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Publisher’s version / Version de l'éditeur:

Journal of the Illuminating Engineering Society, 31, Winter 1, pp. 40-60, 2002-03-01

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NRCC-44745

A version of this paper is published in / Une version de ce document se trouve dans:
Journal of the Illuminating Engineering Society, v. 31, no. 1, Winter 2002, pp. 40-60

The Effects of Fluorescent Lighting Filters on Skin Appearance and Visual Performance

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Published in the *Journal of the Illuminating Engineering Society*, Winter 2002, Vol. 31, No. 1, pp. 40-60.
A version of this paper was presented at the IESNA 2001 Conference, Ottawa, ON, Aug. 2001.

Abstract

Illuminating engineers, lighting designers and others have long debated the importance of providing an artificial light source that mimics the characteristics of natural light. Several products are available that purport to provide more natural light, of which retrofit plastic filters are one. Product testimonials praising these products abound, but there is little empirical data concerning their effects on the visual environment. This paper reports two experiments concerning this issue, the first being a test of the hypothesis that selected retrofit magenta filters improve skin appearance in comparison to other common lighting sources or a placebo condition. The second experiment tested the hypothesis that selected retrofit magenta filters improve short-term visual performance, compared to other common lighting sources or a placebo condition. The results show that the selected filters improved skin appearance relative to unfiltered fluorescent lamps. There were no differences between preferences for skin appearance under comparable magenta filters from two different manufacturers. In general, light sources relatively richer in red than green were preferred. There were no effects of light source spectral composition on short-term visual performance.

Introduction

Context

Illuminating engineers, lighting designers and others have long debated the importance of providing an artificial light source that mimics the characteristics of natural light. Some believe that a more natural light source will produce better health, visibility and productivity. Others have argued that these benefits remain to be conclusively demonstrated in the scientific literature.[1-2]

Several products are available that purport to provide more natural light: enhanced or so-called full spectrum lamps, polarising panels, full spectrum polarised lighting (which combines full spectrum lamps with polarising panels), and retrofit plastic filters. Many of these products carry a price premium compared to standard fluorescent lighting systems, and some reduce energy-efficiency. Full-spectrum fluorescent lamps, for example, generally have lower lighting efficacy (deliver fewer lumens per watt). Filters that increase the operating temperature of fluorescent lamps reduce light output in addition to filtering out selected wavelengths.

Despite these economic and environmental costs, product testimonials praising these products abound. Those who favour such products argue that the costs are minimal in comparison to the benefits. The issue for building owners and managers is whether installing these products will lead to a commensurate return on investment, in the form of improved productivity, more contented workers, and better health leading to reduced absenteeism. The issue for workers is whether the claims about improved indoor environments made for these products have a sound scientific basis, or are the result of placebo effects.

Facilities managers, faced with sales literature or occupant requests, need informed advice concerning the merits of various lighting products. In the case of retrofit plastic filters, it has been difficult to provide such advice in the absence of objective, empirical data concerning the claims that these filters improve visual performance and improve the appearance of objects and people. This project was designed to address these questions.

Scientific Issues

Within the scope of an applied experiment, in which the principal focus was on lighting conditions that are in current use in offices, the experiments reported here also address several outstanding questions regarding light source spectral power distribution and its effects on office workers.

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Spectral power distribution effects on skin appearance preference. At present it is unclear whether or not correlated colour temperature is relevant to evaluations of room or object appearance. Boyce and Simon observed that colour rendering index was a poor predictor of satisfaction with the appearance of a scale model lit by various fluorescent lamp types, but a new criterion, colour discrimination index (CDI), gave a clear result.[3] Lamps with high CDI values (larger gamut areas[§]) were rated as providing a more satisfactory appearance than those with lower CDI values. Boyce and Cuttle found that ratings of room appearance were unrelated to the CCT of lamps illuminating the room (CCT= 2700, 3500, 4200, or 6300, all CRI>80), but were influenced by the presence of natural colour (in the form of fruit and flowers).[4] Boray, Gifford, and Rosenblood observed no differences in ratings of room appearance or of the attractiveness of male and female models (the lamps used were halophosphate T12 lamps with CCT=3000, 4150, or 5000 K and CRI=52, 62, and 90, respectively).[5]

