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PROTOTYPE AND DEMONSTRATION OF VISION-TUNED FLUORESCENT LAMPS

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Attachment A – Grantee Report

PROTOTYPE AND DEMONSTRATION OF VISION-TUNED FLUORESCENT LAMPS

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

The human visual system exhibits peak sensitivity in the three wavelengths regions near 450, 530, and 610 nm. This fact is not embraced in the spectral design of electric light sources, even though it makes intuitive sense that both visual and energy efficiency might be promoted by light sources that exploit the fundamentally trichromatic nature of human vision. We hypothesized that when compared to common fluorescent lamps, lamps with proportionally more power in these three spectral regions (so-called "vision-tuned" or simply VT lamps) would: enhance perceived brightness per watt (Hypothesis 1); produce higher color preference per watt (Hypothesis 2), and; produce no detriment to visual performance (Hypothesis 3). Four experiments were conducted to evaluate these three hypotheses; expert and naïve subjects participated in forced choice, dimming adjustment, brightness matching, and/or visual performance experiments, where vision-tuned spectra were compared against conventional fluorescent lamps. In experiment 1 the VT lamps were perceived to be 4.3% brighter when illuminance was set equal and the lamps were nominally 6500K; at 3500K (nominal) the VT lamps were perceived to be 0.7% brighter at equal illuminance. Experiment 2 showed that a SPD comprised of 450-530-610 nm components required 5% less radiant watts than daylight fluorescent lamplight at equal brightness. Experiment 1 showed that both expert and naïve subjects strongly preferred the vision-tuned environment along color-based questions. At the higher color temperature, for example, 94% of the expert subjects rated the vision-tuned environment as preferred, 100% as more colorful, and 83% as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature. Experiment 4 showed no difference in computer-based visual performance tasks when the environments were illuminated with conventional and VT lamps at nominally 3500K and 6500K. Taken together, these results provide solid support for the above hypotheses, and the findings establish that visual and energy efficiency alike can be promoted if the fundamentally trichromatic nature of human vision is used as a guiding principle in the spectral design of electric light sources.

Key Words: fluorescent, lamp, vision, spectrum, energy, brightness, color, perception, visual performance.

Executive Summary

Introduction

The human visual system exhibits peak sensitivity in the three wavelengths regions near 450, 530, and 610 nm. This fact is not embraced in the spectral design of electric light sources, principally because conventional measures of lamp performance such as lumens per watt and color rendering index are not maximized with the same spectral regions. Yet it makes intuitive sense that both visual and energy efficiency might be promoted by light sources that exploit the fundamentally three-peaked response of human vision. The impetus for this project was our hypothesis that vision could be enhanced – in terms of both brightness perception per radiant watt and color preference – by tuning the spectral power distribution to more closely match the spectral inputs of the normal human visual system.

Project Objective

The broad objective of this project was to make and demonstrate energy efficient fluorescent lamps that have a radiant energy spectrum tuned to the sensitivities of the normal human visual system and to quantify the performance improvements compared to conventional fluorescent lighting.

Project Approach

A series of four experiments were conducted to evaluate three specific hypotheses related to the effects of increasing the proportion of energy in three regions near 450, 530, and 610 nm. We hypothesized that when compared to common fluorescent lamps, fluorescent lamps with the above characteristics (so-called "vision-tuned" lamps) would: enhance perceived brightness per watt (Hypothesis 1); produce higher color preference per watt (Hypothesis 2), and; produce no detriment to visual performance (Hypothesis 3).

In the first experiment, 18 expert (lighting designers and illuminating engineers) and 23 naïve (students and staff at the University of Nebraska Peter Kiewit Institute) subjects completed a forced choice task, comparing pairs of offices illuminated at 538 lux (50 fc) with one of four different prototype lamps that varied in spectral content in the 450-530-610 nm regions. Rooms illuminated with the vision-tuned lamps were perceived as brighter and more colorful. At the higher color temperature, for example, 94% (17/18) of the expert subjects rated the vision-tuned environment as preferred, 100% (18/18) as more colorful, and 83% (15/18) as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature. Expert and naïve observers had similar responses but the experts expressed their opinions more definitively.

The second experiment compared the effectiveness of two different sets of primary stimuli to match the brightness and color of light from a daylight fluorescent source. Thirty-nine naïve subjects (students and staff at the University of Nebraska) made two matches in a horizontally bisected 10° field. The bottom field was illuminated with daylight fluorescent lamps and the top field was illuminated with one of two primary sets. One primary set, at 453-533-619 nm was selected to be near the three peaks of human visual sensitivity (called the "prime color" set). The second set (called the "anti-prime" set) had peaks at 493-581-657 nm. The prime color set

required 5% less radiant power to match the daylight fluorescent reference, while the anti-prime set required 117% more radiant power to achieve the same match.

The third experiment was designed to complement the first experiment, using a slightly different set of lamps in the same apparatus, and asking subjects to complete a brightness adjustment task instead of a forced choice task. Thirty two naïve subjects (students and staff at the University of Nebraska) adjusted the overall brightness in one of the side-by-side rooms so that it matched the brightness in the second, adjacent room. Brightness adjustments were completed using a dimmer; the desktop illuminance required to achieve the same brightness in the two side-by-side rooms was the dependent variable. All subjects completed one series of trials comparing two empty rooms, and a second series of trials matching the brightness of two rooms furnished with a range of colorful objects. We expected that rooms illuminated with the vision-tuned lamps would require less desktop illuminance to achieve a brightness match. However, this was not the case, as we observed no substantive effect of lamp type on the brightness match. With hindsight, we believe that this finding reflects the fact that the adjustment of desktop illuminance based on a brightness match is not sensitive enough to characterize the effects we sought to demonstrate.

The fourth experiment was designed to test the hypothesis that vision-tuned lamps would produce no detriment to visual performance compared to common fluorescent lamps. Computer-based numerical verification proofreading and typing tasks were used to assess the visual performance of 32 naïve subjects (students and staff at the University of Nebraska) working under the same lamps as used in the third experiment. These two tasks provide objective measures of the speed and accuracy with which subjects are able to perform visual tasks similar to those used in offices. The dependent measures were the elapsed time to complete each task, the total number of errors in the numerical verification proofreading task, and the net number of characters typed per second in the typing task. We observed no statistically significant differences in either the numerical verification proofreading or typing tasks that were attributable to lamp type under the same illuminance. The use of vision-tuned lamps therefore produced no decrease in visual performance compared to common fluorescent lamps.

Project Outcomes

With the exception of the third experiment (brightness adjustment), the results reported here provide solid support for the three hypotheses we initially set out to evaluate. The anomalous finding in the third experiment reflects the fact that the adjustment of desktop illuminance was not a sensitive enough dependent measure to characterize the effects we sought to demonstrate. However all the other results confirmed the original hypotheses. We can therefore conclude that increasing the proportion of radiant energy in three regions near 450-530-610 nm will result in fluorescent lamps that: enhance perceived brightness per watt (Hypothesis 1); produce higher color preference per watt (Hypothesis 2), and; produce no measurable detriment to visual performance (Hypothesis 3).

Conclusions

Taken together, these results establish that visual and energy efficiency alike can be promoted if the fundamentally trichromatic nature of human vision is used as a guiding principle in the spectral design of electric light sources. Fluorescent sources, however, may not be the best technology to exploit this important feature of human vision. Fluorescent sources cannot be

designed to fully embrace trichromacy because the mercury discharge and the radiant output of phosphors are not "clean". Even in the best case there is still a considerable amount of energy radiated outside of the 450-530-610 nm regions, which will act to moderate the vision-tuned effect. In the near-term, the vision-tuned concept will most likely succeed using light emitting diodes (LEDs), which can be used to create white light by mixing light from red, green, and blue LEDs. If the wavelengths of the red, green and blue LEDs are selected to correspond to the 450-530-610 nm spectral regions, color mixing with LEDs can be more clearly related to the fundamental nature of vision. LEDs therefore represent the best currently available technology for generating a pure tri-band vision-tuned spectrum.

Recommendations

In consideration of the current state-of-the-art, our recommendation is to continue to pursue the tri-band vision tuned concept with LEDs. And more specifically, to create LED-based white light sources for general illumination where the spectrum is comprised of blue, green, and red narrow band components centered at or near 450, 530, and 610 nm.

Public Benefits to California

This project addresses two priorities identified by EISG in the document titled "Stage Two PIER Program Areas" within the section titled "Residential and Commercial Building End Use Efficiency": 1) energy efficiency, and 2) comfort and productivity. The specific problems targeted were lighting power consumption in commercial buildings and the simultaneous effect on office worker comfort and productivity.

If we assume equal conversion efficiency the potential annual energy savings in California would be between 0.00369 quads (0.045 quads3 8.2% = 0.00369 quads) and 0.016 quads (0.195 quads3 8.2% = 0.016 quads). See body of report for assumptions and qualifications.

Reducing the cost of lighting is not a simple matter of reducing the quantity of light, nor is it a matter of simply reducing the connected lighting power. For businesses, the cost of energy is dwarfed by the cost of employees and the most effective way to increase profits is to improve office worker productivity. Lighting design decisions have a significant impact on the quality of the visual environment and our ability to perform visual tasks. Experiment 1 showed that offices illuminated with lamps that have proportionally more radiant output in the 450-530-610 nm regions are perceived as brighter-per-watt, to have better color-preference-per-watt, better visual-clarity-per-watt, and are the preferred work environments at equal illuminance. Experiment 1 and 2 together showed that proportionally more energy in these key spectral regions enhances brightness-perception-per-watt. Experiment 4 showed that the vision-tuned spectrum leads to no detriment in performance. In fact, subjects performed slightly faster and with fewer errors under the vision-tuned lamps, although this effect was small and failed to reach statistical significance.

The key findings and conclusions are promising: energy efficiency and comfort and productivity can be improved by designing light sources that generate proportionally more power in the 450-530-610 nm regions. This finding is in harmony with the "Stage Two PIER Program Areas" we endeavored to address.

Introduction

Light sources are designed to optimize many factors, including lumen output, color rendering index (Ra), lamp life, size and shape, hazardous waste content, initial cost, and compatibility with existing hardware. In terms of spectral content, electric light sources are primarily designed to simultaneously optimize luminous efficacy and Ra.[1] Unfortunately, this practice fails to address the limitations of these two metrics.[2] For example, several investigators have shown that it is possible to decrease the illuminance in a space while simultaneously making the room appear brighter, so long as the spectrum is adjusted accordingly.[3-10] Other investigators have shown that color preference can be enhanced even while Ra declines.[11, 12] These observations have generally been treated as peripheral phenomena rather than as exploitable features of vision that can be systematically applied to the spectral design of light sources.

The impetus for this project was our hypothesis that vision could be enhanced – in terms of both brightness perception per radiant watt[*] and color preference – by tuning the spectral power distribution to more closely match the spectral inputs of the normal human visual system. This spectral objective is incompatible with the conventional objectives of achieving high luminous efficacy (lumens per watt) and a high Ra. Although we expected our prototype vision-tuned sources to have lower efficacy and Ra, we hypothesized that they would outperform conventional sources on psychophysical measures related to color preference, brightness perception, and overall preference.

The fundamental concept underlying these hypotheses is trichromacy, the idea that vision is fundamentally regulated by three spectral channels. Trichromacy has a long history. It was alluded to by Aristotle and can be traced through history in the work of eminent natural philosophers and scientists:

> ". . . the rainbow appears with three colors. The rainbow has three colors, and these three and no others."[12] Aristotle 350 BC
>
> "Each ray of light is compounded of three other rays only . . ."[14] George Palmer, 1777
>
> "From three simple sensations, with their combinations, we obtain seven primitive distinctions of color; but the different proportions in which they may be combined afford a variety of tints beyond all calculations . . ."[15] Thomas Young, 1845
>
> "The theory which I adopt assumes the existence of three elementary sensations by combination of which all the actual sensations of color are produced. . ."[16] James Clerk Maxwell, 1856

[*] For brevity the phrase "brightness perception" will be used throughout this report an analogue to "brightness perception per radiant watt".

> "When we speak of reducing the colors to three fundamental colors, this must be understood in a subjective sense as being an attempt to trace the color sensations to three fundamental sensations."[17] Herman von Helmholtz, 1866

Much work in the past century has built on these historical foundations leading to a deeper understanding of the three-peaked visual response. In 1933 Stiles and Crawford characterized foveal threshold detection of monochromatic lights and found a three-peaked function with maximum sensitivity at 440, 530 and 610 nm.[18] In 1955 Jameson and Hurvich measured what they call the "chromatic response function" for two observers and found peaks near 440, 520 and 620 nm.[19] In 1971 Thornton showed that color-rendering and luminous efficiency could be optimized with an additive combination of three spectral lines near 450, 540 and 610 nm.[20] Also in 1971, Sperling and Harwerth measured the spectral sensitivity in both humans and rhesus monkeys using test flashes superimposed on a white background, and found peak sensitivity at about 440, 530, and 610 nm.[21] In 1976 King-Smith and Carden corroborated their work by using test flashes superimposed on a white background to measure a three-peaked function with maxima at about 440, 530, and 600 nm.[22] Further, the CIE 1931 and 1964 standard observers each have three peaks, but because their primaries are imaginary we cannot expect their peaks to fall in the same regions as the physiologically meaningful peaks found by other investigators; both standard observers were derived with maximum saturation color matching.[23]

Three-peaked spectral distributions have been widely and fruitfully exploited for practical ends in such fields as television, digital display, photography, image projection, printing, and light sources, among other fields. Thornton has been a leading advocate for trichromacy in the field of light sources, and has studied the subject from several points-of-view, including brightness perception,[24-25] chromaticity errors,[26-28] color preference,[12] and metamerism.[29-32] Thornton has called the spectral regions near 450, 530, and 610 nm the "prime color" regions of the spectrum. His work suggests that these three regions are uniquely efficient at creating white lights with exceptional brightness perception per watt and excellent color preference.

We hypothesized that brightness and color perception would be enhanced by increasing the proportion of power content near 450, 530 and 610 nm, which implies the need to simultaneously limit spectral output in the intermediate regions near 490 and 570 nm. We also tested the hypothesis that people would have different perceptions of brightness under different correlated color temperature (CCT) environments when photopic photometric quantities are held constant, and collected data related to observers' overall preference. Finally, two of the four types of the experiments were replicated with expert and naïve observers, allowing us to independently assess and compare the responses of both groups.

Project Objectives

The broad objective of this project was to make and demonstrate energy efficient fluorescent lamps that have a radiant energy spectrum tuned to the sensitivities of the normal human visual system. The prototype light sources that we studied were created to establish the feasibility of producing commercial fluorescent light sources with superior visual effectiveness per watt using existing manufacturing technologies. Five specific objectives were as follows:

Objective 1: Make prototype fluorescent lamps that maximize radiant energy output in the three regions near 450, 530, and 610 nm while simultaneously minimizing radiant energy in other portions of the spectrum. A minimum of four different types of prototype lamps will be made, varying in the degree that they elicit a response from the human visual system.

Objective 2: Through two demonstration projects, one utilizing expert observers and one utilizing naïve subjects, collect and disseminate quantitative evidence demonstrating that the prototype lamps provide equivalent or superior visual performance with fewer radiant watts.

Objective 3: Through the same demonstration projects, collect and disseminate quantitative evidence that shows that the prototype lamps designed to maximize the human visual response have superior brightness-per-radiant-watt than commercially available fluorescent lamps.

Objective 4: Through the same demonstration projects, collect and disseminate quantitative evidence that shows that the prototype lamps designed to maximize the human visual response provide equivalent or superior color rendering.

Objective 5: Demonstrate an electrical energy savings of 20% or greater with the prototype fluorescent lighting over existing fluorescent lighting used in commercial buildings. Based on the actual energy savings, quantify the electrical savings that would result from using the experimental lamps in California office buildings.

Project Approach

A series of four experiments was conceived to test three hypotheses:

Hypothesis 1: Increasing the proportion of energy in three regions near 450-530-610 nm will enhance brightness perception.

Hypothesis 2: Increasing the proportion of energy in three regions near 450-530-610 nm will produce higher color preference than fluorescent sources optimized for V(λ) and CRI.

Hypothesis 3: Prototype lamps with enhanced energy in the three regions near 450-530-610 nm will produce no detriment to visual performance when compared against common fluorescent lamps when they produce the same illuminance.

Experiment 1 made use of four types of prototype lamps and a side-by-side office arrangement; it was designed to directly test Hypotheses 1 and 2 with a forced choice instrument. Experiment 2 was a color and brightness matching experiment that made use of the University of Nebraska-Lincoln's (UNL) trichromatic colorimeter. Subjects matched sets of three spectral primaries to a daylight fluorescent source so that we could test Hypothesis 1 by determining the efficiency of the tri-band spectrum. Experiment 3 was a follow-on to Experiment 1 that made use of four

second generation prototype lamps and the same side-by-side office arrangement. Instead of using a forced-choice instrument, subjects matched the two rooms in brightness by dimming the lighting in one of the rooms. Experiment 3 was constructed as a direct test of Hypothesis 1 and an indirect test of Hypothesis 2. Experiment 4 was a visual performance experiment where subjects performed proofreading and typing tasks. The tasks were performed under the second generation prototype to test Hypothesis 3 and were quantified using measures of speed and accuracy.

Detailed descriptions of Experiments 1 – 4 are provided in appendices A – D, respectively. What follows in this section are brief synopses that are intended to summarize the main points. The appendices should be referenced for explanations about the choice of dependent and independent variables, descriptions of the apparatuses, subject demographic information, details about the experimental methodologies and protocols, and deeper discussions about the salient findings.

Experiment 1

Expert and naïve subjects completed a forced choice task, comparing pairs of offices illuminated at 538 lux (50 fc) with one of four different prototype lamps that varied in spectral content in the 450-530-610 nm regions. Rooms illuminated with lamps having a higher percentage of their spectral power in these regions were perceived as brighter and more colorful. Expert and naïve observers had similar responses but the experts expressed their opinions more definitively. These data suggest that the perception of brightness, color, and visual clarity can be enhanced by increasing the proportion of the power radiated in the 450-530-610 nm regions, also implying the need to proportionally minimize radiant output in other spectral regions.

An implied premise of this work is that it is beneficial to increase brightness perception per watt and color preference. We believe this will lead to greater occupant satisfaction with the indoor environment. In fact, the data in Table 3 supports this concept: observers who selected a room as having better color, or being brighter, or having greater visual clarity, also tended to select that room as their preferred work environment.

Subjects found visual clarity to be among the most salient perceptual dimensions. There was even greater consensus with regard to the visual clarity question than to the questions related to brightness or color perception. This result suggests that the perception of visual clarity is both color and brightness dependent. Our own observations suggest that this phenomenon is related to the visual contrast (both color and brightness) between objects and their background, which is a perceptual phenomenon that is visually observable within the test environment.

A central conclusion of this experiment was the suggestion that brightness and color perception can be concomitantly enhanced. From this we might infer that color and brightness perception are inseparable psychophysical dimensions in typical interiors. This idea is not embraced with current lighting practice, which treats color and brightness perception as independent perceptual dimensions: “quantity” is defined with lumens and “color” quality is ranked according to Ra. The lumen and Ra are independent metrics with separate optimization criteria.

Lamp companies need reliable repeatable metrics to quantify the visual effectiveness of light sources. In today’s world Ra and V(λ) are the de facto standards for spectral optimization. In the

United States, legislation mandates the quantification of light source performance using these measures, and sources for commercial applications must meet minimum efficacy and Ra standards.[39] This experiment, together with earlier work reported by other investigators,[e.g. 2-12] suggests that these measures are not as usefully related to the acceptability of interior lighting systems as required.

One quantity that has been proposed and which has received wide currency is the S/P ratio. In this first experiment we demonstrated: 1) a pair of lamps with similar S/P ratios but very different perceptions of brightness, and 2) a pair of lamps with very different S/P ratios but equivalent perceptions of brightness. These results cannot be explained with the S/P ratio. Our results suggest that the perception of brightness and visual clarity are highly reliant upon the placement of radiant power within key spectral regions. More energy within the 450-530-610 nm spectral regions leads to enhanced brightness perception and color preference. Adjusting the magnitude of the energy within these regions alters the S/P ratio, chromaticity coordinates, and CCT, but does not alter the perceptions of brightness and visual clarity. This result underscores the significance and potential of light sources designed to feed the three spectral channels of human vision.

The increase in visual effectiveness of lamp light, in terms of brightness per watt and color preference, depends in large measure on the development of new numerical tools that more faithfully represent the experience of vision and color in our visually complex world. We especially need tools that are predictive so that they can be used to optimize light source spectra and reliably quantify their psychophysical performance. This is the most likely path of progress that will lead to visually effective light sources that are also commercially available. Without agreed upon metrics that are repeatable, reliable, and objective, light sources that yield high visually efficiency risk being discredited because they have lower lumens per watt or lower Ra. Conversely, it makes little sense to discredit sources that have lower lumens per watt or lower Ra, but which offer higher visual efficiency: unfortunately the current practice of light source design leads to this unacceptable outcome because it optimizes quantities that are not appropriate for all contexts.

Consider the two middle-wavelength phosphors used in this study. The V(λ)-based luminous efficiency at 545 nm is 0.98 versus 0.86 at 530 nm; repositioning the peak of the middle-wavelength phosphor from 545 to 530 nm therefore degrades luminous efficacy (at equal quantum efficiency). In fact, one of the main reasons the conventional middle-wavelength phosphor is utilized is because it peaks near the apex of V(λ) and is therefore responsible for a disproportionate number of total lamp lumens. By comparison the luminous efficiency at 450 nm is 0.038 and at 610 nm is 0.503; the short- and long-wavelength phosphor components therefore contribute far less to lumen output, despite their importance to color and brightness perception. This important detail is not quantified with current photometry.

Researchers and practitioners have historically treated lighting quality and energy efficiency as separate or even conflicting objectives. Yet salient questions are: how can we take the limited watts available for lighting and use them in the most effective way? Or better still, how can we improve vision and lighting quality while reducing power consumption? An approach consistent with both energy efficiency and lighting quality is to develop light sources that convert

electricity into a spectrum of radiant power most favorable to human vision. What constitutes "most favorable" may be a topic of debate, but brightness perception, color preference, and visual clarity would seem to be important in many environments.

In Experiment 1 we limited our scope to fluorescent lamps and commercially available phosphors. We were therefore unable to create what we thought would be an "ideal" light source that precisely feeds the three visual channels. Nonetheless, the effects presented here provide compelling support for the further development and refinement of light sources that fully embrace trichromacy of vision. Because vision-tuned trichromacy is based on human vision rather than on a specific technology, it generalizes to all light sources. Light emitting diodes, for example, have considerable potential for vision enhancement because of their narrow emission spectra.

Not only do these findings highlight future prospects for the development of better light sources, more fundamentally, they also provide impetus for the development of new metrics that are required to characterize, and optimize, the performance of all sources of electrically-generated lighting.

Experiment 2

Thornton reported discrepancies in chromaticity and power content in Maxwell-method visual matches when using different primary sets. He found that if a lamp were made to generate an ideal tri-band spectral power distribution (SPD) it could elicit the same brightness perception as a broadband fluorescent source while consuming 30% less power, assuming that the radiant energy is generated with equivalent conversion efficiency. Thornton also found particularly large chromaticity differences when a broadband white light was matched with what he refers to as an anti-prime (AP) primary set (blue-green, yellow, deep-red, as for example 497-579-653 nm, mean full width half maximum (FWHM) = 15.6 nm), and comparatively smaller chromaticity differences with a prime-color (PC) primary set (blue-violet, green, orange-red, as for example 452-533-607 nm, mean FWHM = 15.6 nm). In related work, Ábrahám et al. found similar chromaticity discrepancies when subjects reported a visual match, partially attributing the errors to age-related changes in the spectral transmittance of the lens.

Experiment 2 was carried out to explore these findings and to investigate individual differences in color matching. Thirty-nine subjects made two matches in a horizontally bisected 10° field. The bottom field was illuminated with daylight fluorescent lamps and the top field was illuminated with one of two primary sets that were selected to be similar to those used by Thornton and Ábrahám et al.: 1) PC = 453-533-619 nm with a mean FWHM of 18.3 nm, and 2) AP = 493-581-657 nm with a mean FWHM of 23.7 nm. Statistical data screening revealed two outliers which were removed from further analysis. The PC primary set required 5% less radiant power per unit area to match the daylight fluorescent reference and the AP set required 117% more. Thirty-six of the thirty-seven matches with the PC primary set were within a 10-step MacAdam ellipse that was centered at the daylight fluorescent reference. In contrast, just two of the matches with the AP set were within a 10-step ellipse, and twenty-four of the matches were outside of a 20-step ellipse. These trends are similar to those reported by Thornton and later by Ábrahám et al. The primary set and the interaction between primary set and age were statistically significant factors. Gender and subject knowledge were not significant.

Within the architectural lighting community it is widely believed that it is "bad" to have voids in the spectrum. Continuous spectrums like those from daylight and incandescent are considered to be superior for brightness and color perception because power is radiated at all wavelengths within the visual range. With respect to brightness, Experiment 2 provides evidence that this belief is unfounded. We argue that voids, or spectral regions with zero power, are neither universally good nor bad. The voids may be "bad" if they fall in a region of the spectrum where the visual system responds strongly, because the remaining spectrum will require proportionally more power for constant brightness. But the voids may be "good" if radiant power is absent in spectral regions of low visual sensitivity (e.g. near 490-570 nm) and instead radiated at spectral regions of high visual sensitivity (e.g. near 450-530-610 nm).

Some argue that a broadband flat spectrum (a.k.a. equi-energy SPD) may be "best" because it ensures that there is some energy for all regions of spectral reflectance. But this argument disregards the basic operation of the human visual system, which clearly does not have an equivalent response to all wavelengths. The human visual system, instead, selectively samples wavelengths, taking a continuous spectrum and simplifying it into digital impulses fed into a small number of spectral channels. To perceive "white", for example, it is not necessary for all wavelengths to enter the visual system; "white" can be perceived when the spectrum has large regions of zero spectral power. The same argument holds for the perception of other colors.

Experiment 2 showed that a SPD comprised of 453-533-619 nm components with a FWHM of 18.3 nm can elicit an equivalent perception of brightness as a broadband daylight fluorescent lamp with 5% fewer radiant watts. This corroborates the trend, but not the magnitude, found by Thornton, who demonstrated improvements as great as 30% with a 452-533-607 nm primary set with a FWHM of 15.6 nm.

Because the visual system is fundamentally a three-channel system, the goal with the spectral design of light sources should be to most effectively feed these three visual channels. Thornton has argued that the normal visual system has invariant peak spectral sensitivities near 450-530-610 nm, with minima sensitivities near 500 and 580 nm and at the limits of the visual spectrum. The data from Experiment 2 are consistent with these conclusions, and demonstrative of the potential to improve the visual efficiency of electric light sources by adjusting their spectrum.

Experiment 3

Experiment 3 was designed to complement Experiment 1, with the intention of using different experimental methodologies to address the same basic research inquiries. Experiment 3 differed from Experiment 1 in that: 1) we used a dimming adjustment task instead of a forced choice instrument, 2) second generation prototype lamps were used that were a closer match in chromaticity, and 3) the dependent variable was limited to brightness perception (Hypothesis 1), with an indirect analysis of color preference (Hypothesis 2). The data from Experiment 3 does not corroborate the results of Experiment 1. Given the results of the three other experiments performed as part of this grant, and in consideration of past scientific research, Experiment 3 appears to be anomalous.

Statistical principles allow for anomalous occurrences. If we were to repeatedly run an experiment where a real effect existed, statistical theory allows for the fact that on some occasions the effect would fail to be observed. This is one of the reasons that we have in the past advocated and employed converging operations,[81] and why we took a similar approach with this project. One experiment can seldom be used to make definitive conclusions about broad research hypotheses.

In this project we ran four experiments. The reason for doing so is that coming at the same general research inquiry from different directions typically results in a deeper understanding of the salient experimental variables. The possibility exists that data from one experiment will conflict with data from other, and these cases beg the question "which is correct?" In our case, two of three experiments fit the broad hypothesis that light sources with proportionally more power in the 450-530-610 nm regions will enhance brightness and color perception, and a fourth experiment suggested no differences in visual performance. Further, these three experiments corroborate the considerable scientific literature that initially led us to our hypotheses about brightness perception per watt, color preference per watt, and visual performance. Experiment 3 is the outlier in the sense that it does not agree with Experiments 1 and 2 and past research. Experiment 3 has to be interpreted in the context of other compelling evidence that favors the 450-530-610 nm vision-tuned spectrum.

Experiment 4

Experiment 4 was designed to test the hypothesis that vision tuned lamps would produce no detriment to visual performance when compared against common fluorescent lamps. Computer-based proofreading and typing tasks were used to assess subjects' visual performance in environments illuminated by the different lamp types. Visual performance was measured using proofreading and typing tasks developed by the National Research Council Canada (NRC) especially for lighting experiments.[81] Thirty two subjects participated in the visual performance experiments.

Plots of the salient data are shown in Figures 19 and 20. These figures show that the subjects performed faster and more accurately under the vision-tuned lamps, but these effects were small and failed to reach statistical significance. The statistical analyses shows that there are no differences in visual performance under the lamp types studied (see Tables 15 – 18). Although there is no statistically significant difference for the realistic visual tasks employed, the trends in the data suggest that under difficult visual conditions the vision-tuned lamps may be statistically superior. We did not run an experiment to confirm or deny this inference, which would in fact exceed our expectations. At this stage we are pleased to have confirmed Hypothesis 3.

