied to colorimetry. Additivity failures are an important element of both, but the methodologies used for experimentation are notably different. Most notably, visual matching through control and manipulation of individual primaries is replaced by rating, ranking, matching, or forced choices between rooms or spaces illuminated with lamps of different spectral content.

In essence, attempts to understand brightness and perception through both colorimetry and spatial brightness experiments are approaching the same problem in two different ways. The problem in both cases is where energy should be placed within the visible spectrum to elicit maximum perception of brightness, a process that can be referred to as spectral tuning. Whereas colorimetric-based experiments evaluate the primaries of a polychromatic stimulus individually, spatial brightness-based experiments tend to evaluate to overall difference between two polychromatic stimuli. Both approaches are valid, providing complementary insight. The manipulation of individual primaries demonstrates structured relationships, as shown in Figure 2-6. However, when primaries are combined, the overall perception is not as easy to predict, as seen in Figure 2-7.

METHODS
Experiments designed to evaluate the relationship between brightness perception and lamp SPD have been performed in many different ways. While there are many factors to control, four main elements define experimental conditions: size, presentation method, task, and scene. Size may be either booth scale or room scale; presentation method may include side-by-side, sequential, or singular presentations; task may include matching, ranking, or forced choice; and scene may include complex or simple and chromatic or achromatic spaces. Experiments have been conducted using various combinations of these elements, with variable results [FOTIOS 2001A]. There is a need for verification that these methods produce comparable results [FOTIOS 2002].

Several authors have discussed the various types of bias or discrepancies that can be introduced in any combination of the psychophysical experiment elements listed previously, as well as due to other issues such as adaptation. [FOTIOS 2001b, 2006; HOUSER & TILLER 2003; FOTIOS & GADO 2005; FOTIOS & CHEAL 2007, 2008, 2009; FOTIOS ET AL. 2008; FOTIOS & HOUSER 2007]. The presence of bias, such as response-contraction bias, position bias, interval bias, or stimulus frequency bias are well documented and in many cases were not controlled for. Recent reviews of the effect of lamp SPD on architectural brightness perception have generally concluded that an effect exists, though the collection of reliable experiments is reduced by lack of rigorous control [FOTIOS 2001A, FOTIOS & HOUSER 2008; FOTIOS ET AL. 2008]. Variance in findings can partially be linked to the difficulty of designing experiments to examine this phenomenon, though the
relationship is itself complex. Chromatic adaptation is another important difference between studies and when allowed to reach completion can reduce the effect size.

Bias can be reduced, eliminated, or accounted for with proper experimental design techniques. For example, presentations of paired stimuli should be made in both orders or on both sides, null conditions should be included to determine if a bias is present and if so its magnitude, anchors should be used to establish scale limits, and rank scales should include an odd number of ranks, among others.

As Thornton (1992A-c, 1997, 1998, 1999) illustrated, there is no definitive relationship or weighting function that has been developed to accurately predict the brightness perception of polychromatic lights as a whole. However, the same data clearly show that some relationship exists between SPD and brightness perception that is not predicted by luminance. While colorimetry endeavors to quantify brightness perception in detail, illuminating engineers, lamp manufacturers, lighting designers, and the Department of Energy often seek broader guidelines to aid decisions. Until the CIE system of colorimetry can precisely and accurately define brightness perception, these guidelines will be an important aspect of the lighting industry. Along with trichromacy and prime color theory, the use of higher CCT lamps has been promoted based on the correlation between CCT and the ratio of scotopic to photopic lumens, typically called S/P ratio.

TRICHRMACY AND PRIME COLOR THEORY
Thornton (1992A) demonstrated that the brightness of polychromatic stimuli with spectral components in the prime regions is consistently underestimated by luminance, relative to a broadband white fluorescent lamp (Figure 2-7). In other words, at equal perceptual brightness and chromatic match, the measured luminance of the prime color triplet—a three primary stimulus—was less than that of the reference fluorescent. Furthermore, prime color mixtures require less power for equal perceptual brightness compared to a broadband fluorescent lamp. Unfortunately, the same clear polynomial relationship that exists between the minimum power required of a variable third primary, a direct correlate of CMFs, does not exist for brightness perception of polychromatic sources. One thing that is abundantly clear is that energy near 500 nm is particularly detrimental to brightness perception.

Endeavoring to examine further the prime color postulates of Thornton, Houser and colleagues conducted two experiments. In the first, using a colorimeter and a 10° field of view, 39 subjects matched both prime color (453-533-619 nm) and anti-prime (493–581-657 nm) triplets to a broadband fluorescent lamp at approximately 6500 K [HOUSER & HU 2004]. All three primaries were variable in power, and the fluorescent reference could be mechanically dimmed. At the point of visual metamerism, the prime color stimulus required approximately 5% less power than the fluorescent reference, whereas the anti-prime stimulus required 117% more. The effect of relative luminance was less clear. The luminance of the prime color stimulus was not significantly different from that of the reference stimulus, but the measured luminance of the anti-prime stimulus was significantly less than the reference stimulus. In this case, luminance underpredicted the brightness of the anti-prime triplet by approximately 9%. This is not outside the range of values found by Thornton, but is at the extreme of the results that found that luminance typically overpredicted brightness for anti-prime triplets. Similar to Thornton, Houser and Hu found that the differences in computed chromaticity of the matched stimuli compared to the reference was greater for the anti-prime triplet (20 MacAdam ellipses) than the prime color triplet (10 MacAdam ellipses).

Houser and his colleagues also developed prototype fluorescent lamps based on Thornton’s prime color criteria [HOUSER ET AL 2004]. By adjusting the magnitude of optical radiation within the prime color and anti-prime spectral regions, lamps were created at low and high CCTs that had varying trichromatic potential. At equal luminance, the rooms illuminated with a greater percentage of prime color energy
were found to appear brighter and more colorful based on a forced choice. Asked to judge the level of
difference, the mean response was 4.3% brighter. The experiment also demonstrated that a pair of
lamps with similar S/P ratios can elicit statistically different perceptions of spatial brightness and that a
pair of lamps with very different S/P ratios can elicit equivalent perceptions of spatial brightness. Houser
and his colleagues suggested that the perception of brightness is more dependent upon the placement of
optical radiation within key spectral regions than on the absolute amount of radiation within each of
these regions.

**S/P RATIO AND CCT**
Berman and colleagues have advocated the ratio of scotopic lumens to photopic lumens (S/P) as a basis
for spatial brightness perception. The theory suggests that at equal luminance, sources with a higher
proportion of energy in the scotopic region will be perceived as brighter [BERMAN ET AL. 1990; BERMAN
1992]. The quantity $P^* (S/P)^{0.5}$ has been promoted as a correlate for brightness perception [BERMAN &
LIEBEL 1996] and the use of lamps with a high S/P ratio has been publicized as a method for reducing
energy consumption. This has often been extrapolated to suggest that illuminants with a CCT are
perceived as brighter since there is some correlation between CCT and S/P ratio. However, other
researchers have found no correlation between S/P ratio and brightness perception [SMITH & REA 1979;
VRABEL ET AL. 1995; BOYCE ET AL. 2003; HOUSER ET AL. 2004; HU ET AL. 2006; HOUSER ET AL. 2009]. This is perhaps
because S/P simplifies a complex SPD into a ratio of two numbers, much as $V(\lambda)$ unsuccessfully distills a
multi-channel visual response into a single function.

When the S/P ratio was originally proposed, it was presumed that the rod photoreceptors were
contributing to brightness perception at light levels traditionally considered to be photopic. During this
time, ipRGCs had not been formally discovered. Today, Berman and colleagues advocate the cirtopic
spectral sensitivity (C/P) as the true driver of brightness perception while scotopic sensitivity can explain
the effect because the scotopic and cirtopic functions have peaks near to each other [BERMAN 2008].
Berman notes a conversion: $S/P = (0.66*C/P)^{0.74}$. Although the overriding theory remains applicable, this
conversion relationship would not be accurate for narrow band sources, such as LEDs. If C/P ratio is an
accurate predictor of brightness perception over a wide range of architectural lighting situations,
cirtopically efficient sources should appear brighter than those sources with relatively less cirtopic
energy.

Recent work by Houser and colleagues provided direct evidence that S/P may not completely
characterize the spectral composition of illuminants that results in varied perceptions of brightness
[HOUSER ET AL. 2009]. Using two methods for brightness evaluation, four stimuli were presented in all
permutations. The four stimuli were created using the same primary set, but configured to output two
different CCTs, each at two different luminances, by varying the output of the red, green, and blue
channels of an LED source. By selecting appropriate spectra and luminance values, Houser and colleagues
were able to compare sources that produced different luminances but that were predicted to appear
equally bright based on their S/P ratios. They found that when the spectral primaries remain constant,
luminance affects brightness perception while S/P ratio does not. While this evidence is significant, not
all possible conditions can be represented by four fixed stimuli.

Over more than 30 years, numerous studies have examined the impact of CCT on brightness perception.
This work is reviewed by Hu and colleagues [2006]. Despite mixed evidence, the belief that higher CCT
lamps appear brighter is common. Hu and colleagues used three linear models, including those of Guth
and Thornton, as well as the brightness correlates predicted by the Nayatani and Hunt CAMs to compute
the predicted brightness of 32 commercial lamps and 6 CIE Standard Illuminants at constant luminance.
Four of the five models predicted a negative relationship between CCT and brightness, though the
predicted differences were minimal. Psychophysical experiments were also carried out using both forced choice and matching adjustment techniques. The results indicate no difference in perceived brightness between 3500 K or 6500 K lamps for both conventional lamps and those tuned to have more prime color energy.

PROSPECTS FOR SPECTRAL TUNING
There is little disagreement about the opportunity to reduce energy consumption by better aligning the radiant output of lamps with the spectral regions that yield a maximum perception of brightness. Though CCT, S/P, and C/P are often promoted as predictors for architectural brightness perception, there is little physiological basis for their relevance. These measures distill spectral content to a single value or two-value relations. It is likely that more information, rather than less, is necessary to predict brightness perception. Even with the input of three tristimulus values, modern brightness correlates are not perfect in assessing brightness perception. With the addition of complex, chromatic scenes, simple linear relationships are of even less value.

The problem appears simple: find the formula for placement of radiant energy that optimizes brightness perception per watt in architectural spaces. Human psychophysiology, however, is complex and difficult to characterize with numerical models. Despite over 50 studies that have examined the effect of SPD on spatial brightness perception [FOTIOS & HOUSER 2008; FOTIOS ET AL. 2008; FOTIOS 2001A] and the lengthy history of CIE colorimetry, a well-defined, universally adopted model of color vision and brightness perception does not exist. Continued work must carefully consider experimental methods in order to obtain robust results that are applicable to architectural interiors.

The emission characteristics of LEDs permit the creation of white light spectra that are dominated by any number of spectral peaks. When carefully chosen in consideration of prime color theory, LEDs have a high potential to improve the visual benefit per watt compared to conventional illuminants. Similar sources could be designed to maximize C/P ratio. The level of control afforded by LEDs has incredible potential for both research and commercial product development.
4 Light Therapy for Seniors in Long-Term Care

While past work provides evidence that light therapy can be effective for treating many ailments that seniors face, a diverse range of treatment protocols and evaluation methods makes consensus elusive. The numerous physiological and environmental changes faced by seniors indicate that light therapy may be an accessible, effective intervention. An unobtrusive intervention such as purposefully designed light exposure has many advantages, but one of the most pronounced is the ability to treat patients with multiple different diagnoses, as well as those who remain undiagnosed, alongside each other. Pharmacologic treatment of individual ailments such as depression is often successful, but the cost of the drugs, their adverse side effects, and their contribution to polypharmacy are notable concerns and consequences.

This pilot study was designed to examine the effect of light therapy versus placebo on an unrestricted group of seniors in long-term care. A goal of the work was to determine the feasibility of developing and testing an ambient architectural lighting system capable of providing adequate circadian stimulation without the need to rely on a dedicated light therapy device. Such architectural lighting interventions are a promising solution for nursing homes and other long-term care environments where daily routines are often pronounced and many residents can benefit.

Methods

Participants

Participants were residents of a long-term care facility in Pennsylvania. In contrast to previous work that focused on target groups with a diagnosed condition, residents in the highest level of care were permitted to participate regardless of diagnosis and symptoms of mood, sleep, or cognitive disorders.

Subjects were recruited with a written letter sent to both the resident and his or her power-of-attorney. Interested residents were provided additional information about the study and were asked to sign an informed consent form. If consent was given, subjects were tested for light sensitivity using green light provided by the same luminaires as were used in the experiment. No participants expressed discomfort during this screening.

Participants were assigned to either the treatment or placebo group in an alternating fashion based on the sequence of response to the initial recruitment. The treatment group began the experiment with 16 individuals and ended with 15; one subject did not complete the study due to declining health. The placebo group began the experiment with 16 participants and ended with 13; three subjects elected not to participate after consenting. All participants had numerous medical diagnoses and many were in a frail state. Statistics for both groups are presented in Table 4-1.

In general, the participants had a low level of mobility. Of the 28 participants who completed the study, 22 were confined to a wheelchair (13 treatment, 9 placebo). Most of the participants were in skilled nursing care, receiving attention 24 hours per day, although five were in personal care, requiring at most one hour of attention per day. All study participants lived in private rooms with a window. The living quarters were arranged in neighborhoods, each with common living and dining rooms. The participants did not spend much time outdoors.