When measures of preference (what the observer likes, rather than how they would describe the appearance of the space or the object) are the outcome, we see clearer evidence of differences related to CCT. It appears that warmer colour temperatures are preferred over cooler ones, with a definite dislike for conventional T12 cool-white lamps.[6-9] Colour rendering quality is also important: Preferences are higher for lamps that render colours better.[8-9] In addition, people are best able to discriminate between lamps when skin colour, rather than arbitrary object colours, are the basis for discrimination.[8] The finding that skin colour is the most discriminable stimulus for lamp judgements suggests that it be used for further investigations in this area.

At present the literature does not support generalisable conclusions about the most-preferred lamp colour characteristics. Most investigators have changed CCT by changing lamp type, but this often results in such dramatic changes in spectral power distribution (SPD) that no general conclusions have emerged. This experiment, by virtue of using filters on fluorescent lamps, offers the opportunity to examine changes in CCT with minimal changes in the overall shape of the SPD viewed.

Spectral power distribution effects on visual acuity. Claims have been made concerning the beneficial effects of fluorescent lighting filters that reduced the transmission of green and yellow wavelengths (producing a noticeably magenta colour appearance). These claims, based largely on evidence collected anecdotally and on research results not submitted to independent peer review in the scientific community, include reduced eyestrain and fatigue and increased productivity.[10]

By contrast, others argue that increasing the relative contribution of short-wavelength (blue) light will reduce pupil size and increase visual acuity.[11,12] Berman has argued that using lamps with appropriate light source spectral power distribution (SPD) to trigger this effect would allow reduced luminance levels and energy savings while maintaining the same level of visual performance.[13]

Veitch and McColl examined the visual performance of university students in relation to light source spectral power distribution (full-spectrum, cool-white, and filtered-T12 cool-white fluorescent lamps) and ballast type.[14] No effects of SPD were found. One criticism of this work was that the experimental design was insensitive to the effect of SPD as compared to its sensitivity to ballast type effects.[15] Experiment 2A (described below) is designed to examine this issue, by comparing SPD conditions as a within-subject variable, and ballast type as a between-subjects variable [the opposite to the design used by Veitch & McColl[14]].

General Procedures

Setting

In order to facilitate participant recruitment, data collection for the laboratory experiments was conducted in a temporary laboratory, set up in a windowless corner of an atrium space in a large office complex. Figure 1 shows two photographs of the temporary space and equipment. The ambient lighting was incandescent, approximately 200 lx overall, with higher illuminance at the desk (approximately 700 lx) and in the colour appearance booth when it was in use.

Participants

The two laboratory experiments were conducted concurrently, using the same participants (a total of 80, 40 men and 40 women). The sample size was chosen in order to give sufficient statistical power to each experiment, taking into account the expected effect sizes and the limitations of time both for participants and for the research personnel.

The participants were volunteers drawn from the population of employees in the office complex. An e-mail notice from management announced the project to occupants and invited them to participate, provided that their

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§ The gamut area for a light source is the area on the 1960 CIE colour diagram[16] enclosed by the eight colours used for the calculation of the colour rendering index[3].

immediate supervisors permitted them to take the time from their duties. Potential participants contacted the research team by e-mail or telephone to set up an appointment to participate. Sessions were offered in English or French.

Potential participants were required to meet the following criteria (all were self-reported):

- at least 18 years of age;
- normal or corrected-to-normal vision and hearing;
- no colour vision abnormalities;
- no upper-body impairments (the skin appearance experiment required a comparison of the appearance of the participant's right and left hands, each illuminated by a different light source);
- no use, in the 24 hours before participation, of decongestants or of medication for blood pressure, diabetes, epilepsy, depression, allergies or muscle or back pain (all of which might affect alertness and/or vision). [Four participants reported during data collection that they had taken one of these medications. Their data was excluded from analyses, and other participants were recruited to replace them.]

Participation required approximately 30 minutes. At the end of the session, each participant received a voucher for the purchase of coffee and a muffin at a local café.