Project Outcomes

The outcomes can be assessed with respect to the project objective. The five specific objectives and associated outcomes are discussed in the following sections.

Design and Manufacture of Prototype Lamps

Objective 1 was to make prototype fluorescent lamps that maximize radiant energy output in the three regions near 450, 530, and 610 nm while simultaneously minimizing radiant energy in

other portions of the spectrum, creating a minimum of four different types of prototype lamps varying in the degree that they elicit a response from the human visual system.

Four types of prototype fluorescent lamps were designed in consultation with General Electric (GE). Four types of prototype lamps were fabricated by GE and delivered for use in Experiment 1. Although the first set of prototype lamps were very good, their color tolerance was slightly outside of our ideal targets. To address this GE made six new types of prototype lamps, which we have referred to as the second generation prototypes. Two of the six were found to be outside of our color tolerances and were not used for any testing. The other four were used for Experiments 3 and 4. Spectral power distributions (SPDs) for the first set of prototype lamps are shown in Figure 2a, for the second set in Figure 2b, and key summary measures are given in Table 1.

In total we therefore produced eight prototype lamps. Half of them used the same phosphors as off-the-shelf tri-band fluorescent lamps and were designated as conventional (CV). The other half used a different middle wavelength phosphor that increased the proportion of energy in the spectral region near 430 nm while reducing the energy near 480 nm; we designated these lamps as vision-tuned (VT). Further, half the lamps were created at a warm CCT near 3500K (CV35, VT35) and the other half at a cool CCT near 6500K (CV65, VT65). These different lamp types allowed us to design experiments where we were able to study the CV / VT effect together with a possible CCT effect.

Early in the grant period we evaluated three different options for the middle-wavelength phosphors. The phosphor we selected peaked nearest to our 530 nm target with reduced output in the 570-580 nm range in comparison to the conventional middle-wavelength phosphor. The two middle-wavelength phosphors used are shown in Figure 1. We believe the middle-wavelength phosphor selected is the best of those that are available. But importantly, none of the available phosphors at the short-, middle-, or long-wavelengths are ideal. All of them generate power outside of the 450, 530, and 610 nm target regions, which is superimposed upon the spectrum created directly by the mercury discharge. The result is that it is not presently possible to create an ideal vision-tuned spectrum with fluorescent light source technologies. It therefore must be recognized that the spectrum we were able to achieve was considerably different than our ideal target spectrum.

Visual Performance

Objective 2 was to collect and disseminate quantitative evidence demonstrating that the prototype vision-tuned lamps provide equivalent or superior visual performance with fewer radiant watts.

Experiment 4 was created to address this objective using realistic tasks representative of work that happens in typical office environments. When the environment was illuminated with vision-tuned lamps the subjects performed faster and more accurately than when the environment was illuminated with conventional lamps. This effect was small and it did not achieve statistical significance, but it was nonetheless present and measurable. This outcome therefore exceeded our objective.

Brightness per Radiant Watt

Objective 3 was to collect and disseminate quantitative evidence to show that the prototype vision-tuned lamps have superior brightness-per-radiant-watt than commercially available fluorescent lamps. Results from Experiments 1 and 2 most clearly support this objective.

In Experiment 1, after subjects selected one of the two rooms as being brighter they were then asked select from a seven point scale to estimate "How much brighter?" These data were used to approximate the percentage increase in brightness perception associated with the vision-tuned lamps. At the higher color temperature the VT lamps were perceived to be 4.3% brighter when illuminance was equal, and at the lower color temperature the VT lamps were perceived to be 1.5% brighter when illuminance was equal. Tables 4a through 4d summarize the responses by subject type (expert / naïve) and color temperature (6500 K /3500 K).

Experiment 2 showed that a SPD comprised of 450-530-610 nm components required 5% less radiant watts than daylight fluorescent at equal brightness, and that the 500-580-650 components are less effective at stimulating brightness perception requiring 117% more power. We expect that it is possible to achieve greater improvements than reported here as the spectral lights approach the ideal peak wavelengths and bandwidths.

Color Rendering per Radiant Watt

Objective 4 was to collect and disseminate quantitative evidence to shows that the prototype vision-tuned provide equivalent or superior color rendering.

Experiment 1 showed that both expert and naïve subjects strongly preferred the vision-tuned environment along color-based questions, as summarized in Table 3. At the higher color temperature, for example, 94% of the expert subjects rated the vision-tuned environment as preferred, 100% as more colorful, and 83% as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature. The one case where the conventional lamps were considered to be superior was to the naïve subjects at the lower color temperature on the question of the "naturalness" of the colors overall. This data point can perhaps be explained by the fact that the first generation VT35 lamp was further from the blackbody locus than the first generation CV35 lamp.

The CV and VT lamps have also been quantitative compared on a series of color-based measures, including Ra, CPI, CDI, CSA, and Pointer's Index. The VT lamps are ranked considerably higher on most color-based measures, as shown in Table 1. The lone exception is Ra for the VT35 lamps compared to the CV35 lamps, but as we stated up front we put little faith in the conventional color rendering index as a measure of real color rendering abilities. The other measures appear to more effectively capture the color-rendering attributes of the vision-tuned lamps. For a complete explanation of Ra, CPI, CDI, CSA, and Pointer's Index see Guo and Houser.[83]

We experimentally and theoretically showed that the vision-tuned lamps have superior color-rendering abilities, fully satisfying Objective 4.

Energy Savings Potential

Objective #5 was to demonstrate an electrical energy savings of 20% or greater with the vision-tuned prototype fluorescent lighting over existing fluorescent lighting used in commercial buildings, and to quantify the electrical savings that would result from using the experimental lamps in California office buildings based on actual energy savings.

The Department of Energy's (DOE) "Guide for Evaluation of Energy Savings Potential"[81] indicates that fluorescent lighting in the current commercial building stock consumes 2.5 quads of energy nationwide. The maximum potential penetration of vision-tuned fluorescent lamps into this market is near 100%. Based on the results of Experiments 1 and 2, equal brightness-per-radiant-watt could be achieved with the vision-tuned lamps with between 1.5% and 5% less radiant power. If we assume equal conversion efficiency the potential energy savings nationwide is therefore between 0.0375 quads (1.5% 3 2.5 quads3 100% = 0.0375 quads) and 0.125 quads (5% 3 2.5 quads3 100% = 0.125 quads). An additional benefit of reducing the connected lighting power is a reduction in the building cooling load. The DOE guide indicates that the total energy use of space cooling is 1.66 quads. Lighting typically accounts for 30% to 50% of the cooling load. Therefore, by reducing lighting power by between 1.5% and 5%, and conservatively assuming the lighting accounts for 30% of the cooling load, there is the potential to reduce the total energy used by space cooling by between 0.00747 quads (1.5% 3 1.66 quads3 100%3 30% = 0.00747 quads) and 0.0249 quads (5% 3 1.66 quads3 100%3 30% = 0.0249 quads). Considering these two factors together, the potential national total energy savings is between 0.045 and 0.195 quads. According to the Energy Information Administration (EIA),[85] California is the top ranked state for energy consumption for commercial use, with 8.2% of the nation's total. If we assume this percentage is representative of California's share of the nation's energy consumption for fluorescent lighting, the potential annual energy savings in California would be between 0.00369 quads (0.045 quads3 8.2% = 0.00369 quads) and 0.016 quads (0.195 quads3 8.2% = 0.016 quads).

This analysis assumes equal conversion efficiency. That is, it assumes that the conversion of input watts to radiant watts within the visible spectrum is equivalent for the conventional lamps and the vision-tuned lamps. Within our context, this means that the alternate middle-wavelength phosphor that was used in the VT lamps (Figure 1b) must have a conversion-efficiency at least as good as the conventional middle-wavelength phosphor that was used in the CV lamps (Figure 1a). But in reality the conversion-efficiency is lower for the middle wavelength phosphor that was used in the vision-tuned lamp. This can be seen quantitatively by comparing the values in the last column of Table 1. This result was not unexpected since the conventional middle-wavelength phosphor of Figure 1a has been refined and developed over many years, whereas the alternate middle-wavelength phosphor that we used in the vision-tuned lamps has not gone through this same evolutionary enhancement. Therefore, in order to achieve the potential energy savings, the middle-wavelength phosphor we used, or another suitable phosphor, would need to be developed to the point of equal conversion efficiency. Preliminary patent searches suggest that there are other suitable phosphors that have the desired output spectrum, quantum efficiency, and lumen maintenance to be viable in a commercial version of a vision-tuned fluorescent lamp.

Conclusions

With the exception of the third experiment (brightness adjustment), the results reported here provide solid support for the three hypotheses we initially set out to evaluate. The finding in the

third experiment reflects the fact that the adjustment of desktop illuminance was not a sensitive enough dependent measure to characterize the effects we sought to demonstrate. However, all the other results confirmed the original hypotheses. We can therefore conclude that increasing the proportion of radiant energy in three regions near 450 nm, 530 nm, and 610 nm will result in fluorescent lamps that enhance perceived brightness per watt (Hypothesis 1), produce higher color preference per watt (Hypothesis 2), and produce no detriment to visual performance at the same illuminance levels (Hypothesis 3).

Taken together, these results establish that visual and energy efficiency alike can be promoted if the fundamental trichromacy of human vision is used as a guiding principle in the design of artificial light sources. Fluorescent sources, however, may not be the best technology for developing an artificial light source to exploits this important feature of human vision. Fluorescent sources cannot be designed to fully embrace trichromacy because the mercury discharge and the radiant output of phosphors are not "clean". Even in the best case there is still a considerable amount of energy radiated outside of the 450-530-610 nm regions, which will act to moderate the vision-tuned effect. The vision-tuned lamp concept will most likely succeed using light emitting diodes (LED's), which can be used to create white light by mixing light from red, green, and blue LED's. Provided that the wavelengths of red, green and blue LED's are selected to correspond to the 450-530-610 nm spectral regions, color mixing with LED's can be more clearly related to the fundamental nature of vision. LEDs therefore represent the best currently available technology for generating a pure tri-band vision-tuned spectrum.

Historically, researchers and practitioners have treated lighting quality and energy efficiency as separate or even conflicting objectives. An important aspect of this project was the effort to treat these issues as harmonious goals to be simultaneously optimized. Salient questions are: how can we take the limited watts available for lighting and use them in the most effective way? Or better still, how can we improve vision and lighting quality while reducing power consumption? An approach consistent with <u>both</u> energy efficiency and lighting quality is to develop light sources that convert electricity into a spectrum of radiant power most favorable to human vision. While this goal is logically simple, practice falls well short. This research supports the idea that increasing the proportion of power radiated in the 450-530-610 nm regions will provide light sources of exemplary brightness and color perception, and energy efficiency.

Recommendations

One limitation of fluorescent sources is that they cannot be designed to fully embrace trichromacy because the mercury discharge and the radiant output of phosphors are not "clean"; even in the best case there is still a considerable amount of energy radiated outside of the 450-530-610 nm regions. In the best case we would have been able to create vision-tuned fluorescent lamps with a more highly structured spectrum, but that is beyond the reach of present fluorescent and phosphor technologies. It may be possible to develop new phosphors that meet our requirements, but this would require a different research path than the solution we initially proposed of using off-the-shelf materials. If it were possible to create a more highly structured spectrum that better matches the vision-tuned target spectrum with fluorescent technologies, then we would expect considerably better performance than what we achieved with the present prototypes. The fact that we found a meaningful effect even with a spectrum that shares much in

common with conventional tri-phosphor fluorescent lamps provides support for the further development of the tri-band vision-tuned concept.

Recent work with LEDs has focused on their long life and high conversion efficiency. Comparatively little effort has been spent on understanding how the spectral attributes of LEDs compares to more conventional sources such as incandescent, fluorescent, and high intensity discharge (HID). The two common methods for creating white light with LEDs are by combining a short wavelength LED with phosphor(s), or with red, green, and blue color mixing. The first method seems to be aimed at achieving high lumens per watt and a high CRI, but this method retains the weaknesses inherent in these measures. The RGB method has much stronger ties with the fundamental nature of vision, provided that the wavelengths are selected to correspond to the 450-530-610 nm spectral regions. With present technology, LEDs are the only practical source for generating a pure tri-band vision-tuned spectrum.

In consideration of the current state-of-the-art, our recommendation is to continue to pursue the tri-band vision tuned concept with LEDs. And more specifically, to create LED-based white light sources for general illumination where the spectrum is comprised of blue, green, and red narrow band components centered at or near 450, 530, and 610 nm. LEDs with peak output in these spectral regions have recently become available, but at present there are no white-light LEDs that make use of them. We believe this represents the best near-term path to achieve vision-tuned light sources for general illumination, along with the concomitant enhancements in brightness perception per watt, color preference per watt, and general satisfaction with the indoor environment. Further, LEDs have additional appealing characteristics such as long life, high conversion efficiency, compact size, and good lumen maintenance, making them more attractive than the alternate phosphor we explored in creating vision-tuned fluorescent sources.

Public Benefits to California

This project addresses two priorities identified by EISG in the document titled “Stage Two PIER Program Areas” within the section titled “Residential and Commercial Building End Use Efficiency”: 1) energy efficiency, and 2) comfort and productivity. The specific problems targeted were lighting power consumption in commercial buildings and the simultaneous effect on office worker comfort and productivity.

Reducing the cost of lighting is not a simple matter of reducing the quantity of light, nor is it a matter of simply reducing the connected lighting power. For businesses, the cost of energy is dwarfed by the cost of employees. A 1990 survey of large office buildings indicated that the average annual cost per square foot for office worker salaries was $130. Electricity, repair and maintenance costs for all building systems totaled just over $3 per square foot.[86] These values suggest that the most effective way to increase profits is to improve office worker productivity.

Lighting design decisions have a significant impact on the quality of the visual environment and our ability to perform visual tasks. Lighting has been shown to affect office workers’ comfort and sense of well-being,[87] which may further contribute to their productivity.[88] When considering the cost of lighting it is important to acknowledge that there may be indirect costs on workers’ comfort, health, satisfaction, job performance, absenteeism, staff turnover and/or customer retention. Although it has been an elusive goal to prove a cause and effect relationship

between office lighting and productivity, a significant amount of anecdotal evidence in the form of case studies supports this idea.[89] Saving energy at the expense of individual performance and satisfaction is bad economics.

Experiment 1 showed that offices illuminated with lamps that have proportionally more radiant output in the 450-530-610 nm regions are perceived as brighter-per-watt, to have better color-preference-per-watt, better visual-clarity-per-watt, and are the preferred work environments at equal illuminance. Experiment 1 and 2 together showed that proportionally more energy in these key spectral regions enhances brightness-perception-per-watt. Experiment 4 showed that the vision-tuned spectrum leads to no detriment in performance. In fact, subjects performed slightly faster and with fewer errors under the vision-tuned lamps, although this effect was small and failed to reach statistical significance. The key findings and conclusions are promising: energy efficiency and comfort and productivity can be improved by designing light sources that generate proportionally more power in the 450-530-610 nm regions. This finding is in harmony with the "Stage Two PIER Program Areas" we endeavored to address.

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Abbreviations

ANSI	American National Standards Institute
AP	Anti-prime (3-band SPD with nominal peaks at 500-580-650 nm)
CCT	Correlated Color Temperature
CDI	Color Discrimination Index
CIE	International Commission on Illumination
CPI	Color Preference Index
CRC	Color Rendering Capacity
CSA	Cone Surface Area
CV	Conventional tri-phosphor fluorescent lamp
CV35	Conventional tri-phosphor fluorescent lamp with nominal CCT of 3500K
CV65	Conventional tri-phosphor fluorescent lamp with nominal CCT of 6500K
DOE	United States Department of Energy
Ds	MacAdam unit of color difference
EIA	United States Energy Information Administration
EISG	Energy Innovations Small Grant Program (of the California Energy Commission)
NRC	National Research Council Canada
PC	Prime-color (3-band SPD with nominal peaks at 450-530-610 nm)
Ra	CIE Color Rendering Index
S/P	Ratio of scotopic lumens to photopic lumens
SPD	Spectral Power Distribution
UNL	University of Nebraska-Lincoln
VT	Vision-Tuned
VT35	Vision-Tuned tri-phosphor fluorescent lamp with nominal CCT of 3500K
VT65	Vision-Tuned tri-phosphor fluorescent lamp with nominal CCT of 6500K

Appendix A – Experiment 1

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1. Abstract

Expert and naïve subjects completed a forced choice task, comparing pairs of offices illuminated at 538 lux (50 fc) with one of four different prototype lamps that varied in spectral content in the 450-530-610 nm regions. Rooms illuminated with lamps having a higher percentage of their spectral power in these regions were perceived as brighter and more colorful. Expert and naïve observers had similar responses but the experts expressed their opinions more definitively. These data suggest that the perception of brightness, color, and visual clarity can be enhanced by increasing the proportion of the power radiated in the 450-530-610 nm regions, also implying the need to proportionally minimize radiant output in other spectral regions.

2. Methods

2.1. Independent Variables

The independent variable was light spectrum, which can be considered in two categories each with two levels: the middle-wavelength phosphor and CCT. We focused on modifying the middle-wavelength phosphor because we believed it presented the best opportunity for spectral improvement. In conventional triphosphor fluorescent lamps the short-, middle-, and long-wavelength phosphors peak near 450, 545, and 610 nm. The short- and long-wavelength phosphors peak near our target spectral regions. The long-wavelength phosphor has an undesirable secondary peak near 580 nm, but there is no better substitute so we did not change it.

The peak of the conventional middle-wavelength phosphor is 15 nm away from our target region and it has secondary peaks near 490, 580 and 610 nm (Figure 1a). We substituted a phosphor with a peak nearer to the 530 nm target and with reduced power near 490 and 580 nm (Figure 1b). This phosphor also has a broader emission spectrum, although that was not a governing feature. Note that the SPDs in Figures 1a and 1b are relative. They have been normalized so that the maximum value peaks at 1.0 and are not adjusted for equal radiant or photometric content.

Four lamp types were created by blending the short-, middle-, and long-wavelength phosphors in appropriate proportions to create a pair of “warm” lamps near 3500K and a second pair of “cool” lamps near 6500K. The SPDs for the four lamps used in Experiment 1 are given in Figure 2a. We later created second generation prototypes for use in Experiments 3 and 4; for ease of

comparison SPDs for the second generation prototypes are given in Figure 2b. Table 1 is a summary of chromaticity coordinates, Ra, CCT, Color Preference Index (CPI), and other spectrally dependent measures for all of the lamp types studied. We refer to the lamps using the alternative middle-wavelength phosphor as "Vision-Tuned" and the others as "Conventional". The designations "VT35" and "VT65" are used throughout the text to refer to vision-tuned lamps at 3500K and 6500K, respectively. The lamps with the conventional phosphor blends are designated as "CV35" and "CV65". Note that these are nominal CCTs, the exact values are given in Table 1.

2.2. Dependent Variables

A forced choice survey instrument was developed to assess pairwise comparisons of rooms illuminated with the different lamp types. The first two pages of the survey packet are given as Figures 3a and 3b. The first page gives basic instructions; the second page is a typical survey instrument. Each observer used an identical instrument to rate eight pairs of light settings (1 practice trial, 1 control trial, 6 regular trials).

2.3. Apparatus

Two rooms with the dimensions of 3.5 meters (length) × 3.0 (width) × 2.7 (height) were furnished as mirror-image side-by-side offices as shown in Figure 4. Indirect luminaires (Litecontrol catalog number: P-I-55-MOD-8-T8-CWM-ECO10-NPS) were selected to maintain a near-constant luminance distribution within the rooms. The luminaires were modified by the manufacturer to house up to eight different lamp types, but for this study we used just four lamp types; the other spaces within the luminaire were left empty. The luminaires were suspended so that the top aperture was 38 cm from the ceiling. There was no appreciable difference in the luminance distribution when a different lamp type was used. Either room could be illuminated with any of the four lamp types.

The light settings were controlled with a Lutron Grafik 5000 control system. Lamps were dimmed using ECO10 dimming ballasts and the levels were set in order to maintain a constant 538 lx (50 fc) on the center of the desktops. The photocell positions can be seen on the desktops in Figure 4.

When the experimenter switched from one pair of light settings to the next pair of settings, lamp output was not immediately stable. In past work one of us (KH) attempted to use a closed loop photocell/data acquisition system to monitor lamp output in real-time and automatically maintain a desired horizontal illuminance level.[34] That earlier system would overshoot the target illuminance in both directions, resulting in visually apparent modulations in light output. As a result, for this project we employed a less technical, but more effective solution: the experimenter monitored horizontal illuminance and either raised or lowered the light level in real time to maintain 538 lx. The adjustment was performed by tapping a raise/lower switch. Adjustment was most active when the lamps were first energized. As output increased due to the normal warm-up cycle the experimenter compensated by dimming. One tap on the raise/lower switch corresponded to an illuminance change of 2-3 lx; this real-time adjustment was not perceptible to the subjects.

2.4. Statistical Design

With four lamp types in each room there are sixteen permutations of lamp pairs. Four of the sixteen pairs represent lighting both rooms with the same lamp type. We concluded that it was unnecessary to ask the subjects to rate all these combinations, as this would have significantly increased the time commitment from each subject while providing little substantive information. However, we included one such pair as a control trial. Six of the other twelve permutations are mirror images; for example, VT35 in the left room and CV35 in the right is a complement to CV35 in the left room and VT35 on the right. Each subject rated only one of the complementary combinations; left/right presentation was randomized between subjects. Each subject therefore rated a total of eight pairs of light settings. The first two trials were fixed for all subjects – a practice trial followed by a control trial. The next six trials were presented in random order, and represented the six pairwise combinations of the four lamp types. An example sequence is given in Table 2. Note that the experimenter operating the control system was given a code corresponding to a scene number on the control apparatus but remained blind to lamp type.

2.5. Subjects

Eighteen expert and twenty-three naïve observers participated in this study. The expert observers were members of the Illuminating Engineering Society of North America (IESNA) Quality of the Visual Environment (QVE) Committee. They participated in the experiment as part of a Spectral Effects Workshop hosted by the University of Nebraska in March 2003. Nine of the expert observers were female with a range of 27 to 63 years, a mean of 46, and standard deviation of 13. Male expert observers had a range of 34 to 79 years, a mean of 51, and standard deviation of 14. Twelve of the naïve observers were female with a range of 20 to 68 years, a mean of 32, and a standard deviation of 13. Male naïve observers had a range of 22 to 58 years, a mean of 35, and a standard deviation of 13.

2.6. Experimental Procedures

Observers began by reading a basic overview of the study and signing an informed consent. We then administered the Keystone Visual Skills Test and Ishihara's Tests for Color Blindness. The Keystone tests evaluate simultaneous vision at the far point, vertical and lateral posture, far point stereopsis, fusion at the near and far points, vertical posture at the far point, lateral posture for near and far points, and usable vision for each eye separately and both eyes together at both the near and far points. Ishihara's tests screen for congenital color deficiencies. Observers that normally wore glasses or contact lenses were asked to wear them during the vision screening and throughout the experiment. None of the subjects exhibited seriously deficient vision and all had normal color vision. None of the subjects were discarded from the analysis based on visual deficiencies or for any other reason.

Before the subjects entered the test environment both rooms were illuminated with VT35 at 538 lx. Upon entering the research space the observer was handed a survey packet and asked to be seated at a desk. They were positioned at the desk so that the wall between the two rooms corresponded to the sagittal plane, although observers were free to move within their chair as they made their ratings.

The experimenter then read the instructions aloud (Figure 3) and made sure the observer understood their task. The observer was then asked to turn to the first survey form and the experimenter switched Room A to CV35 at 538 lx. The subject was reminded to wait until

prompted to make their ratings. During this time the subject was asked to simply observe the objects contained within the two rooms while the experimenter monitored lamp output to maintain 538 lx on the desktops. The experimenter continued this task while the subject made their ratings. After the subject finished the practice trial the experimenter asked if anything was unclear. Once questions were answered the experimenter switched to the first trial, the subject was given 30 seconds to adapt to the new conditions while the experimenter monitored lamp output, the subject then completed the forced choice instrument, and this process was continued until all trials were finished. It took about 35 minutes for each subject to complete the ratings for the eight pairs of light settings.

3. Results and Discussion

We hypothesized that increasing the proportion of energy in the spectral regions near 450, 530, and 610 nm would enhance brightness perception and color preference. To investigate these hypotheses consider the data in top part of Table 3, which summarizes the observers' choices for questions seven through ten when a vision-tuned lamp was in one room and a conventional lamp was in the other. Question seven is a general inquiry about color, question eight asks which room is brighter, nine asks which room has greater visual clarity, and ten asks in which environment the observer would prefer to work. The mean response across questions seven through ten can be considered as a surrogate for the gestalt response. At the higher color temperature, for example, 92% of the expert and 81% of the naïve-observer responses favored the vision-tuned lamps.

There was variation in the degree of agreement from one question to the next. At the higher color temperature, for example, the experts unanimously agreed that the rooms illuminated with the vision-tuned lamps appeared more colorful and had greater visual clarity than rooms illuminated with conventional lamps. Also at the higher color temperature, 38 of 41 (93%) subjects selected the room with the vision-tuned lamps as having greater visual clarity.

Table 3 may at first suggest that the vision-tuned effect was not as strong at the lower color temperature; 75% of the expert responses favored the vision-tuned lamps, but the naïve observers exhibited no clear preference for either of the lower color temperature lamps. Considering the results of Experiment 1 only, we tentatively attribute the fact that we found a weaker effect to an unavoidable aspect of lamp design that resulted in a confound in the experimental task. Figure 5 is a plot of the chromaticity coordinates of the four lamp types along with 3-, 6- and 9-step MacAdam ellipses for each VT lamp. Ideally the counterpart lamp pairs (e.g. VT35 vs. CV35; and VT65 vs. CV65) would have identical chromaticity coordinates. As a practical matter, while it is very difficult to achieve identical lamp chromaticity, it is important that lamps at one color temperature be as close as possible, otherwise the experimental task will be confounded. A 3-step MacAdam ellipse is generally considered to be a just-perceptible chromaticity difference.[35] At the lower CCT the lamps differ by 9.2 units and at the higher CCT the lamps differ by 7.5 units, indicating that there were perceptible differences in CCT between the lamp pairs, but that the difference was more pronounced for the pair at the lower CCT. Judd proposed using reciprocal mega-Kelvin (rmK) to quantify color difference with a value of 5.5 units indicating a just noticeable difference.[36] The lower CCT lamps differed by 26.2 rmK and the higher CCT lamps differed by 3.1 rmK. Taken together these data indicate that the chromaticity difference between the lower CCT lamps was greater than between the higher CCT lamps. We believe the visually apparent chromaticity difference at the lower color temperature complicated the

comparison task. The vision-tuned / conventional effect is confounded by a chromaticity difference. At the higher color temperature, the lamps are much closer in their chromaticity so the experimental task is less confounded.

The bottom part of Table 3 is an analysis of variance (ANOVA) summary. Questions 1 – 10 were used for this analysis. The three main effects (subject type, middle-wavelength phosphor, and question) were significant ($\alpha < 0.05$). The interaction between subject type and phosphor was also significant ($\alpha < 0.05$), although the other interactions were not. These results suggest that although there were substantive differences between experts and naïve subject's ratings, both groups reported similar differences between rooms illuminated with vision-tuned lamps versus conventional lamps. The lack of statistical interaction between subject type (experts versus naïve) and question is important, because it indicates that the expert and naïve subjects interpreted the questions in the same general way. In short, the ANOVA provides statistical support for the observed trends summarized in Table 3.

Question seven, which addressed overall color appearance, inquired about three aspects of color, namely preference, colorfulness, and naturalness. Expert subjects responded similarly to all questions, although not identically. The vision-tuned lamps were preferred as they made the offices look more colorful and natural.

The observed pattern of responses for the naïve subjects was more complex. For the lower color temperature lamps, 65% considered the vision-tuned environment more colorful, but only 26% considered it more natural. We are hesitant to draw any firm conclusions because of the chromaticity differences between the two lamp types at this color temperature, but it may be that the environment appeared less natural because the VT35 lamp was further from the blackbody locus.

Ra does not appear to suitably explain or predict the color enhancing effects of the vision-tuned lamps. Ra for VT35 and CV35 are 81 and 84, respectively. Despite the lower Ra, 15 of the 18 (83 %) experts considered the room lighted with the vision-tuned lamps to be more colorful, 14 of 18 (78 %) as more preferred, and 13 of 18 (72 %) as more natural. Despite a lower Ra, the lower CCT vision-tuned lamps have a color preference index (CPI) of 117 versus 100 for the conventional lamps, and a color discrimination index (CDI) of 79 versus 68. These alternative color metrics may more faithfully predict the colorimetric performance of these light sources. Likewise, the very strong color preference for the vision-tuned lamps at the higher CCT is easier to explain with the 29% difference in CPI or the 24% difference in CDI, rather than with the 9 point (12%) difference in Ra.