The study was approved by The Penn State College of Medicine Institutional Review Board, The Ethics and IRB Committee of the Masonic Village at Elizabethtown and The Pennsylvania Board of Health.
INDEPENDENT VARIABLE: SPECTRUM
One notable criticism of past trials of light therapy by others is the failure to completely document the independent variable: the light stimulus at the eye of the participants. In order to achieve maximum treatment efficacy, many properties of the light stimulus including spectrum, intensity, timing, photic history, and geometry factors must be carefully controlled. Additionally, maintaining the integrity of the placebo has been difficult due to inherent visual differences.

For this experiment, both treatment and placebo stimuli were provided by Color Kinetics ColorGraze Powercore luminaires, which are typically used for architectural lighting. Independent control of the RGB LEDs produced a comparable visual experience for the treatment and placebo groups, with only the spectrum and lumen output of the light stimuli varying. The luminaires were mounted to the edge of tables positioned to form two continuous rows and were aimed so that the peak of the beam spread was approximately at seated eye level. Each luminaire’s rotation angle was locked in place and remained fixed for the duration of the experiment. The setup is shown in Figure 4-1.

The tables were set up at one end of a large assembly room, with the participants facing an existing stage. Each row could seat 10 participants. During the session, the regular overhead linear fluorescent lighting system was left on. It provided between 300 and 500 horizontal lux on the table surface and between 50 and 100 vertical lux at the eye of the participants, typical of an interior environment. All curtains were lowered to minimize the amount of daylight entering the room.

The treatment stimulus used the luminaire’s blue LEDs that have a peak wavelength of 464 nm. They provided approximately 400 lux at the eye. The placebo stimulus used the red LEDs that have a peak wavelength of 628 nm and provided 75 lux at the eye. SPDs (Figure 4-2) were measured using a StellarNet EPP2000C spectrometer, with a remote integrating sphere positioned with the opening perpendicular to the surface of the table and 114 cm above the floor, representing standard seated eye height. Illuminance was measured using a Minolta T-10 illuminance meter at the same position and facing the same direction. The CS values [REA ET AL. 2005] were 1.714 for the treatment (blue) and 0.014 for the placebo (red), excluding ambient light, indicating that the circadian stimulation provided by the blue light was over 125 times that of the red light.

Both treatment and placebo groups received the light exposure in the morning. Because they could not participate at the same time, the groups were alternated on a weekly basis between a 9:30 AM and 10:30 AM start time. It was not possible to schedule earlier start times due to the daily schedules of the residents. The experiment began Monday, May 17, 2010 and lasted for four weeks, ending Friday, June 11. Exposure occurred Monday through Friday each week, thus totaling 20 sessions. During the exposure periods, both groups participated in an identical background activity, such as reminiscence or bingo.

### Table 4-1  Study Demographics
Subjects were divided into two groups, treatment and placebo. The groups were comparable in terms of age, gender, care type, cognitive ability, and mood disorders.

<table>
<thead>
<tr>
<th>Group</th>
<th>Size</th>
<th>Age</th>
<th>Gender</th>
<th>Care Type</th>
<th>Dementia Diagnosis</th>
<th>Mood Disorder Diagnosis</th>
<th>Cataracts (not removed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>15</td>
<td>84.3</td>
<td>8 Female</td>
<td>3 Personal Care 12 Skilled Nursing</td>
<td>53%</td>
<td>67%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10.0)</td>
<td>7 Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Placebo</td>
<td>13</td>
<td>86.4</td>
<td>10 Female</td>
<td>2 Personal Care 11 Skilled Nursing</td>
<td>54%</td>
<td>77%</td>
<td>31%</td>
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<tr>
<td></td>
<td></td>
<td>(5.9 )</td>
<td>3 Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INDIVIDUALS WITH NO DATA
DEPENDENT VARIABLES: COGNITION, MOOD, AND SLEEP

A battery of behavioral measures was completed by participants before and after light exposure. These included neurocognitive measures from the MicroCog Assessment of Cognitive Functioning [POWELL ET AL.
1993], the Profile of Mood States [POLLOCK ET AL. 1979], and the Geriatric Depression Scale (GDS) [YESAVAGE ET AL. 1982]. Pre-exposure examinations were given two weeks prior to the beginning of the treatment period. Post-exposure examinations were given during the week after the final exposure.

The MicroCog is an objective, computerized assessment of cognitive functioning. We utilized the short version, which consists of 12 subtests that are grouped into five functional domains: Attention/Mental Control, Memory, Reasoning/Calculation, Spatial Processing, and Reaction Time. The scores for each of the subtests, which have a mean of 10 and standard deviation of three, were calculated. From the subtest scores, three levels of index scores, which have a mean of 100 and standard deviation of 15, were obtained. Index scores are sensitive to both speed and accuracy, with higher scores indicating quicker and more accurate responses.

The Profile of Mood States was completed by each participant. It is comprised of 65 adjectives that subjects rated on a 5-point scale. From the ratings, six factors were evaluated: Tension-Anxiety, Depression-Dejection, Anger-Hostility, Fatigue-Inertia, Vigor-Activity, and Confusion-Bewilderment. Lower scores on this scale indicate fewer symptoms.

The short form of the GDS was completed by each participant. It is a 15-item, self-report survey that is commonly used to identify depressive symptoms in experimental situations. All questions are answered yes or no, with one point given for each response that suggests depression. A score greater than five is suggestive of depression and a score greater than 10 usually indicates depression. The GDS was used in several prior trials of light therapy for seniors [LOVING ET AL. 2005; TSAI ET AL. 2004; SUMAYA ET AL. 2001].

Daytime sleepiness was evaluated using a modified Epworth Sleepiness Scale [JOHNS 1991], a self-report questionnaire. Subjects completed the survey each week beginning one week prior to treatment, resulting in five collection points. The questionnaire consists of eight elements that are rated on a scale of 0-3. An overall score in the 0-9 range is considered normal, whereas a score in the 10-24 range indicates a potential sleep problem. The average for a healthy adult is approximately five.
A subset of the participants (9 treatment, 8 placebo) was monitored with Phillips Respironics Actiwatch 2 actigraphy devices. Actigraphy is an accepted method for measuring sleep quality [SADEH & ACEBO 2002] and has been used in many light therapy trials, including some involving seniors [ALESSI ET AL. 2005; DOWLING ET AL. 2008; FETVEIT & BJORN 2004; FETVEIT ET AL. 2003]. The selected participants wore the accelerometer-based devices for five days prior to the experiment and five days during either week three or week four of the experiment. Data were analyzed using Phillips Respironics Actiware 5 Software, which was used to calculate a number of sleep measures. The software’s scoring algorithm, which determines whether the subject was sleeping or active, was set to medium sensitivity. Rest intervals were set individually for each participant using both light and activity data.

**Results**
All measures were analyzed using general linear mixed model analysis of variance (ANOVA), a robust method for analyzing repeated measures data. All analyses are based on a significance level of $\alpha = 0.05$.

**BEHAVIOR AND MOOD**
One subject in the treatment group was suffering from pneumonia and did not complete the post-exposure behavioral assessments, leaving $n = 14$ for the treatment group and $n = 13$ for the placebo group.

Both of the MicroCog’s first order index scores, General Cognitive Functioning (GCF) and General Cognitive Proficiency (GCP), showed significant effects for the treatment group compared to the placebo group ($F = 6.15, p = 0.020$ and $F = 6.40, p = 0.018$, respectively). The mean GCF score for the treatment group increased from 85.8 to 98.3 (0.83 SD), whereas the mean GCF score for the placebo group increased from 97.7 to 100.8 (0.21 SD). The average GCP score for the treatment group increased from 92.9 to 104.8 (0.79 SD), whereas the average GCP score for the placebo group increased from 103.4 to 106.9 (0.23 SD). Difference scores are shown in Figure 4-3. The overall positive effect of participation in the study, regardless of group, was also significant for both scores ($F = 16.81, p = 0.000$ and $F = 21.32, p = 0.000$).

In addition to the first order index scores, the second order index score for Information Processing Accuracy also showed a significant treatment versus placebo effect ($F = 8.27, p = 0.008$). The mean increased from 85.43 to 95.93 (0.70 SD) for treatment and decreased from 98.46 to 97.38 (0.07 SD) for placebo. Both second order index scores showed a significant effect for participation. Of the five functional domain scores, Reasoning/Calculation and Spatial Processing showed significant improvement for the treatment group compared to placebo ($F = 6.59, p = 0.017$ and $F = 5.63, p = 0.026$, respectively).

Of the six factors that make up the Profile Of Mood States, Tension-Anxiety showed a significant treatment versus placebo effect ($F = 5.16, p = 0.032$), with the mean score for the treatment group decreasing from 52.93 to 47.07 and the mean score for the placebo group increasing from 55.15 to 55.62. None of the other factors showed a statistically significant participation effect and the changes in mean score for the two groups were not significantly different. The results are shown in Figure 4-4.

GDS scores showed no significant difference due to participation ($F = 1.31, p = 0.263$) or treatment versus placebo ($F = 0.00, p = 0.967$). The mean score for the treatment group decreased from 3.21 to 2.71, whereas the mean score for the placebo group decreased from 3.69 to 3.15. Three participants in the treatment group and four participants in the placebo group had initial assessment scores of five or greater, suggesting they were depressed. One of those participants, from the treatment group, had a score of less than five in the post-treatment assessment.
SLEEP, DAYTIME SLEEPINESS, AND ACTIVITY LEVELS

Several Epworth Sleepiness Scale data points were missing, but the analysis included all subjects. Scores for daytime sleepiness exhibited no significant trends and the differences between the treatment and placebo groups were not significantly different ($F = 1.58$, $p = 0.187$).

Aggregate actigraphy counts were plotted for both of the subgroups that were monitored (Figure 4-5). The data are summed over 15 minute increments, which are averaged for a four day period beginning Thursday at 12:00 AM and ending Sunday at 11:59 PM. Visual inspection indicates that circadian rhythms were not altered for either group. Twenty-three sleep statistics were calculated, including bedtime, wake time, nighttime sleep duration, sleep efficiency, sleep onset latency, wake after sleep onset, and fragmentation, among others. None of these measures showed a statistically significant treatment versus placebo effect.

**Analysis**

After four weeks of treatment with blue light, significant improvements in cognition were identified in elderly, long-term care residents with multiple medical conditions and functional deficits. These gains
occurred in the absence of significant changes to nighttime sleep statistics or daytime sleepiness reports, suggesting that cognitive benefits of light therapy are not necessarily linked to better rest and may be a direct result of light exposure. Improved sleep, seen in some other light therapy trials, may contribute to gains in cognition but it may not be the only notable mechanism. Similarly, the cognitive gains occurred without significant improvements in depression scales. However, they were accompanied by a significant reduction in reports of tension and anxiety amongst the treatment group. Thus, controlled light exposure may induce both primary and secondary beneficial effects on cognitive symptoms. This is particularly important given the escalating prevalence of dementia and the absence of any current disease altering therapies.

The unrestricted sample for this pilot study had a large number of both cognitively impaired and depressed participants, at least some of whom were undergoing conventional pharmacological treatment. The fact that light therapy was associated with improved cognitive function in long-term care residents is a notable finding that underscores the need for more comprehensive studies. For example, it will be important to investigate the translation of measured cognitive improvements into activities of daily living. With regard to depression, only a small number of the participants’ GDS scores were in the depressed range and many were already receiving pharmacological treatment. In addition, the late spring treatment period was outside the timeframe where any seasonal depression would likely exist. Based on these factors, finding an antidepressant effect for the treatment versus placebo was unlikely. A larger sample size in future studies will increase the chance of including depressed but undiagnosed and untreated people who have the most potential to benefit. While including only a specific subpopulation has merit for examining specific effects, the strategy of non-selection directly translates to evaluating architectural lighting interventions for long-term care facilities.

Numerical and graphical analysis of actigraphy data indicate that circadian rhythms were not affected for participants in this study. While some changes were seen in averages for specific parameters, the large variance, and small sample sizes may have made finding significant changes improbable. Additionally, the
Ascertaining the ideal source and exposure patterns for light therapy remains an ongoing investigation. While the spectral response of the human circadian system is established, intensity (dose), source
geometry, and timing are all factors that can be controlled, but are not completely understood, especially for seniors. Other factors, such as photic history will remain highly variable in non-laboratory trials. The ability of RGB LED luminaires to provide both treatment and placebo stimuli is noteworthy.

Participants in this study were not included or excluded based on any a priori diagnosis and are thus more representative of a general long-term care population than a specifically selected subgroup. Light therapy using short-wavelength optical radiation, commonly referred to as blue light—thirty minutes at 400 lux at the eye, in the morning, five days per week over four weeks—significantly improved cognitive function compared to placebo red light. Further examination of the functional benefits and longevity of the effects is needed. No significant changes were detected in nighttime sleep statistics, reports of daytime sleepiness, circadian rhythms, or depression inventory parameters.