Procedure

Details of the experimental procedures for each subexperiment are provided below. The general procedure was as follows:

Participants arrived at the laboratory facility one at a time, and were greeted by one of two experimenters. They were given verbal instructions, in the language of their choice (English or French) concerning the nature of the experiment, the tasks that would be required of them, and their rights as research participants. Before continuing they were asked to sign a consent form.

All participants completed the 21 paired comparisons of the skin appearance experiment immediately following the signing of the consent form. This was followed by a short break to allow the experimenters to set up the required conditions for the visual performance experiment. Each participant completed the Vision and Lighting Diagnostic Kit (VALiD) task under two lighting conditions (from one of the three sub-experiments described below).

Between the two VALiD tests there was another short break. During this break one experimenter set up the second lighting condition, while the other experimenter guided the participant through the completion of a background questionnaire to provide demographic information. This experimenter also rated the participant's skin colour using two scales, one for skin colour and one for skin darkness. These scales were developed from classifications used in the cosmetics industry, and validated in an informal pilot test.

Following the second VALiD test, participants were given a verbal explanation of the purpose of the investigations. Those who wished were invited to contact the principal investigator for feedback on their VALiD test performance. Sixteen participants did so.

Experiment 1: Effects of Fluorescent Lighting Filters on Skin Colour Appearance

Experimental Design

The aim of this study was to characterise the effects of green-corrected fluorescent lighting filters on apparent skin colour. Some manufacturers claim that green-corrected fluorescent lighting filters are designed to correct the green-magenta balance of common fluorescent lamps so that their spectral qualities are comparable to that of natural daylight. Adding such a filter to an interior lighting installation will have dramatic effects on the appearance of objects and people. Skin colour is arguably one of the most important factors affecting the acceptability of a lighting installation, as people are better able to discriminate between light sources when apparent skin colour is the basis of the discrimination.[8] Lighting systems that render skin colour poorly will be unacceptable and rejected by occupants.

This study compared participants' preferences for their own skin colour as viewed under several different filtered and unfiltered fluorescent light sources: two lamp types, 3500 K / 80 CRI F32T8 lamps, and 4100 K / 80 CRI lamps (both on electronic ballasts), and three filter conditions: Filter 1, Filter 2, and unfiltered. Filters 1 and 2 are green-corrected filters from two different manufacturers, but having similar transmission characteristics (see Figure 2). (Two variants of Filter 1 were used, one with 3500 K lamps and one with 4100 K lamps.) The six light source conditions are within the range of conditions in the offices in the complex where data collection occurred.

Method

*Subjects***.** All participants completed this experiment (N=80). Table 1 shows a summary of the demographic characteristics of the participants. Those participants who required vision correction at the distance required for the tasks wore their prescription lenses. The few participants reporting hearing impairments showed no signs of communication difficulties that would have impaired their performance, and their data was retained.

Apparatus. The participants compared the appearance of the backs of their own hands in side-by-side comparisons of two light sources. A diagram of the apparatus is shown in Figure 3, and photographs in Figure 4. The participant was seated in front of the apparatus, and placed his or her hands on the inclined board on either side of the felt partition (Fig. 4A), hooking the thumb of each hand under the peg. All of the surfaces that were visible to the seated participant were black, to maximise the colour contrast with their hands.

The inclined board was illuminated from above, separately on each side, by light emitted through an aperture in a black-painted plywood cover, on top of which were two 1' x 4' two-lamp luminaires. A sliding mechanism allowed the experimenter to change the luminaire positions over the aperture, thereby changing the lamp type (Figure 4B). Filters, held in stiff cardboard frames, were applied over the aperture and laid in a grooved holder in the plywood cover. Cardboard baffles were included as part of the filter frames, to create equivalent illuminance on the inclined plane. A target illuminance of approximately 650 lx was chosen as being both within the range of illuminances used in offices, and achievable given the design of the apparatus.