After subjects selected one of the two rooms as being brighter they were to select from a seven point scale to estimate "How much brighter?" The seven choices were less than 5%, between 5 and 10%, between 10 and 20%, between 20 and 30%, between 30 and 40%, between 40 and 50%, and more than 50%. These data were used to approximate the percentage increase in brightness perception associated with the vision-tuned lamps. In computing the percentage increase a response of "less than 5%" was taken to be equal to 2.5%, a response of "between 5 and 10%" was taken to be equal to 7.5%, and so on for the other categories. At the higher color temperature the VT lamps were perceived to be 4.3% brighter when illuminance was equal, and

at the lower color temperature the VT lamps were perceived to be 0.7% brighter when illuminance was equal. Tables 4a summarizes the responses at 6500K and Table 4b summarize the responses at 3500K.

In Experiment 1 we also studied subjects' preference for different color temperature environments. The percentages of observers choosing the 6500K lamps over the 3500K lamps are given in Table 5. In these comparisons the phosphors were identical, but the short-, middle- and long-wavelength components were blended in different proportions to modify the chromaticity coordinates and associated CCT. Table 5 suggests that subjects had a strong preference for the lower color temperature sources. The interpretation of the ANOVA table is analogous to that given for the vision-tuned versus conventional lamp comparisons.

The preference for a warmer source was stronger when two conventional lamps were viewed, and weaker when two vision-tuned lamps were viewed. It may have been more difficult for subjects to choose between vision-tuned sources because the color enhancing features of the vision-tuned spectra complicated the decision. For example, the VT35 and VT65 lamps have the same CPI (117), whereas the CV35 and CV65 lamps have a difference of 10% (100 vs. 91). As with the vision-tuned versus conventional comparisons, the expert subjects were again more discriminating; they converged on a stronger consensus than the naïve observers.

There was no clear preference for either color temperature with respect to brightness or visual clarity: the rooms were considered to be equally bright regardless of whether they were illuminated with 3500K or 6500K sources. The visual clarity preference was also independent of color temperature.

Taken together, these data suggest that the perception of brightness and visual clarity depend more on the placement of radiant power within key spectral regions (e.g. VT vs. CV leads to strong brightness and visual clarity effect) than on the relative magnitude of the energy contained within these regions (e.g. 3500K vs. 6500K leads to no brightness or visual clarity effect). This result is incompatible with the notion that perceived brightness relates to the ratio of scotopic and photopic spectral content.[37] Berman has suggested that the square root of the ratio of scotopic to photopic lumens (S/P) will approximate brightness perception.[38] The S/P ratios for the lamps studied are listed in Figure 2. Table 5 shows no difference in perceived brightness when subjects compared the 3500 K and 6500 K lamps. Yet $(S/P)^{0.5}$ are equal to 1.11 and 1.08 for the VT35 and CV35 lamps, respectively, versus 1.44 and 1.40 for the VT65 and CV65 lamps, respectively. Despite $(S/P)^{0.5}$ differences greater than 25%, the different color temperature lamps did not affect perceived room brightness. Further, Table 3 shows that there were differences in brightness perception between the vision-tuned and conventional lamps when viewed at approximately the same CCT. The VT65 and CV65 lamps have similar S/P ratios, with a difference of less than 3% on the $(S/P)^{0.5}$ metric, yet the rooms lighted with the VT65 lamps were selected as brighter by 15 of 18 (83%) expert observers and 18 of 23 (78%) naïve observers. These results cannot be explained by the S/P ratio, but can be explained by the trichromatic theory of visual function.

4. Conclusions

An implied premise of this work is that it is beneficial to increase brightness perception per watt and color preference. We believe this will lead to greater occupant satisfaction with the indoor

environment. In fact, the data in Table 3 supports this concept: observers who selected a room as having better color, or being brighter, or having greater visual clarity, also tended to select that room as their preferred work environment.

Despite the fact that experts cannot agree on a definition for visual clarity, the subjects found this to be among the most salient perceptual dimensions. There was even greater consensus with regard to the visual clarity question than to the brightness question. These results suggest that the perception of visual clarity is both color and brightness dependent. Our own observations suggest that this phenomenon is related to the visual contrast (both color and brightness) between objects and their background; a dilemma is that we do not yet have a method for quantifying this effect, despite the fact that it is an apparent perceptual phenomenon that is readily observable within the test environment.

A central conclusion of this work is the suggestion that brightness and color perception can be concomitantly enhanced. From this we might infer that color and brightness perception are inseparable psychophysical dimensions in typical interiors. This idea is not embraced with current lighting practice, which treats color and brightness perception as independent perceptual dimensions: "quantity" is defined with lumens and "color" quality is ranked according to Ra. The lumen and Ra are independent metrics with separate optimization criteria.

Lamp companies need reliable repeatable metrics to quantify the visual effectiveness of light sources. In today's world Ra and V(λ) are the de facto standards for spectral optimization. In the United States, legislation mandates the quantification of light source performance using these metrics, and sources for commercial applications must meet minimum efficacy and Ra standards.[39] It should be clear from the work reported here, and earlier work reported by other investigators, that these metrics are not as usefully related to the acceptability of interior lighting systems as required.

The increase in visual effectiveness of lamp light, in terms of brightness per watt and color preference, depends in large measure on the development of new numerical tools that more faithfully represent the experience of vision and color in our visually complex world. We especially need tools that are predictive so that they can be used to optimize light source spectra and reliably quantify their psychophysical performance. This is the most likely path of progress that will lead to visually effective light sources that are also commercially available. Without agreed upon metrics that are repeatable, reliable, and objective, light sources that yield high visually efficiency risk being discredited because they have lower lumens per watt or lower Ra. Conversely, it makes little sense to discredit sources that have lower lumens per watt or lower Ra, but which offer higher visual efficiency: unfortunately the current practice of light source design leads to this unacceptable outcome because it optimizes quantities that are not appropriate for all contexts.

One quantity that has been proposed and which has received wide currency is the S/P ratio. In this study, we demonstrated: 1) a pair of lamps with similar S/P ratios but very different perceptions of brightness, and 2) a pair of lamps with very different S/P ratios but equivalent perceptions of brightness. These results cannot be explained with the S/P ratio. Our results suggest that the perception of brightness and visual clarity are highly reliant upon the placement

of radiant power within key spectral regions. More energy within the 450-530-610 nm spectral regions leads to enhanced brightness perception and color preference. Adjusting the magnitude of the energy within these regions alters the S/P ratio, chromaticity coordinates, and CCT, but does not alter the perceptions of brightness and visual clarity. This result underscores the significance and potential of light sources designed to feed the three spectral channels of human vision.

Consider the two middle-wavelength phosphors used in this study. The V(λ)-based luminous efficiency at 545 nm is 0.98 versus 0.86 at 530 nm; repositioning the peak of the middle-wavelength phosphor from 545 to 530 nm therefore degrades luminous efficacy (at equal quantum efficiency). In fact, one of the main reasons the conventional middle-wavelength phosphor is utilized is because it peaks near the apex of V(λ) and is therefore responsible for a disproportionate number of total lamp lumens. By comparison the luminous efficiency at 450 nm is 0.038 and at 610 nm is 0.503; the short- and long-wavelength phosphor components therefore contribute far less to lumen output, despite their importance to color and brightness perception. This important detail is not quantified with current photometry.

Within this study the expert subjects shared similar opinions with the naïve observers, but as a group they expressed their opinion more definitively. This suggests that it is indeed useful to use expert subjects in psychophysical lighting research, but that their responses should always be complemented by data collected from naïve subjects.

Researchers and practitioners have historically treated lighting quality and energy efficiency as separate or even conflicting objectives. Yet salient questions are: how can we take the limited watts available for lighting and use them in the most effective way? Or better still, how can we improve vision and lighting quality while reducing power consumption? An approach consistent with both energy efficiency and lighting quality is to develop light sources that convert electricity into a spectrum of radiant power most favorable to human vision. What constitutes "most favorable" may be a topic of debate, but brightness perception, color preference, and visual clarity would seem to be important in most environments.

In this pilot study we limited our scope to fluorescent lamps and commercially available phosphors. We were therefore unable to create what we thought would be an "ideal" light source that precisely feeds the three visual channels. Nonetheless, the effects presented here provide compelling support for the further development and refinement of light sources that fully embrace trichromacy of vision. Because vision-tuned trichromacy is based on human vision rather than on a specific technology, it generalizes to all light sources. Light emitting diodes, for example, have considerable potential for vision enhancement because of their narrow emission spectra.

Not only do these findings highlight future prospects for the development of better light sources, more fundamentally, they also provide impetus for the development of new metrics that are required to characterize, and optimize, the performance of all sources of electrically-generated lighting.

Appendix B – Experiment 2

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1. Abstract

Thornton reported discrepancies in chromaticity and power content in Maxwell-method visual matches when using different primary sets. He found that if a lamp were made to generate an ideal tri-band spectral power distribution (SPD) it could elicit the same brightness perception as a broadband fluorescent source while consuming 30% less power, assuming that the radiant energy is generated with equivalent conversion efficiency. Thornton also found particularly large chromaticity differences when a broadband white light was matched with what he refers to as an anti-prime (AP) primary set (blue-green, yellow, deep-red, as for example 497-579-653 nm, mean full width half maximum (FWHM) = 15.6 nm), and comparatively smaller chromaticity differences with a prime-color (PC) primary set (blue-violet, green, orange-red, as for example 452-533-607 nm, mean FWHM = 15.6 nm). In related work, Ábrahám et al. found similar chromaticity discrepancies when subjects reported a visual match, partially attributing the errors to age-related changes in the specular transmittance of the lens. This present study was carried out to explore these findings and to investigate individual differences in color matching. Thirty-nine subjects made two matches in a horizontally bisected 10° field. The bottom field was illuminated with daylight fluorescent lamps and the top field was illuminated with one of two primary sets that were selected to be similar to those used by Thornton and Ábrahám et al.: 1) PC = 453-533-619 nm with a mean FWHM of 18.3 nm, and 2) AP = 493-581-657 nm with a mean FWHM of 23.7 nm. Statistical data screening revealed two outliers which were removed from further analysis. The PC primary set required 5% less radiant power per unit area to match the daylight fluorescent reference and the AP set required 117% more. Thirty-six of the thirty-seven matches with the PC primary set were within a 10-step MacAdam ellipse that was centered at the daylight fluorescent reference. In contrast, just two of the matches with the AP set were within a 10-step ellipse, and twenty-four of the matches were outside of a 20-step ellipse. These trends are similar to those reported by Thornton and later by Ábrahám et al. The primary set and the

interaction between primary set and age were statistically significant factors. Gender and subject knowledge were not significant.

2. Introduction

Thornton has studied the human spectral response with respect to intersections of metameric stimuli,[29-43] color preference,[12] color discrimination,[45] chromaticity errors,[46-51] and brightness-per-watt of radiant power.[46-25] His body of work suggests that the spectral regions near 450, 500, 530, 580, and 610 nm have special significance; the human visual system responds most strongly to the spectral regions near 450-530-610 nm and most weakly to the regions near 500 and 580 nm (as well as to the extents of the visible spectrum in the deep violet and deep red). In his work toward an improved system of colorimetry,[46-51] Thornton uses the term prime-color (PC) to refer to the primary set with peaks near 450-530-610 nm, and the term anti-prime (AP) to refer to the set with peaks near 500-580-650 nm. We adopt these terms in this section and in subsequent sections of this report.

In part I of his series, Thornton described a series of color-matching experiments that he used to derive color-matching functions. In part of his work he used the Maxwell method of color matching, where a triplet of spectral lights was adjusted in a test field to visually match a reference field that was illuminated with a broadband fluorescent lamp. Figure 7 of his article shows that the ratio of measured power in the broadband fluorescent light (P_{FL}) in the reference field to the measured power in the 3-band light in the test field (P_3) has a value of about 1.3 when the PC lights are used in the test field, and a value of about 0.6 when the AP lights are used. These numbers suggest that if a lamp were made to generate an ideal PC spectral power distribution (SPD) it could elicit the same brightness perception as a broadband fluorescent source while consuming 30% less power (assuming that the radiant energy is generated with equivalent conversion efficiency). And similarly, 40% energy could be wasted if a broadband fluorescent SPD were replaced with an AP SPD at equal brightness. These findings are suggestive of the potential to improve the visual efficiency of electric light sources, which could in turn reduce energy consumption and the depletion of natural resources.

The experiment reported here was designed as a replication of a part of Thornton's work, and as an exploratory study to investigate individual differences in color matching experiments. With reference to Thornton's work, we designed this experiment to determine the radiant power required by PC and AP SPDs in order to achieve a visual match with daylight fluorescent. A secondary objective was to examine the reported chromaticity mismatches with these two primary sets. Part of our motivation was the fact that Thornton's results are based on a small number of subjects. Thornton's Figure 7 cited above, for example, is based on data from just three subjects.

With respect to individual differences, we sought to investigate the effects of age, gender and subjects' knowledge of light. Age may be significant because the aging process reduces acuity and the spectral transmission of the ocular media. Ábrahám et al., for example, concluded that the magnitude of Thornton's results were consistent with age related changes in the spectral transmission of the lens.[54] We became interested in gender when observing differences between male and female matches while collecting pilot data. After female subjects pronounced a match, the test field often appeared red (to the experimenter) in comparison to the reference field. The

test field appeared slightly green (to the experimenter) for male subjects. We could not explain these phenomena but wondered if the difference was significant and systematic. Due to the complexity of experimental procedures in color-matching research, it is common for investigators to act as subjects in their own experiments and to ask expert colleagues to participate. This practice is uncommon in other types of psychophysical research because of the potential to bias the data. We investigated the subjects' knowledge of light to determine if the use of expert subjects in color matching experiments is a reasonable practice. Part of our motivation for studying individual differences was to plan for color-matching studies that are now underway.

3. Methods

3.1. Apparatus

The experiments were performed using the UNL colorimeter, which is a specially designed apparatus for performing color-matching under a range of stimulus conditions, and is shown in Figure 6. Spectral lights are created by using theatrical projector luminaires in conjunction with a set of dichroic filters. The projector luminaires house 750 Watt HPL lamps (21,900 lumens) and are fully dimmable with rotary controls. Spectral lights are created by introducing sharp-cutoff filters into the path of the projector's beam. A set of approximately 75 low-pass, high-pass and band-pass filters are used to create spectral lights through the visible spectrum. For this experiment we used six spectral lights, three in each primary set. The PC primary set comprised components at 453 nm with full width half maximum (FWHM) of 15 nm, 533 nm with a FWHM of 19 nm, and 619 nm with a FWHM of 21 nm. The AP set comprised components at 493 nm with a FWHM of 17 nm, 581 nm with a FWHM of 27 nm, and 657 nm with a FWHM of 27 nm. These primary sets are similar to those used by Thornton but they are not identical. Thornton reports primary sets of 452-533-607 nm and 497-579-653 nm with an average FWHM of 15.6 nm. The spectral lights are uniformly mixed in an integrating enclosure, then scattered to uniformly illuminate the top half of the viewing field.

Broadband daylight fluorescent lamps (F15T8/Day, x = 0.343, y = 0.378, Correlated Color Temperature = 5100 K, Color Rendering Index = 75) were used to illuminate the reference (bottom) field for both primary sets. Figure 7 shows the triangle of our two primary sets plotted with the chromaticity of the daylight fluorescent reference. Note that the chromaticity of the daylight fluorescent lamp falls just outside of the AP triangle in the CIE 1964 10° diagram, which in theory should mean that it is not possible for a subject with good color discrimination to make a complete visual match. For comparison, the daylight fluorescent reference falls near the centroid of the AP triangle on the CIE 1931 2° diagram, as shown in on the right side of Figure 7.

The brightness of the reference field could be adjusted with mechanical dimming by turning lamps on or off and/or by moving the lamps in or out of the integrating enclosure with a linear actuator. We used mechanical dimming so that the shape of the spectral power distribution would remain constant in the reference field.

The 10° circular field is created by placing an opaque barrier with an appropriately sized aperture at the front opening of the colorimeter, as shown in Figure 6. The subject's head is positioned

within a chin and forehead rest to fix the geometry between eyes and the viewing field. When sitting at the apparatus, the subject is enveloped by the colorimeter as can be seen in Figures 6. This was done to maintain the proximal and surround fields at approximately uniform luminance. For the work reported here the surround field had a mean luminance of 2.6 cd/m^2 with a range of 0.9 to 5.8 cd/m^2 and standard deviation of 1.27 cd/m^2.

A pair of Stellarnet EPP2000C spectroradiometers are coupled to the colorimeter to measure the SPD of each viewed lights. Once a subject pronounces a match, the SPDs of both the test and reference fields are measured from 380 to 760 nm with a step size of 0.5 nm and stored on a host computer. These SPDs represent a visual match. Luminance of the test and reference fields is also measured with a Minolta CS-100 Chroma Meter. For this experiment the luminance meter was affixed to a tripod six feet from the viewing field and at the same elevation. The luminance meter was tilted in the vertical plane to measure the top and bottom fields. As part of the post-experiment data processing the luminance measurements were used to scale the SPDs measured with the Stellarnet spectrometer so that their absolute units agreed with the visual match.

One of the authors (KH) visited Thornton's lab in 1998 and much of the UNL colorimeter is adopted from his setup, including the use of sharp-cutoff filters to create spectral lights, the use of broadband fluorescent lamps for the reference white, mechanical dimming of the reference field, and the direct measurement of absolute spectral power distributions for all viewed lights.

3.2. Experimental Design

Small sample sizes are often used in color matching studies because of the complexity of the experiments, but results from a small sample may not generalize to a large population. Established principles of experimental design and statistical analysis caution that small sample sizes are only acceptable when the variance is small, which is not typically the case with color matching research. This experiment made use of a moderate sample size of 39 subjects.

The viewing field was a horizontally bisected circle subtending a 10° visual angle. The top field was the variable field, which contained either the PC or AP primary set, and the bottom field was illuminated with daylight fluorescent lamplight. A thin sheet of aluminum divided the top and bottom fields, such that a border appeared between the two fields as a thin (dark) line. Half the subjects made the PC match first and the AP match second; the other half made the matches in reverse order.

3.3. Subjects

The same set of 39 observers participated in Experiment 1 and Experiment 2. Exploratory data analysis revealed two subjects that were considered to be outliers for Experiment 2, and they were removed from the analyses as described in the Section 3.2.5.1. Demographic information for the remaining 37 subjects is reported in Table 6.

3.4. Procedures

The Spectral Effects Workshop included two experiments, the one described in this article and a second experiment reported elsewhere.[55] Observers began by reading a basic overview of both experiments and signing an informed consent. We then administered the Keystone Visual Skills Test and Ishihara's Tests for Color Blindness. The Keystone tests evaluate simultaneous vision at

the far point, vertical and lateral posture, far point stereopsis, fusion at the near and far points, vertical posture at the far point, lateral posture for near and far points, and usable vision for each eye separately and both eyes together at both the near and far points. Ishihara's tests screen for congenital color deficiencies. Observers that normally wore glasses or contact lenses were asked to wear them during the vision screening and throughout the experiment. None of the subjects exhibited seriously deficient vision and all had normal color vision.

The subject began the color-matching experiment by reading an introductory training sheet that briefly describes the task, as given in Figure 8. Each subject made two matches, one with each primary set. As part of the matching process subjects were permitted to adjust the brightness of the bottom reference field. So, while the relative SPD was constant in the reference field, the luminance varied from 17.2 to 200 cd/m^2. Implicit in this method is assumption that Grassman's law of proportionality holds within this range of field luminance. This is comparable to the methods used by Thornton.

Many subjects had problems making a match with the AP primary set, and some subjects indicated that they could not achieve a perfect match. This can in part be explained by the fact that the daylight reference is just outside the AP primary triangle for the 10° standard observer, but subjects also described the presence of what we recognize as the Maxwell spot. We asked the subjects to ignore this apparent non-uniformity in their central field of view and to make the best possible match. Subjects reported few matching problems with the PC primary set, and the Maxwell spot was generally not perceptible.

Once a subject achieved the best possible match the SPDs for the test and reference fields were recorded with the spectroradiometers. The experimenter then measured the luminance and chromaticity of both fields using a Minolta CS100 Chroma Meter. It required about a half-hour for most subjects to make the two matches.

4. Results

4.1. Descriptive Summary Statistics

Standardized z-scores were computed for the ratios of radiant power and the ratios of luminances in the reference field to those in the test field. Two of the thirty-nine subjects were dropped from further analysis because they were considered to be extreme outliers (z-scores > 3.29, $p < 0.001$). Table 7 provides summary statistics for radiant power, luminance, color difference, ratio of radiant power in the reference field to that in the test field, and ratio of luminance in the reference field to that in the test field. Radiant power was computed as the area under the absolute SPD curve. Color difference has been characterized with the MacAdam unit of color difference (ds). Three MacAdam units define a discrimination ellipse and represent a just-perceptible chromaticity difference under the 2° conditions used by MacAdam. Our use of MacAdam units of color difference assumes these values to have some meaningfulness in the 1964 10° chromaticity diagram, at least within the region surrounding the daylight fluorescent reference.

As can be seen from Table 7, the luminance of the bottom field ranged from 17.2 to 200 cd/m^2, which is representative of the typical luminance range within indoor environments. The average

luminance of the test field was 123 cd/m^2 for PC matches and 38.5 cd/m^2 for AP matches. The average ratio of radiant power in the reference field to that of the test field was 1.05 for the PC matches and 0.46 for AP matches, which have the same trends but different magnitudes when compared to Thornton's results of 1.3 and 0.6, respectively. The value 1.05 suggests that about 5% less radiant power is needed for a PC light distribution to elicit the same brightness perception as a broadband daylight fluorescent lamp. The later analyses investigate whether this represents a statistically significant and systematic improvement.

Table 7 shows that the mean color difference is 6.5 ds for the PC matches and 55.7 ds for AP matches; said another way, the mean color difference for the AP matches is 8.6 times greater than for the PC matches. This result is comparable with those of Thornton, who showed that the mean color difference for AP matches is about 6.5 times greater than PC matches when characterized with Simon-Goodwin just noticeable differences.[†] Although the daylight fluorescent reference lies just outside of the AP triangle for our matches, the color difference between the PC and AP matches is greater than can be ascribed to this attribute of the experimental set-up. Figures 9a and 9b show the dispersion of the matches on the 1964 10° and 1931 2° chromaticity diagrams, respectively. The PC matches cluster into a smaller area, suggesting that there is greater visual precision with the PC primary set when compared against the AP set. Although our matching data are based on a 10° field, we have included the 2° diagram because of the ability to construct MacAdam ellipses. There is reasonably good agreement between the 2° and 10° diagrams in the sense that they both illustrate the poorer accuracy and precision associated with the AP primary set when compared to the PC primary set.

4.2. Luminance and Radiant Power of the Matches

A repeated measures multivariate analysis of variance (MANOVA) was carried out to analyze whether the radiant power and luminances in the reference field were significantly different from those in the test field when they matched to the subjects. The data for this analysis were organized as shown in Table 8. The repeated measures analysis treats field type as a within-subject factor with two levels (i.e. test field, reference field) and four measures (a.k.a. dependent variables), radiant energy in PC matches, radiant energy in AP matches, luminance in PC matches, and luminance in AP matches. Multivariate test shows that the within-subject factor, the matching field, is significant ($F_{(4, 33)} = 63$, $p < 0.001$). Univariate tests for the four measures were computed with type III sum of squares. Radiant power in the top field when illuminated with the PC primary set was significantly different than the radiant power in the bottom field when illuminated by the daylight fluorescent reference when the subject pronounced a match ($F_{(1, 36)} = 7.8$, $p < 0.01$). Similarly, there was a significant difference in the radiant power in the matching fields for the AP / daylight fluorescent visual matches ($F_{(1, 36)} = 4.0$, $p < 0.001$). There was not a significant difference in the luminance of the matching fields for the PC / daylight fluorescent visual matches, but there was a significant difference for the AP / daylight fluorescent visual matches ($F_{(1, 36)} = 8.5$, $p < 0.01$).

These results show that the different SPDs have a statistically significant difference in the radiant power required to achieve a brightness match. In the PC matches the radiant power was significantly less than that of the daylight fluorescent reference, with the mean radiant power of

[†] See Table XVII of reference 49 and Figures 9 and 13 of reference 46.

1.13 w/m^2 in the test field to 1.23 w/m^2 in the reference field as shown in Table 7. For the AP matches the radiant power of the AP primary field is significantly greater than that of the reference with the average power of 0.4 w/m^2 in the test field to 0.86 w/m^2 in the reference field. The PC set was set at a mean luminance that was 2% lower than the luminance of the reference (at equal brightness), but this difference was too small to achieve statistical significance. The AP set was set at a mean luminance that was 7% lower than the daylight fluorescent, which was statistically significant.

4.3. Individual Differences

A general linear model (GLM) was used to analyze whether primary set, subject type, gender, and/or age have significant effects on the color matches. Since each subject completed both PC and AP matches, the primary set is a within-subject factor with two levels. Subject type, gender, and age are between-subject factors, as summarized in Table 9. Age has been binned into two groups, younger than 50 and 50 years and older. The color match has been characterized with three dependent variables: the ratio of the radiant power in the reference field to that in the test field (P_{ref}:P_{test}), the ratio of the luminance in the reference field to that in the test field (L_{ref}:L_{test}), and the MacAdam unit of color difference between the two fields. The analysis was performed using a repeated measures method of a GLM. The main effect and all 2-way interactions were considered in the analysis; higher order interactions were pooled as error.

Multivariate tests show that the main effects of the three between-subject factors, subject type, gender, and age are not significant. The within-subject factor, primary set, is significant ($F_{(3, 31)}$ = 250, $p < 0.001$), and the interaction of primary set with age is significant ($F_{(3, 31)} = 4.3$, $p < 0.01$). Univariate tests using type III sum of squares for the three dependent variables show that for the above significant effects, the two dependent variables, the ratio of radiant power and color difference are significant. The luminance ratio is not significant.

This analysis supports the conclusion that the primary set has a substantive effect on the ability to make a visual match. None of the three between-subjects factors (i.e. age, gender, subject type) have statistically significant main effects, but the interaction between age and primary set is significant. This interaction is illustrated in Figure 10, which shows the trends for the ratio of radiant power, ratio of luminance, and chromaticity differences as a function of age group. The two age groups have the same trend with respect to the ratio of luminance, but different trends along the other dimensions. Persons in the older age group tended to have smaller differences between the two primary sets with respect to chromaticity difference and ratio of radiant power, when compared to subjects in the younger age group. Our results corroborate those of Ábrahám et al., despite the fact that we approached this problem using different methodologies and analyses.

5. Discussion

5.1. Efficiency of the Spectrum

The SPDs of the PC and AP matches for a typical subject are shown as Figure 11a and 11b. The SPD for the daylight fluorescent reference is the same in both figures. The area under each curve represents the radiant power of the viewed light. These figures show that in order to match

daylight fluorescent, the AP triplet required 117% more power, while the PC triplet requires 5% less.

Our experiments are suggestive of the energy saving potential of the PC spectral distribution. These results have the same trend as found by Thornton, but the magnitude of the effect is different. The difference may be attributed to differences between our primary sets and those used by Thornton and/or to differences in the subject sample. Thornton used 450-533-610 nm as his PC primary set, with a FWHM of 15.6 nm. Because of availability of filters, we used 453-533-619 nm with a FWHM of 21 nm. Thornton has shown that the visual system responds most strongly to the spectral regions near 450-530-610 nm, and there are many corroborating studies.[e.g. 56-22] Our long-wavelength primary is beyond the target wavelength. We would therefore expect it to have lower visual efficiency and require greater power to achieve a match. In addition to supplying power in these three key spectral regions, it is important to limit the spectral output in other parts of the spectrum. It is therefore likely that the wider bandwidths used in our work led to lower visual efficiency. The ideal primary lights are more likely near-monochromatic spectral lights, as opposed to the wider Gaussian shapes that we are able to achieve with dichroic filters and tungsten sources. We expect that the wider width and the fact that our long-wavelength component was away from the target can account for some of the difference between our data and Thornton's data.

Experiment 2 supports the concept that a SPD comprised of 450-530-610 nm components leads to enhanced brightness when compared against daylight fluorescent, and that the 500-580-650 components are less effective at stimulating brightness perception. We expect that it is possible to achieve greater improvements than reported here as the spectral lights approach the ideal peak wavelengths and bandwidths.

5.2. Luminance as a Predictor of Brightness

Luminance is defined by integrating the product of radiant power and the V(λ) function per unit of viewed area and solid angle. It was originally introduced by the CIE as a photometric unit to correlate with brightness; yet it has been known for decades that under many conditions luminance and brightness do not correlate well.[e.g. 61-76]

In our PC matches, the luminance in test and reference fields was not significantly different, while in the AP matches luminance was statistically different. As shown in Table 7, the PC matches were set at a luminance that was on average 2% lower than the daylight reference and the AP matches were set 7% lower.

The analysis of luminance shows that brightness perception is consistent with luminances for the PC / daylight fluorescent matches, at least within the range between 11.7 and 200 cd/m^2 and for this specific subject sample and field size. Luminance and brightness were not as well correlated for the AP match. These results are generally compatible with past research. Larger brightness/luminance mismatches occur with strongly colored lights. Thornton showed that metameric white lights can appear equally bright at unequal luminance, as we found with the AP primary set. This phenomenon does not appear to be widely recognized, despite its obvious importance to our understanding of the visual system and its implications for the spectral design of lamp light.