**FUTURE DIRECTION—LIGHT THERAPY AND ARCHITECTURAL LIGHTING**

In combination with results from other trials, the findings from this study support the need for an extensive, longitudinal study of the broader effects of light therapy for the elderly. Past studies have found light therapy to induce significant improvements for seniors with mood, sleep, and cognitive disorders. However, findings regarding the effect of light therapy on specific outcome measures, such as sleep quality or depression scales, are not universal. Many studies have relied upon small samples, though more recently published results have reported extensive trials [RIEMERSMA-VAN DER LEK ET AL 2008; LIEVERSE ET AL. 2011]. Past studies have typically relied upon specific, homogeneous groups. The results of this study provide additional support for the value of light therapy for seniors and demonstrate its effect in a heterogeneous sample.

Continued trials of light therapy are necessary to gain more insight into the specific efficacy of treatment for various ailments. Rigorous protocols, proper quantification of the stimulus, and larger sample sizes are critical to producing robust results. Future studies may continue to examine mood, sleep, and cognition, or may investigate new areas of potential benefit such as immunology. Ultimately, it will be most beneficial to conduct trials of facility-wide interventions that utilize properly tuned optical radiation. With such an intervention, generalized outcome measures such as mortality, morbidity, health system utilization, need for higher-level care, mood, falls, and quality of life can be assessed.

In addition to new clinical trials, experiments examining specific stimulus properties will be critical to increasing the efficacy of light therapy. While much is known about the spectral response of the circadian system, less is known about the impact of photic history, source size, source location, and other factors affecting circadian phototransduction. Tightly controlled laboratory experiments with objective, quantifiable outcome measures are necessary to explore these domains.

Light therapy is an effective tool for treating many ailments across many population groups. The growing population of seniors, which faces notable environmental and physiological changes, is particularly well suited for circadian-tuned architectural lighting interventions. Aside from improved quality of life, if light therapy interventions can be shown to reduce healthcare costs, justification for the increased expense of an advanced lighting system will be readily available. However, tuning the optical radiation provided by architectural lighting systems to increase nonvisual impact is not without consequences. Careful examination of the relationships between visual efficacy, nonvisual efficacy, and color quality are necessary before a circadian-tuned architectural lighting intervention can be initiated.
Perceived Brightness of Trichromatic Light Sources

Enquiry into the human visual system has occurred for centuries, with the last hundred years seeing the establishment of numerical quantifications that describe photoreception for vision. It is only in the last decade that the abundance of knowledge on the relationship between optical radiation and nonvisual functioning has been established. The fusion of these two systems has been hypothesized, but little has been done to examine the link between circadian and visual photoreception.

Most models of vision and brightness perception include only cone photoreceptors, with rods recognized for their importance in mesopic and scotopic vision. Recently, Berman [2008] has proposed a translation of S/P theory that attributes improved brightness perception to ipRGCs. Standard RGCs are the last link between retinal and cortical processing, although the effect of ipRGCs on vision remains hypothetical.

Thornton, Houser, and others have conducted experiments on the brightness perception of metameric stimuli composed of three spectral primaries. These experiments have utilized adjustment techniques to produce visual matches to daylight fluorescent lamps. They have shown that the use of prime color components increases the potential for maximum brightness perception per watt in addition to maximizing the brightness to luminance ratio [Thornton 1992a, 1997; Houser & Hu 2004; Houser et al. 2004].

An experiment was conducted to test the effect of both spectrum and age on brightness perception using direct comparison, forced choice of stimuli composed of three primaries. Forty subjects evenly divided into two age groups evaluated the brightness of pairs of lighting conditions presented in a rapid sequential manner by choosing which of the pair appeared brighter. Two distinct sets of four SPDs were created by varying the peak wavelength of either the blue or the red primary of an RGB LED source. Including all possible permutations, subjects evaluated 16 pairs for each group of four stimuli. The two sets, referred to as the blue series and red series, were analyzed independently.

Methods

Independent Variable: Spectrum

The primary independent variable was SPD. Two sets of four SPDs were created using a Telelumen spectrally tunable source. For all eight SPDs, RGB LEDs were mixed to create white light matching the chromaticity of a blackbody radiator at 3500 K. Thus, all stimuli were metamers based on the CIE 1931 2° Standard Observer (colorimetric metamers). One set of four SPDs varied the peak wavelength of the blue primary while holding the peak wavelengths of the green and red primaries constant. Another set of four SPDs was created by varying the peak wavelength of the red primary while holding the peak wavelengths of the blue and green primaries constant. The SPDs are shown in Figure 5-1. The gamut areas created by the eight primary sets are shown in Figure 5-2.

The peak wavelengths of the nominally blue primaries in the blue series were measured to be 435, 448, 461, and 480 nm, whereas the green and red primaries had peak wavelengths of 535 and 623 nm, respectively. These four SPDs are referred to as A, B, C, and D. The peak wavelengths of the nominally red primaries in the red series were measured to be 602, 616, 635, and 661 nm, whereas the blue and green primaries had peak wavelengths of 448 and 535 nm, respectively. These four SPDs are labeled as W, X, Y, and Z. The blue and red primaries represent the full range of LEDs that might be employed in an RGB architectural lighting system. The properties of the 10 total primaries used in this experiment are shown in Table 5-1. SPDs were measured using a StellarNet EPP2000C spectrometer, which the manufacturer claims has an optical resolution of 3 nm, is accurate to less than 0.25 nm, and has a repeatability of less than 0.05 nm. Measurements were output from 360 to 830 nm, recorded in 0.25 nm
The primaries were mixed using custom control software. Target chromaticity coordinates of (0.4053, 0.3907) in the CIE 1931 chromaticity diagram—the chromaticity of a blackbody radiator at 3500 K—and a target illuminance at the eye of 555 lux, were used to calibrate the eight stimuli. The drive currents necessary to produce stimuli matching these requirements was programmed prior to the experiment. SPDs were measured with the spectrometer as described above and output to text with a range of 360 to 830 nm using 1 nm increments. Illuminance was measured using a Minolta T-10 illuminance meter and the equivalence of the eight stimuli was verified with the spectrometer. Figure 5-4 illustrates the location of the measurement devices.

Because the output of LEDs varies with the temperature of the p-n junction, the luminaire cycled the eight stimuli in 5-second intervals for at least one hour prior to the first subject of a session beginning the
The same warm-up procedure was followed for the final calibration of the stimuli before the experiment began. It was found that the temperature was approximately stable at this point. Due to both the instability of the light output and tolerance of the measurement devices, the properties of the stimuli varied over time. However, careful calibration and procedural consistency kept this variability to a minimum. A quantitative description of each stimulus is given in Table 5-2. These values were calculated

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**Figure 5-2** | Gamut areas enclosed by the primaries of the blue series (left) and red series (right), with the target chromaticity of the mixture shown by the star symbol on the blackbody locus.

**Figure 5-3** | The *Light Replicator Dashboard* used to control the Telelumen spectrally tunable luminaire.
from the average of SPD measurements taken at the beginning and end of the experiment (e.g.
immediately before the first subject participated and immediately after the last subject participated).
Additionally, spot measurements were taken on a regular basis to confirm the stimuli were within a tight
tolerance. Illuminance was measured at 554 ± 2 lux, whereas chromaticity was measured at (0.405 ±
0.002, 0.391 ± 0.002). Both chromaticity and illuminance varied evenly across all SPDs rather than
disparately, resulting in consistently matched stimuli despite minor changes in measured values.

**INDEPENDENT VARIABLE: AGE**
A second independent variable was subject age. Forty subjects were recruited, evenly divided between a
younger and an older age group, in order to investigate the effect of the aging eye on brightness
perception. Subjects in the younger age group ranged from 20 to 24 years of age, with an average of 21.8
years and standard deviation of 1.37 years. Subjects in the older group ranged from 50 to 63 years of
age, with an average of 56.2 years and a standard deviation of 4.07 years. The younger group included 12
males and 8 females, whereas the older group included 5 males and 15 females. One subject in the older
group was completely colorblind. No subjects had prior knowledge of the stimuli presented to them.

**PRESENTATION METHOD**
Stimulus pairs were presented in a rapid-sequential sequence, with each stimulus appearing for 5
seconds with a dark period of 0.01 seconds in between. The sequence alternated for a minimum of 30
seconds before a judgment was made. This alternation sequence results in the observer experiencing
mixed chromatic adaptation [FAIRCHILD & RENIFF 1995]. Rapid-sequential ranking is an accepted method
for evaluating brightness perception, and has been used in several previous experiments [MCELIS ET AL
1985; BERMAN ET AL. 1990; VRABEL ET AL. 1995; HOUSER ET AL. 2009]. It produces results that are comparable
to side-by-side comparison methods [HOUSER ET AL. 2009]. Interval bias, an effect of presentation order,
can result in unintended preference for the first or second stimulus [KLEIN 2001; YESHURUN ET AL. 2008].
This effect was reduced by utilizing multiple alternations and was counterbalanced by presenting
stimulus pairs in both orders. Null condition trials were recorded to evaluate the extent of the effect.

<table>
<thead>
<tr>
<th>Peak Wavelength (nm)</th>
<th>Full Width Half Maximum (FWHM) (nm)</th>
<th>CIE 1931 Chromaticity Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>435</td>
<td>22</td>
<td>0.167 0.024</td>
</tr>
<tr>
<td>448</td>
<td>24</td>
<td>0.156 0.034</td>
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<tr>
<td>461</td>
<td>28</td>
<td>0.143 0.062</td>
</tr>
<tr>
<td>480</td>
<td>30</td>
<td>0.110 0.188</td>
</tr>
<tr>
<td>493</td>
<td>34</td>
<td>0.094 0.377</td>
</tr>
<tr>
<td>535</td>
<td>43</td>
<td>0.265 0.668</td>
</tr>
<tr>
<td>602</td>
<td>16</td>
<td>0.604 0.382</td>
</tr>
<tr>
<td>616</td>
<td>18</td>
<td>0.650 0.338</td>
</tr>
<tr>
<td>623</td>
<td>18</td>
<td>0.674 0.321</td>
</tr>
<tr>
<td>635</td>
<td>19</td>
<td>0.689 0.301</td>
</tr>
<tr>
<td>661</td>
<td>19</td>
<td>0.711 0.281</td>
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Table 5-2 | Colorimetric, photometric, and other quantitative properties of the eight RGB LED mixtures.

<table>
<thead>
<tr>
<th></th>
<th>Blue Series (XXX-535-623)</th>
<th>Red Series (448-535-XXX)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Peak Wavelength of Variable Primary</td>
<td>435</td>
<td>448</td>
</tr>
<tr>
<td>CIE 1931 Chromaticity X Coordinate</td>
<td>0.405</td>
<td>0.406</td>
</tr>
<tr>
<td>CIE 1931 Chromaticity Y Coordinate</td>
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<td>0.393</td>
</tr>
<tr>
<td>Watts</td>
<td>1.50</td>
<td>1.49</td>
</tr>
<tr>
<td>Luminous Efficacy of Radiation</td>
<td>369</td>
<td>373</td>
</tr>
<tr>
<td>Circadian Stimulus (CS)</td>
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<td>0.093</td>
</tr>
<tr>
<td>CS/w*100</td>
<td>5.74</td>
<td>6.26</td>
</tr>
<tr>
<td>S/P Ratio</td>
<td>1.45</td>
<td>1.53</td>
</tr>
<tr>
<td>P*S/P^0.5</td>
<td>666</td>
<td>686</td>
</tr>
<tr>
<td>Correlated Color Temperature (CCT)</td>
<td>3513</td>
<td>3503</td>
</tr>
<tr>
<td>Color Rendering Index (CRI)</td>
<td>73.2</td>
<td>78.1</td>
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<tr>
<td>Color Discrimination Index (CDI)</td>
<td>84.4</td>
<td>81.8</td>
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<tr>
<td>Farnsworth Munsell Gamut Area (FMG)</td>
<td>80.3</td>
<td>78.6</td>
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<td>Illuminance (lux) V(λ)</td>
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<td>554</td>
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<tr>
<td>V_M(λ)</td>
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<tr>
<td>V_10(λ)</td>
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<tr>
<td>V_b,2(λ)</td>
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<td>V_b,10(λ)</td>
<td>795</td>
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<table>
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<tr>
<th></th>
<th>VSRS Ranks, 18-25 Group</th>
<th>VSRS Ranks, 50+ Group</th>
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</thead>
<tbody>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2*</td>
</tr>
</tbody>
</table>

Figure 5-4 | Calibration of the viewing booth. The apertures for the illuminance meter and spectrometer used to calibrate the stimuli were located at the approximate location of the observers’ eyes.
**DEPENDENT VARIABLE**
The dependent variable was perceived brightness. Subjects were asked to choose which of the two stimuli in each pair appeared brighter. This was a forced choice. If the subject declared that they were equal, the experimenter instructed him or her that some of the judgments might be difficult, but that an honest assessment of which of the pair appeared brighter was required.

**STATISTICAL DESIGN**
The four conditions in each series result in 16 permutations of stimulus pairs, including four pairs of null condition trials where the two stimuli were the same. Each permutation was assigned a comparison number and each subject evaluated the combinations in a computer-generated random order. The 12 permutations with mixed stimuli were comprised of six pairs of stimuli that were presented in two orders—for example, AB and BA. Presenting the stimuli in both orders counterbalanced any order bias. During analysis, each of the six pairs of counterbalanced stimuli was combined as a single condition, resulting in six unique, non-null condition comparisons.