Luminance values were measured using a reflectance standard (?=.98) placed on the inclined board. Although the luminance was not precisely even across the board, it was symmetrical on the two sides of the apparatus and the pattern was constant across all six light source conditions. Table 2 summarises the photometric conditions for the six light sources used in the experiment. For all sources, the photopic luminance of a reflectance standard on the pad was approximately constant around 217 cd/m^2. (Scotopic luminance is included because it figures in the discussion below.) Figure 5 shows the spectral power distribution curves for the six light source conditions. Prior to data collection, the filters were tested by an independent laboratory, to verify their transmission characteristics and to determine whether or not they were polarised. None were polarised, and the characteristics of the two filters were very similar one to another, as is evident from the SPD curves in Figure 5.

Procedure. Each participant completed 21 paired-comparison trials. For each trial, the participant was asked to tell the experimenters whether side A, side B, or neither side, was the side with his or her preferred colour appearance to the backs of the hands. One experimenter recorded the answer directly into a Visual Basic™ data collection program written for this experiment. The second experimenter took care of manipulating the luminaires and filters to set up each comparison.

The order of presentation of the 21 trials was randomised separately for each of the 80 participants, to control order effects. For six of the trials, both sides were illuminated with the same light source (lamp+filter combination). For fifteen trials, the left and right sides were illuminated with two different light sources. For each of these trials, the assignment of light sources to left and right sides was random (to control for any systematic preferences for left or right on the part of the participants). Between trials, the aperture was fully blocked until the new set of conditions had been set up.

Results

Control trials. For six trials, both the left and right light sources were the same. The stated preferences for these trials were examined to determine whether or not participants systematically favoured one hand or the other. The responses for these trials were coded -1 (left), 0 (no preference), and +1 (right). For each of the 80 participants, a total hand preference score was created by summing the responses for these six trials (possible range -6 to +6). The mean of this variable was 0.325 (SD=1.81), which was not statistically significantly different from zero ($t(79)=1.60$, $p>.05$). Overall, there was no evidence that participants favoured one hand over the other, although some individuals may have done so. This was judged not to be problematic because of the counterbalancing of stimulus presentations in the experimental trials.

Light source comparisons. A two-step procedure was used to analyse the responses for the other 15 trials. In these trials, left and right light sources varied, in all possible pairs of the two lamp types x three filter conditions. Left and right presentation of the light sources were counterbalanced. After correcting for the counterbalancing, scores were recorded as -1 (left), 0 (no preference), or +1 (right).

In the first step, the responses for the 15 comparisons were quantified into scores reflecting preferences for the six stimulus conditions using a design matrix for paired comparisons (see Appendix). These 6 scores (each having a possible range of -1 to +1) were then analysed using a 2 (Lamp) by 3 (Filter) analysis of variance (ANOVA) in which both Lamp and Filter were within-subjects factors. Table 3 gives the descriptive statistics (means and standard deviations) for the six light source conditions and the marginal means and standard deviations for the Lamp and Filters effects.

There were five single-degree-of-freedom tests in the ANOVA, summarised in Table 4. The Lamp main effect contrasted the marginal means for the 3500 K and 4100 K lamps. This effect was not statistically significant. The Filters contrast of Filter 1 versus Filter 2 was not statistically significant, indicating that there was no difference in relative preference for skin colour appearance under the two filters. There was, however, a large effect for the contrast of Filtered versus Unfiltered lamps ($F(1,79)=31.55$, $p<.001$), explaining 28.5% of the variance in relative light source preference. Examination of the marginal means (Table 3) reveals that the relative light source preference was greater for filtered than unfiltered lamps.

Interpretation of this main effect, however, is somewhat qualified by the small significant Lamp X Filter interactions (each having $R^2 = .05$), displayed graphically in Figure 6. Both effects were statistically significant, indicating that the influence of Filter 1 versus 2 was different for the two lamp types, and that the addition of filters (in comparison to unfiltered lamps) also differed for the two lamps. In general, the addition of a filter had a stronger effect on preference for skin appearance under the 3500 K lamp than the 4100 K lamp. Filter 2, in comparison to Filter 1, had an opposite effect on relative preference for the two lamp types.

Additional tests were conducted to examine whether skin colour, skin darkness, age, or sex related to relative preference. None were statistically significant.