5.3. Chromaticity Errors and Choice of Primary Set

Most subjects reported that the matching trials with the PC primary set were easier than those with the AP primary set, and that they were more satisfied with the quality of the match. This was to be expected since the daylight fluorescent lamp falls outside the triangle of primaries for the AP set. Different primary sets have large effects on the ratio of radiant power between the test and reference fields, and on the magnitude of color difference between the test and reference fields. The effect on color difference is especially great, with a mean of 6.49 ds for the PC set and greater than 55.68 ds for the AP set. These data suggest that our group of observers had a much easier time making matches with the PC primary set when compared against the AP set, consistent with the subjects' informal remarks.

Historically, different primary sets have been used in color matching experiments, including Wright's 460-530-650 nm,[77] Guild's 453.8-546.1-700 nm,[78] Stiles and Burch's 445.3-526.4-648.6 nm,[79] and Speranskaya's 465-545-640 nm.[80] These differences in primary-set wavelengths would be expected to lead to inconsistencies between their color matching results, at least in the matching accuracy of color. These matching inconsistencies cannot be resolved with linear transformation between primary sets.

5.4. Interaction between Primary Set and Age

We did not find statistically significant effects related to gender or subjects' knowledge of light, which suggests that it is less important to control these potential sources of variance in future color matching experiments. Because the interaction between age and primary set was significant, these factors should be systematically controlled. Ábrahám et al. suggest that chromaticity differences can at least in part be accounted for by the age-related change in the spectral transmittance of the lens, but this cannot explain the differences we found in the radiant watts required to achieve a match. At this stage we simply wish to call attention to these factors as sources of variance that should be controlled. At the very least, we suggest that researchers report average and standard deviations of ages of their subjects, and that the primary sets are considered as integral to the experiment, rather than as arbitrary wavelength regions that can be freely transformed with post-hoc manipulations.

6. Conclusions

Within the architectural lighting community it is widely believed that it is "bad" to have voids in the spectrum. Continuous spectrums like those from daylight and incandescent are considered to be superior for brightness and color perception because power is radiated at all wavelengths within the visual range. With respect to brightness, the data presented here provide evidence that this belief is unfounded. We argue that voids, or spectral regions with zero power, are neither universally good nor bad. The voids may be "bad" if they fall in a region of the spectrum where the visual system responds strongly, because the remaining spectrum will require proportionally more power for constant brightness. But the voids may be "good" if radiant power is absent in regions of low spectral sensitivity and instead radiated at spectral regions of high visual sensitivity (e.g. near 450-530-610 nm).

These data show that a SPD comprised of 453-533-619 nm components with a FWHM of 18.3 nm can elicit an equivalent perception of brightness as a broadband daylight fluorescent lamp with 5% fewer radiant watts. This corroborates the trend, but not the magnitude, found by

Thornton, who demonstrated improvements as great as 30% with a 452-533-607 nm primary set with a FWHM of 15.6 nm.

Because the visual system is fundamentally a three-channel system, the goal with the spectral design of light sources should be to most effectively feed these three visual channels. Thornton has argued that the normal visual system has invariant peak spectral sensitivities near 450-530-610 nm, with minima sensitivities near 500 and 580 nm and at the limits of the visual spectrum. The data presented here are consistent with these conclusions, and demonstrative of the potential to improve the visual efficiency of electric light sources by adjusting their spectrum.

Statistical analyses show the gender and subjects' knowledge of light do not significantly affect color matches, but primary set and the interaction between primary set and age are significant independent variables. These results may partly explain the inconsistency of past color matching results and also indicate the importance of primary set selection and subject age in color matching experiments.

Appendix C – Experiment 3

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1. Abstract

Experiment 3 was designed to complement Experiment 1, with the intention of using different experimental methodologies to address the same basic research inquiries. Experiment 3 differed from Experiment 1 in that: 1) we used a dimming adjustment task instead of a forced choice instrument, 2) second generation prototype lamps were used that were a closer match in chromaticity, and 3) the dependent variable was limited to brightness perception (Hypothesis 1), with an indirect analysis of color preference (Hypothesis 2). The data from Experiment 3 does not corroborate the results of Experiment 1. Given the results of the other three experiments performed as part of this grant, and in consideration of past scientific research, Experiment 3 appears to be anomalous. The rationale for this inference is discussed.

2. Methods

2.1. Independent Variables

The principal independent variable was conceptually identical to that in Experiment 1. Specifically, light spectrum considered in two categories each with two levels: the middle-wavelength phosphor and CCT. The lamps were not identical to those used in Experiment 1 because we were seeking a closer chromaticity match between the VT and CV lamps. The SPDs for the second-generation prototype lamps are given in Figure 2b, which can be compared with the first-generation SPDs of Figure 2a. Chromaticity coordinates and MacAdam ellipse for the second-generation lamp types used in Experiment 3 are shown in Figure 5b; this figure can be compared with Figure 5a which is for the first-generation prototypes. All lamps were burned in for 100+ hours and the open symbols on Figures 5a and 5b are representative of the chromaticity of the lamps as experienced by the subjects. Finally, Table 1 can be referenced for summary measures for all lamp types used, including Ra, CCT, CPI, CDI, CSA, Pointer's Index, S/P ratio, and efficacy measures. These data show that the VT and CV lamps have a slightly better chromaticity match for the second generation prototypes, as desired, but the differences are subtle.

Experiment 3 was designed to exclusively study the VT vs. CV effect on brightness perception at two different CCTs. Accordingly, we confined the scope of the experiment to two types of visual

comparisons: VT35 vs CV35 and VT65 vs CV65. This is different than Experiment 1 where subjects also made 35K vs. 65K comparisons. The general organization of the experiment was that one room was set at a fixed level of 300 lx and the other room was set at either 150 or 450 lx. The subject instructed the experimenter to adjust the brightness in the variable room, while the fixed room was held at a constant 300 lx. When the subject pronounced that the rooms had equivalent brightness, the experimenter recorded the illuminance in both rooms and moved on to the next trial.

We considered several other sources of variance as independent variables in an effort to counterbalance potential biases: whether or not the lamp was adjusted or held constant (fixed/variable), whether the intensity of the variable lamps were raised or lowered (up/down), the side the lamps were in (left/right), and whether or not the room was furnished with colorful or achromatic objects (achromatic/chromatic). This last variable was incorporated as an indirect method for determining if the colorfulness of room furnishings affected the perception of brightness.

2.2. Dependent Variables

The dependent variable was the measured illuminance level at a calibration point in the center of each side-by-side room. When the subject pronounced a match in brightness the illuminance in each room was recorded by the experimenter. Every illuminance value was coded with the potential sources of variance associated with the lamp type and brightness matching conditions so that the data could be analyzed using an analysis of variance (ANOVA). The complete set of data for Subject 1 is given in ANOVA-coded format as Table 10. The entire set of data includes one such table for each subject, totaling 1,920 measured illuminance values.

The dependent variable was characterized using an illuminance meter positioned at the center of the desktops, one in each room. The reasonableness of this procedure rests on the assumption that this measurement position is suitably representative of the light distribution in the room. In the analysis for Experiment 1 we commented that there was no appreciable difference in the luminance distribution when a different lamp type was used, and between the left and right rooms. We formalized this assertion with systematic measurements and a formal statistical analysis. A grid of 30 points was created on the back wall of each room on 2’ centers. The room was set to 300 lx as calibrated with the illuminance meter, and luminance was measured at each of the 30 locations with a Minolta LS-100 luminance meter, which was affixed to a tripod and positioned at seated eye height (45”, 114 cm) at the location where the subjects were positioned during the experiments. This measurement procedure was carried out for the left and right rooms under all four lamp types (eight combinations total, 240 luminance measurements). An analysis of variance was performed on these data which shows that lamp type and room type were not significant. The ANOVA summary is given as Table 11. This analysis lends credibility to our method of characterizing the dependent variable by measuring the illuminance at a fixed location in the center of each room.

2.3. Apparatus

Subjects evaluated the same side-by-side rooms that were used in Experiment 1. Light settings were controlled as before with a Lutron Grafik 5000 control system using ECO10 dimming ballasts. The fixed room was always set at 300 lx, and it was maintained as near to this value as

possible. The variable room was set at either 150 or 450 lx, and after adaptation the subject instructed the experimenter on whether to raise or lower the light level until a brightness match was achieved.

Minor fluctuations in output were unavoidable because the output of fluorescent lamps is temperature dependent, but maintaining an exact set level was not critical to the experimental protocol. When a subject pronounced equality of brightness the actual measured illuminance values were always recorded. For example, if the fixed room was actually at 305 instead of 300 lx, and the subject perceived a brightness-match when the variable room was adjusted to 315 lx, then the values recorded were the actual measured values of 305 and 315 lx. These data were then coded for the independent variables and used in the statistical analyses.

2.4. Statistical Design

Each subject rated a total of 34 pairs of light settings in two sessions with (17 pairs per session). One session was carried out in a sparsely furnished environment that only contained grayscale objects (i.e. achromatic environment); the second session was carried out in an environment with file folders, binders, towels, wall-hung prints, plastic plants and foodstuff, and other colorful objects (i.e. chromatic environment).

When subjects entered the rooms and were given instructions both rooms were illuminated at 300 lx with the VT35 lamps. The first trial was always a control trial with VT65 on the left (variable, starting level of 150 lx) and VT65 on the right (fixed level of 300 lx). Each subject made the two types of visual comparisons (VT35 vs. CV35 and VT65 vs. CV65) for all fixed/variable, up/down, left/right, and achromatic/chromatic combinations for a total of 32 comparisons per subject ($2^5 = 32$). The standard order for these trials is listed in Table 12. The presentation order was randomized with a different random sequence for each subject. The experimenter used a worksheet with a code corresponding to one of the preset scenes; a typical worksheet showing a randomized presentation sequence is given as Figure 12.

2.5. Subjects

Thirty-two naïve observers participated in this study. Exploratory data analysis revealed two outliers that were dropped from subsequent analyses. Seventeen of the remaining observers were female with a range of 19 to 64 years, a mean of 32, and standard deviation of 13. Male observers had a range of 22 to 47 years, a mean of 32, and standard deviation of 8. Eighteen of the subjects wore glasses and three wore contact lenses. Sixteen of the subjects were Caucasian, thirteen were Asian, and one was Hispanic.

2.6. Experimental Procedures

As with all of the experiments observers began by reading a basic overview of the study and signing an informed consent. We then administered the Keystone Visual Skills Test and Ishihara's Tests for Color Blindness. Observers that normally wore glasses or contact lenses were asked to wear them during the vision screening and throughout the experiment. None of the subjects exhibited seriously deficient vision and all had normal color vision. None of the subjects were discarded from the analysis based on visual deficiencies.

Before the subjects entered the test environment both rooms were illuminated with VT35 at 300 lx. Upon entering the research space the observer was handed a one-page instruction sheet asked to be seated at a desk. They were positioned at the desk so that the wall between the two rooms corresponded to the sagittal plane, although observers were free to move within their chair as they made their ratings.

The experimenter then read the instructions out loud, as shown in Figure 13, and made sure the observer understood their task. The experimenter then switched to the first trial with VT65 on the left (variable, starting level of 150 lx) and VT65 on the right (fixed level of 300 lx). The subject was given 30 seconds to adapt to the new conditions while the experimenter monitored lamp output. After the adaptation time had elapsed the experimenter reminded the subject which room was the variable room, and the subject instructed the experimenter whether it needed to be raised or lowered. The experimenter followed the subject's instructions by adjusting the light output in the variable room until the subject was content that they both rooms were set at the same brightness. Upon pronouncing a match, the experimenter recorded the illuminance levels in both rooms and continued on to the next trial.

It required about 10 minutes to change from the achromatic to chromatic room conditions, so the subject was given a break between these sessions. The subjects also performed Experiment 4 (visual performance) between the achromatic and chromatic sessions. Half the subjects performed the brightness adjustment task in the chromatic environment first and the achromatic environment second, with the other half of the subjects making their assessments in the reverse order. The typical daily schedule for Experiments 3 and 4 is given as Table 13.

3. Results

An ANOVA was carried out to determine the relationship between the dependent variable (illuminance level) and the independent variables (35K/65K, VT/CV, Chromatic/Achromatic, Left/Right, and Subject).

The dimming adjustment task was intended to be a direct test of Hypothesis 1 (increasing the proportion of energy in the spectral regions near 450, 530, and 610 nm would enhance brightness perception) and an indirect test of Hypothesis 2 (increasing the proportion of energy in the spectral regions near 450, 530, and 610 nm would enhance color preference). Visual inspection of exploratory data plots revealed two outlying subjects, whose data were discarded. The subsequent analyses are based on the data from the remaining 30 subjects. The ANOVA summary, given as Table 14, shows the main effects and all 2-way interactions. Higher order interactions were initially analyzed, but they were not significant and were therefore pooled as error. The data can be effectively explained with an examination of the main effects.

Figure 14a gives a main effects plot for illuminance based on means across Adjustment (fixed/variable), CCT (35K/65K), Phosphor (CV/VT), Room (Achromatic/Chromatic), and Side (Left/Right). Figure 14b is a similar plot across the 30 subjects. As illustrated in Figures 14a and 14b, and supported with the statistical tests of Table 13, Subject, CCT, and Room, and were not significant (p-value > 0.05), which can be interpreted to mean the variance associated with these independent variables was random rather than systematic. The significant effects were whether

or not the lamp was adjusted (fixed/variable), the phosphor type (VT/CV), and the side that the lamp was on (left/right).

4. Discussion

In Experiment 1 we found that CCT had no effect on brightness perception. In Experiment 3 subjects were not asked to make 35K versus 65K comparisons so the effect of CCT on brightness perception can not be directly evaluated with this experiment. However, within this experiment subjects made VT35 versus CV35 and VT65 versus CV65 comparisons, and as shown in the ANOVA summary table of Table 14 these comparisons were essentially equivalent (i.e. the main effect of CCT was not significant, p-value > 0.05). Descriptive summary statistics exemplify this conclusion, as shown if Figures 15a and 15b. The data for Experiment 3 is therefore discussed simply in terms of VT vs. CV comparisons, without regard to CCT.

Experiment 1 showed that at equal illuminance, the VT65 environment was perceived to be brighter than the CV65 environment by 78.0% of the observers, and the VT35 environment was perceived to be brighter than the CV35 environment by 66.0% of the observers. By analyzing the response to the question "how much brighter?" we concluded that the environments illuminated with the vision-tuned lamps were perceived to be 4.3% brighter at the higher color temperature and 1.5% brighter at the lower color temperature at equal illuminance. But these conclusions were based on categorical results, not continuous data, and as such were intended to be an exploratory assessment. One of the reasons for using a dimming adjustment task in Experiment 3 was to be able to more confidently assign a percentage to the magnitude of difference in illuminance at equal brightness perception.

Basic summary statistics are given by lamp type as Figure 15a for the CV lamps and Figure 15b for the VT lamps. When the rooms were set to equal brightness perception the CV lamps were set at a mean level of 301.2 lx and the VT lamps were set at a mean level of 307.8 lx. This trend is not consistent with that found in Experiment 1, where the VT environments were perceived to be brighter than the CV environments when illuminance was held constant. This 2% difference found in Experiment 3 was statistically significant ($p < 0.05$), although for reasons outlined below it is not thought to be substantive.

As shown in Figures 15a and 15b, the median value for the VT lamps is 303 lx compared with a median value of 302 lx for the CV lamps (0.3% difference), which is of no practical importance. This was a result of the larger high-end skewness of the illuminance settings in the VT environment, which affects the mean but not the median. This can be observed by comparing the histograms of Figure 15a and 15b.

When designing an experiment it is critically important to carefully define the dependent and independent variables. Although we proceeded carefully in our selection and definition of variables, hindsight suggests that our choice of dependent variable was imperfect. The VT effect we found in Experiment 1 appeared to be related to an interaction between brightness and color perception, which may be related to the perception of visual clarity. At 6500 K, for example, the most salient response was to the visual clarity question, where 92.7% of the responses favored the VT lamps versus 78.0% along the brightness dimension. The brightness and visual clarity

response was similar at 3500 K, with 63.6% of the visual clarity responses and 66.0% of the brightness responses favoring the VT lamps.

We believe that the instructions we gave to the subjects did not get to the root of the issue. We emphasized to the subjects that they were to match the rooms for brightness, which is a different question then asking them to match the rooms for "visual equality", or "equal visual clarity", or "equal pleasantness of illumination". We believe that one of these latter questions would have more effectively captured the visual benefits of the VT-illuminated environment.

5. Conclusions

Statistical principles allow for anomalous occurrences. If we were to repeatedly run an experiment where a real effect existed, statistical theory allows for the fact that on some occasions the effect would fail to be observed. This is one of the reasons that we have in the past advocated and employed converging operations,[81] and why we took a similar approach with this project. One experiment can seldom be used to make definitive conclusions about broad research hypotheses.

In this project we ran four experiments. The reason for doing so is that coming at the same general research inquiry from different directions typically results in a deeper understanding of the salient experimental variables. The possibility exists that data from one experiment will conflict with data from other, and these cases beg the question "which is correct?" In our case, three of four experiments fit the broad hypothesis that light sources with proportionally more power in the 450-530-610 nm regions will enhance vision. Further, these three experiments corroborate the considerable scientific literature that initially led us to our hypotheses about brightness perception per watt, color preference per watt, and visual performance. Experiment 3 is the outlier in the sense that it does not agree with Experiments 1, 2, 4, and past research. Experiment 3 has to be interpreted in the context of other compelling evidence that favors the 450-530-610 nm vision-tuned spectrum.

Appendix D – Experiment 4

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1. Abstract

Experiment 4 was designed to test the hypothesis that vision tuned lamps produce equivalent visual performance to the common fluorescent lamps. Computer-based proofreading and typing tasks were used to assess subjects' visual performance in environments illuminated by the different lamp types. Visual performance was measured using proofreading and typing tasks developed by the National Research Council Canada (NRC) especially for lighting experiments.[81] Thirty two subjects participated in the visual performance experiments. The results show that there is no statistical difference for visual performance for the lamp types studied. This conclusion supports Hypothesis 3.

2. Methods

2.1. Independent Variables

The principal independent variable was conceptually identical to that in Experiment 1 and Experiment 3. Specifically, light spectrum considered in two categories each with two levels: the middle-wavelength phosphor and CCT. The lamps were identical to those used in Experiment 3. In fact Experiment 3 and Experiment 4 were designed as different subtasks of an experimental session, which was completed by the subjects during a half day session at the UNL lighting laboratory. The typical daily schedule of the experiment sessions is listed in Table 13.

2.2. Dependent Variables

The dependent variables were the outputs from the proofreading and typing tasks, which are computer-based programs designed to measure office worker performance under different light settings. The proofreading task measured the speed and accuracy with which a subject is able to proofread columns of numbers. Two columns of numbers were presented side by side on a computer screen. The visual task was to identify the rows with different number sets in the left and right columns. The outputs of the proofreading task are a series of quantitative parameters describing the subject's performance, including elapsed time, total number of errors, number of identical rows that were not marked, number of false positives (i.e. number of identical rows that were marked), number of discrepant rows that were marked, number of discrepant rows that were not marked, and the total number of times that the spacebar was pressed.

The typing task measured the speed and accuracy with which a subject was able to retype a given text. This task was designed to resemble the typing proficiency test used to hire temporary office workers. The outputs of the typing task are a series of quantitative parameters describing the subject's performance, including the net number of characters typed per second, elapsed time, total number of keystrokes, number of erase keys used, and the number of cursor keys pressed.

All of these output measures provide information to assess different aspects of the subjects' visual performance. However, only three outputs were taken as dependent variables in the statistical analyses since there is a strong relationship between the dependent measures, and because too many dependent variables would decrease the power of the statistics. The dependent measures used for the proofreading task were elapsed time and the total number of errors, and the net number of characters typed per second was used to characterize the typing task. These measures were selected because they quantify both speed and accuracy of the tasks performed, and in this sense provide an inclusive characterization of performance.

2.3. Apparatus

Only one room was needed for Experiment 4; subjects were seated inside of the right room of the two side-by-side rooms that were used in Experiments 1 and 3. Light settings were controlled as with previous experiments, with a Lutron Grafik 5000 control system using ECO10 dimming ballasts. The room was set up with normal grayscale office furnishings, identically to the achromatic environment used in Experiment 3.

The subject was seated at a desk and facing the back wall of the room. The subject was required to perform the proofreading and typing tasks on a notebook computer. A user-friendly program guided the subject through the entire experiment process including on-screen instructions, a practice trial, and four trials of proofreading and typing for the four different light settings. The interface was written by us in Visual C++ especially for this experiment; it was written to work with the NRC proofreading and typing tasks.

The subjects performed five trials, where each trial was comprised of four on-screen pages of proofreading and a one-paragraph typing task. The five trials comprised one practice trial and four test trials, one each under the VT35, CV35, VT65 and CV65 lamp types. The test room was set at an illuminance level of 300 lux for all trials, and was measured by the Minolta T10 illuminance meter with the photocells on the center of the desktop, as with Experiments 1 and 3.

The proofreading task comprised 80 rows of numbers. Each row had two columns of 5-digit numbers. Each proofreading task had four screen pages with 20 rows per page; an example is given as Figure 16. Of the 80 rows, there were exactly 9 discrepant rows per trial, where a discrepant row is one where a single digit mismatches between the left and right columns. All numbers were randomized, as was the locations of the discrepant digits.

Each typing task was comprised of one paragraph of text, as shown in the example of Figure 17. The paragraphs selected are highly similar in their numbers of words, characters, and readability. They were also selected to be rather difficult so that they would require the subject to concentrate in order to complete the task. The paragraphs were selected from Charles Darwin's "The Voyage of the Beagle" with minor editing to increase similarity between the paragraphs. Table 15 lists

summary characteristics for the five paragraphs. All paragraphs have a Flesch-Kincaid grade level of 12. Readability measures are primarily based on factors such as the number of words in the sentences and the number of letters or syllables per word. It is not necessary for the paragraphs to be identical because the presentation order of the four lamp types was randomized. Different subjects therefore typed different paragraphs under different lamp types, in a counterbalanced rotation. The dependent measure that we used to characterize performance was net characters per second, which effectively adjusts the data so that different length paragraphs can be compared on an apples-to-apples measure.

2.4. Statistical Design

There are in total five trials for each subject, one practice trial and four test trials for four different lamp types. In each trial, the subject was required to perform one proofreading task and one typing task. The lamp types used when subject entered the office and for the practice trial were randomized. The presentation order of the four lamp types for four test trials were also randomized for each subject. Examples of the presentation sequences are given in Table 16. As with the other experiments, the experimenter operating the control system was given a code corresponding to a scene number on the control apparatus but remained blind to lamp type.

2.5. Subjects

Thirty-two naïve observers participated in this study. Exploratory data analysis revealed no outliers so subsequent analyses are based on all subjects. Eighteen of the observers were female with a range of 19 to 64 years, a mean of 31.8, and standard deviation of 12.5. Male observers had a range of 22 to 47 years, a mean of 32.5, and standard deviation of 7.6. Nineteen of the subjects wore glasses and four wore contact lenses. Eighteen of the subjects were Caucasian, thirteen were Asian, and one was Hispanic.

2.6. Experimental Procedures

As with all of the experiments observers began by reading a basic overview of the study and signing an informed consent. We then administered the Keystone Visual Skills Test and Ishihara's Tests for Color Blindness. Observers that normally wore glasses or contact lenses were asked to wear them during the vision screening and throughout the experiment. None of the subjects exhibited seriously deficient vision and all had normal color vision. None of the subjects were discarded from the analysis based on visual deficiencies or for any other reason.

Before the subjects entered the test environment, the room was illuminated with one of the four lamp types (selected at random) at 300 lx. Upon entering the research space the observer was seated by the desk, and was told to follow the screen instructions of the on the notebook computer.

As shown in Figure 18a, the first screen in front of the subject is the Welcome Screen, which provides the simple introduction to the tasks and tells the subject that both speed and accuracy are important when they perform the proofreading and typing tasks. By clicking the Next button, the subject enters the Instructions screen, which provides the detailed instructions of how to perform the two tasks, as shown in Figure 18b.

Then the subject enters the Practice Trial screen, as in Figure 18c. As commanded by this screen, the subject notifies the experimenter that he/she is ready for the practice trial. Then the experiment changes to the appropriate light setting for the practice trial. When the subject first enters this screen, the Next button on the right corner is inactive. This button remains inactive for one minute so that the subject is forced to adapt to the new lighting conditions before proceeding. After the Next button becomes active and it is pressed by the subject the proofreading trial immediately commences (Figure 16), at which time the computer begins recording speed and accuracy data. Upon finishing the proofreading task, the typing task immediately begins (Figure 17), where there is one paragraph of text for the subject to retype. When subject makes an error, the program points it out right away. For example, the last word in the typing window of Figure 17 has an error which the system identifies with a double strike through. The subject is required to correct errors before continuing.

After the subject finishes the typing task of the practice trial, a new screen appears with the heading Light Setting 1, and the subject is directed to tell the experimenter that he/she is ready for next trial. Then the experimenter sets the next lamp type to 300 lux and the subject is forced to wait one minute before starting for the next trial. After a minute has passed, the subject performs one proofreading task (on four screen-pages) and one typing task for the new lighting setting. This process continues for Light Settings 2, 3 and 4. When the subject has finished all the trials the finish screen appears, as shown in Figure 18d.

3. Results

Summary results for the proofreading task averaged across the thirty two subjects are listed in Table 17 and illustrated in Figure 19 As we can see from the figure, the differences between the means for all outputs is marginal compared to the magnitudes of the standard deviations. However the vision tuned lamps produced fewer totals errors than the conventional lamps, with 0.97 errors for both VT35 and VT65, and 1.13 for CV35 and 1.19 for CV65. There was not clear trend for the elapsed time: subjects performed a bit slower under the VT35 lamps than under the CV35 lamps, but a bit faster under the VT65 lamps compared to the CV65 lamps.

The summary for the typing task for thirty two subjects is given as Table 18 and illustrated in Figure 20. Similar to the proofreading task, the differences of the means of the typing task outputs were not large compared to the magnitudes of standard deviations. The net characters typed were almost the same for all four lamp types, with 2.5 characters per second. However the subjects did take less time under vision tuned lamps than that under the conventional lamps, with about 401 seconds for vision tuned lamps and about 403 seconds for conventional lamps.

A repeated measures multivariate analysis of variance (MANOVA) was carried out to analyze whether the visual performances were significantly different under the illumination of four different types of lamps to the thirty two subjects. The three measures or dependent variables in the statistic analysis were the net number of characters typed per second in the typing task, the elapsed time and the total number of errors in the proofreading task. The repeated measures analysis took CCT and middle phosphor types as two within-subject factor with two levels respectively (i.e. CCT includes 3500 and 6500 K, middle phosphor types include vision tuned and conventional lamp phosphors). Multivariate test shows that neither CCT nor middle phosphor types were significant (CCT: $F(3, 29) = 0.463$, $p = 0.71$; middle phosphor: $F(3, 29) =$

0.499, p = 0.686). Further, the interaction between CCT and middle phosphor was not significant ($F(3,29)=0.491$, $p=0.692$). Univariate tests for the three measures were computed with type III sum of squares. None of the three measures were significant to any within subject factors.

The statistical results showed that neither CCT nor middle phosphor has significant influence in the visual performance of the subjects. This experiment concluded that the vision tuned lamps produced equivalent visual performance to the conventional fluorescent lamps

4. Discussion and Conclusions

This project includes three hypotheses. Hypothesis 1 is that vision tuned lamps enhance brightness perception. Hypothesis 2 is that vision tuned lamps produce higher color preference than conventional fluorescent sources. Hypothesis 3 is that prototype lamps produce equivalent visual performance to common fluorescent lamps. Experiment 1 was designed to test Hypothesis 1 and 2. Experiment 2 and Experiment 3 were designed to test Hypothesis 1 with different methods and apparatuses. And Experiment 4 was designed to test the Hypothesis 3.

The proofreading and typing tasks utilized are proven methods for assessing the visual performances of subjects under different lighting conditions. Experiment 4 showed that there was no significant difference in visual performance under the different lamp types, whether they were at 3500 K or 6500 K, or vision tuned lamps or conventional. This result supports our hypothesis.

The results of Experiment 4 support Hypothesis 3, which is that prototype lamps produce equivalent visual performance to common fluorescent lamps.

Appendix E – Figures

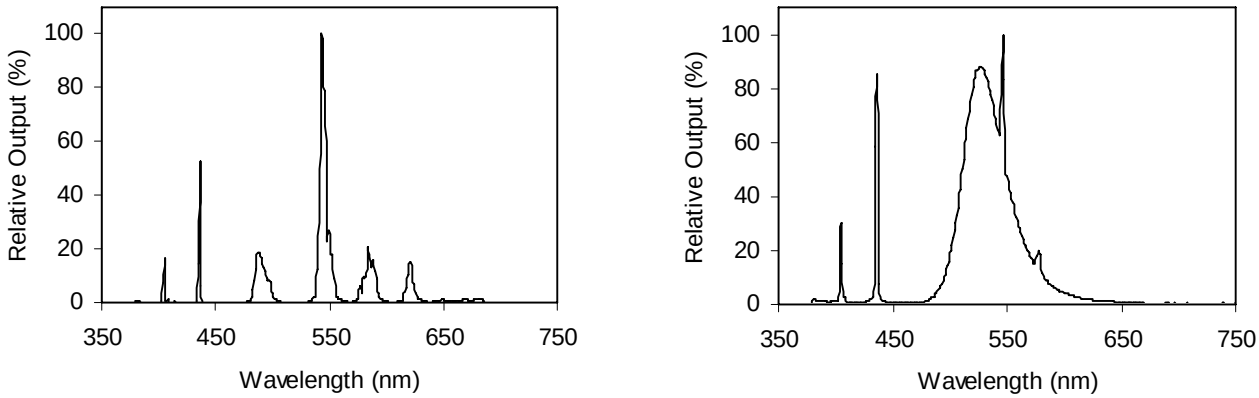

Figure 1 Relative SPDs for middle-wavelength phosphors. Both SPDs include the mercury lines at 405, 436, 546, and 577-579 nm. The phosphors on the left was used for the middle wavelength component for the conventional lamps and the phosphor on the right was used for in the vision-tuned lamps.