**APPARATUS**
The stimuli were presented in a viewing booth constructed of medium density fiberboard, which also supported the luminaire. The booth is shown in Figure 5-5. The inside of the booth was 0.81 m wide, 0.41 m deep, and 1.04 m tall. The front side of the booth was partially enclosed, with the bottom 0.61 m open to allow the observer to view the surfaces but not the luminaire itself. The luminaire was mounted in the center of the top surface, with a circular hole allowing the lens and cylindrical diffuser to penetrate into the booth. The side and bottom surfaces extended 0.39 m out towards the observer. A chin-forehead rest was mounted at this point, centered on the opening, with eye height approximately 0.41 m above the bottom surface of the booth.

All visible surfaces were painted with Behr Premium Plus Ultra Paint and Primer in One, Ultra Pure White Interior Flat Enamel. This high reflectance paint has a relatively even reflectance distribution across the visible spectrum. The exact distribution is not critical to the experiment as the stimulus was measured at the eye.

The Telelumen luminaire was connected to a computer through a local area network. Custom software provided by Telelumen was used to establish settings for the four stimuli. The settings for each stimulus were saved and combined into 16 script files, one for each comparison. The script files were opened and played in a predetermined sequence by the experimenter.

**EXPERIMENTAL PROCEDURES**
This study was approved by the Penn State University Institutional Review Board.

Upon arrival, subjects read a brief description of the experiment and signed an informed consent form. The Keystone Visual Skills Test and 24 Plate Ishihara Color Vision Test were then administered; no volunteer was excluded from the experiment based on the results of these tests, or for any other reason. Each subject also completed a general information survey that included information such as gender, age, and known visual impairments.

Following vision testing, the subject was escorted to the viewing booth and provided with general instructions. Once the subject was comfortable, the room lights were turned off and the experiment proceeded with two practice comparisons to ensure comprehension of the task. After answering any questions, the experiment continued with the presentation of the 16 comparisons for either the blue or red series, then the other series. The series presented first was alternated between subjects to counterbalance any order effect.
For each pair of stimuli the experimenter loaded a script that alternated the light in the booth every 5 seconds with a dark period of 0.01 seconds between each alternation. This 0.01 second dark period was implemented to provide the subject with a visual cue that the stimuli were changing; this signal was particularly important for the null condition trials. The experimenter also spoke aloud “A, B, A, B…” as the settings changed. The subject was instructed to wait for at least three alternations—A-B-A-B-A-B—before

Figure 5-5  |  Top: The Telelumen luminaire mounted above the viewing booth, out of the subjects’ view. Bottom: The viewing booth and the computer. During the experiment, the computer was situated behind the subject, out of view.
providing a response, but was allowed to observe as many alternations as desired. Once a response was
given, the script was stopped and the judgment was recorded. The experimenter then loaded the next
script, which also provided a brief dark period of less than 0.5 seconds during downloading.

Results
Subjects’ choices of either A or B were recorded during the experiment and later converted to binary
digits (0 or 1) for analysis. Inverse combinations (e.g. AB and BA) were combined as a single condition.
Because both inverse combinations were seen by all subjects, the number of observations for each
combination is twice the number of subjects. For all statistical analyses, the number of subjects was used
rather than number of observations because the observations were dependent. Essentially, the two
observations per pair of inverse combinations have been averaged.

DATA RELIABILITY: NULL CONDITION TRIALS
With rapid sequential presentations, interval bias—the proclivity to select either the first or the second
stimulus when the two are perceived to be identical—must be considered. Even though the repeatability
of the stimuli was very high, adaptation of individual photoreceptors or other visual phenomena as well
as basic psychological tendencies could result in a bias. Presenting both inverse combinations of a
stimulus pair counterbalances interval bias, but including null condition trials provides insight into the
robustness of the experimental apparatus and procedures.

With null condition trials, or the presentation of two identical stimuli, random chance suggests an even
number of choices for the first and second stimulus. Table 5-3 shows the results of the four null condition
trials seen by all subjects for each series. In the blue series, subjects chose the second stimulus in the BB
null condition trial 75% of the time, regardless of age group. This was statistically significant at the \( \alpha = 0.05 \) level according to the Z-test for proportions—a normal approximation to the binomial test—for
each group individually (\( p = 0.025 \)) and for the combined group (\( p = 0.002 \)). In the red series, no trials
resulted in subjects selecting one stimulus with significantly greater frequency, individually or combined.

### Table 5-3
Results of the null condition trials. Shaded, bold values represent results that are statistically
different from 50/50 at the \( \alpha = 0.05 \) level according to the Z test for proportions (normal approximation to
binomial test).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Younger</td>
<td>Older</td>
</tr>
<tr>
<td>First</td>
<td>AA [435]</td>
<td>30%</td>
<td>45%</td>
</tr>
<tr>
<td>Second</td>
<td>BB [448]</td>
<td>70%</td>
<td>55%</td>
</tr>
<tr>
<td>First</td>
<td>CC [461]</td>
<td>55%</td>
<td>50%</td>
</tr>
<tr>
<td>Second</td>
<td>DD [480]</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td>First</td>
<td>TOTAL</td>
<td>43%</td>
<td>48%</td>
</tr>
<tr>
<td>Second</td>
<td></td>
<td>58%</td>
<td>53%</td>
</tr>
</tbody>
</table>
Although both series show a tendency for subjects to select the second stimulus (55% for the blue series, 56% for the red series), this overall inclination is not statistically different from random chance ($p = 0.527$ and $p = 0.477$, respectively). This helps to establish reliability of the data. Regardless, all pairs of mixed stimuli were presented in both orders to counterbalance any interval bias.

**EFFECT OF SPD ON BRIGHTNESS PERCEPTION**

The effect of SPD on brightness perception was examined by evaluating the pairs of mixed stimuli. Table 5-4 provides the percentage of choices for each comparison, for both age groups and with the age groups combined. A Z-test for proportions was performed on each comparison as an approximation for the binomial test. Comparisons with a p-value less than the $\alpha = 0.05$ level are shaded. This analysis method considers each comparison independently. Alternatively, Figure 5-6 displays the results of Variance Stable Rank Sums (VSRS) analyses that were completed for each age group and each series. VSRS is an adaptation of two-way analysis of variance by ranks developed by Dunn-Rankin [DUNN-RANKIN ET AL. 2004] which has been used in previous lighting research [QUELLMAN & BOYCE 2002; HOUSER ET AL. 2009]. VSRS ranks the stimuli using all comparisons, with larger differences in rank indicating a greater perceptual difference. With 4 stimuli and 20 subjects, a difference of at least 20.98 is required to achieve statistical significance at the $\alpha = 0.05$ level.

The results from the red series are very clear. Participants overwhelmingly felt that the stimulus with the longer wavelength red primary was brighter. Table 5-4 shows that each comparison had one stimulus that was favored with statistical significance, based on the Z-test for proportions. The rank order of the VSRS (Figure 5-6) also indicates a preference for a longer wavelength red primary; however statistical significance at the $\alpha = 0.05$ level was only achieved for non-consecutively ranked stimuli.

**Table 5-4** | Results of the mixed condition trials, with each pairing representing a combination of both presentation orders. Shaded, bold values represent results that are statistically different from 50/50 at the $\alpha = 0.05$ level according to the Z test for proportions. Red, underlined values indicate combinations where the proportions for the younger and older groups were significantly different at the $\alpha = 0.05$ level.

<table>
<thead>
<tr>
<th>Combo</th>
<th>Blue Series (XXX-535-623)</th>
<th>Combo</th>
<th>Red Series (448-535-XXX)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Younger</td>
<td>Older</td>
<td>Combined</td>
</tr>
<tr>
<td>[435] A</td>
<td>93%</td>
<td>45%</td>
<td>69%</td>
</tr>
<tr>
<td>[448] B</td>
<td>8%</td>
<td>55%</td>
<td>31%</td>
</tr>
<tr>
<td>[435] A</td>
<td>98%</td>
<td>83%</td>
<td>90%</td>
</tr>
<tr>
<td>[461] C</td>
<td>3%</td>
<td>18%</td>
<td>10%</td>
</tr>
<tr>
<td>[435] A</td>
<td>63%</td>
<td>50%</td>
<td>56%</td>
</tr>
<tr>
<td>[480] D</td>
<td>38%</td>
<td>50%</td>
<td>44%</td>
</tr>
<tr>
<td>[448] B</td>
<td>90%</td>
<td>80%</td>
<td>85%</td>
</tr>
<tr>
<td>[461] C</td>
<td>10%</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>[448] B</td>
<td>60%</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>[480] D</td>
<td>40%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>[461] C</td>
<td>55%</td>
<td>35%</td>
<td>45%</td>
</tr>
<tr>
<td>[480] D</td>
<td>45%</td>
<td>65%</td>
<td>55%</td>
</tr>
</tbody>
</table>
The results from the blue series do not exhibit a clear pattern and the choices for several comparisons were not conclusive. For the older group, stimuli A, B, and D are ranked as having approximately equal brightness according to VSRS analysis. Stimulus C is significantly different from stimulus A, but falls just short of reaching significance at the $\alpha = 0.05$ level when compared to stimuli B and D. When evaluated with the Z-test for proportions, the older group found statistically significant differences only for stimulus pairs AC and BC. The younger group found stimulus A to be significantly brighter than stimuli C and D, according to the VSRS analysis. Analysis with the Z-test for proportions indicates younger subjects found stimulus A to be significantly brighter than stimuli C and D, in addition to finding stimulus B significantly brighter than stimulus C.

**Effect of Age on Brightness Perception**

The known physical changes that occur as the eye ages had an impact on the evaluations of the older group when compared to the younger group. While there was little difference in choice between the two groups for the red series, likely because the blue primary was fixed, the results from the blue series are notable. In all combinations involving stimulus A, which has a blue primary with a peak wavelength at 435 nm, the older group chose stimulus A as brighter less times than the younger group. The combination with the greatest difference was AB, where younger subjects chose A 93% of the time compared to just 45% for the older group ($p = 0.003$, Z-test for two proportions). Combining all six mixed condition comparisons, younger subjects were more likely to choose the stimulus with a blue primary having a shorter peak wavelength (76%) than were the older subjects (55%) with statistical significance ($p = 0.001$).
Examining the number of times subjects in each group had a split decision, or chose the opposite stimulus for the inverse presentation, reveals differences in the difficulty of the evaluations for younger and older subjects. There were 240 total decisions for each series, 120 per group. For the red series, the overall group had 15 split decisions (6%), with 7 being made by the younger group and 8 being made by the older group. For the blue series, the overall group had 40 split decisions (17%), with 15 for the younger group (13%) and 25 for the older group (21%). When evaluated within a given series, the difference between groups does not reach significance at the $\alpha = 0.05$ level. However, the overall difference between the two series is significant ($p = 0.001$), as is the difference between the two series for the older group ($p = 0.003$). The difference in number of split decisions between the series is not significant for the younger group.

**Analysis**

In this experiment, two sets of four fixed stimuli were evaluated via forced choice. The stimuli were colorimetric metamers—they were measured to have equal luminance and equal chromaticity coordinates—within a small tolerance. However, the stimuli were not visual metamers, confirmed in descriptions provided by observers when informally questioned after finishing the procedure. This is the conceptual inverse of the method used by Thornton [1992A] and Houser and Hu [2004], where the power of the primaries was modified by the observers to create a visual match to a reference, and thus by assumed translation to all other sets of trichromatic stimuli.

These two methods, choice and matching, have distinct advantages and disadvantages. Requiring only a choice simplifies the task for the observer and presents an experience similar to everyday life. When stimuli are compared directly in this manner, however, the magnitude of differences remains unknown. Visual matching is a more difficult task for observers, but allows for analysis that is more complex. With matching, ratios of brightness to luminance and brightness to watts of optical power can be calculated. Furthermore, color difference can be examined by calculating the chromaticity of the reference and stimuli when matched. Because visually matched stimuli have different tristimulus values, linear and nonlinear models can be fit to predict the resulting difference in brightness perception.

Because the stimuli in this experiment were compared and not matched, it is not possible to determine brightness per watt or brightness to luminance ratios. This does not make the data less meaningful, however. The choice method allows for a direct test of predictors such as C/P, CCT, visual efficiency functions, or prime color theory. It also demonstrates rather dramatically the effect of metameric mismatches on brightness perception. Stimuli composed of three spectral primaries and mixed to equal chromaticity and equal luminance do not appear equally bright.

**Peak Power Per Channel and Luminous Efficacy of Radiation**

When matched at a constant chromaticity and constant luminance, a variable third primary requires the least amount of power when at a prime color, as was seen with the stimuli in this experiment that are shown in Figure 5-1. This relationship was first documented by Thornton, who then showed that the same relationship holds when brightness perception is held constant instead of luminance (Figure 2-6). This relationship is a direct correlate of CMFs, which show that the human visual system is most sensitive to energy at the peaks of the three functions. These peaks coincide with the prime color regions. What cannot be implied absolutely, however, is that a triplet of prime color primaries maximizes the lumens per watt of optical radiation (LER) or perceived brightness per watt.