Prediction of preference from photometric data. The significant interaction effects suggested that the explanation for the changes in relative preference might be better explained by a more subtle change in the overall luminous conditions associated with the six light sources, than by lamp type or filter as categorical variables. Because the continuous photometric variables were attributes of the light sources, and both the attributes and the light sources were nested within subjects, these data were analyzed using Hierarchical Linear Modelling (HLM).[17] As one would expect, the set of photometric variables (Table 2) were highly intercorrelated, which prevented the use of multiple predictors in the models. Instead, separate models were created for each photometric variable in order to identify whether any were statistically significant predictors of relative preference, and if so, which predicted the most variance.[**] The results, summarised in Table 5, showed that there were four statistically significant predictors, but the *x:y* ratio was the best in terms of percentage of explained variance. The effect, explaining 9.6% of the variance, is medium-sized.[26]

Discussion

The relative preferences for skin colour appearance under various light sources — combinations of common fluorescent lamps and retrofit filters — show a subtle relationship to the photometric properties of the light sources. Lamp and filter combinations had interactive effects on relative preference. This interactive pattern corresponded to the pattern of relative values of the chromaticity co-ordinates, *x* and *y* but less well to the pattern of *x* itself, CCT, or photopic luminance (see Figure 7 or Table 2). Although CCT was a statistically significant predictor of relative preference, its predictive power was less than for the *x:y* ratio. Moreover, there was no statistically significant overall main effect of lamp type (a contrast for which CCT varies from 3500 K to 4100 K), whereas there was a large statistically significant effect of using filters versus unfiltered lamps (a contrast for which, within lamp type, CCT changed less than the change across lamp types).

The direction of the effect is positive: the higher the *x:y* ratio, the higher the relative preference for skin appearance under that light source. Sources richer in reds than in greens are preferred. This is precisely the change in spectral qualities that the green-correcting (magenta) filters are intended to achieve. Figure 8 illustrates this relation by plotting the chromaticity co-ordinates on the CIE 1931 colour space.

The overall conclusion to be drawn from the available information in this experiment and elsewhere is that, for populations of people with relatively light skin tone, in rose or olive colours, there appears to be a preference for light sources that are more rich in red wavelengths than in green, although this finding requires replication. Light sources rich in green are not well liked.[6-8] CCT alone does not appear to predict light source preferences for skin appearance. People of other skin colours or tones might have other light source preferences for skin colour, but no data are available concerning this hypothesis.

[**] Conceptually, this analysis consists of creating separate regression lines for each participant, and then testing the distribution of regression weights against the null hypothesis that the average regression weight equals zero.

Experiment 2: Effects of Fluorescent Lighting Filters on Visual Performance
Research Design

This investigation has three parts, each comparing visual acuity of human subjects when performing a standardised test of visual acuity viewed under filtered fluorescent light with measured visual acuity when performing the same test under other lighting conditions. The lighting conditions can all be found in present-day North American offices.

The three parts address the following questions:

- Is visual acuity improved by adding a retrofit filter (Fil-1) to a common T8 lamp?
- Is visual acuity better under filters from different manufacturers (Fil-1 and Fil-2)?
- Is visual acuity better under filtered T8 lamps than under a full-spectrum fluorescent lamp?

The experimental design addressed the three research questions using three sub-experiments involving various lighting conditions, all of which are realistic office lighting sources and levels. Comparisons involving two other lighting variables (illuminance and ballast type) were also included to demonstrate the sensitivity of the test to conditions known to affect visual acuity, and to provide further information for lighting decision-makers about the effects of common lighting choices.

Experiment 2A. This experiment had two independent variables: ballast type (electronic or magnetic ballasts [a randomly-assigned, between-subjects comparison]), and light source spectrum (filtered [Fil-1] T8 4100 K, 80 CRI lamps and unfiltered T8 5000K, 90 CRI lamps [a within-subjects comparison]). Thus, every participant completed the VALiD task under two light source spectra, run by either magnetic or electronic ballasts. All lighting conditions maintained 200 lx on the task surface. Based on the literature, we predicted that visual performance would be better for the electronic ballast group than for the magnetic ballast group, but that light source spectrum would not influence visual performance.