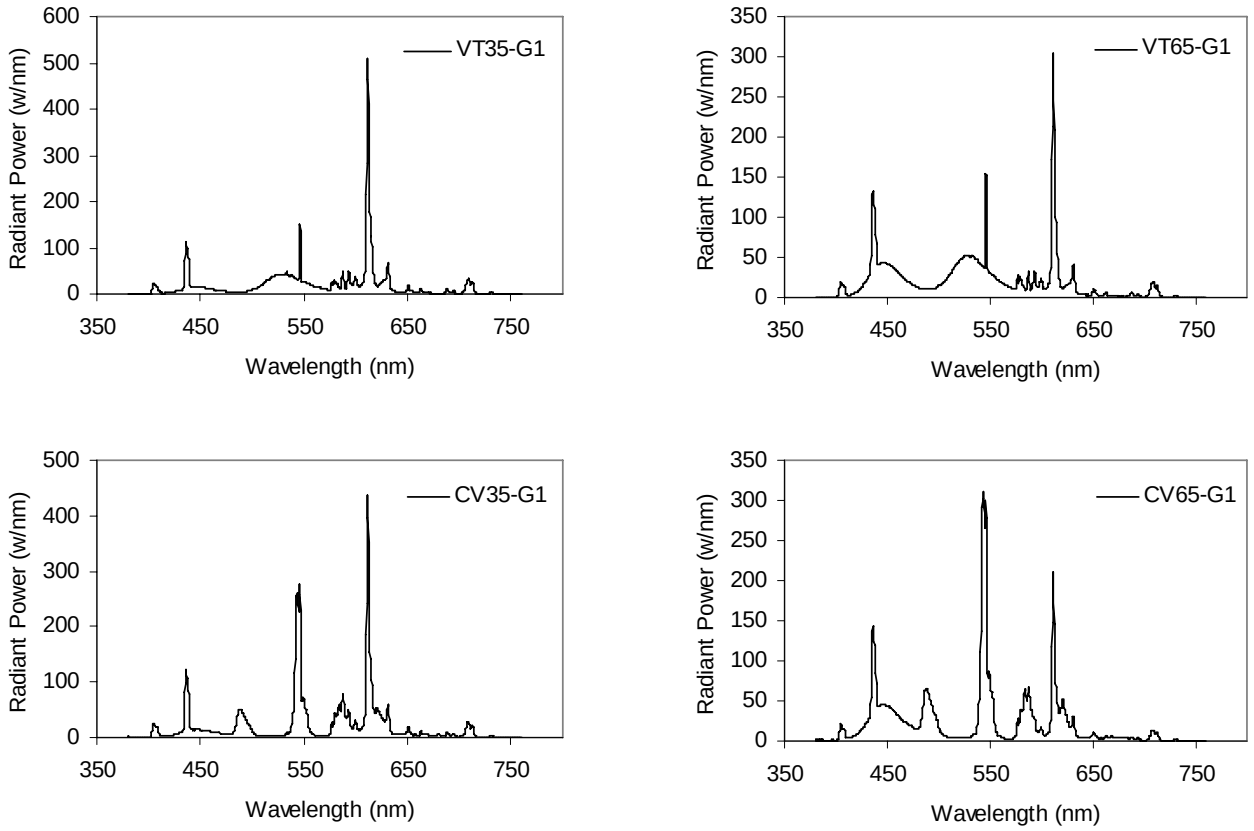

Figure 2a SPDs for the four first generation lamp types used in Experiment #1. See Table 1 for key summary measures.

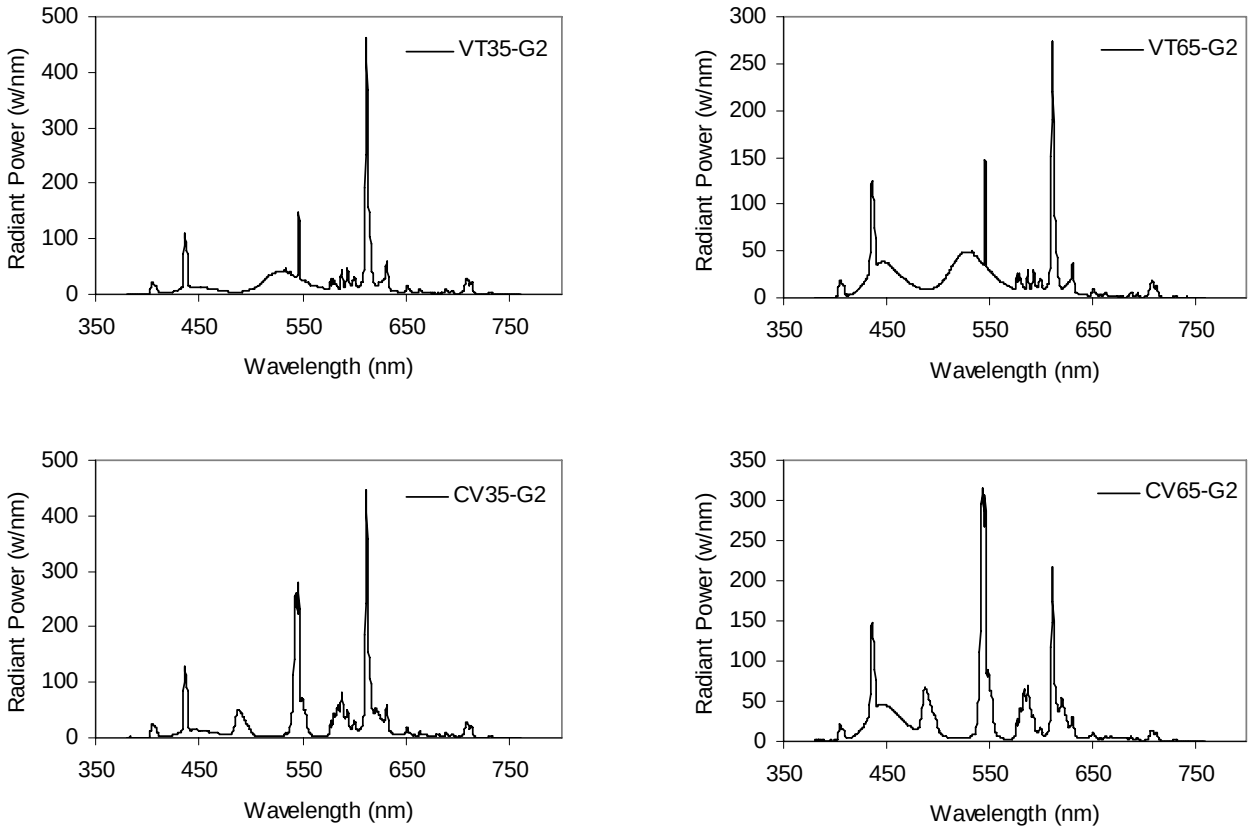

Figure 2b SPDs for the four second generation lamp types used in Experiments #3 and #4. See Table 1 for key summary measures.

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Instructions for Room Comparison Experiment

Project Title:
Spectral Effects Workshop

Identification of this Research:
This experiment involves evaluating the appearance of side-by-side rooms lighted with different types of light sources. It will take approximately 45 minutes to complete this experiment.

Instructions:
This experiment deals with how lighting affects the appearance of rooms and the objects contained within these rooms. Your task is to compare the two rooms by answering a series of short questions. The questions relate to brightness, color, and your overall preference. For example, we will ask you which room appears brighter, room "A" or room "B". For each question you will be asked to pick one of the two rooms, room "A" or room "B". Even if you think they look the same it is important that you pick one of the two rooms. In making your selection your first reaction is best. Similar questions will be asked about room and object color, and your overall preference.

Before we start the experiment we will administer practice trials to help familiarize you with the equipment and procedures.

Figure 3a The first page of the survey packet used in Experiment #1, showing an overview of the experiment and instructions for the subject. An example of the subsequent pages is given as Figure 3b.

For experimenter's use
Subject No. _____
Session No. _____
Date _____

"A" is the room on your left
"B" is the room on your right

In which room do the flowers appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
	natural?	☐ A	☐ B
In which room do the plants appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
	natural?	☐ A	☐ B
In which room does the food (overall) appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
	natural?	☐ A	☐ B
In which room does the sweatshirt appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
In which room do the towels appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
In which room does the office equipment (e.g. file folders, binders) appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
In which room do colors (overall) appear more	preferred?	☐ A	☐ B
	colorful?	☐ A	☐ B
	natural?	☐ A	☐ B

Which room is brighter?	☐ A	☐ B
How much brighter?	☐ less than 5%	
.....	☐ between 5 and 10%	
.....	☐ between 10 and 20%	
.....	☐ between 20 and 30%	
.....	☐ between 30 and 40%	
.....	☐ between 40 and 50%	
.....	☐ more than 50%	

Which room has greater visual clarity?	☐ A	☐ B
Which room would you prefer to work in?	☐ A	☐ B

Comments: _____

_____

_____

Figure 3b A typical survey instrument used in Experiment #1. One such sheet was used for each of the eight pairs of light settings that were evaluated.

Figure 4 Photograph of the side-by-side arrangement used in Experiment #1 and the chromatic environment of Experiment #3. During an experimental session the observer was seated in the chair in the center of the photograph. A fabric wall placed behind the subject was removed for this photograph. The achromatic environment of Experiment #3 was created by removing all of the props (i.e. prints on the walls, plastic plants and fruit, 3-ring binders, silk flowers, towels, etc.).

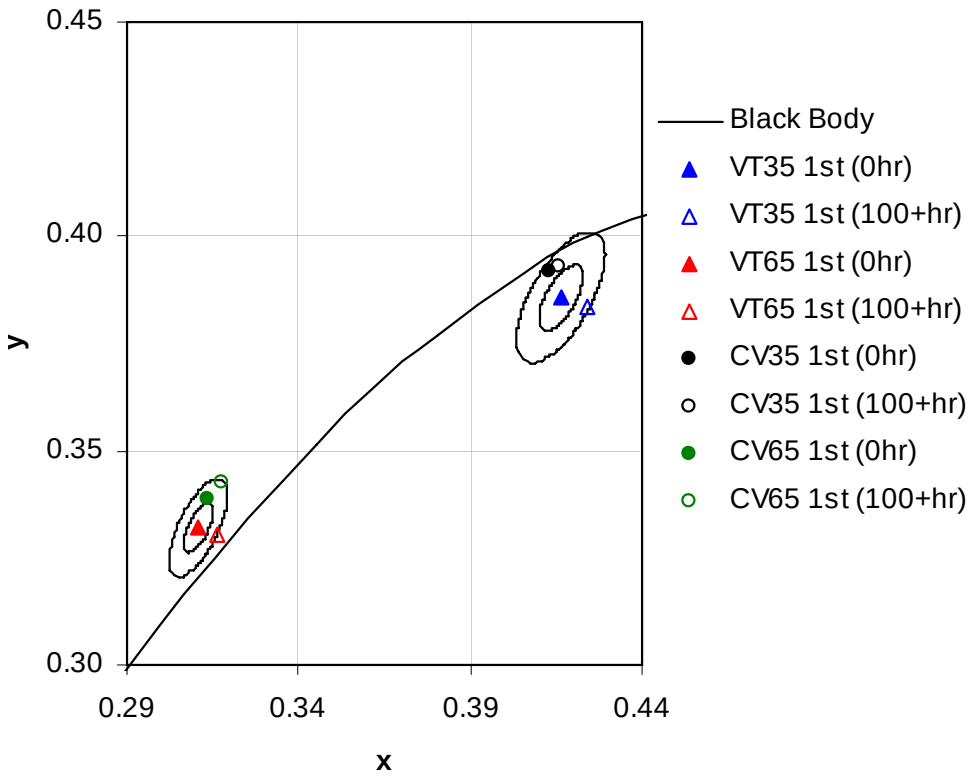

Figure 5a Chromaticity coordinates for the first-generation lamp types on the CIE 1931 2° diagram along with 3- and 6-step MacAdam ellipses for the vision-tuned lamps. These data are for the lamps used in Experiment #1. Compare with Figure 11, which is for the second-generation lamp types used in Experiment #2.

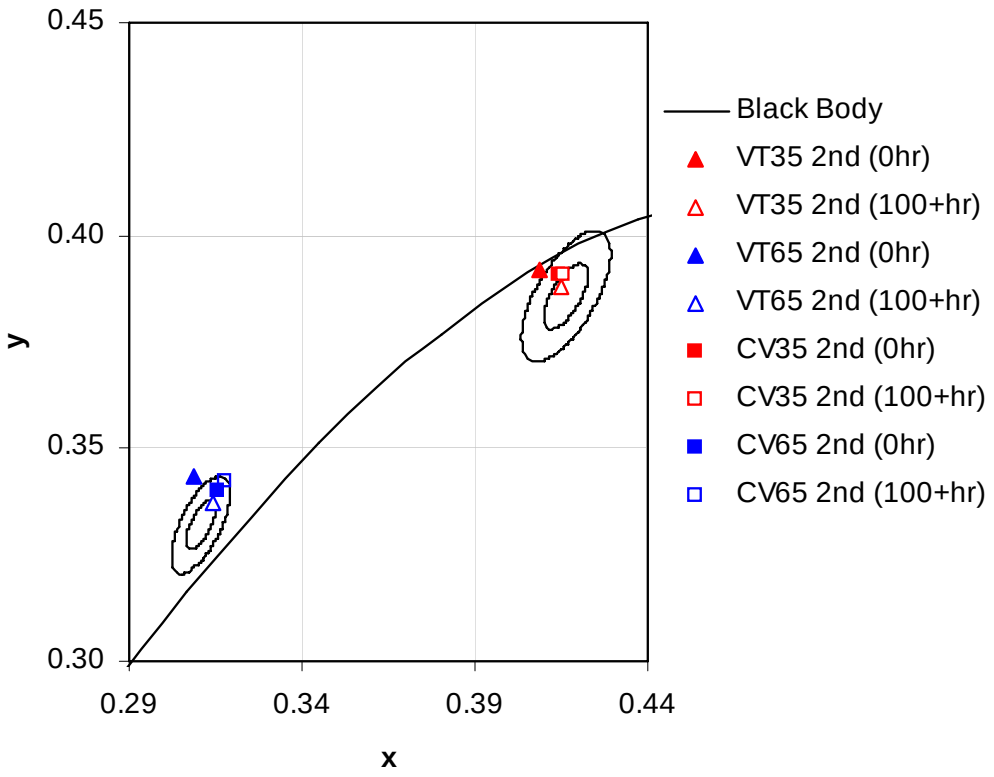

Figure 5b Chromaticity coordinates for the second-generation lamp types on the CIE 1931 2° diagram along with 3- and 6-step MacAdam ellipses for the vision-tuned lamps. These data are for the lamps used in Experiment #2. Compare with Figure 5, which is for the first-generation lamp types used in Experiment #1.

Figure 6 Photographs of the UNL colorimeter used in Experiment #2. Upper Left: The 10° bipartite field viewed through the chin / forehead rest with light in bottom half. Lower Left: Exterior view showing the light sources (far left), integrating chamber (top center), and subject's seating position (far right). Right: View from behind the subject's seated position.

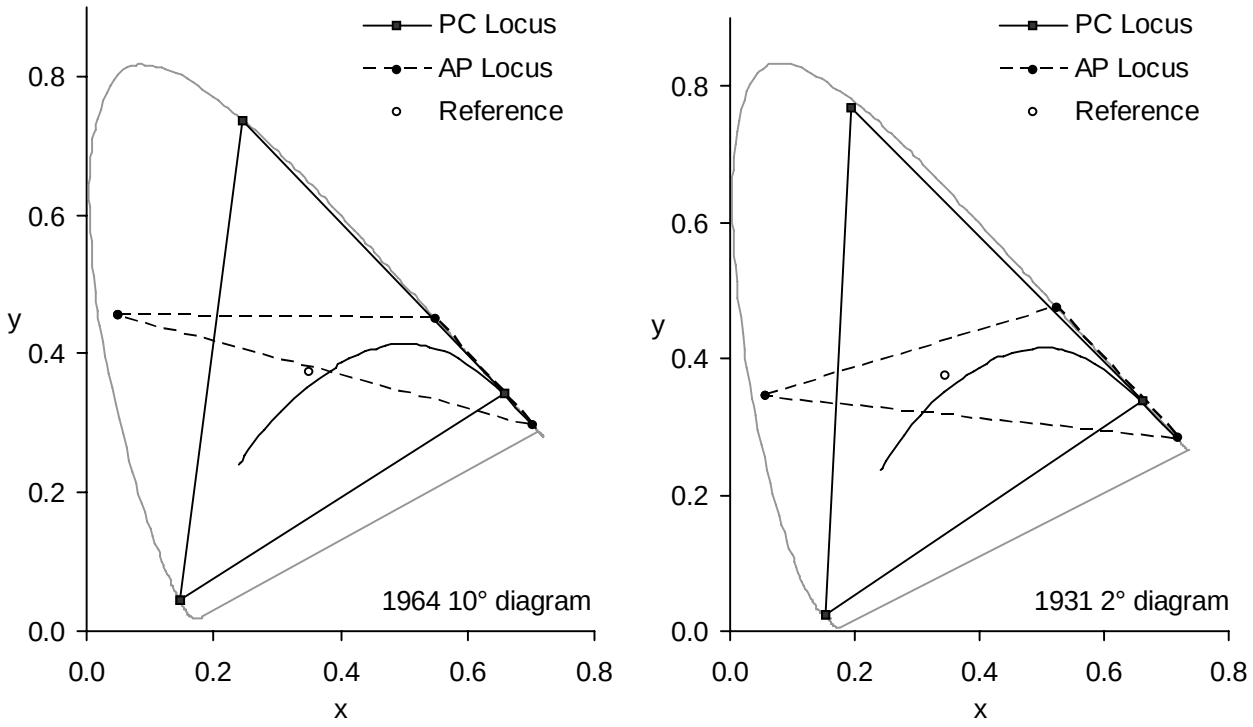

Figure 7 Left: CIE 1964 10° chromaticity diagram with PC and AP primary sets used in Experiment #2, the coordinates of the daylight fluorescent reference, and the blackbody locus. Right: As above but for the 1931 2° diagram.

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Instructions for Colorimeter Adjustment Experiment

Project Title:
Spectral Effects Workshop

Identification of this Research:
This experiment involves matching the brightness and color of two lights. It will take approximately 45 minutes to complete this experiment.

Instructions:
This experiment deals with your perception of the brightness and color of lights. Your task is to adjust two different patches of light so they have the same brightness and color. Your head will be held in a fixed position using a chin/forehead rest. This ensures that everyone views the same visual stimulus. The task is to adjust the brightness and color so the top and bottom fields are identical. The color of the light in the top field is adjusted with rotary dials. When making the match you may notice the color is not uniform across your field of view. This is normal. Please ignore any nonuniformity in the center of your visual field when making your match. When the top and bottom fields appear identical, please tell the experimenters so they can record your results and set up the next trial.

Figure 8 The instructions read by the subjects at the start of Experiment #2.

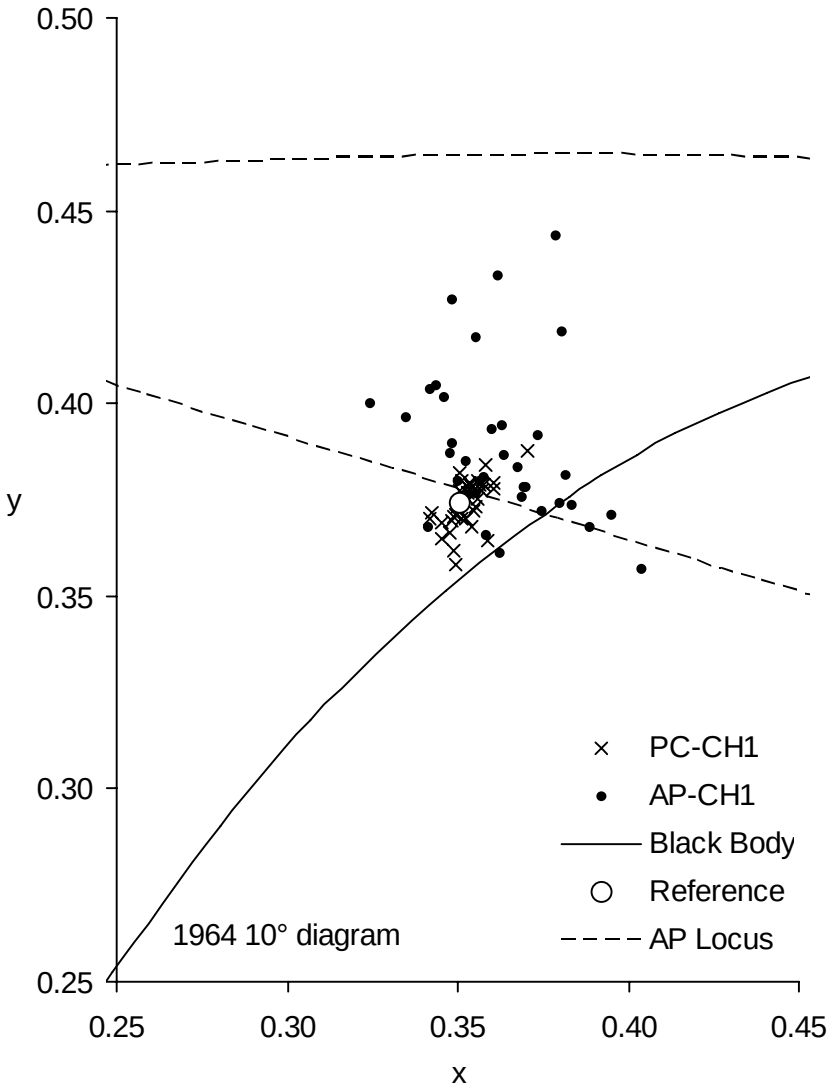

Figure 9a The dispersion of PC and AP matches in the 1964 10° chromaticity diagram. Data collected in Experiment #2, see text for details.

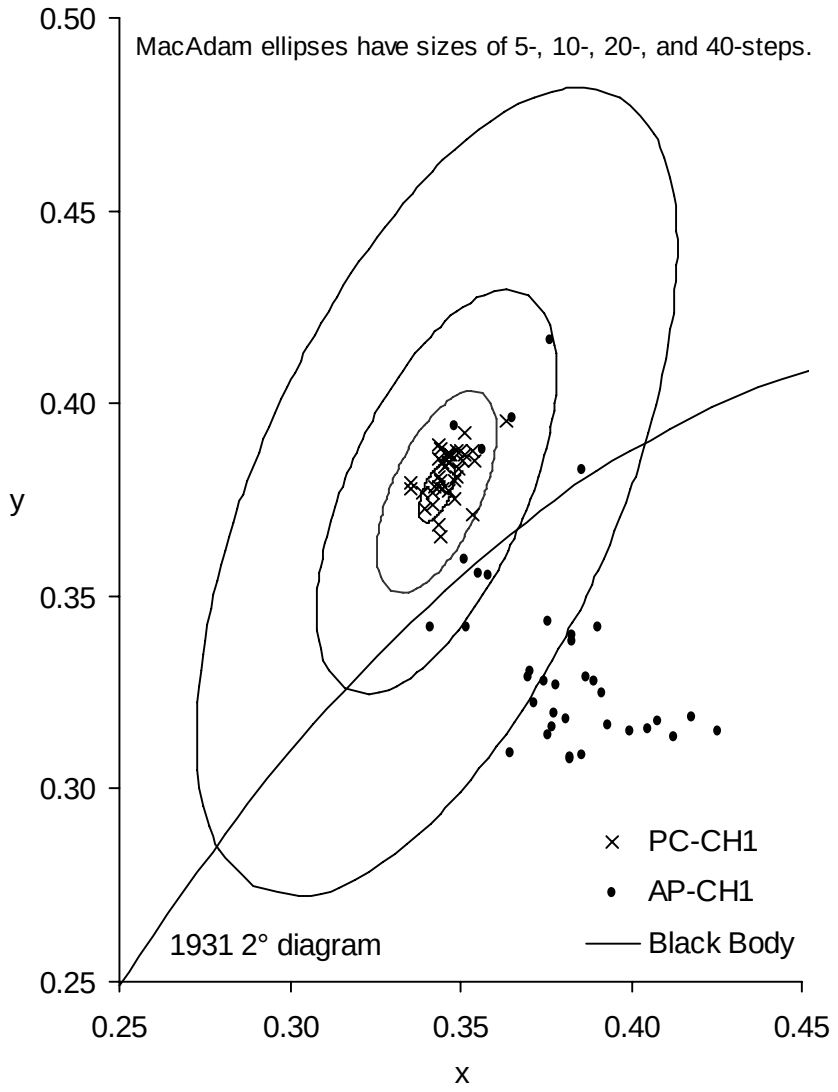

Figure 9b The dispersion of PC and AP matches in the 1931 2° chromaticity diagram with MacAdam ellipses centered at the chromaticity coordinates of the daylight fluorescent reference. Data collected in Experiment #2, see text for details.

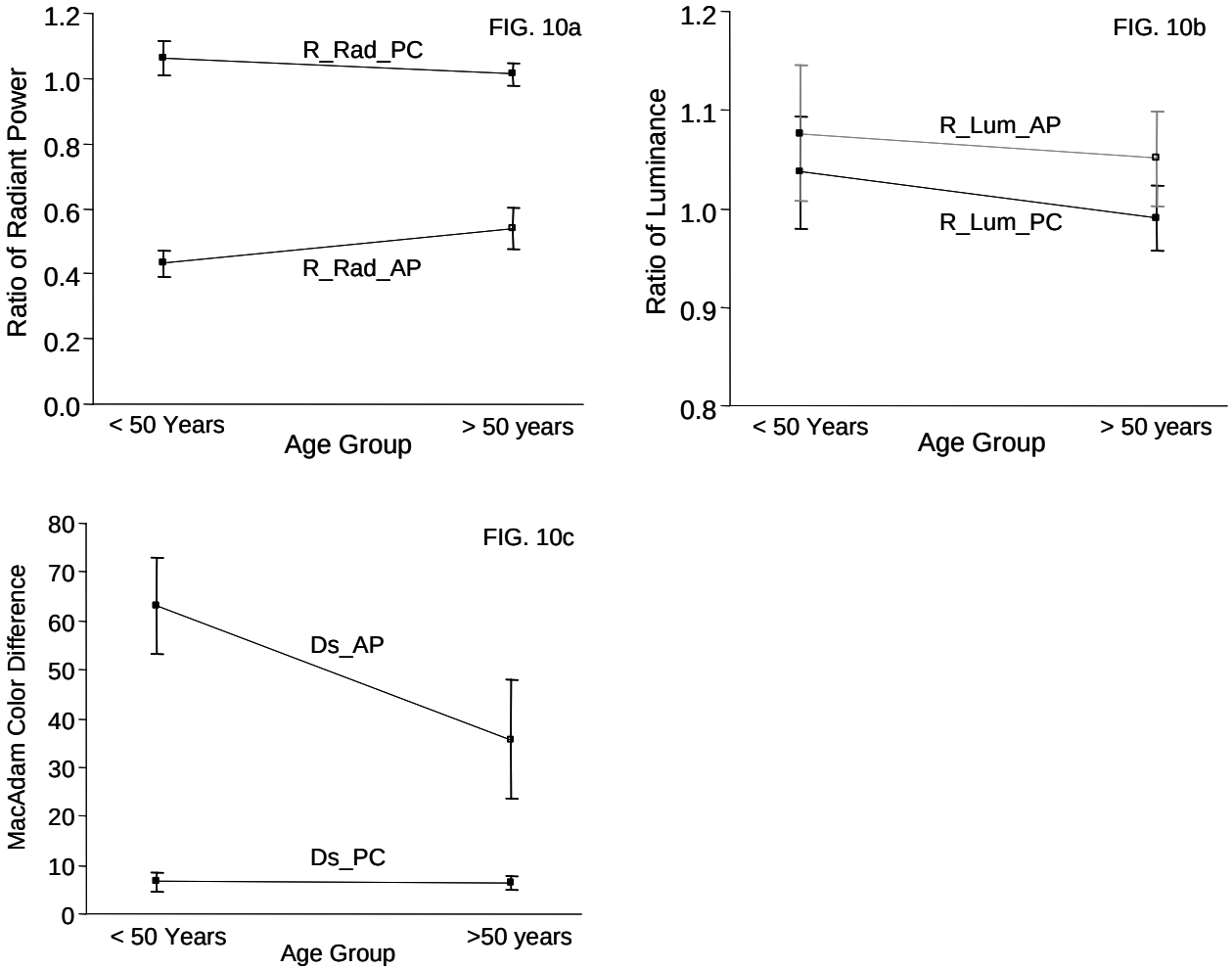

Figure 10 Mean and standard deviations as a function of age group for: a) ratio of radiant power, b) ratio of luminance, and c) chromaticity differences in MacAdam units. Data collected as part of Experiment #2, see text for details.