Computer optimizations, like those described in Chapter 6, show that LER is maximized with a bimodal distribution, with primaries at approximately 450 and 580 nm, depending on the specific chromaticity desired. Note that this relationship is limited to stimuli near the blackbody locus and within a practical range of CCTs. Thornton [1992A] demonstrated that this relationship holds when luminance (lumens) is
replaced by perceived brightness (Figure 2-7a). This relationship is seen in the LER values calculated for the stimuli in this experiment, which are shown in Table 5-2. When the blue primary is varied, the peak LER occurs for stimulus B with a blue primary at 448 nm. When the red primary is varied, the peak LER occurs for stimulus W with a red primary at 602 nm. The red primaries did not vary over a wide enough range for LER to reach its absolute maximum. Implied in this bimodal distribution is the ineffectiveness of energy in the 500 nm region, which provides little contribution to luminance—or the achromatic channel of brightness perception—and requires significantly more energy than a shorter wavelength primary to result in a color match. This is demonstrated in Figure 2-7a: when the blue primary is fixed in the anti-prime set, the peak of the red-green part of the bimodal relationship is shifted to below 1, compared to the prime color set where it is approximately 1.6. The variation in the graphs of Figure 2-7a, where perceived brightness is the matching characteristic, is likely due to individual differences. The relationship is much smoother if luminance, based on an average observer, is used as the matching factor.

It is important to remember that while they might be efficient, bichromatic mixtures do not make practical light sources due to very poor color rendition properties.

**PREICTORS OF BRIGHTNESS PERCEPATION**

The most advanced models of brightness perception available today cannot be used to predict the results of this experiment. CAMs, such as the Nayatani or CIECAM02 versions, rely on tristimulus values as the primary form of input, in addition to adapting conditions and other related criteria. The eight stimuli used in this experiment all have the same tristimulus values by design. Though visually different, they are identical according to CAMs and thus theoretically should elicit equal perceptions of brightness. Thornton [1998B] has demonstrated that numerical algorithms can improve the prediction capability of CMFs, though precise prediction of strong metamers is elusive. Using optimized CMFs to generate the stimuli would reduce the visual difference seen in this experiment. However, even using CMFs developed for an individual does not result in a perfect match. This problem is a critical element for colorimetry research.

It is possible that calibrating the stimuli to be colorimetric metamers using an alternative Standard Observer would have resulted in the stimuli being more similar in appearance. However, as Thornton has demonstrated, the difference cannot be eliminated. Although utilizing alternative CMFs to derive different tristimulus values post-hoc for input into CAMs is possible, the theoretical problem caused by strong metamers would still exist. It is expected that if the experiment were repeated with stimuli matched according to a different Standard Observer that the results would be similar.

Table 5-2 lists values computed for various lighting metrics, many of which have been considered correlates for spatial brightness perception. By design, CCT was equivalent within the tolerance of calibration. Hu and Houser [2006] demonstrated that lamps with very different CCTs could appear equally bright, whereas this experiment demonstrates that stimuli with the same CCT can elicit different perceptions of brightness. The fact that the stimuli appeared different in color illustrates another error in using CCT as a correlate for brightness perception: two lamps with the same CCT can have not only a different appearance but also very different chromaticity coordinates.

Thornton [1992B] demonstrated a clear relationship between CRI and prime color theory, as previously discussed. Therefore, it is possible to use CRI as an indicator of adherence to prime color theory. Like many correlations, any relationship between CRI and perceived brightness does not imply causation. This is especially true for this experiment, since the viewing booth was painted white and no chromatic objects were present. Furthermore, though peaks for maximum CRI, and to a lesser extent maximum CDI, fall within prime color regions, neither of these metrics accurately predict color perception of highly
structured SPDs, such as the ones in this experiment [OHNO 2004; DAVIS & OHNO 2005; ROYER ET AL. 2011]. Regardless, CRI was a poor predictor of perceived brightness. Although CRI was highest for the stimuli with primaries closest to the prime color regions, those stimuli were not judged the brightest.

Of all the color quality metrics, CDI had the highest correlation with brightness perception. CDI is maximized when the blue and red primaries are shifted to shorter and longer wavelengths, respectively. In the red series, brightness perception clearly increased as the wavelength of the red primary increased. A similar though less definitive trend exists for the blue series. No physiological explanation exists for this correlation; the dataset is too small to imply causation. The one stimulus seemingly out of order with this correlation is stimulus D, with a blue primary at 480 nm. It is notable that this coincides with the peak sensitivity of ipRGCs (Figure 2-10), though there are other potential explanations for this occurrence. Rod intrusion is not likely an explanation because the illuminance at the eye (554 lux) and luminances of the booth surfaces (165-195 cd/m²) were high [THORNTON & FAIRMAN 1998; TREZONA 1996]. However, stimulus D was notably one of the most chromatic in appearance, a phenomenon that is discussed subsequently. Because ipRGCs are not known to respond to short bursts of light, it is unlikely they would contribute directly to brightness perception in this experiment.

Several theoretical estimates of brightness perception based on scotopic or cirtopic photoreception are shown in Table 5-2. If analysis were limited to the red series, these measures would be an accurate predictor of the rank order of perceptual brightness. However, they are very poor predictors for the blue series, almost predicting the inverse of perception. Although individual variation is large, the color difference in the stimuli appeared to be sequential for both series. The progression was more subtle for the red series, moving from slightly pink to more achromatic in appearance as the wavelength of the red primary increased. The progression of the blue series was more pronounced, moving from achromatic or cool in appearance to yellow-green or warm in appearance. Several observers made unsolicited comments about the extreme color difference. These progressions in color appearance are not unprecedented, however. The bowtie effect demonstrated by Thornton [1992A] indicates that stimuli with primaries near 480-500 nm will have the largest difference between chromaticity coordinates and appearance (Figure 2-8). This was also the case in this experiment.

It is notable that the area of greatest difference between chromaticity coordinates and perceived color is in the 480-500 and 580 nm regions. These regions are also the crossover points for the chromatic channels in the opponent signals model [HURVICH 1981], as shown in Figure 2-3. It is plausible that individual differences in these crossover points result in a different response than is predicted by a Standard Observer, which is an average response.

It is difficult to estimate or understand the relationship between different color appearance and brightness perception for colorimetric metamers. A color space with hue, chroma, and brightness representing orthogonal dimensions has been called ideal [THORNTON 1992A], but that is not the case with current systems.

**POLYCHROMATIC SOURCES OF THE SAME CHROMATICITY BUT DIFFERENT VISUAL APPEARANCE**

Thornton [1992A] demonstrated that at equal perceived brightness, a purely prime color source would have a lower measured luminance than a purely anti-prime source when matched to the same reference. This relationship is less clear if two of the primaries are at the prime color wavelengths and one is not. In Figure 2-7b, the left third of the prime color plot is data from varying the blue primary and the right third is data from varying the red primary. In both cases, the other two primaries were held constant at the prime wavelengths. These data are the direct correlate of the results of this experiment, which also involved systematically varying one primary of a triplet with two other being prime color primaries. Although the results of this experiment do not provide strong evidence in support of prime color theory,
they do not fall outside the limits of Thornton’s data. Figure 2-7b shows that the perceived brightness of the stimuli were consistently underpredicted by luminance relative to a daylight fluorescent reference, but that there is no clear relationship between brightness perception and the peak wavelength of the variable primary.

Based on the format of the data from this experiment, it is impossible to evaluate whether or not stimuli comprised of prime color primaries elicit greater brightness perception per watt. Both watts and brightness perception were changing simultaneously. In the red series, the stimuli that appeared brighter also consumed more energy. The results of the blue series were less conclusive, and the predictors were less distinct.

One of the downsides of the choice method of evaluating colorimetric metamers is that in addition to different brightness, stimuli also appear different in color. The Helmholtz-Kohlrausch effect refers to the phenomenon of colored stimuli appearing brighter than nominally white stimuli of the same luminance, which has been documented in numerous experiments [WYSZECKI & STILES 1982]. In these cases, the brightness to luminance ratio was derived for stimuli of very different chromaticity and appearance. For this experiment, the stimuli had matching chromaticity coordinates but still appeared different in color. Though it is not the typical scenario for which the Helmholtz-Kohlrausch effect is prescribed, it is possible that the disparate color appearance of the stimuli influenced judgments. Of particular note is stimulus D, with a blue primary peaking at 480 nm, which was likely the most chromatic appearing of the blue series stimuli. This stimulus was ranked out of sequence, appearing brighter than stimulus C. The results of the red series are similar to what was documented by MacAdam [1950]. When the quantity of optical radiation from the red primary was reduced, the mixture changed color and appeared brighter. In this experiment, a similar trend occurred when the red primary was shifted to a longer wavelength: the mixture changed color and appeared brighter.

THE INFLUENCE OF AGE
Vision changes with age. Acuity, brightness perception, and color perception are all altered by physical changes to the components of the eye and these changes may interact with each other to produce compound effects. With the proliferation of LEDs providing many opportunities to utilize specific primaries in commercial lamps, identifying the consequences of using a very short-wavelength blue primary is important.

The AB comparison, with the peak wavelength of the blue primary varying between 435 and 448 nm, exhibited a statistically significant difference between the two age groups. It is plausible that the decrease in transmission of the lens with age, specifically for short-wavelength energy, is responsible for this disparity. Though these findings require additional research with more specific aims, they support the current effort of the CIE to develop CMFs for specific age groups [CIE 2006; CSUTI & SCHANDA 2008].

MAXWELL SPOT
Similar to comments by Thornton [1992A], a Maxwell spot [WYSZECKI & STILES 1982] was experienced by many participants, especially in relation to stimulus D of the blue series. If observers noted this during the experiment, they were directed to ignore it as best as possible. It is not known what effect the Maxwell spot has on large-field brightness perception.

SPATIAL BRIGHTNESS
Several observers provided an unsolicited description of different stimuli appearing to originate from a different location, often more overhead, or elicit a greater sensation of peripheral brightness. This was typically noted for the red series. This specific effect is undocumented. The stimuli originated from the same luminaire, which included a diffusing lens. Within tight tolerances, the luminance distributions
were as identical as reasonably possible. The Stiles-Crawford Effect [STILES & CRAWFORD 1933b; SNYDER & PASK 1973] describes the optical phenomenon of illumination of different incident angle appearing more or less bright. The observation of participants in this experiment is not precisely explained by this known effect, but it may be related in some way. Further investigation is warranted.

**PRACTICAL IMPLICATIONS FOR LAMP DEVELOPMENT**

Lamp manufacturers must make choices about spectral primaries based on colorimetric and photometric properties, such as chromaticity and luminance. While other experimental methods may provide better data for developing new metrics, the forced choices made in this experiment could aid in the development of new products. This experiment indicated that at equal chromaticity and luminance, perceived brightness will vary as a function of spectral content.

The exact relationship between SPD and brightness perception remains undefined, but brightness perception should be among the many factors that are considered when selecting primaries for an RGB LED system. Furthermore, while it is not possible to rule out contributions from ipRGCs, it is unlikely that they contribute to the difference in brightness perception noted for the stimuli in this experiment due to the mechanics of their response to radiant energy. Finally, the results suggest that the choice of red primary in an RGB system is more important to brightness perception than the choice of blue primary. This is particularly relevant to the design of circadian-tuned architectural lighting systems that could be used to replace tabletop light therapy devices. The short-wavelength primary of an RGB system is very important to nonvisual phototransduction; the possibility to change this variable without affecting visual efficacy is noteworthy.
6 Optimizing RGB LED Mixtures

Commercial software for analyzing spectral data is not widely available. Furthermore, no standard file format exists for transferring spectral data, despite a proposal for such a system [Houser 2005]. Thus, work to optimize the spectral content of lamps has remained fragmented and lamp manufacturers consider such information proprietary. As the market share of LEDs has surged, so too has the ability to carefully tune the spectral output of illuminants. With physical stimuli, it is possible to test human perception and develop new models of visual and nonvisual photoreception. In contrast, software can be used to compare existing and theoretical sources using current metrics and models rather than human perception. Computer simulations are advantageous because they can evaluate a large number of SPDs in a very short period.

Setting aside the bounds of commercial availability, researchers can use computational models to establish LED-based SPDs that maximize or minimize any chosen metric. Such SPDs can serve as targets and guide development of LEDs and other commercial lamps. This theoretical process can be used to understand the properties necessary for maximizing circadian efficacy, color rendition, luminous efficacy, or other properties.

A program was developed and used to optimize the SPD of RGB LED mixtures according to several metrics while simultaneously meeting various constraints. The results of the optimization calculations reveal trends in the placement of optical radiation that can be exploited to create sources with maximum benefit per watt. One goal for developing the software was to determine the most effective combination of primaries to use in an RGB LED system designed to maintain an adequate visual environment while providing maximum nonvisual stimulation. An RGB LED architectural lighting system could be utilized in a long-term care environment or other facilities where circadian disorders are prevalent.

Methods

OVERVIEW

Microsoft Excel 2007 and Microsoft Visual Basic 6.5 were used to create a simple interface for optimization calculations. The interface allows the user to input the peak wavelength and full width half maximum (FWHM)—the width of the distribution at half of the maximum value—of between three and five LEDs that are combined to create a mixed, white-light spectrum. In addition, the user must enter the CCT of a blackbody radiator to establish the chromaticity to which the mixed LED spectrum is matched. This limits the mixed spectrum to effectively white light. An illuminance value, considered to be measured at the point of interest (e.g. the human eye), must also be specified to determine the CS value.