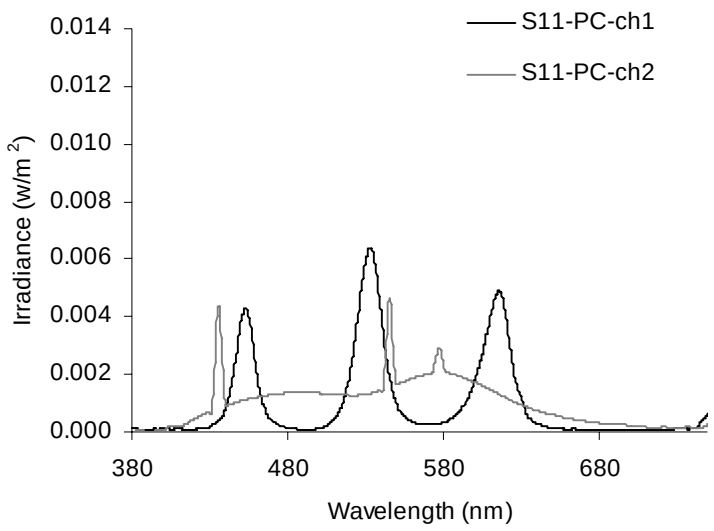

Figure 11a Representative data from Experiment #2 showing a typical PC match (ch1) to the daylight fluorescent reference (ch2).

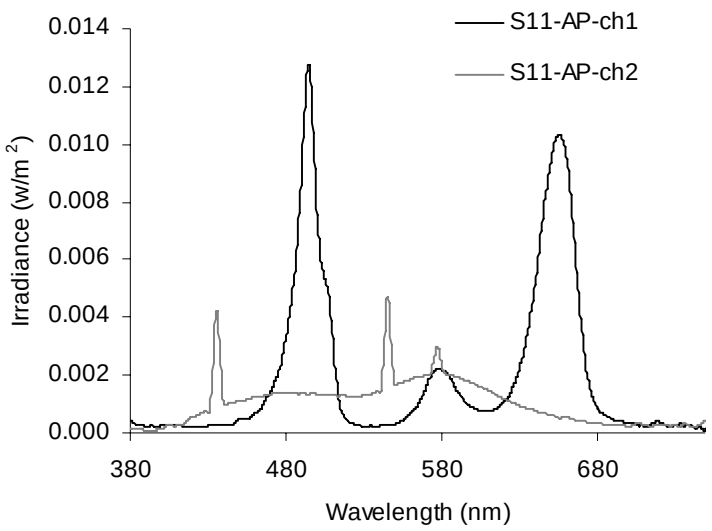

Figure 11b Representative data from Experiment #2 showing a typical AP match (ch1) to the daylight fluorescent reference (ch2).

Subject Name: _____

Subject ID: _____

Trials:
Chromatic / Achromatic

Subject Number	Trial Number	Left Scene (A)			Right Scene (B)		
		Scene #	F/V	End E	Scene #	F/V	End E
1	-1	6			6		
1	0	3	V		7	F	
1	1	8	F		10	V	
1	2	10	V		8	F	
1	3	13	V		7	F	
1	4	2	V		8	F	
1	5	7	F		5	V	
1	6	11	V		9	F	
1	7	7	F		13	V	
1	8	12	V		6	F	
1	9	4	V		6	F	
1	10	8	F		2	V	
1	11	5	V		7	F	
1	12	6	F		12	V	
1	13	9	F		11	V	
1	14	6	F		4	V	
1	15	9	F		3	V	
1	16	3	V		9	F	

Figure 12 An example of a typical worksheet used by the experimenter with administering Experiment #3. There were two such worksheets per subject, one each for the chromatic and achromatic environments.

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INSTRUCTIONS FOR ROOM COMPARISON EXPERIMENT

Project Title:
Evaluation of Fluorescent Light Sources

(The following will be read out loud by the experimenter)
This experiment deals with how lighting affects the appearance of rooms and the objects contained within these rooms. For this experiment we are specifically interested in your impressions of brightness. Your task will be to compare the brightness of the two rooms, and to instruct me to adjust the intensity of the lighting in one of the rooms so that they both appear equally bright. Room "A" is on the left as indicated, and room "B" is on the right.

For example, I will now reduce the intensity of the lighting in room "B". In this example, and in all cases, one room will be fixed and the other will be variable. Sometimes room "A" will be the variable room and other times it will be room "B". I will always tell you which room – for this example room "B" is the variable room. I will not adjust the lighting in the fixed room, but I will raise and lower the intensity of the lighting in the variable room as you instruct me. Please tell me how I need to adjust the lighting in the room "B" so that it has equal brightness as room "A". If it needs to be brighter say "brighter" or "higher". If it needs to be darker say "darker" or "lower". Remember your task is to visually match the brightness in the two rooms. I will follow your instructions and adjust the lighting until you are content that we have achieved the best possible brightness match. Do you have any questions?

We will make a total of 17 comparisons – each time one room will be fixed and the other will be variable, and I will tell you the room that is to be adjusted. When we change from one pair to the next do not begin to instruct me right away. We will wait about 30 seconds for your eyes to adapt to the new lighting conditions. During this time please just look into the rooms and observe the objects within them. I will prompt you when enough time has passed and it is OK for you to instruct me on how to make the adjustments. Again, you will tell me to adjust the brightness in one room so that both rooms are the same brightness.

We will have a practice trial to help familiarize you with the equipment and procedures. If the procedures are unclear during the practice trial then please ask for clarification. Do you have any questions?

Figure 13 The instructions read out loud to the subjects at the start of Experiment #3.

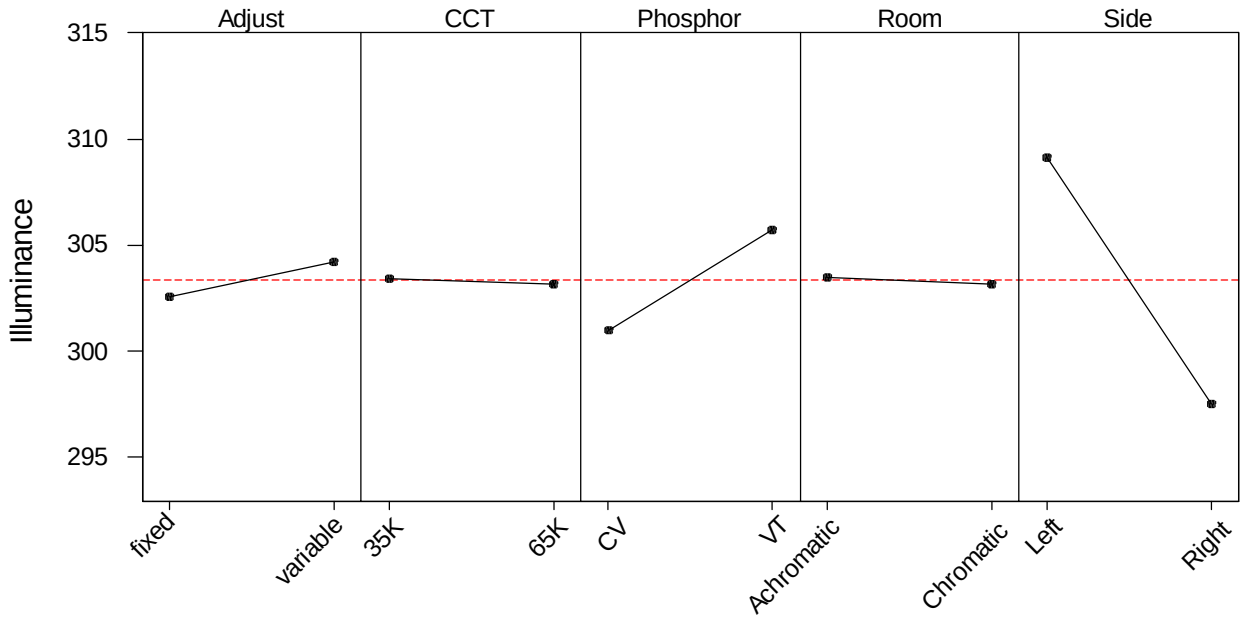


Figure 14a Main effects plot for Experiment #3 showing data means for illuminance by Adjust, CCT, Phosphor, Room, and Side.

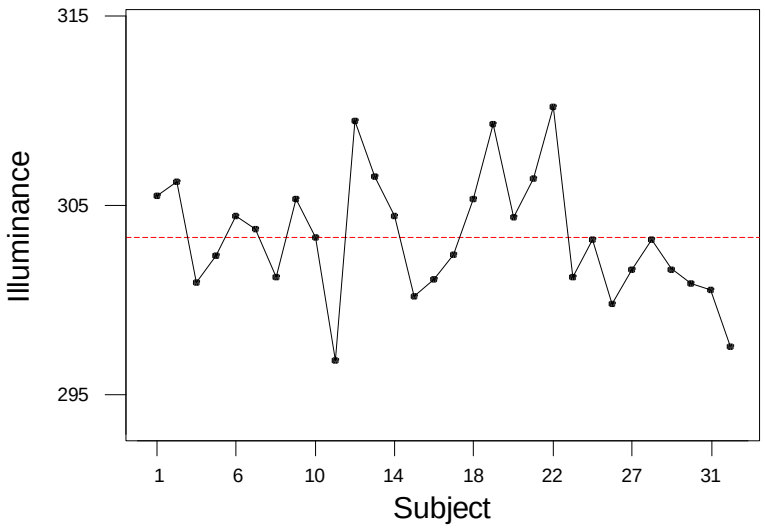
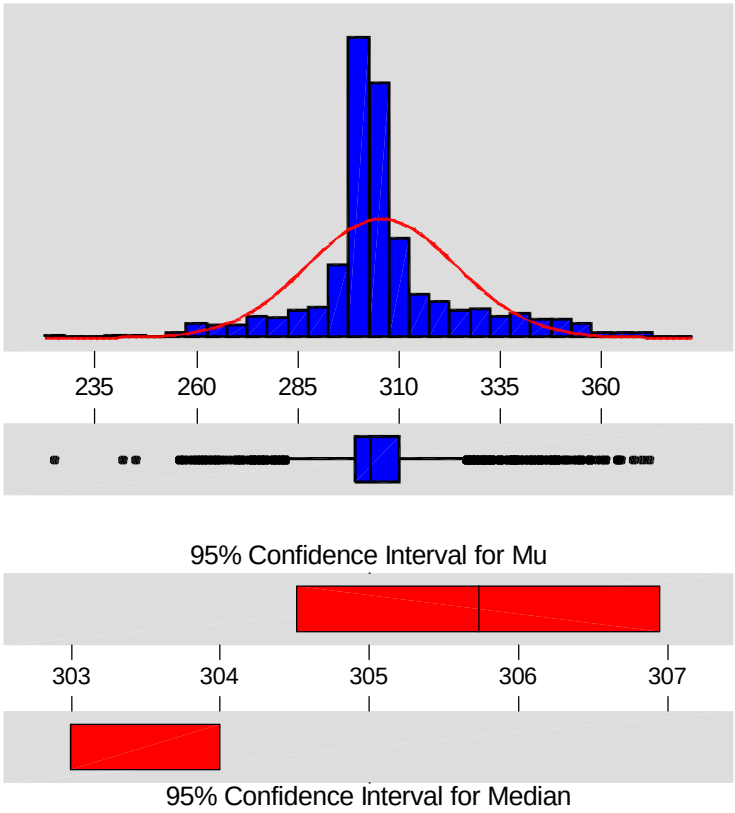


Figure 14b Main effects plot for Experiment #3 showing data means for illuminance by subject.



Variable: Illuminance
Phosphor: VT

Anderson-Darling Normality Test

A-Squared:	38.267
P-Value:	0.000
Mean	305.730
StDev	18.466
Variance	340.980
Skewness	0.463471
Kurtosis	2.18054
N	890
Minimum	225.000
1st Quartile	299.000
Median	303.000
3rd Quartile	310.000
Maximum	372.000

95% Confidence Interval for Mu

304.516	306.945

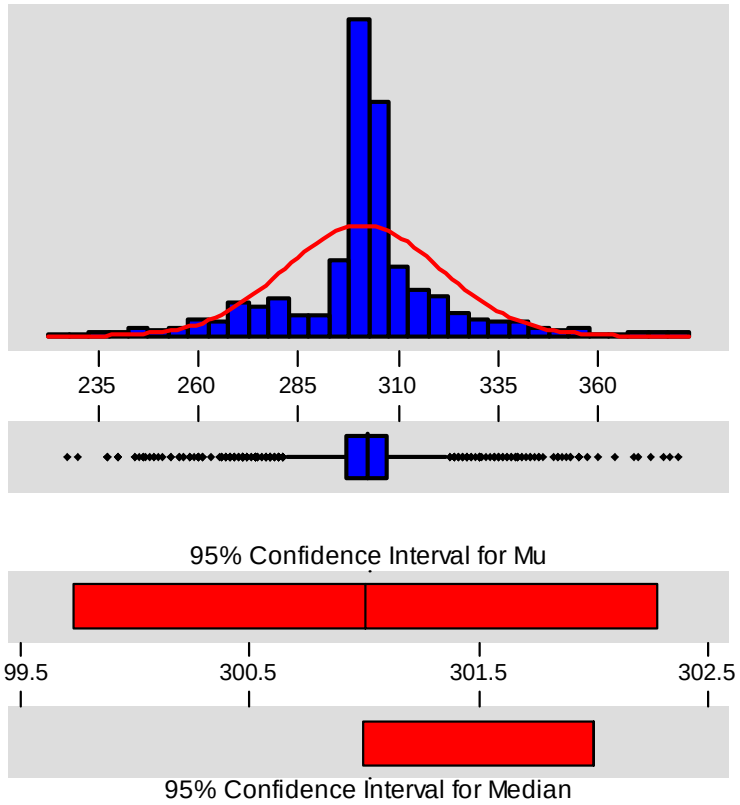
95% Confidence Interval for Sigma

17.646	19.366

95% Confidence Interval for Median

303.000	304.000

Figure 15a Descriptive summary statistics for Illuminance for the VT lamps used in Experiment #3; for comparison with Figure 15b.



Variable: Illuminance
Phosphor: CV

Anderson-Darling Normality Test

A-Squared:	39.182
P-Value:	0.000
Mean	301.007
StDev	19.489
Variance	379.803
Skewness	-1.1E-01
Kurtosis	2.74943
N	906
Minimum	227.000
1st Quartile	297.000
Median	302.000
3rd Quartile	307.000
Maximum	380.000

95% Confidence Interval for Mu

299.736	302.277

95% Confidence Interval for Sigma

18.631	20.430

95% Confidence Interval for Median

301.000	302.000

Figure 15b Descriptive summary statistics for Illuminance for the CV lamps used in Experiment #3; for comparison with Figure 15a.

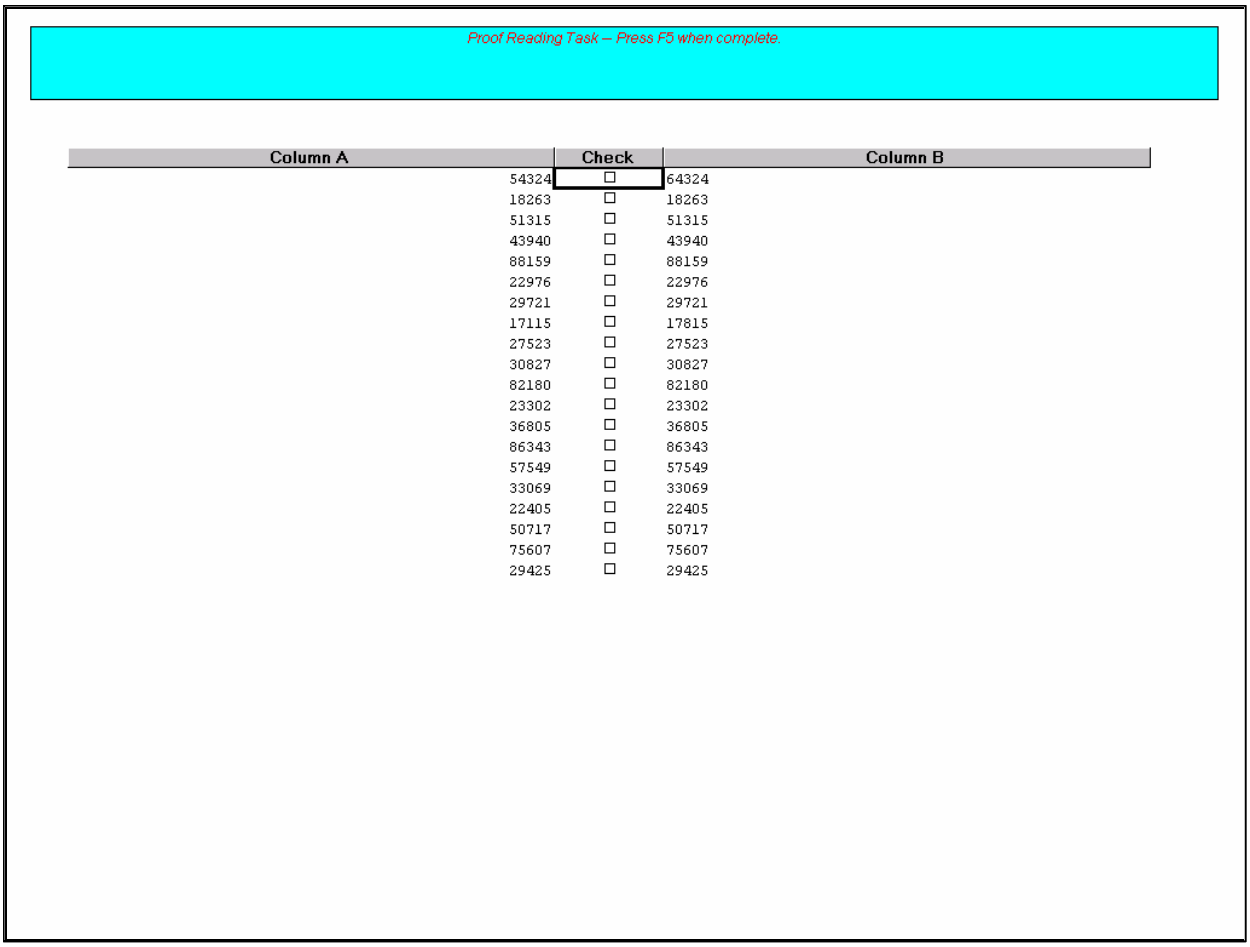


Figure 16 An screen-shot of an example proofreading task used in Experiment #4.

Figure 17 A screen-shot of an example typing task used in Experiment #4.

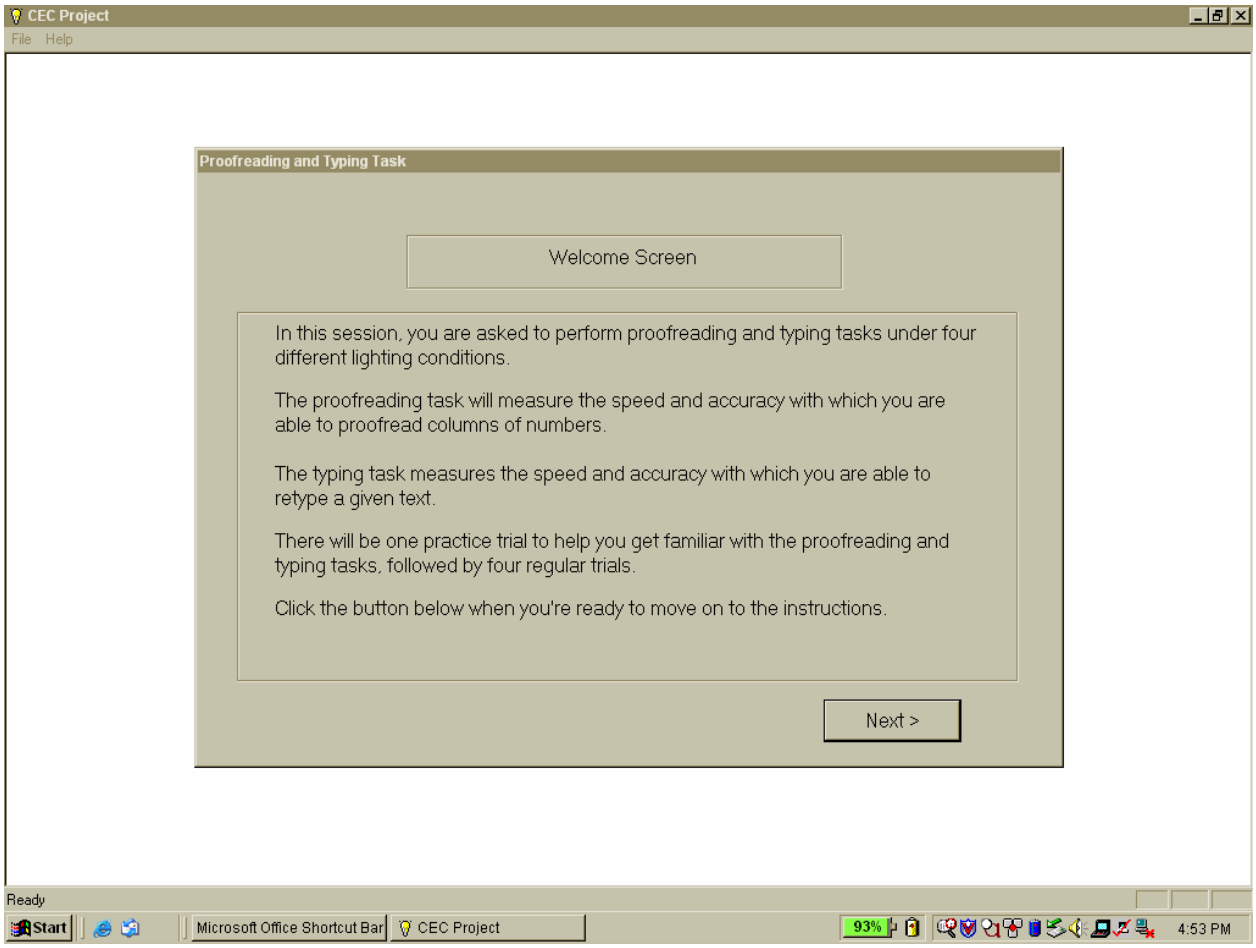


Figure 18a A screen-shot of the "Welcome Screen" used to introduce Experiment #4.

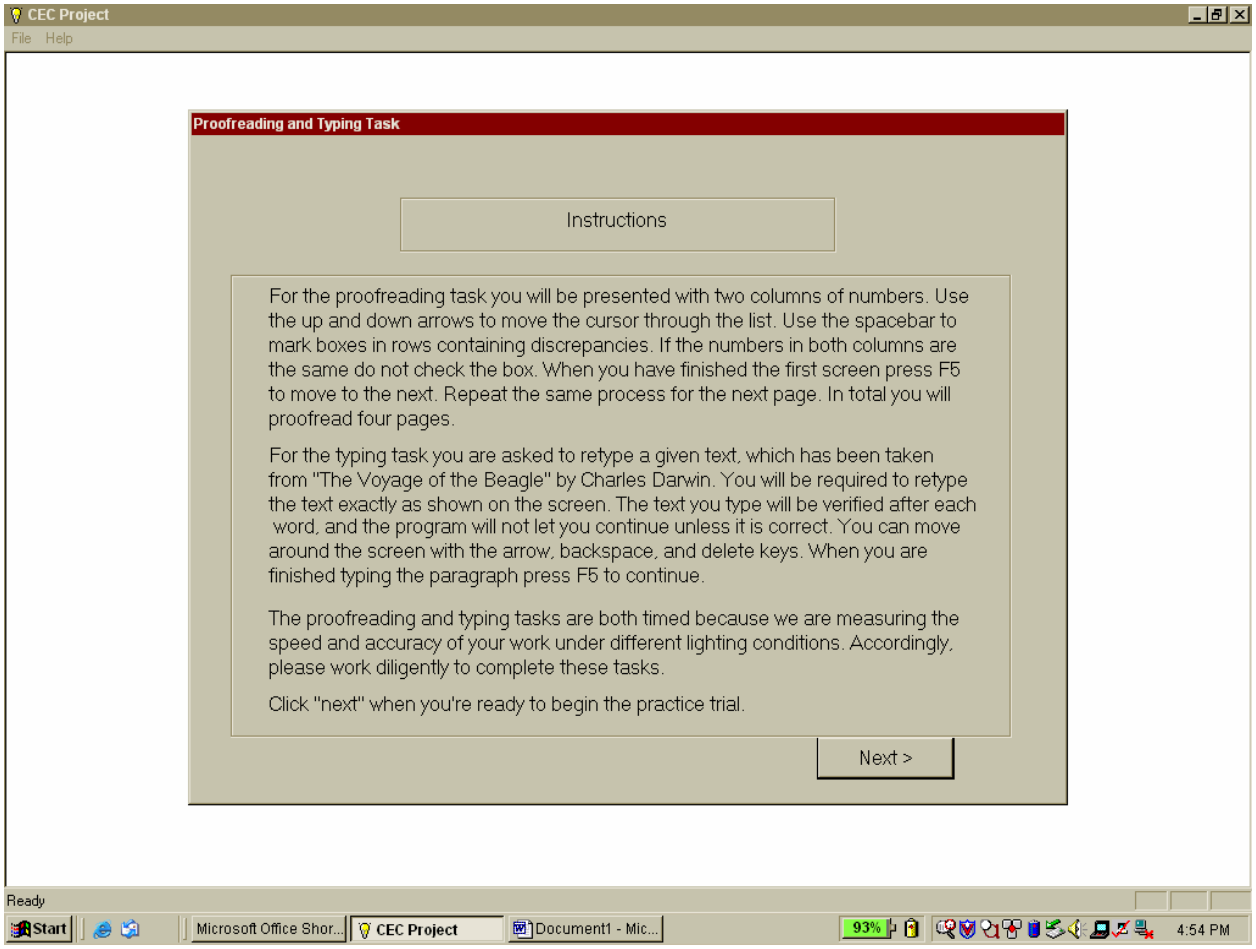


Figure 18b A screen-shot of the "Instructions" screen used in Experiment #4.

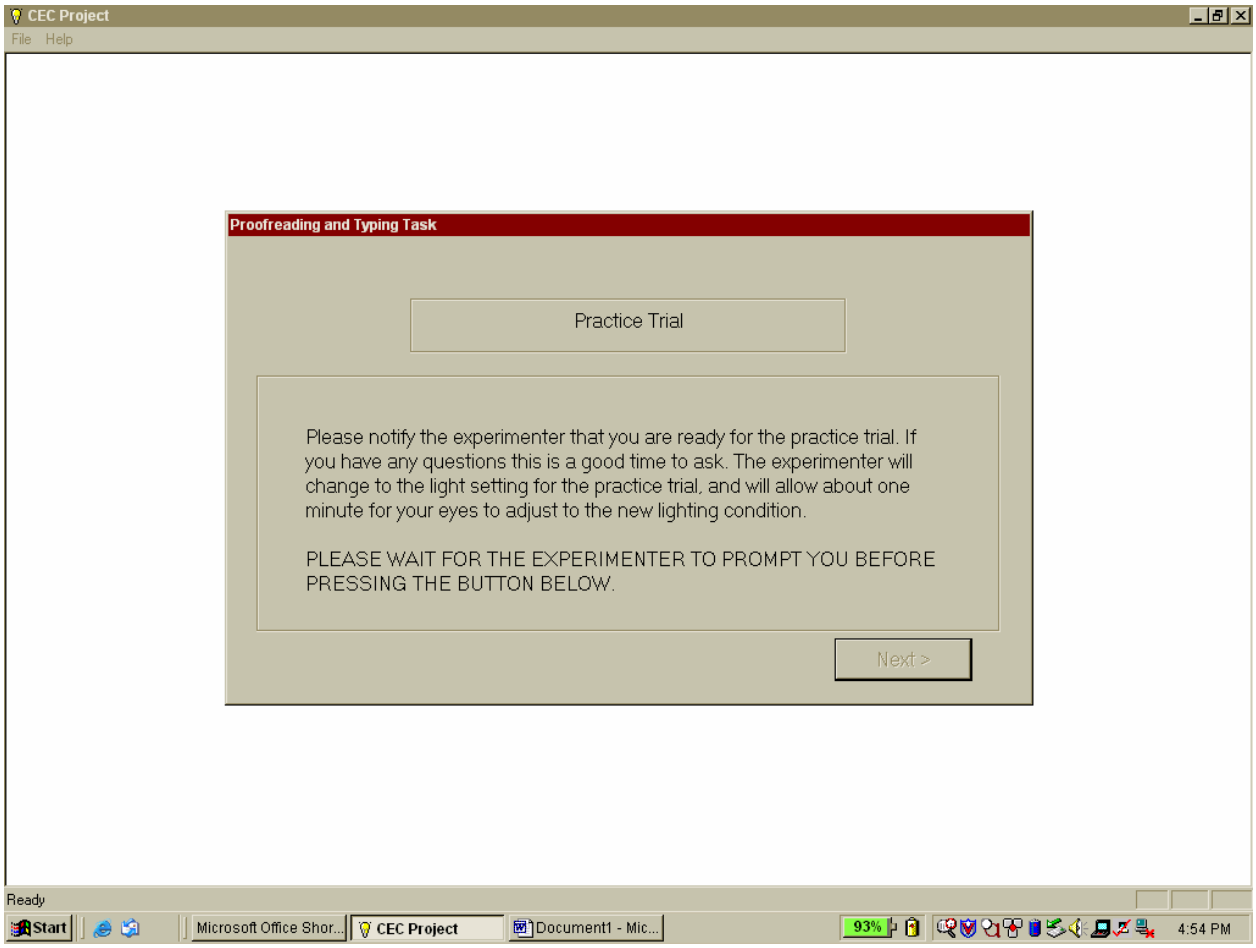


Figure 18c A screen-shot of the screen appearing at the start of the Practice Trial of Experiment #4. Notice that the "Next" button is inactive in this screen-shot. It only becomes active after 60 seconds have elapsed, forcing the subject to adapt to the new lighting condition.

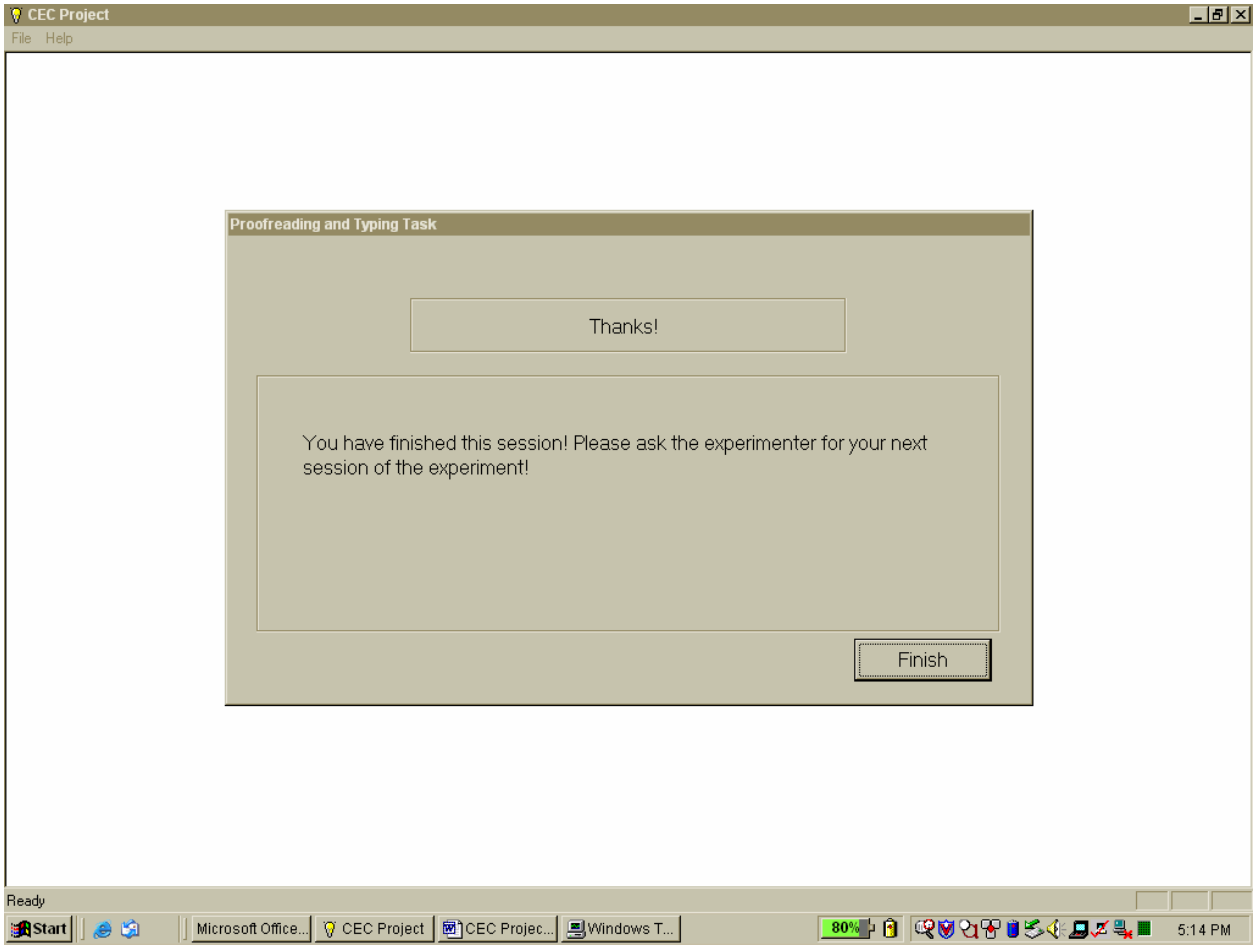
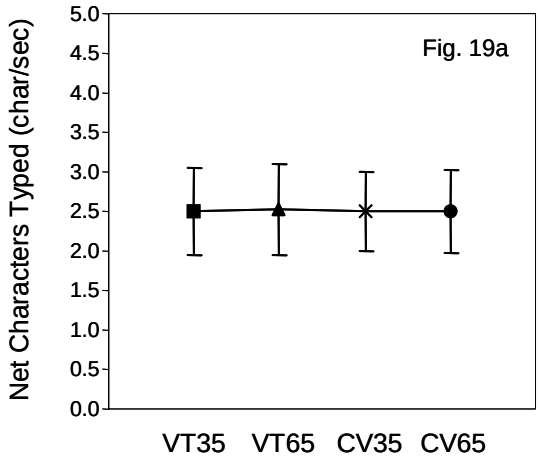
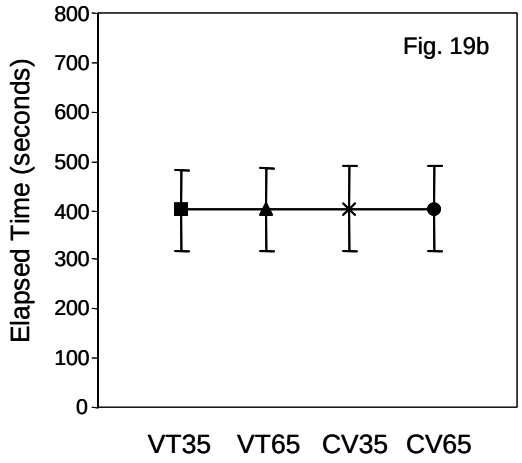
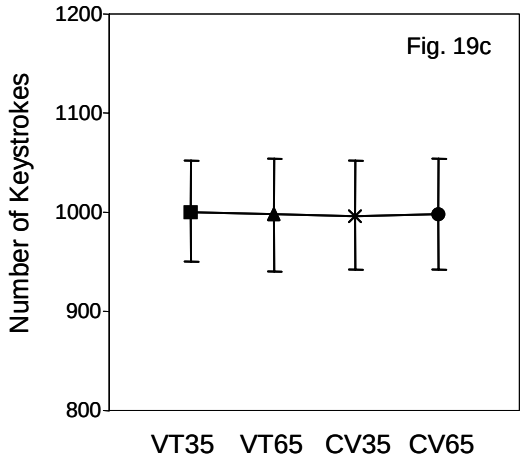
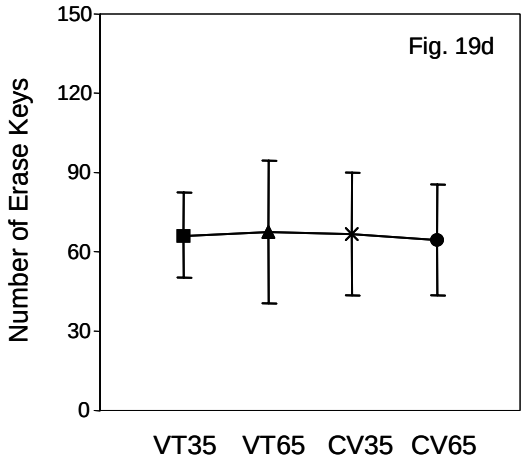


Figure 18d A screen-shot of the final screen of Experiment #4.









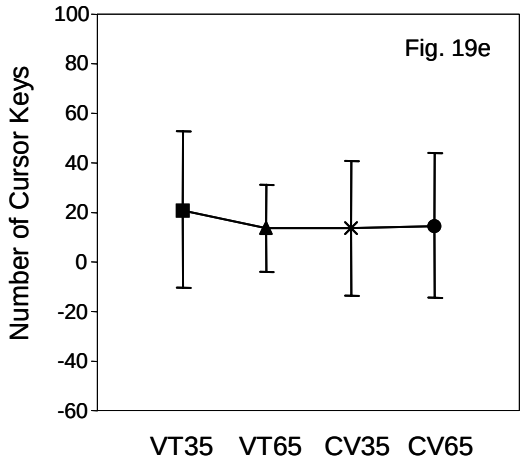
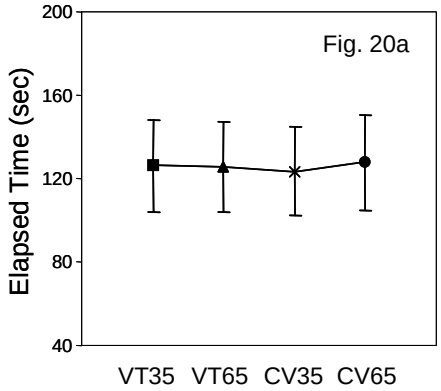
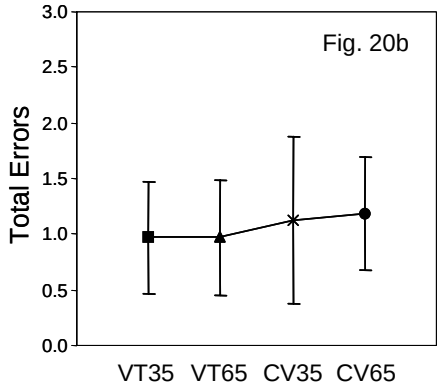
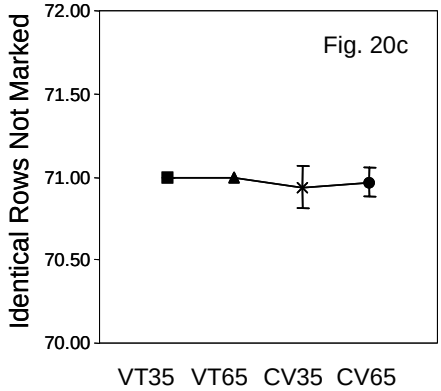
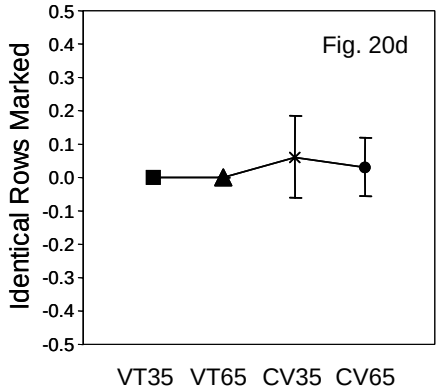


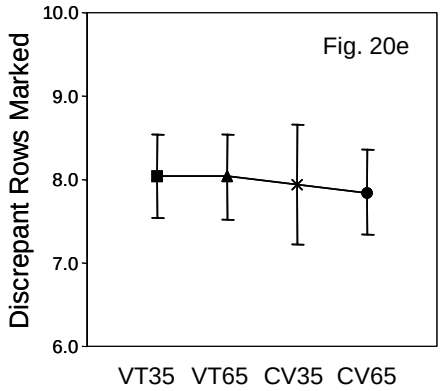
Figure 19a - 19e Summary plots of the mean and standard deviations of the dependent measures for the typing task: a) net characters per second, b) total elapsed time, c) number of keystrokes, d) number of erase keys, and e) number of cursor keys.

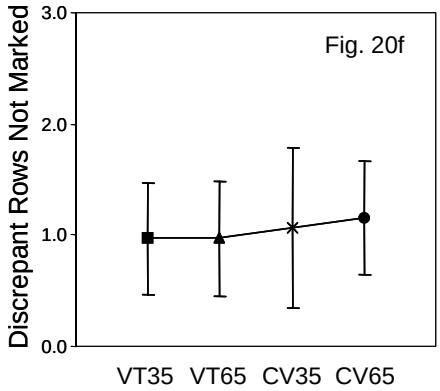












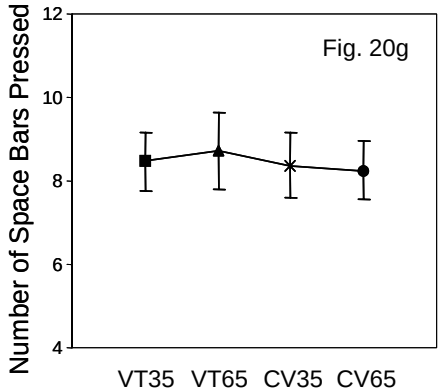


Figure 20a – 20g Summary plots of the mean and standard deviations of the dependent measures for the proofreading task: a) elapsed time, b) total errors, c) identical rows not marked, d) identical rows marked, e) discrepant rows marked, f) discrepant rows not marked, and g) number of space bars pressed.

Appendix F – Tables

Table 1 Summary measures for the eight types of prototype lamps used in this project. The postfix "G1" designates first-generation lamps that were used in Experiment #1; G2 lamps were used in Experiments #3 and #4.

Lamp Type	Chromaticity Coordinates[1] (x, y)	Ra	CPI	CDI	CSA	Pointer's Index	CCT	S/P Ratio	Luminous Flux for a 32W lamp at 100 hrs (Lumens)	Radiant Flux for a 32W lamp at 100 hrs (Watts)	Luminous Efficacy "A"[2] (Lumens/Watt)	Luminous Efficacy "B"[3] (Lumens/Watt)
VT35-G1	(0.4232, 0.3837)	80.7	117.1	78.8	0.0308	76.1	3050	1.19	2355	6.98	73.6	337.5
CV35-G1	(0.4156, 0.3934)	83.9	100.2	67.9	0.0289	76.5	3301	1.15	2773	7.92	86.7	350.0
VT65-G1	(0.3162, 0.3317)	82.7	117.1	107.2	0.0486	94.9	6291	2.03	2253	7.28	70.4	309.7
CV65-G1	(0.3183, 0.3436)	74.0	91.1	86.3	0.0426	77.0	6133	1.88	2720	8.35	85.0	325.8
VT35-G2	(0.4151, 0.3863)	81.8	118.5	79.2	0.0316	76.3	3244	1.23	2220	6.57	69.4	337.9
CV35-G2	(0.4157, 0.3910)	84.1	100.6	69.1	0.0292	76.4	3276	1.16	2779	6.71	86.8	414.4
VT65-G2	(0.3143, 0.3369)	82.5	113.7	103.8	0.0478	94.8	6361	2.01	2102	7.99	65.7	263.2
CV65-G2	(0.3177, 0.3425)	74.0	91.3	86.7	0.0428	77.0	6149	1.89	2761	8.49	86.3	325.4

1. CIE 1931 2° Standard Observer.
2. Luminous Flux (Lumens) per Input Power (Watts) when operated under ANSI reference conditions at 100 hours.
3. Luminous Flux (Lumens) per Radiant Flux (Watts) when operated under ANSI reference conditions at 100 hours.

Table 2 An example of the randomized presentation order of the light settings for Experiment #1.

Subject	Trial	Left Scene		Right Scene	
		Code	Lamp	Code	Lamp
4	0*	2	VT35	2	VT35
4	1†	6	CV35	2	VT35
4	2‡	4	VT65	4	VT65
4	3	2	VT35	6	CV35
4	4	2	VT35	8	CV65
4	5	4	VT65	8	CV65
4	6	4	VT65	6	CV35
4	7	6	CV35	8	CV65
4	8	2	VT35	4	VT65

*Settings when subject entered the room.

† Practice trial.

‡ Control trial.

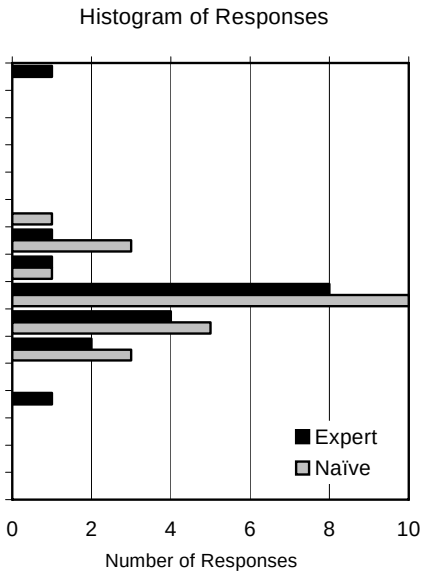
Table 3 Summary of key data for the comparisons between vision-tuned and conventional lamps in Experiment #1. Top: percentage of observers selecting the room lighted with vision-tuned lamps. Bottom: ANOVA summary table.

VT vs CV Comparison	Subject Type	Q7 Colors Overall			Q8 Brightness	Q9 Visual Clarity	Q10 Work Preference	Mean (Q7-10)
		Preferred	Colorful	Natural				
VT65 vs CV65	Expert	94	100	83	83	100	89	92
	Naïve	83	83	74	78	87	83	81
VT35 vs CV35	Expert	78	83	72	61	72	83	75
	Naïve	57	65	26	70	57	52	54

Source of Variance	DF	Seq SS	Adj SS	Adj MS	F	P
Subject Type (ST)	1	0.3510	0.3510	0.3510	34.86	< 0.001
Middle Phosphor (MP)	1	0.6292	0.6292	0.6292	62.49	< 0.001
Question (Q)	20	1.1097	1.1097	0.0555	5.51	< 0.001
ST*MP	1	0.1257	0.1257	0.1257	12.49	0.002
ST*Q	20	0.1741	0.1741	0.0087	0.86	0.626
MP*Q	20	0.1599	0.1599	0.0080	0.79	0.694
Error	20	0.2014	0.2014	0.0101		
Total	83	2.7511				

Table 4a Summary of the responses to the question "How Much Brighter?" for the side-by-side comparison at 65K. See text for details.

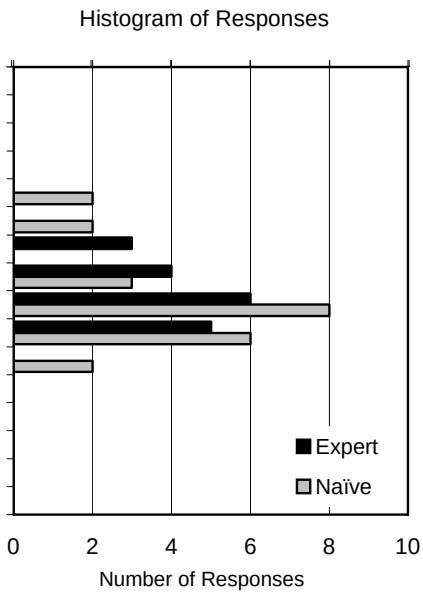
Number of Expert Responses	Number of Naïve Responses	Description of Response		Expert Weighted Response	Naïve Weighted Response
		Lamp	How much brighter?		
1	0	CV	No Answer	0	0
0	0	CV	Greater than 50%	0	0
0	0	CV	Between 40 and 50%	0	0
0	0	CV	Between 30 and 40%	0	0
0	0	CV	Between 20 and 30%	0	0
0	1	CV	Between 10 and 20%	0	-15
1	3	CV	Between 5 and 10%	-7.5	-22.5
1	1	CV	Less than 5%	-2.5	-2.5
8	10	VT	Less than 5%	20	25
4	5	VT	Between 5 and 10%	30	37.5
2	3	VT	Between 10 and 20%	30	45
0	0	VT	Between 20 and 30%	0	0
1	0	VT	Between 30 and 40%	35	0
0	0	VT	Between 40 and 50%	0	0
0	0	VT	Greater than 50%	0	0
0	0	VT	No Answer	0	0
			Mean Weighted Response =	6.2	2.9
			Overall Mean Weighted Response =	4.3	



Interpretation: When illuminance was equal, the environment illuminated with VT65 lamps was considered to be 4.3% brighter than the environment illuminated with the CV65 lamps when averaged across the expert and naïve observers.

Table 4b As with Table 4a but for 35K. See text for details.

Number of Expert Responses	Number of Naïve Responses	Description of Response		Expert Weighted Response	Naïve Weighted Response
		Lamp	How much brighter?		
0	0	CV	No Answer	0	0
0	0	CV	Greater than 50%	0	0
0	0	CV	Between 40 and 50%	0	0
0	0	CV	Between 30 and 40%	0	0
0	2	CV	Between 20 and 30%	0	-50
0	2	CV	Between 10 and 20%	0	-30
3	0	CV	Between 5 and 10%	-22.5	0
4	3	CV	Less than 5%	-10	-7.5
6	8	VT	Less than 5%	15	20
5	6	VT	Between 5 and 10%	37.5	45
0	2	VT	Between 10 and 20%	0	30
0	0	VT	Between 20 and 30%	0	0
0	0	VT	Between 30 and 40%	0	0
0	0	VT	Between 40 and 50%	0	0
0	0	VT	Greater than 50%	0	0
0	0	VT	No Answer	0	0
			Mean Weighted Response =	1.1	0.3
			Overall Mean Weighted Response =	0.7	



Interpretation: When illuminance was equal, the environment illuminated with VT35 lamps was considered to be 0.7% brighter than the environment illuminated with the CV35 lamps when averaged across the expert and naïve observers

Table 5 Summary of key data for the comparisons between 3500K and 6500K lamps in Experiment #1. Top: percentage of observers selecting the room lighted with 6500K lamps. Bottom: ANOVA summary table.

CCT Comparison	Subject Type	Q7 Colors Overall			Q8 Brightness	Q9 Visual Clarity	Q10 Work Preference	Mean (Q7-10)
		Preferred	Colorful	Natural				
CV65 vs CV35	Expert	0	6	0	39	28	11	14
	Naïve	26	17	35	52	57	30	36
VT65 vs VT35	Expert	11	17	28	44	50	11	27
	Naïve	30	22	39	61	65	35	42

Source of Variance	DF	Seq SS	Adj SS	Adj MS	F	P
Subject Type (ST)	1	0.1943	0.1943	0.1943	37.96	< 0.001
CCT	1	0.1219	0.1219	0.1219	23.82	< 0.001
Questions (Q)	20	0.9172	0.9172	0.0459	8.96	< 0.001
ST*CCT	1	0.0369	0.0369	0.0369	7.20	0.014
ST*Q	20	0.2473	0.2473	0.0124	2.42	0.028
CCT*Q	20	0.1386	0.1386	0.0069	1.35	0.252
Error	20	0.1024	0.1024	0.0051		
Total	83	1.7587				

Table 6 Subject demographic summary for Experiment #2.

Gender	Subject Knowledge	n	Age	
			Mean	Std. Dev.
Male	expert	8	51.3	15.0
	naïve	11	34.5	13.2
	Subtotal	19	41.6	16.0
Female	expert	8	48.0	13.3
	naïve	10	29.7	6.4
	Subtotal	18	37.8	13.5
Totals	expert	16	49.6	13.8
	naïve	21	32.2	10.6
	Grand Totals	37	39.8	14.8

Table 7 Descriptive statistics for the matches in Experiment #2.

Quantity	Symbol	Mean	Max	Min	Std. Dev.
Radiant Power (w/m^2)					
Test Field in PC Match	Rad_t_PC	1.13	1.43	0.27	0.29
Reference Field in PC Match	Rad_r_PC	1.23	1.91	0.44	0.30
Test Field in AP Match	Rad_t_AP	0.86	1.42	0.40	0.21
Reference Field in AP Match	Rad_r_AP	0.40	0.56	0.17	0.09
Luminance (cd/m^2)					
Test Field in PC Match	Lum_t_PC	123.0	158.7	11.7	33.9
Reference Field in PC Match	Lum_r_PC	131.0	200.0	46.0	32.3
Test Field in AP Match	Lum_t_AP	38.5	70.4	14.5	9.9
Reference Field in AP Match	Lum_r_AP	41.3	58.1	17.2	9.9
Ratios (decimal percentages)					
Radiant Power of Reference to Test Field in PC Match	R_Rad_PC	1.05	1.38	0.89	0.10
Radiant Power of Reference to Test Field in AP Match	R_Rad_AP	0.46	0.75	0.33	0.10
Luminance of Reference to Test Field in PC Match	R_Lum_PC	1.02	1.39	0.86	0.11
Luminance of Reference to Test Field in AP Match	R_Lum_AP	1.07	1.55	0.80	0.13
Color Difference (Ds)					
Color Difference in PC Match	Ds_PC	6.49	20.44	0.93	3.77
Color Difference in AP Match	Ds_AP	55.68	104.70	12.08	24.29

Table 8 Data structure for the MANOVA analysis of radiant energy and luminance of the matches in Experiment #2.

Subj. No.	Dependent Variable 1: Radiant power in the PC matches		Dependent Variable 2: Radiant power in the AP matches		Dependent Variable 3: Luminance in the PC matches		Dependent Variable 4: Luminance in the AP matches	
	test field	ref. field	test field	ref. field	test field	ref. field	test field	ref. field
	Rad_t_PC	Rad_r_PC	Rad_t_AP	Rad_r_AP	Lum_t_PC	Lum_r_PC	Lum_t_AP	Lum_r_AP
1	0.68	0.67	0.65	0.46	69.75	70.87	44.71	48.15
2	1.03	1.03	0.62	0.29	112.17	109.77	29.45	30.17
3	1.08	1.24	0.65	0.49	120.14	132.84	51.41	51.11
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
37	1.06	1.04	0.77	0.31	113.74	110.2	29.74	31.52

Table 9 Data Classifications for the GLM analyses of individual differences in Experiment #2.

Factor	Data Type	Levels	No. Cases
Subject Type	Between	1 = Expert	16
		2 = Naïve	21
Gender	Between	1 = Male	19
		2 = Female	18
Age Group	Between	1 = < 50 years	27
		2 = = 50 years	10
Primary Set	Within	1 = PC	37
		2 = AP	37

Table 10 Example data for Subject #1 in Experiment #3 in ANOVA-coded format.

Independent Variables						Dependent Variable
Adjust	CCT	Phosphor	Room	Side	Subject	Measured Illuminance (lux)
1 = fixed 2 = variable	1 = 35K 2 = 65K	1 = VT 2 = CV	1 = Chromatic 2 = Achromatic	1 = Left 2 = Right	= 1 … 32	
1	1	1	1	1	1	305
1	1	1	1	1	1	303
2	1	1	1	1	1	321
2	1	1	1	1	1	324
1	2	1	1	1	1	301
1	2	1	1	1	1	306
2	2	1	1	1	1	339
2	2	1	1	1	1	316
1	1	2	1	1	1	307
1	1	2	1	1	1	299
2	1	2	1	1	1	303
2	1	2	1	1	1	302
1	2	2	1	1	1	301
1	2	2	1	1	1	302
2	2	2	1	1	1	291
2	2	2	1	1	1	299
2	1	2	1	2	1	277
2	1	2	1	2	1	278
1	1	2	1	2	1	300
1	1	2	1	2	1	300
2	2	2	1	2	1	316
2	2	2	1	2	1	253
1	2	2	1	2	1	299
1	2	2	1	2	1	308
2	1	1	1	2	1	316
2	1	1	1	2	1	301
1	1	1	1	2	1	301
1	1	1	1	2	1	302
2	2	1	1	2	1	325
2	2	1	1	2	1	307
1	2	1	1	2	1	305
1	2	1	1	2	1	303
1	1	1	2	1	1	310
1	1	1	2	1	1	299
2	1	1	2	1	1	347
2	1	1	2	1	1	297
1	2	1	2	1	1	308
1	2	1	2	1	1	302
2	2	1	2	1	1	345
2	2	1	2	1	1	304
1	1	2	2	1	1	301
1	1	2	2	1	1	304
2	1	2	2	1	1	320
2	1	2	2	1	1	313
1	2	2	2	1	1	304
1	2	2	2	1	1	302
2	2	2	2	1	1	267
2	2	2	2	1	1	353
2	1	2	2	2	1	310
2	1	2	2	2	1	260
1	1	2	2	2	1	301
1	1	2	2	2	1	304
2	2	2	2	2	1	320
2	2	2	2	2	1	294
1	2	2	2	2	1	300
1	2	2	2	2	1	305
2	1	1	2	2	1	286
2	1	1	2	2	1	299
1	1	1	2	2	1	307
1	1	1	2	2	1	304
2	2	1	2	2	1	338
2	2	1	2	2	1	296
1	2	1	2	2	1	305
1	2	1	2	2	1	300

Table 11 Analysis of variance for luminance as measured in the two side-by-side rooms and under the four lamp types (Experiment #3). This analysis supports our method of characterizing the quantity of light in the rooms by using a single horizontal illuminance measurement.

Source of Variance	DF	Seq SS	MS	F	P
Room	1	220.4	220.4	0.75	0.386
Lamp	3	117.9	39.3	0.13	0.940
Room*Lamp	3	0.3	0.1	0	1
Error	232	67875.8	292.6		
Total	239	68214.4			

Table 12 Standard (non-randomized) order for the brightness comparison trials of Experiment #3.