The program calculates a variety of properties for the mixed spectrum, including CIE 1931 chromaticity coordinates, watts of optical radiation, LER, CCT, CRI, CDI, Farnsworth Munsell 100 Hue Gamut Area, S/P, P(S/P)\(^{0.5}\), CS, and CS per watt of optical radiation (CS/w) [Note: CS/w is always multiplied by 100 in this document]. If possible, the programming of the calculations for these metrics was verified using published data for commercially available lamps or with duplicate calculation methods. The program can be used to examine a set of LEDs with characteristics input by the user or Solver—an optimization tool integral to Excel—can be used to find a maximum or minimum value for any of the calculated metrics given the cells to vary, such as the peak wavelengths, and a set of constraints related to those cells or other calculated values.

As with most optimization calculations, a tolerance must be specified in order to reduce the calculation time to a finite level. The following options were implemented in Excel 2007 Solver:

- Precision: 0.0001
- Tolerance: 0.01%
- Convergence: 0.00001
- Estimates: Tangent
- Derivatives: Forward
- Search: Newton

Even with precise calculation parameters, it is possible for Solver to find an incorrect solution. For example, it could find a local maximum instead of the global maximum. Additionally, it is possible for two or more sets of parameters to result in a value that is within the tolerance of the true maximum value. While these occurrences are a concern, they can be alleviated with visual inspection and running many calculations. In some cases, results were verified using a different computer and a different version of the Solver application.

SPD MODEL
While the output of every LED cannot be modeled perfectly, mathematical equations provide an excellent representation. The following equation returns the power output at a specified wavelength ($\lambda$) based on a peak wavelength ($\lambda_0$) and FWHM ($\Delta\lambda_{0.5}$):

$$S_{LED}(\lambda, \lambda_0) = \{g(\lambda, \lambda_0) + 2g\left(\lambda, \lambda_0, \Delta\lambda_{0.5}\right)\}/3$$  \hspace{1cm} (2)

Where

$$g(\lambda, \lambda_0) = \exp\left[-\frac{(\lambda - \lambda_0)}{\Delta\lambda_{0.5}}^2\right]$$  \hspace{1cm} (3)

The mathematically derived SPD for each primary—referring to a single LED—is added together to determine the mixed SPD. By deriving a multiplier for the peak power of each primary, the chromaticity of the mixed SPD is matched to the chromaticity of the specified blackbody radiator. The multipliers are determined using matrix multiplication of the tristimulus values for both the blackbody radiator and exactly three primaries. With three primaries, there is only one unique solution to create a metamer match based on a CIE system of colorimetry. For this software, the CIE 1931 2° Standard Observer was employed. With more than three primaries, the problem is unconstrained. For this software, if four or five primaries are desired in the final mixed SPD, the lack of constraint is avoided by specifying the peak power for the fourth and fifth primaries relative to one of the other primaries. Though the user interface consists of five primaries, a peak power multiplier of zero can be specified for up to two of them, removing them from the algorithm. A minimum of three independent primaries is required.

The chromaticity-matched mixed SPD is scaled to provide the illuminance specified by the user. The final SPD has units of W/m²/nm, or irradiance. From this SPD all subsequent single-number metrics, previously listed, are calculated with Visual Basic functions using equations documented elsewhere.

Mixed SPDs produced with Equation 2 are described below with the notation: (BBB.B|##.#, GGG.G|##.#, RRR.R|##.#). The B, G, and R represent the peak wavelength, whereas the concatenated number is the FWHM.

OBJECTIVE AND PROCESS
The program was used to examine the following questions:

- How does the nonvisual stimulation provided by RGB LED mixtures compare to traditional illuminants such as halophosphate fluorescent, triphosphor fluorescent, CIE models of daylight, and blackbody radiation?
- For RGB LED mixtures, do tradeoffs exist between luminous efficacy, color rendition, and nonvisual efficacy?
- Does adding a fourth primary improve CS/w of polychromatic LED mixtures?
Can a single set of RGB LEDs provide efficient visual and nonvisual stimulation while simultaneously maintaining good color rendition?

To answer these questions, optimization calculations were performed by systematically varying key parameters. One important consideration was CCT, since a unique characteristic of RGB LED mixtures is the ability to produce light of varying CCTs with the same primary set. Calculations were performed to find the set of primaries that maximize CS, CS/w, CRI, CDI, or LER. In some cases, CCT—and thus chromaticity—was fixed while in others it was allowed to vary in order to determine the overall maximum value for a given metric. The advantage of allowing FWHM to vary was also evaluated. Additional constraints and considerations for the optimization parameters that related two or more of the metrics are discussed subsequently.

**MODELING NONVISUAL STIMULATION**

The CS model [REA ET AL. 2005] is the only available model of circadian phototransduction and has thus been implemented in the software described herein. The model, which uses constant criterion methodology, was built upon knowledge from neuroanatomy, electrophysiology, and psychophysics. However, particular emphasis was placed on melatonin suppression by optical radiation, especially the work of Brainard et al. [2001] and Thapan et al. [2001]. There are many nonvisual responses to optical radiation with varying levels of direct correlation to circadian rhythms and melatonin suppression. The CS model characterizes the input to the circadian system (e.g. the SCN), not the responses emanating from the circadian system. Additionally, the constant criterion methodology separates circadian phototransduction from differences in stimulus conditions, experimental protocol, or outcome measures.

While melatonin suppression was used in developing the CS model, it is assumed to predict the relationship between optical radiation and other circadian markers such as core body temperature or cortisol. In theory, the CS model can also be used to predict the response of other systems with a less obvious link to circadian rhythms. For example, the exact causation between circadian stimulation and improved cognition is undefined, but the correlation is clear. The CS model is valid from threshold sensitivity to saturation, but does not account for the minor change in spectral sensitivity that occurs throughout the day [FIGUEIRO ET AL. 2005], nor other elements of circadian photoreception such as spatial distribution, timing, duration, or photic history.

The CS model includes terms for the response of all three classes of photoreceptors: ipRGCs, cones, and rods. According to the model, circadian phototransduction is dominated by the ipRGCs, but also relies on additive input from S cones and inhibitive input from the rods. Rods also set a high threshold for circadian phototransduction that requires a certain amount of optical radiation before the ipRGCs and cones begin to signal the SCN.

The CS model predicts nonadditivity and spectral opponency through diode operators and multiple functions. A key component is the blue-yellow opponent signal arising from the S cone bipolar, which has a cross point at approximately 500 nm. The ‘blue’ input to the bipolar is modeled by S cone sensitivity, whereas the ‘yellow’ input is modeled by V10(λ), a combination of the sensitivities of L and M cones. When the response of the blue-yellow channel is negative (i.e. yellow), the CS model predicts that circadian response is solely reliant upon ipRGCs. When the response of the blue-yellow channel is positive (i.e. blue), the CS model predicts that circadian phototransduction is based on the additive response of ipRGCs and S cones but is also inhibited by the rod response. Rod inhibition can be modeled as either an instantaneous switch or a gradual effect as saturation increases. Figure 2-10 demonstrates these characteristics for monochromatic stimuli: Above 500 nm CS matches the sensitivity of ipRGCs, but below 500 nm rod inhibition reduces sensitivity until inhibition is less than the additional stimulation.
provided by the S cones. The shaded range of the CS function indicates the difference between instantaneous (sharp discontinuity, bottom) and gradual (curve, top) rod inhibition.

The features of the model can also be seen when analyzing polychromatic sources. Figure 6-1 shows CS/w versus CCT for both an RGB LED source and blackbody radiation, using both models of rod inhibition. The discontinuity predicted by the model occurs at a CCT of approximately 3750 K, however the underlying cause is the change polarity of the blue-yellow opponent signal. At CCTs less than 3750 K, the blue-yellow signal is positive, making CS solely a function of ipRGCs. At CCTs greater than 3750 K, the blue-yellow signal is negative, which enables rod inhibition of the additive signal of ipRGCs and S cones. As CCT increases, the combined signal of ipRGCs and S cones continues to increase because the SPDs have increasingly more short-wavelength energy. The same relationships hold for different SPDs, though the exactly cross point varies between approximately 3700 K and 3900 K. The same relationship also holds if CS/w is replaced with CS.

The implications of the discontinuity seen in the CS values of both highly structured and continuous SPDs are profound. Very little change in spectral composition results in drastic changes in circadian phototransduction, underscoring the importance of careful tuning. The model negates the concept that increasing CCT will always result in greater circadian stimulation, a common conjecture. Recent experimental results have confirmed that sources with a higher CCT will not always provide greater circadian stimulation [REA ET AL. 2006; FIGUEIRO ET AL. 2006]. It is notable that sources with CCTs typically found in architectural interiors may provide superior circadian stimulation. While illuminances commonly found in architectural interiors are typically too low to effect circadian functions over a short duration, when experienced for a long duration the effect is detectable [ZIETZER ET AL. 2000]. In combination, properly tuned sources used over long durations in architectural interiors may provide enough stimulation to have a positive effect on nonvisual systems.

![Figure 6-1](image)

**Figure 6-1** | CS/w as a function of CCT for both a blackbody radiator and an RGB LED mixture. Both proposed models of rod inhibition are shown: model [a] predicts an instantaneous switch, whereas model [b] predicts gradual inhibition as rod saturation increases.
The CS model is biologically plausible, but this does not mean it is perfectly accurate. Although it has been shown to predict experimental data very well, the large discontinuity in CS resulting from such a small change in SPD stands out. Careful experimentation is necessary to investigate the effect of subtle changes in SPD. The CS model is relatively simple, but the few coefficients could be altered if new data becomes available. Over time, the model will likely be improved upon and extended to include other factors affecting circadian phototransduction such as spatial distribution and temporal effects.

**CONSTRAINTS**

With any type of optimization model, constraints must be established in order to obtain realistic results. For all calculations performed, peak wavelengths were limited to between 430 and 499.99 nm for the nominally blue primary, 500 and 579.99 nm for the nominally green primary, and 580 and 700 nm for the nominally red primary. While these limits do not perfectly capture the true range of LEDs available to manufacturers, they serve as effective constraints in developing generalized conclusions. They are also necessary to ensure that at least three primaries are used in the calculation due to the functional constraints of matching chromaticity.

Constraints on FWHM were also employed. One set of calculations allowed FWHM to vary between 15 and 40 nm, whereas in others the FWHM was fixed at 30 nm for each primary. Although the range employed is not inclusive of all physically realizable LEDs, having such limits is important when simulating SPDs. In all calculations with a variable FWHM, at least one primary reached either the minimum or the maximum constraint. This does not invalidate the results, but rather provides insight into whether narrow or broad primaries are preferable for the metrics under consideration. When all other constraints are held constant, fixing the FWHM of each primary at 30 nm resulted in a 2-8% decrease in maximum CS/w, with the exact decrease dependent on other factors (Figure 6-2).

![Figure 6-2](image)

**Figure 6-2** | Maximum CS/w versus CCT with different constraints. Allowing the FWHM to vary between 10 and 40 nm, as opposed to being fixed at 30 nm, increases the maximum CS/w by less than 8%. Reducing the CRI constraint from 85 to 55 results in an increase in the maximum CS/w of up to 30%.
In addition to the basic constraints on input parameters for the LED model, constraints on color quality metrics are very important. Because a goal of this work was to investigate sources intended for use in architectural lighting systems, adequate color rendition could not be sacrificed for visual or nonvisual efficacy. The choice of color quality metrics is discussed in subsequent sections.

**Reference Sources**
CIE Standard Illuminants were used as comparison standards. Both calculated and reference SPDs were scaled to produce 1000 lux at the theoretical point of measurement. Removing source efficacy as a factor creates equivalence between sources to facilitate direct comparisons. This reduction is not trivial, however, as source efficacy—lumens per watt of input power—is an important design parameter that varies dramatically between source types. The implications of this decision are discussed in the analysis.

**Results**

**Maximizing Circadian Stimulus (CS)**
Without constraining any other metric, such as CRI or LER, maximizing CS results in SPDs that are very inefficient and render colors poorly. For example, at a CCT of 4000 K on the blackbody locus, an RGB LED source has a maximum CS of 0.711 (498.7|15.0, 500|15.0, 699.6|15.0). While this mixture has a CS value nearly three times the highest CS value for any of the CIE F-series illuminants (CS = 0.272) and more than twice the CS value of CIE Illuminant D65 (CS = 0.334), the SPD has a very low CRI of -119.23 and a CDI of 21.43. It also has an extremely poor LER of just 9 lumens per watt of optical radiation. Thus, it could not be used in an architectural lighting installation.

In general, when optimizing CS without color quality constraints, the ideal SPD has a bimodal distribution with one primary near the peak of the CS function and the other with a peak wavelength as long as possible. If lumen output is fixed, the greatest CS occurs when the highest percentage of lumens is generated by the short-wavelength primary. The long-wavelength primary contributes as few lumens as possible when it is as long as allowed by constraints. Such a primary requires much more power to create a mixture of the desired chromaticity, as modeled by CMFs, dramatically reducing LER.

The difference between maximizing CS and CS/w is important. When CS/w is targeted for maximization, a bimodal distribution still results, but the long-wavelength primary is near 610 nm. Falling in the prime color region, a 610 nm long-wavelength primary requires the least amount of power to produce the desired chromaticity of the mixed SPD. When lumen output is artificially fixed, the more desirable source will have a higher CS/w, even though it is possible for a different primary set to have a greater CS value. Thus, all optimizations described herein were based on CS/w.

**Maximizing Luminous Efficacy of Radiation (LER)**
Similar to CS, LER is maximized with a bichromatic SPD with peaks near 450 and 580 nm. The exact peaks vary based on the desired chromaticity of the mixture. An ideal source would have a primary peaking where V(\(\lambda\)) is at a maximum, but with a 555 nm primary it would be impossible to create a nominally white mixture with a practical CCT. Although luminance and perceived brightness lack a defined relationship, perceived brightness per watt of optical radiation is also maximized with a blue and yellow bichromatic SPD [Thornton 1992a].

As noted previously, bichromatic SPDs have very poor color rendition properties because all surfaces are rendered as a mixture of just two colors. This can easily be visualized on a chromaticity diagram: the gamut of a two-primary system is a line connecting two points, whereas a three-primary system has a triangular gamut. In order to limit the results obtained when maximizing CS/w or LER to those suitable for architectural lighting, adding color rendition constraints is necessary.
MAXIMIZING COLOR RENDERING INDEX (CRI) AND COLOR DISCRIMINATION INDEX (CDI)

In theory, either CRI or CDI can be employed to ensure that an SPD is appropriate for architectural illumination. Unfortunately, neither of these metrics, or any accepted metric, excels at characterizing highly structured SPDs [Ohno 2004; Davis & Ohno 2005; Royer et al. 2011]. Although they are based on the same eight test color samples, CRI and CDI cannot be maximized simultaneously for a trichromatic source, and different primaries are required for maximization in each case.

The maximum possible CDI for an RGB LED system increases when CCT increases and when the FWHM of each primary is reduced. In contrast, the maximum possible CRI occurs at a low CCT and when the FWHM of each primary is increased. For a three-primary source with a variable FWHM (15-40 nm), the maximum CRI of 94.19 occurs at 3008 K (469.4|40.0, 548.9|40.0, 620.8|40.0) and the SPD has an LER of 350 and a modest CS/w of 5.87. Under the same constraints, the maximum CDI of 187.07 occurs at 10140 K (432.5|15.0, 518.0|15.0, 659.6|15.0) and the SPD has an LER of 124 and CS/w of 5.66. These maximized properties are not necessarily based on color perception, but rather on the intricacies of colorimetry and the metrics themselves. For example, it is logical that CDI maximizes at a higher CCT because the CIE 1960 Uniform Chromaticity Scale is not perceptually uniform, despite its name. However, these two results illustrate that increasing CDI is more detrimental to LER and CS/w than increasing CRI.

The relationship between CRI and CDI is shown in Figure 6-3a. The left arm of the roughly parabolic function is the minimum possible CDI for an RGB LED system at a CCT of 4100 K. The right arm is the maximum possible CDI. The same relationship exists for the full range of CCTs seen in architectural lighting (Figure 6-3b). The apex represents the SPD that produces the maximum CRI possible; because it is a unique solution, the minimum and maximum CDI are the same at this point. As CRI increases, the range of possible CDI values decreases because a higher CRI is more restrictive of the placement of radiant energy. The existence of this relationship illustrates the antagonistic relationship between the two color rendition metrics. If only one metric is used as a constraint when maximizing CS/w, using CRI produces results that are more appropriate because when CRI is high, CDI is not extremely low. Contrarily, if CDI is used as a constraint, the SPD still trends toward a two primary source. This results in consistently low CRIs regardless of CDI.

Neither CRI, a reference-based measure, nor CDI, a gamut based measure, accurately characterize the perceived color rendition of LED sources. However, a source with a very low value in either would likely distort colors to a degree unacceptable for general illumination. Thus, evaluating sources based on both CRI and CDI, or similar pairs of metrics, has been proposed [Guo & Houser 2006; Rea & Freyssinier-Nové 2008]. While a dual-metric system would inherent the flaws of each, the increased degrees of freedom would likely result in a better correlation between numerical and perceived color rendition.

MAXIMIZING CIRCADIAN STIMULATION (CS) WITH COLOR RENDITION CONSTRAINTS

Whether constrained by CRI, CDI, or both, CS/w has a distinct relationship with CCT, as shown in Figure 6-4. CS/w generally increases as CCT increases, a result that is expected because sources with a higher CCT require a greater percentage of energy in the short-wavelength blue primary. However, this relationship is more complex and is dependent upon the specific SPD, as previously discussed. Because CRI and CDI do not use the same scale, it is difficult to conclude which metric is more limiting of CS/w.

As CCT increases, both raw CS value and watts of optical radiation increase. This occurs because higher CCTs require a greater proportion of energy to be in the short-wavelength region, which is both circadian effective and visually ineffective. However, the net effect for CS/w is positive since CS is increasing at a greater rate than watts. In additional to changing proportions, as CCT increases the peak wavelengths necessary to maximize CS/w become shorter for all three primaries. The difference between the longest and shortest wavelength for each primary is between 10 nm and 20 nm, as shown in Figure 6-5. The
The exact difference is dependent on the specific primary, variable or fixed FWHM, and the color quality constraint.

When only CRI is constrained to a minimum value during calculations to maximize CS/w, CDI increases as CCT is increased, with approximately uniform increases as CRI is constrained to a higher value (Figure 6-6). As previously discussed, the relationship between CDI and CCT is predominantly an effect of the nonuniformity of the CIE 1960 Uniform Chromaticity Scale. Conversely, when only CDI is constrained to a minimum value during calculations to maximize CS/w, CRI remains consistently low, never exceeding 30, and decreases beyond a CCT of 3500 K. Despite these relationships, CS/w has similar relationships with
CCT when either CRI or CDI is used individually as a constraint, or when both are constrained simultaneously (Figure 6-4).

Increasing the minimum CRI constraint results in a lower maximum CS/w, a greater minimum CS/w, and thus a smaller range of possible CS/w values. This occurs because a higher CRI is more restrictive of the placement of radiant energy, and is just one example of the complex tradeoffs that occur between luminous efficacy, nonvisual efficacy, and color quality. Specifically, an increase in the minimum CRI constraint from 55 to 85 causes a decrease in maximum possible CS/w of between 10% and 25% (Figure 6-2) but an increase in LER of between 3% and 6%, depending on the specified CCT. Similarly, at a CRI of 85 and a CCT of 3500 K there is a 30% difference between the minimum and maximum CS/w (6.25 compared to 8.95), but this potential improvement is accompanied by a decrease in CDI from 73.85 to 59.97. These and other relationships are discussed in the analysis.

In the future, other color quality metrics such as a vector model [ŽUKAUSKUS ET AL. 2009] or an improved reference-based system such as the Color Quality Scale [DAVIS & OHNO 2005] may supplant CRI and CDI. It is possible that these metrics could be programmed in the software and used to perform new calculations. The effect this may have is unknown.

**THREE VERSUS FOUR PRIMARIES**

A logical idea to boost CS/w of LED mixtures is to add a fourth primary. Adding amber LEDs to traditional RGB systems can improve CRI. Extending this idea to circadian phototransduction, a cyan primary could potentially be added to improve circadian efficacy. However, calculations to maximize CS/w using a tetrachromatic system reveal negligible benefit over a trichromatic system (approximately 0.03 CS/w). Such minor benefits do not warrant the additional complexity and cost of a tetrachromatic system.

![Figure 6-4](image_url) | Maximum CS/w versus CCT with different color rendition constraints (CRI, CDI) or a combination of constraints.
When maximizing CS/w, the peak wavelength for each primary becomes shorter as CCT increases. The peak wavelengths also vary based on the CRI constraint.
Analysis

As knowledge of circadian phototransduction increases, light therapy stands to transition from tabletop devices to a comprehensive architectural lighting solution. Already, researchers have called for complete, 24-hour lighting schemes [FIGUEIRO ET AL. 2008] that not only consider the positive benefits of properly tuned optical radiation, but also the benefits of darkness [GOOLEY ET AL. 2010]. Perhaps the most intriguing benefit of using LEDs for architectural lighting is the ability of an RGB LED system to meet changing visual and nonvisual needs throughout the day. An RGB LED system can be controlled with a digital protocol to provide high circadian stimulation in the morning and low circadian stimulation in the evening while maintaining a consistently acceptable visual environment. In contrast, traditional sources have a fixed SPD.

In the commercial realm, the choice of primaries includes many factors, with availability and cost being key concerns. Theoretical solutions do not address these points, but do create targets to drive future development. After performing many calculations that varied the primaries at different CCTs while maximizing CS/w under various color quality constraints, three different sets of fixed primaries were chosen. The FWHM for each primary was fixed at 30 nm for all configurations, whereas the peak wavelengths were chosen as follows:

- **Configuration 1:** Peak wavelengths of 478, 553, and 617 nm were the average of the peak wavelengths for the set of calculations across CCT (250 K increments from 2750 K to 7000 K) where the minimum CRI was 85 and the FWHM was fixed at 30 nm. Peak wavelengths from 3000 K to 4000 K were double-weighted to emphasize the range of CCTs typically found in architectural interiors.
- **Configuration 2:** Peak wavelengths of 471, 545, and 613 nm were the average of the peak wavelengths for the set of calculations across CCT (250 K increments from 3500 K to 7000 K)
where the minimum CRI was 80, minimum CDI was 80 and the FWHM was fixed at 30 nm. Peak wavelengths from 3500 K to 4000 K were double-weighted to emphasize the range of CCTs typically found in architectural interiors. [Note: both color rendition constraints could not be met simultaneously at CCTs below 3500]  

- **Configuration 3:** Peak wavelengths of 450, 530, and 610 nm were chosen based on Thornton’s prime color theory [THORNTON 1992A-C].

The properties of these sources are listed in Table 6-1 and shown in Figure 6-7. Each configuration was analyzed over a range of CCTs since they have the potential to be used in such a manner in an architectural lighting installation. The collection of data for each configuration represents a single source that can be compared to traditional sources that have a fixed CCT.

In general, all three configurations perform acceptably across the metrics examined, but small tradeoffs between circadian efficacy and color quality are apparent. For example, CDI has an inverse relationship with CS/w—configurations with a higher CDI typically have a lower CS/w. To illustrate the dramatic impact of tuning optical radiation, four additional RGB LED mixtures were analyzed. The properties of these systems are shown with the original three in Figure 6-8. The peak wavelengths, listed in the figure legend, were chosen based on various metrics, such as maximum CDI, but were not intended to represent the full range of possible RGB primaries. Like the first three configurations, these four configurations also have a fixed FWHM of 30 nm.

Examining the four charts in Figure 6-8 reveals several important considerations. There do not appear to be strong, well-defined relationships between LER and CS/w, CRI, or CDI. This indicates that tuning

<table>
<thead>
<tr>
<th>Table 6-1</th>
<th>Minimum, maximum, and average values of luminous efficacy of radiation (LER), Color Rendering Index (CRI), Color Discrimination Index (CDI), circadian stimulus (CS) and circadian stimulus per watt of optical radiation (CS/w) for three high-performing RGB LED mixtures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration:</td>
<td>1</td>
</tr>
<tr>
<td>Primaries (nm):</td>
<td>478-553-617</td>
</tr>
<tr>
<td>LER</td>
<td>Min</td>
</tr>
<tr>
<td>Ave</td>
<td>279.3</td>
</tr>
<tr>
<td>Max</td>
<td>367.7</td>
</tr>
<tr>
<td>CRI</td>
<td>Min</td>
</tr>
<tr>
<td>Ave</td>
<td>66.8</td>
</tr>
<tr>
<td>Max</td>
<td>89.5</td>
</tr>
<tr>
<td>CDI</td>
<td>Min</td>
</tr>
<tr>
<td>Ave</td>
<td>46.0</td>
</tr>
<tr>
<td>Max</td>
<td>88.2</td>
</tr>
<tr>
<td>CS</td>
<td>Min</td>
</tr>
<tr>
<td>Ave</td>
<td>0.161</td>
</tr>
<tr>
<td>Max</td>
<td>0.430</td>
</tr>
<tr>
<td>CS/w</td>
<td>Min</td>
</tr>
<tr>
<td>Ave</td>
<td>5.92</td>
</tr>
<tr>
<td>Max</td>
<td>12.00</td>
</tr>
</tbody>
</table>
optical radiation for nonvisual efficacy does not necessarily affect luminous efficacy negatively. Likewise, CRI and CS/w do not appear to be strongly correlated, although previous calculations show that increasing the minimum required CRI decreases the maximum possible CS/w. CDI does appear to have a negative relationship with CS/w. Any time that color quality is a consideration, the maximum CS/w will be reduced because at least three primaries are necessary. However, Figure 6-8 demonstrates that within trichromatic sources, CS/w and color quality can both be high simultaneously without sacrificing luminous efficacy.

**LEDs versus Other Sources**
Table 6-2 summarizes the colorimetric properties of the CIE F-series illuminants as well as blackbody radiation and D-series illuminants at the given CCTs. These CIE Standard Illuminants are representative of the traditional lamp market. Illuminants F1-F6 are considered ‘standard’ fluorescent lamps, and use broad halophosphate phosphors. Illuminants F7-F9 are considered ‘broadband’ or high color rendering lamps and rely on multiple phosphors. Illuminants F10-F12 are considered ‘narrowband’ fluorescent lamps, and utilize rare earth phosphors and are based on RGB color mixing theory. The F-series
illuminants represent a range of lamps, from warm white to daylight fluorescent. The D-series illuminants are based on a mathematical model of daylight and are not easy to physically reproduce. Blackbody radiation is a conceptual idealization of the radiation emitted as an object is heated. It is approximated by an incandescent lamp. Together, blackbody radiation (below 5000 K) and D-Series illuminants (above 5000 K) are the reference sources used when calculating CRI.