Left Room						Right Room					
Scene #	Adjust	CCT	Phosphor	Room	Start E	Scene #	Adjust	CCT	Phosphor	Room	Start E
6	fixed	35	VT	chromatic	300 lx	12	variable	35	CV	chromatic	150 lx
6	fixed	35	VT	chromatic	300 lx	4	variable	35	CV	chromatic	450 lx
10	variable	35	VT	chromatic	150 lx	8	fixed	35	CV	chromatic	300 lx
2	variable	35	VT	chromatic	450 lx	8	fixed	35	CV	chromatic	300 lx
7	fixed	65	VT	chromatic	300 lx	13	variable	65	CV	chromatic	150 lx
7	fixed	65	VT	chromatic	300 lx	5	variable	65	CV	chromatic	450 lx
11	variable	65	VT	chromatic	150 lx	9	fixed	65	CV	chromatic	300 lx
3	variable	65	VT	chromatic	450 lx	9	fixed	65	CV	chromatic	300 lx
8	fixed	35	CV	chromatic	300 lx	10	variable	35	VT	chromatic	150 lx
8	fixed	35	CV	chromatic	300 lx	2	variable	35	VT	chromatic	450 lx
12	variable	35	CV	chromatic	150 lx	6	fixed	35	VT	chromatic	300 lx
4	variable	35	CV	chromatic	450 lx	6	fixed	35	VT	chromatic	300 lx
9	fixed	65	CV	chromatic	300 lx	11	variable	65	VT	chromatic	150 lx
9	fixed	65	CV	chromatic	300 lx	3	variable	65	VT	chromatic	450 lx
13	variable	65	CV	chromatic	150 lx	7	fixed	65	VT	chromatic	300 lx
5	variable	65	CV	chromatic	450 lx	7	fixed	65	VT	chromatic	300 lx
6	fixed	35	VT	achromatic	300 lx	12	variable	35	CV	achromatic	150 lx
6	fixed	35	VT	achromatic	300 lx	4	variable	35	CV	achromatic	450 lx
10	variable	35	VT	achromatic	150 lx	8	fixed	35	CV	achromatic	300 lx
2	variable	35	VT	achromatic	450 lx	8	fixed	35	CV	achromatic	300 lx
7	fixed	65	VT	achromatic	300 lx	13	variable	65	CV	achromatic	150 lx
7	fixed	65	VT	achromatic	300 lx	5	variable	65	CV	achromatic	450 lx
11	variable	65	VT	achromatic	150 lx	9	fixed	65	CV	achromatic	300 lx
3	variable	65	VT	achromatic	450 lx	9	fixed	65	CV	achromatic	300 lx
8	fixed	35	CV	achromatic	300 lx	10	variable	35	VT	achromatic	150 lx
8	fixed	35	CV	achromatic	300 lx	2	variable	35	VT	achromatic	450 lx
12	variable	35	CV	achromatic	150 lx	6	fixed	35	VT	achromatic	300 lx
4	variable	35	CV	achromatic	450 lx	6	fixed	35	VT	achromatic	300 lx
9	fixed	65	CV	achromatic	300 lx	11	variable	65	VT	achromatic	150 lx
9	fixed	65	CV	achromatic	300 lx	3	variable	65	VT	achromatic	450 lx
13	variable	65	CV	achromatic	150 lx	7	fixed	65	VT	achromatic	300 lx
5	variable	65	CV	achromatic	450 lx	7	fixed	65	VT	achromatic	300 lx

Table 13 Typical daily schedule for Experiments #3 and #4.

Morning Subject		
8:30 AM	Arrival, informed consent, expense voucher, demographic survey, Keystone visual skills test	1
9:00	Brightness adjustment experiment with chromatic environment (CV vs. VT)	2, 3, 4
9:30	Break & room modification (change from chromatic to achromatic)	
9:40	NRC computer based visual performance tasks (w/in achromatic environment, right room) Proofreading and Typing tasks (5 trials: 1 practice trial and 1 trial under each source)	5, 6
11:00	Brightness adjustment experiment with achromatic environment (CV vs. VT)	2, 3, 4
11:30	Brightness adjustment experiment within achromatic environment (3500K vs. 6500K)	2, 3, 7
Noon	Adjourn	
	Experimenter: Copy Visual Performance Result Files into Subject Folder	

Afternoon Subject		
1:00 PM	Arrival, informed consent, expense voucher, demographic survey, Keystone visual skills test	1
1:30	Brightness adjustment experiment with achromatic environment (CV vs. VT)	2, 3, 4
2:00	Brightness adjustment experiment within achromatic environment (3500K vs. 6500K)	2, 3, 7
2:30	NRC computer based visual performance tasks (w/in achromatic environment, right room) Proofreading and Typing tasks (5 trials: 1 practice trial and 1 trial under each source)	5, 6
3:50	Break & room modification (change from achromatic to chromatic)	
4:00	Brightness adjustment experiment with chromatic environment (CV vs. VT)	2, 3, 4
4:30	Adjourn	
	Experimenter: Copy Visual Performance Result Files into Subject Folder	

Notes:
1. Preliminaries take place outside of test rooms but at a similar illuminance level.
2. For the brightness adjustment experiments the subject is positioned just outside of test rooms and looking in, as shown in Figure 4.
3. Test for Hypothesis #1 (brightness perception)
4. Test for Hypothesis #2 (color preference)
5. Visual performance experiments takes place within the test room on the right (Room B)
6. Test for Hypothesis #3 (visual performance)
7. Supplementary test about CCT

Table 14 Analysis of Variance for Illuminance in Experiment #3.

Source of Variance	DF	Seq SS	MS	F	P
Subject	29	16316.9	562.7	0.22	1.000 x
Adjust	1	5678.8	5678.8	13.54	0.001
CCT	1	72.1	72.1	0.31	0.582
Phosphor	1	20711.3	20711.3	10.20	0.003
Room	1	341.7	341.7	1.05	0.314
Side	1	78183.1	78183.1	48.57	0.000
Subject*Adjust	29	12167.1	419.6	0.82	0.735
Subject*CCT	29	6735.1	232.2	0.46	0.995
Subject*Phosphor	29	58882.6	2030.4	3.98	0.000
Subject*Room	29	9425.9	325.0	0.64	0.933
Subject*Side	29	46680.2	1609.7	3.15	0.000
Adjust*CCT	1	19.2	19.2	0.04	0.846
Adjust*Phosphor	1	17532.9	17532.9	34.36	0.000
Adjust*Room	1	732.6	732.6	1.44	0.231
Adjust*Side	1	87210.2	87210.2	170.92	0.000
CCT*Phosphor	1	4826.0	4826.0	9.46	0.002
CCT*Room	1	589.6	589.6	1.16	0.283
CCT*Side	1	1270.8	1270.8	2.49	0.115
Phosphor*Room	1	99.9	99.9	0.20	0.658
Phosphor*Side	1	76.8	76.8	0.15	0.698
Room*Side	1	29.0	29.0	0.06	0.812
Error	1730	882689.5	510.2		
Total	1919	1250271			

Table 15 Readability statistics for the typing tasks of Experiment #4.

Texts	Counts				Averages			Readability		
	words	characters	paragraphs	sentences	sentences per paragraph	words per sentence	characters per word	passive sentences	Flesch reading ease	Flesch-Kincaid grade level
Text for Practice Trial	142	695	1	4	4.0	35.5	4.7	50%	35.6	12.0
Text for Trial 1	136	688	1	5	5.0	27.2	4.8	40%	42.3	12.0
Text for Trial 2	145	713	1	5	5.0	29.0	4.7	0%	46.7	12.0
Text for Trial 3	143	688	1	5	5.0	28.6	4.6	40%	50.7	12.0
Text for Trial 4	145	741	1	5	5.0	29.0	4.9	40%	38.7	12.0
mean	142.2	705	1	4.8	4.8	29.9	4.7	34%	42.8	12.0
Lower range	4.36%	2.41%	0%	16.67%	16.67%	8.91%	2.95%	100%	16.82%	0%
Higher range	1.97%	5.11%	0%	4.17%	4.17%	18.89%	3.38%	47.06%	18.46%	0%

Table 16 Example randomized presentation orders for the light settings in Experiment #4. The numbers 6, 7, 8 and 9 are scenes on the control apparatus and correspond to VT35, VT65, CT35 and CT65, respectively.

Subject Number	When entering the room	Practice Trial	Trial 1	Trial 2	Trial 3	Trial 4
1	7	9	8	6	7	9
2	6	8	7	9	6	8
⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	9	8	7	6	9	8

Table 17 Summary of the raw dependent variable data for the Typing Task of Experiment #4.

Lamp Type	Net characters typed per second	Elapsed time (seconds)	Number of Keystrokes	Number of Erase Keys	Number of Cursor Keys
VT35	2.504	400.50	1000.84	66.31	21.16
VT65	2.533	401.28	997.25	67.75	13.47
CV35	2.501	402.47	996.97	66.66	13.53
CV65	2.502	403.75	997.22	64.59	14.69

Table 18 Summary of the raw dependent variable data for the Proofreading Task of Experiment #4.

Lamp Type	Elapsed Time (seconds)	Total errors	Identical rows not marked	Identical rows marked	Discrepant rows marked	Discrepant rows not marked	Space bars pressed
VT35	126.13	0.97	71.00	0.00	8.03	0.97	8.47
VT65	125.53	0.97	71.00	0.00	8.03	0.97	8.72
CV35	123.56	1.13	70.94	0.06	7.94	1.06	8.38
CV65	127.63	1.19	70.97	0.03	7.84	1.16	8.25

California Energy Commission Energy Innovations Small Grant (EISG) Program **PROJECT DEVELOPMENT STATUS**	

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Questions	Comments:
Overall Status	
1) Do you consider that this research project proved the feasibility of your concept?	*Yes. We demonstrated that interior environments illuminated with light sources that radiate proportionally more power in the 450-530-610 nm regions are perceived as brighter, more colorful, and as the more preferred work environments.*
2) Do you intend to continue this development effort towards commercialization?	*Yes. We are presently working to develop these concepts further with light emitting diodes (LEDs) because these sources afford more control of the radiated spectrum than presently available fluorescent phosphors.*
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	*If we were to continue this work with fluorescent lamps we would need to find or develop a middle-wavelength phosphor with higher conversion efficiency than used in the prototype lamps.*
4) Have you defined a development path from where you are to product demonstration?	*Yes.*
5) How many years are required to complete product development and demonstration?	*Pending funding, we believe we can develop and demonstrate an LED-based vision-tuned lighting system for general illumination in one year.*
6) How much money is required to complete engineering development and demonstration?	*Approximately $150,000.*

7) Do you have an engineering requirements specification for your potential product?	*Yes. We have defined the tolerances, peaks, and full-width at half maximum for the three wavelength regions that will be combined to create white light, and we have worked with a LED company to ensure that are requirements are physically achievable.*
Marketing	
8) What market does your concept serve?	*Our initial target market for the vision-tuned fluorescent lamps was commercial. The LED-based vision-tuned lamps will also compete in this market, but they may first be seeded as a replacement for incandescent lamps. We have the opportunity to create tri-band LEDs that match the dimming performance of incandescent, while having a similar size and shape and greater luminous efficacy. Vision-tuned tri-band LEDs may therefore be targeted to the residential market.*
9) Is there a proven market need?	*Yes. This project has proven the vision-tuned concept, which, importantly, is not tied to a single type of light source. Our proof-of-concept made use of fluorescent sources (Experiments 1, 3, & 4) but also highly structured spectra created with incandescent sources and sharp-cutoff filters (Experiment 2). We now believe LEDs offer the best hope for a commercial product. LEDs have been identified as the light source of the future by virtually every forward looking association affiliated with energy consumption and/or lighting. Many groups are working to create LED-based lighting systems for general illumination, and there are many commercially available products. The key distinguishing feature of this work is the identification of the spectral regions to which the visual system responds most strongly, thus allowing the spectrum to be constructed in the way that is most visually and energy effective.*
10) Have you surveyed potential end users for interest in your product?	*With informal conversations, but not with a formal survey.*
11) Have you performed a market analysis that takes external factors into consideration?	*No.*
12) Have you compared your product with the competition in terms of cost, function, maintenance etc.?	*No.*
13) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*Yes. One potential barrier that was discussed in the original proposal is the fact that energy efficiency is defined with efficacy and has units of lumens per watt.*
14) What is the size of the potential market in California?	*The size of the commercial fluorescent market was discussed in Section 4.5 (Energy Savings Potential). We have not yet analyzed the size of the incandescent market.*
15) Have you clearly identified the technology that can be patented?	*Yes. A patent application is in process.*

16) Have you performed a patent search?	*We performed a self search and our patent does not appear to infringe on any other patents.*
17) Have you applied for patents?	*No.*
18) Have you secured any patents?	*No.*
19) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*No.*
Commercialization Path	
20) Can your organization develop and produce your product without partnering with another organization?	*No. We are a university and would need to work with the private sector to bring a product to market. In this project we worked with a major fluorescent lamp manufacturer. We are presently negotiating with a LED manufacturer to extend this work into LED products.*
21) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*Yes. They are a leading company in the LED industry.*
22) Have you developed a commercialization plan?	*We have a commercialization concept map, but not a detailed plan.*
23) What are the commercialization risks?	*First cost. Copycat potential.*
Financial Plan	
24) If you plan to continue development of your concept, do you have a plan for the required funding?	*We are endeavoring to partner with a LED company to continue this work.*
25) Have you identified funding requirements for each of the development and commercialization phases?	*No.*
26) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*No.*
27) Have you identified milestones or key go/no go decision points in your financial plan?	*No.*
28) What are the financial risks?	*First cost of the product may be too high to be competitive with similar technologies.*
29) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*No.*
Public Benefits	
30) What sectors will receive the greatest benefits as a result of your concept?	*Residential and commercial.*
31) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*See Section 4.5 (Energy Savings Potential) for analysis related to fluorescent lighting in commercial applications. We have not yet analyzed the size of the incandescent market and the potential impact on incandescent lighting in residential interiors.*
32) Does the proposed technology impact emissions from power generation?	*Yes. Detailed analysis has not been performed.*

33) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*No.*
Competitive Analysis	
34) Identify the primary strengths of your technology with regard to the marketplace.	*1. More energy efficient while at the same time improving the quality of the visual environment.* *2. Greater brightness per watt.* *3. Greater color preference per watt.*
35) Identify the primary weaknesses of your technology with regard to the marketplace.	*1. It is a complex idea, and there is skepticism in accepting the benefits of vision-tuned lighting without first-hand experience.* *2. The vision-tuned concept is incompatible with the two most common ways of quantifying the spectral performance of light sources (e.g. the lumen and the color rendering index).* *3. First cost, at least initially, may be higher.*
36) What characteristics (function, performance, cost etc.) distinguishes your product from that of your competitors?	*The vision-tuned spectrum leads to greater brightness perception per watt, greater color preference per watt, and greater satisfaction with the interior environment. In addition to these positive features, there may be indirect benefits on performance, comfort, and satisfaction with the lighting system, thus leading to improvements in productivity.*
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
37) If selected, would you be interested in receiving development assistance?	*Yes. We would be interested in intellectual property assessment, market assessment, and business plan development.*

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)

- Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

The human visual system exhibits peak sensitivity in the three wavelengths regions near 450, 530, and 610 nano-meter (nm). This fact is not embraced in the spectral design of electric light sources; even though it makes intuitive sense that both visual and energy efficiency might be promoted by light sources that exploit the fundamentally trichromatic nature of human vision. The researchers hypothesized that when compared to common fluorescent lamps, lamps with proportionally more power in these three spectral regions, so-called “vision-tuned” lamps would: enhance perceived brightness per watt (Hypothesis 1); produce higher color preference per watt (Hypothesis 2), and; produce no detriment to visual performance (Hypothesis 3). Four experiments were conducted to evaluate these three hypotheses; expert and naïve subjects participated in forced choice, dimming adjustment, brightness matching, and/or visual performance experiments, where vision-tuned spectra were compared against conventional fluorescent lamps. In Experiment 1, the vision-tuned lamps were perceived to be 4.3 percent brighter when illuminance was set equal and the lamps were nominally 6500° Kelvin (K); at 3500° K (nominal) the vision-tuned lamps were perceived to be 0.7 percent brighter at equal illuminance. Experiment 2, showed that a spectral power distribution composed of 450-530-610 nm components required five percent less radiant watts than daylight fluorescent lamplight at equal brightness. Experiment 1, showed that both expert and naïve subjects strongly preferred the vision-tuned environment along color-based questions. At the higher color temperature, for example, 94 percent of the expert subjects rated the vision-tuned environment as preferred, 100 percent as more colorful, and 83 percent as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature. Experiment 4, showed no difference in computer-based visual performance tasks when the environments were illuminated with conventional and vision-tuned lamps at nominally 3500° K and 6500° K. Taken together, these results provide solid support for the above hypotheses, and the findings establish that visual and energy efficiency alike can be promoted if the fundamentally trichromatic nature of human vision is used as a guiding principle in the spectral design of electric light sources.

Key words: fluorescent, lamp, vision, spectrum, energy, brightness, color, perception, visual performance.

Introduction

The consumption of electricity in California has grown steadily each year.[1] An increase of 29 percent between 1980 and 1993 was attributed more to added population than to increases in energy intensity per square foot. The same source shows that lighting accounted for 10 percent to 14 percent of the electricity consumed in the residential sector and 42 percent within the commercial sector. The commercial and residential sectors account for 36.3 percent and 30.3 percent of electricity usage, respectively.[2] According to estimates prepared by the California Energy Commission, electrical consumption for 2005 will total 268,099 gigawatt-hours.[3] Lighting accounts for almost 51,000 gigawatts-hours of this total.

The human visual system exhibits peak sensitivity in the three wavelengths regions near 450, 530, and 610 nanometers (nm). This fact is not embraced in the spectral design of electric light sources; even though it makes intuitive sense that both visual and energy efficiency might be promoted by light sources that exploit the fundamentally trichromatic nature of human vision. When compared to common fluorescent lamps, lamps with proportionally more power in these three spectral regions are called "vision-tuned fluorescent lamps." "Vision-tuned fluorescent lighting" could produce significant savings in energy and costs for commercial building ratepayers and other end users of conventional fluorescent lighting technology.

Beginning in 1931 and continuing steadily into the 1990s, researchers have discovered and published detailed knowledge involving human visual performance as it relates to electric light sources. This collective body of research indicates that the human visual system performs at its best level when a light source is augmented around the 450, 530, and 610 nm wavelengths. Unfortunately, designs of conventional electric light sources, especially fluorescent lighting systems, do not reflect this knowledge. Current designs spend excess radiant energy in adjacent wavelengths to produce the desired amount of light in the specified wavelengths. Existing fluorescent lamp design and manufacturing doctrines rely on color rendering index and efficacy (expressed in lumens of light output per watt of power input) parameters. Neither measure reflects the effect of these most desirable wavelengths of light on known human visual performance characteristics. Despite many recent advances in the energy efficiency of fluorescent lighting systems, current designs based on color rendering index and efficacy values still result in wasted radiant energy in areas of the spectrum that are of minimal value to the human eye. Lamps capable of maximizing light output at the desired 450, 530, and 610 nm wavelengths would be an attractive solution for enhancing the performance of fluorescent lighting systems. Limiting the lamp's radiant energy to these wavelengths would eliminate excess energy wasted on other areas of the spectrum, thus reducing the overall energy consumption of such a vision-tuned fluorescent lighting system.

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[1] Electrical Consumption Data for Buildings, Electricity Use Data for California, October 21, 2002, http://www.ccst.us/ccst/pubs/pier/library/ftp/Buildings/MeetingBackground/5_EnergyUse/Energypercent20UseData.doc Accessed 2005 May 7.

[2] California Energy Commission. Electricity Consumption page, California Electricity Consumption with Forecasts to 2007. http://www.energy.ca.gov/electricity/index.html>, Accessed 2005 May 1.

[3] California Energy Commission. 1998 Baseline Energy Outlook, Energy Commission Staff Report Table B1. http://www.energy.ca.gov/reports/300-98-012.PDF, Accessed May 1, 2005.

Objectives

This project was to prove the feasibility of a design for vision-tuned fluorescent lamps that are capable of maximizing light output at the 450, 530, and 610 nm wavelengths and reducing energy consumption by 20 percent. The researchers identified five main objectives:

1. Design and manufacture a set of prototype fluorescent lamps that maximize radiant energy in the three regions near 450, 530, and 610 nm while simultaneously minimizing it in the remaining portions of the spectrum. Make a minimum of four different types of prototype lamp.
2. Perform laboratory tests using both expert and naïve subjects to collect quantitative evidence that will determine if the vision-tuned lamps provide equivalent or superior visual performance. These tests will further determine if the requisite levels of visual performance are attainable with fewer radiant watts than standard fluorescent lamps.
3. Perform laboratory tests using both expert and naïve subjects to determine if the vision-tuned lamps exhibit measurably greater brightness per watt than standard fluorescent lamps.
4. Perform laboratory tests using both expert and naïve subjects to determine if the vision-tuned lamps exhibit greater color rendering than standard fluorescent lamps.
5. In conjunction with the laboratory tests of lighting quality, demonstrate that vision-tuned lamps are capable of delivering energy savings of 20 percent or greater compared to current fluorescent lamps. Once the actual energy savings value is identified in the laboratory tests, extrapolate this value to estimate the overall savings that could be realized in California's non-residential end use sector.

Outcomes

1. The researchers satisfied their first objective. Eight prototype lamps were produced in conjunction with General Electric. One half of the lamps had the same phosphors as off-the-shelf tri-color lamps. These lamps were used for comparison and control. The primary factor in manufacturing the prototype lamps was the development of specialized phosphor configurations that would yield the desired light output. Unfortunately, none of the available phosphors enabled the creation of a truly optimized light source. All of the phosphor configurations generated undesirable levels of radiant power in areas outside the 450, 530, and 610 nm target regions. Nevertheless, the prototypes exhibited sufficient performance in these wavelengths to make the subsequent laboratory experiments possible.

2. The laboratory experiments yielded statistically significant data that demonstrated enhanced visual performance in test rooms illuminated with the vision-tuned lamps. Test subjects in both the expert and naïve categories reported that the test rooms with the vision-tuned lamps were brighter and more colorful.

3. The researchers demonstrated that their third objective was mostly satisfied. A statistical analysis of the test results involving both expert and naïve subjects determined that vision-tuned lamps exhibited equivalent levels of brightness (compared to broadband daylight fluorescent reference source) with 5 percent fewer radiant watts.

4. The researchers showed that both expert and naïve subjects strongly preferred the room illuminated with vision-tuned lamps. At the higher color temperature 94 percent of the expert subjects rated the vision-tuned environment as preferred, 100 percent as more colorful, and 83 percent as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature.

5. The researchers failed to fulfill their fifth and final objective of demonstrating electrical energy savings of 20 percent or greater for the prototype vision-tuned lamps. Test results suggested energy savings estimates of 1.5 percent to 5 percent.

Conclusions

The researchers did not prove the feasibility of using vision-tuned fluorescent lamps to reduce energy consumption by 20 percent, but improved productivity may well overshadow the energy savings of the lamps tested in this project.

1. While the prototype lamps demonstrated definitive performance improvements in the desired spectral regions near 450, 530, and 610 nm wavelengths, they did not sufficiently minimize the light from other portions of the spectrum. The researchers noted some disappointment with the actual spectral performance of the lamps. They ultimately determined that fluorescent lamp technology rendered it unsuitable for the selective targeting of wavelengths required for optimized vision-tuned lighting.

2. The researchers provided considerable qualitative and quantitative data with statistical validation based on the results from the various operational tests of the prototype lamps, as well as the experiments conducted with the panels of test subjects. These analyses, combined with the lamp test data, fundamentally reinforce the researchers' hypotheses regarding the enhanced visual performance enabled by the vision-tuned lamps. While the researchers effectively quantified and validated the test results demonstrating the superior visual performance of the prototype lamps, they provided little information to clarify any differences in power consumption attributable to the lamps. A portion of this objective had been the stated intent of enabling enhanced visual performance with the use of fewer radiant watts than conventional fluorescent lamps. Unfortunately, the researchers' discourse was limited to the issues of visual performance and did not quantify any reductions in radiant watts achieved by the prototype lamps during this specific test.

3. Despite the range and depth of data provided by the researchers about the visual elements of the tests, they supplied no information for the input wattage values recorded for the test fixtures during the course of the experiments. As part of the assessment of how well the experiments fulfilled the project's objectives, the researchers estimated energy savings of 5 percent for the vision-tuned lamps, but they identified no electrical test data in support of this estimate. While the result confirms the researchers' hypothesis regarding a greater visual response to vision-tuned lamps, the differential power consumption was less than expected.

Historical research cited by the researchers suggested that the use of vision-tuned lamps could produce a 30 percent reduction in power requirements (Thornton, IES 1980). While the researchers estimated a more conservative 20 percent reduction in power consumption for the experiment, the resulting 5 percent value represents a significant underperformance for the vision-tuned lamps. The spectral analyses and experiment designs addressed only the performance of the lamps and did not consider any influence of the ballasts and their impact on the stated goal of achieving energy savings. The lamp represents only a portion of a fluorescent lighting system, which depends critically upon the ballast for its function. Thus, the ability of the prototype lamps to yield energy savings requires further analysis in relation to the various ballasts currently operated in fluorescent systems (electro-magnetic, electronic, hybrid electronic, dimmable, DALI programmable, and so forth.).

4. The researchers met the objective of proving overwhelming preference of users for vision-tuned lighting.

5. The researchers supplied no power measurements or other standard electrical test data in support of the estimated 5 percent energy savings. One hypothesis put forward by the researchers suggests nearly 100 percent potential penetration of vision-tuned fluorescent lamps into the commercial building market. This statement fails to acknowledge the continuing resistance of some end users to modify their existing lighting systems to operate even the current generation of fluorescent lighting technology.

   The researchers suggest that the 5 percent energy savings achieved by the vision-tuned lamps would be applicable throughout the commercial building market. This 5 percent savings estimate was derived from the results of two of the researchers' experiments involving assessments of brightness-per-watt for the vision-tuned lamps. A description of these experiments provided by the researchers indicates how dimmable ballasts were used to modulate lighting levels for the vision-tuned lamps in order to match perceived levels from adjacent reference lighting sources. Thus, the stated energy savings values depend upon the use of complex dimmable ballasts that are uncommon in most fluorescent lighting systems. Savings consistent with the researchers' results would require corresponding modifications to contemporary ballast characteristics as part of the conversion to vision-tuned lamps.

   Fluorescent lamp technology inherently allows excess levels of undesirable radiant energy in portions of the spectrum that defeat the goal of vision-tuned lighting. Furthermore, the energy savings achieved by the prototype lamps was minimal and not well understood in the context of the most common types of fluorescent ballasts operated in the target market.

Recommendations

Based on the test results for the prototype lamps in this project and the researchers' own conclusions, further efforts to derive energy savings from vision-tuned lighting should be directed toward LED technologies.

Benefits to California

Public benefits derived from Public Interest Energy Research Program are assessed within the following context:

- Reduced environmental impacts on the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to ratepayers from this research is increased affordability of electricity in California. The researchers claimed a 5 percent reduction in energy consumption for the vision-tuned fluorescent lamps. According to a report by Heschong Mahone Group in 1997[4], 22.4 percent of all the electricity used in California is used for lighting. The same source estimated that, assuming full theoretical penetration of compact fluorescent lighting in the residential and commercial sector, 10,603 gigawatt-hours per year savings is possible by 2010. An incremental 5 percent savings based on the vision-tuned lamps tested in this project results in an additional 503 gigawatt-hours saving. At $0.10 per kilowatt-hours this saving is equivalent to $53 million per year. Unfortunately the energy savings is neither big enough nor well enough documented to lead to rapid commercialization and market penetration. It is not likely that the ratepayers will benefit soon from the vision-tuned fluorescent lamps tested in this project.

[4] Heschong Mahone Group. Lighting Efficiency Technology Report, California Energy Commission, http://www.energy.ca.gov/efficiency/lighting/lighting_reports.html Accessed 2005 May 7.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, including all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers in this project had a relationship with General Electric. GE modified the phosphors and manufactured the lamps for this project. Since GE is a major supplier of lamps, this is an excellent connection to the market. In addition, the researchers had a linkage with Litecontrol. This company provided custom luminaries.

Engineering/Technical

No further engineering work is planned for the vision-tuned fluorescent lamps. The researchers suggest that new efforts should begin to develop vision-tuned LED lighting lamps.

Legal/Contractual

An initial search by the researchers did not produce any potential infringements. A patent application was in process. The technology, as developed in this effort, may represent a sufficiently innovative and unique approach to be patent worthy.

Environmental, Safety, Risk Assessments/ Quality Plans

If a vision-tune fluorescent lamp is produced in quantity, an experienced manufacturer already in the lighting business will produce it. A major lamp manufacturer would assume all environmental, safety, risk assessment, and quality plans. There is no evidence that these plans have been prepared for the vision–tuned lamp.

Production Readiness/Commercialization

The participation by GE and Litecontrol is very significant as is the sponsorship by the University of Nebraska. Corporate linkages will continue to be indispensable in this effort. There is no evidence that a production readiness or commercialization plan has been prepared.

Appendix A: Final report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)