Figure 6-8 plots the sources listed in Table 6-2 along with the three LED configurations previously discussed (Table 6-1 and Figure 6-7). All trichromatic LED mixtures outperform the traditional sources based on CS/w. The RGB LED mixtures also perform well in LER and CDI, though they are not necessarily superior. The CRIs of the LED configurations are comparable to or better than those of the F-series illuminants, though by definition the CRI of blackbody radiation and the D-series illuminants is 100 and cannot be exceeded. Collectively, these results are supportive of RGB LED light sources.
While LER has been considered in the calculations and is shown in Figure 6-9, source efficacy—lumens per input watt—is critical when incorporating circadian stimulation into general illumination. LEDs have long been heralded as the future of sustainable, efficient lighting, but while extremely high source efficacies exceeding 150 lumens per watt have been realized in laboratories, the efficacy of commercial sources is lagging well behind. The Department of Energy has instituted the CALiPER program to measure currently available products both in-situation and stand-alone. The tests have shown great variability in commercially available products. In recent testing of linear LED products, efficacy ranged from 70-93 lm/w for bare lamps and 57-78 lm/w for lamps installed in a parabolic louvered troffer. For comparison, T8 fluorescent lamps were also tested, achieving 101-105 lm/w bare lamp and 69-74 lm/w in a lensed troffer. Notably, the luminaires were not equivalent. Though they are improving, the efficacy of commercially available linear LED products is still less than that of fluorescent lamps, with other LED products even further behind their counterpart traditional lamps. As LED development continues, efficacy will almost certainly exceed that of today’s most prevalent sources.

Table 6-2 | CIE 1931 chromaticity coordinates, correlated color temperature (CCT), Color Rendering Index (CRI), Color Discrimination Index (CDI), circadian stimulus (CS), watts of optical radiation, luminous efficacy of radiation (LER) and circadian stimulus per watt of optical radiation (CS/w) for the CIE Standard Illuminants used as comparison standards.

<table>
<thead>
<tr>
<th>Source</th>
<th>Chromaticity (x, y)</th>
<th>CCT</th>
<th>CRI</th>
<th>CDI</th>
<th>CS</th>
<th>Watts</th>
<th>LER</th>
<th>CS/w</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>(0.3131, 0.3371)</td>
<td>6428</td>
<td>75.82</td>
<td>78.4</td>
<td>0.291</td>
<td>3.422</td>
<td>292.23</td>
<td>8.50</td>
</tr>
<tr>
<td>F2</td>
<td>(0.3721, 0.3751)</td>
<td>4224</td>
<td>64.15</td>
<td>61.4</td>
<td>0.142</td>
<td>2.972</td>
<td>336.47</td>
<td>4.78</td>
</tr>
<tr>
<td>F3</td>
<td>(0.4091, 0.3941)</td>
<td>3446</td>
<td>56.68</td>
<td>52.1</td>
<td>0.162</td>
<td>2.871</td>
<td>348.31</td>
<td>5.64</td>
</tr>
<tr>
<td>F4</td>
<td>(0.4402, 0.4031)</td>
<td>2938</td>
<td>51.35</td>
<td>43.8</td>
<td>0.120</td>
<td>2.701</td>
<td>370.23</td>
<td>4.44</td>
</tr>
<tr>
<td>F5</td>
<td>(0.3138, 0.3452)</td>
<td>6345</td>
<td>71.66</td>
<td>73.7</td>
<td>0.272</td>
<td>3.321</td>
<td>301.11</td>
<td>8.19</td>
</tr>
<tr>
<td>F6</td>
<td>(0.3779, 0.3882)</td>
<td>4148</td>
<td>59.02</td>
<td>56.7</td>
<td>0.114</td>
<td>2.829</td>
<td>353.48</td>
<td>4.03</td>
</tr>
<tr>
<td>F7</td>
<td>(0.3129, 0.3292)</td>
<td>6495</td>
<td>90.19</td>
<td>92.7</td>
<td>0.314</td>
<td>3.945</td>
<td>253.49</td>
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While LER has been considered in the calculations and is shown in Figure 6-9, source efficacy—lumens per input watt—is critical when incorporating circadian stimulation into general illumination. LEDs have long been heralded as the future of sustainable, efficient lighting, but while extremely high source efficacies exceeding 150 lumens per watt have been realized in laboratories, the efficacy of commercial sources is lagging well behind. The Department of Energy has instituted the CALiPER program to measure currently available products both in-situation and stand-alone. The tests have shown great variability in commercially available products. In recent testing of linear LED products, efficacy ranged from 70-93 lm/w for bare lamps and 57-78 lm/w for lamps installed in a parabolic louvered troffer. For comparison, T8 fluorescent lamps were also tested, achieving 101-105 lm/w bare lamp and 69-74 lm/w in a lensed troffer. Notably, the luminaires were not equivalent. Though they are improving, the efficacy of commercially available linear LED products is still less than that of fluorescent lamps, with other LED products even further behind their counterpart traditional lamps. As LED development continues, efficacy will almost certainly exceed that of today’s most prevalent sources.

While current RGB LED products may not be economical based on energy consumption or device expense, a strong case can be made for RGB LEDs when nonvisual impact is considered. For example, if properly tuned RGB LED mixtures can reduce depression and increase cognitive capabilities for residents of a long-term care facility, the reduced healthcare costs will far exceed the additional expense of the
lighting system. As the source efficacy of RGB LED mixtures increases, such justifications will become unnecessary.

**FUTURE SOFTWARE UTILITY**

The software described herein has significant utility beyond the scope of this assessment. As a research tool, the software can be used as a precursor to psychophysical experiments, helping to identify stimuli and establish precise hypotheses. For example, the software can be used to identify SPDs within a narrow region surrounding the discontinuity in the CS function.

While the focus of this assessment was circadian stimulation, the software can be used to optimize RGB LEDs for any metric that can be calculated from an SPD. New metrics could easily be added to the program. Depending on the application, it may be more beneficial to maximize CDI or CRI rather than CS/w. The current software can accommodate these calculations.
The configurations described previously are targets for future development that likely are not achievable with currently available LEDs. However, it would be possible to modify the software to include physically realized LEDs. Regardless, the software is a valuable tool for understanding the consequences of tuning optical radiation. While no known RGB LED lamp or luminaire manufacturers account for nonvisual efficacy when primaries are selected, new tools and new knowledge may change this in the near future.

**PATHWAY TO CIRCADIAN-INSPIRED ARCHITECTURAL LIGHTING SYSTEMS**

The CS model of circadian phototransduction is a useful metric for tuning optical radiation, but more work is necessary to expand the variables that are accounted for in the function. This will require experimental work that relies on easily quantifiable measures of circadian phototransduction. Functions that predict the response of specific nonvisual systems, such as cognition or mood, will fundamentally change the way lighting systems are specified. Obtaining this knowledge will require extensive clinical trials. However, even with the current knowledge of circadian photoreception, it is possible to design lighting systems that consider nonvisual needs.

While architectural lighting systems are not capable of providing the high illuminance levels delivered by dedicated light therapy devices, spectrally targeted systems providing variable circadian stimulation throughout the day have the potential to affect circadian rhythms due to increased exposure durations. RGB LED mixtures are best suited for this application. In this assessment, three configurations of RGB LED mixtures with superior performance characteristics—considering luminous efficacy, nonvisual efficacy, and color quality—were identified. This information can be synthesized with data on commercially available LEDs to design a first generation, circadian-inspired architectural lighting system.

As white-light sources tuned for circadian efficacy are developed, it is paramount to approach spectral tuning holistically. Luminous efficacy will dominate lamp catalogues until a new system of photometry is adopted, but increasing brightness perception remains an overriding goal, even if it is underappreciated. Likewise, CRI will remain in use until a better metric is accepted and adopted, but CRI, CDI, and other metrics should be considered in combination when choosing primaries for an RGB LED system. More experimental results and improved models are necessary to better quantify both brightness perception and color perception. With improved quantification, SPDs optimized with numerical methods will better match human perception.
7 Conclusions

This research investigated the visual and nonvisual impacts of optical radiation—two components of illuminating engineering that are reliant on the spectral content of lamps—using both experimental and computational methods. The results of these endeavors can be summarized as follows:

**LIGHT THERAPY FOR SENIORS IN LONG-TERM CARE**
- Treatment with tuned optical radiation—circadian stimulus value of 1.714, for 30 minutes, in the morning, five days per week, for four weeks—improved cognitive function compared to placebo for an unregulated sample of seniors in long-term care.
- No significant changes were detected in nighttime sleep statistics, reports of daytime sleepiness, circadian rhythms, or depression inventory parameters. This indicates the potential for a direct link between optical radiation and cognitive functioning, likely mediated by excitation of the suprachiasmatic nucleus.

**PERCEIVED BRIGHTNESS OF TRICHROMATIC LIGHT SOURCES**
- Light stimuli measured to be identical according to CIE photometry and colorimetry do not appear equally bright or the same color to either younger or older subjects.
- Age may affect brightness perception when short-wavelength primaries are used, especially those with peak wavelengths shorter than 450 nm.
- Scotopic to Photopic or Cirtoptic to Photopic ratio theory, prime color theory, correlated color temperature, photometry, color quality metrics, linear brightness models, and color appearance models all failed to predict or correctly order the difference in the participants’ perception of brightness.
- The choice of long-wavelength primary has greater bearing on perceived brightness than the choice of short-wavelength primary.

**OPTIMIZING RGB LED MIXTURES**
- Bichromatic systems provide the highest luminous efficacy and nonvisual efficacy, but are not suited for architectural lighting applications.
- Trichromatic systems can outperform traditional sources when luminous efficacy, nonvisual efficacy, and color quality are considered simultaneously.
- Misplacement of radiant energy can result in poor performing trichromatic systems.
- When radiant energy is manipulated by changing primaries, tradeoffs occur between nonvisual efficacy, color quality, and luminous efficacy.

Critical knowledge of the relationship between optical radiation and humans is redefining the role of illumination. The importance of optical radiation in stimulating a multitude of biological functions can no longer be overlooked in favor of luminous efficacy. Likewise, lamps should not sacrifice brightness per watt to maximize lumens per watt, nor should color quality be disregarded for increased energy efficiency.

A logical extension of supplementary light therapy is the pursuit of architectural lighting systems that satisfy both visual and nonvisual needs. Such systems would be particularly useful for specific population groups who are unable to receive adequate stimulation from natural daylight. If architecturally
integrated light therapy can be proven to improve quality of life, delay the need for higher-level care, and reduce overall healthcare costs, there is strong justification for installing advanced lighting systems.

Advanced, circadian-tuned architectural lighting systems demand proper tuning of radiant energy. RGB LEDs can be mixed to create white light that has greater luminous efficacy, elicits an increased perception of brightness, provides better color rendition, and increases circadian stimulation per watt compared to fluorescent or incandescent sources. Additionally, RGB LED mixtures have the capacity to provide adaptable illumination suitable to biological needs that vary throughout the day and night. Choice of primaries is critical to creating high-performing systems; even small changes in peak wavelength can have a very detrimental effect on performance metrics.

There are many areas of illuminating engineering that require continued refinement in order for lighting systems to meet increasingly rigorous requirements. Brightness perception remains without a definitive model, the CIE system of colorimetry is imperfect, metrics that accurately characterize the color rendition capability of highly structured SPDs remain hypothetical, the model of circadian phototransduction is promising but requires further verification, and the ability to accurately predict specific nonvisual responses to optical radiation is lacking. Continued research in all of these areas will help future lighting systems meet visual and nonvisual needs while consuming less energy.
### Appendix: M(λ) Spectral Data

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References


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Michael grew up in State College, PA and earned his BAE / MAE from Penn State in 2008. He began working toward his PhD in 2008 and intends to pursue a career in academia after graduating. He has worked as a graduate research assistant and undergraduate research assistant throughout his time in school. Michael has also worked for Haas Building Solutions and Ashland.

Michael has completed research in many areas of illuminating engineering including light loss metrics, sports lighting uniformity, brightness perception, spectral tuning, color rendition, and lighting for nonvisual human needs. One of his research goals is to develop strategies and technologies for implementing energy-efficient architectural lighting systems that provide increased circadian stimulation while maintaining an appropriate visual environment. However, he expects to build a broad research portfolio by conducting transformative research that solves existing problems and confronts the unknown challenges of the future.

Michael was recently awarded the Jonas Bellovin Scholar Achievement Award from the Nuckolls Fund for Lighting Education and received an Honorable Mention for the National Science Foundation’s Graduate Research Fellowship. As an undergraduate, Michael was awarded the Acuity–Lithonia Award for the most outstanding thesis project in the lighting and electrical option. He also received awards for Outstanding Performance and Record of Study in Illumination and Outstanding Electronic Portfolio, among other scholarships.

He is a member of the Illuminating Engineering Society of North America and was vice-president of the Penn State student chapter as an undergraduate. He has served as the treasurer of the Architectural Engineering Department’s Graduate Student Association for the past three years.

Michael looks forward to a career in academia where he can pursue both teaching and research interests. He is passionate about lighting and believes continued research and increased education will transform the built environment and the way in which human needs are met by architecture.