Experiment 2B. This experiment had two independent variables: illuminance level (100 lx or 1000 lx [a randomly-assigned, between-subjects comparison]), and light source spectrum (filtered [Fil-1] and unfiltered T8 4100 K, 80 CRI lamps [a within-subjects comparison]). Thus, every participant completed the VALiD task under two light source spectra, at either 100 or 1000 lx horizontal illuminance on the task surface. We predicted that visual performance would be better at 1000 lx than 100 lx, but that the presence or absence of the filter would not influence visual performance.

Experiment 2C. This experiment had one independent variable: filter type, Fil-1 or Fil-2, both used with T8 4100K, 80 CRI lamps at 200 lx. We predicted that visual performance under the two filter types would not differ.

Method

Subjects. Table 1 displays the characteristics of participants in the three sub-experiments concerning visual performance. The sub-experiments were conducted sequentially, such that the first 16 men and first 16 women completed experiment 2A, the next 16 men and 16 women completed experiment 2B, and the final 8 men and 8 women completed experiment 2C. The distributions of age, use of visual correction, and degree of fatigue, were not significantly different for participants in the three groups.

Apparatus. Visual acuity was measured using the VALID Kit.[18] The task is to identify the direction of the gap in a Landolt ring, which are circles with a gap that can be oriented in any cardinal direction. In this case, the gaps are either on the top, bottom, right, or left of the ring. The VALiD kit consists of 12 rows (labelled A to L) and thirteen columns (numbered one to thirteen) of Landolt rings, printed onto a white card of high quality paper (18 cm x 19 cm) mounted on a metal plate. The rings vary systematically in size and luminance contrast. From the top left corner, ring size and gap size decrease across the columns (gap size ranges from 0.051 cm to 0.009 cm). Moving down columns, from top to bottom, the luminance contrast decreases systematically by rows of two (from .90 to .08). This provides two equivalent forms of the task (odd- and even- rows). The contrast is greatest for the top two adjacent rows and the least for the bottom two rows.

In this experiment, the VALiD task was illuminated indirectly. The task is placed on a flat platform under a Plexiglas dome (113 cm in diameter) coated with high-reflectance, spectrally flat, barium sulphate coating. The platform is placed on top of a 1'x4' fluorescent luminaire such that light shines through apertures in the platform and is reflected from the dome onto the task. The participant views the task by looking through a 10.2 cm x 3.8 cm viewport located in the top of the dome, directly over the VALiD task and 47 cm above. The participant cannot see the apertures that admit direct light into the dome. For this experiment, pairs of luminaires were mounted at a 45-degree angle in a custom stand so that participants could stand to reach the viewport, rather than leaning over a table. The drawing in Figure 9 shows the apparatus schematically for one 2-lamp luminaire, placed horizontally on a table; for this experiment the apparatus was mounted to allow participants to stand, shown in Figure 1.

The procedure was the same for all three sub-experiments; only the lighting conditions illuminating the task differed. Separate luminaires were used for each lamp/ballast combination. Filters held in cardboard frames were added or removed as necessary from a slot in the luminaire cover before the platform holding the dome and the task was placed on top. One of the experimenters moved the dome and its platform into place over the appropriate luminaire while the other explained the procedure to the participant. All lamps were burned-in for 100 hours prior to use and ran continuously for an hour before and throughout each experimental session, to ensure consistent lamp temperatures and constant lamp aging. Table 6 displays the photometric data for the lighting conditions in the three subexperiments, and Figures 10-12 show the SPD curves. An illuminance sensor and external meter were used to ensure that illuminance conditions were as specified for the applicable experimental condition.

Procedure. As described above, the visual performance tests took place after the colour appearance judgements. For sub-experiments 2A and 2B, participants were randomly assigned to one of the between-groups conditions (electronic or magnetic ballasts, expt 2A; 100 or 1000 lx, expt 2B). Each participant completed the VALiD task twice, under two different lighting conditions determined by the sub-experimental design in which they participated. The order of presentation of the within-groups conditions was counterbalanced within each experiment (or sub-experimental group), so that half of the participants in each group started with one of the two conditions, and half with the other. To complete each visual performance test, the participant stood (using a step-stool if necessary) at the VALiD apparatus, looking through the viewport to the task below. The viewport was large enough to accommodate spectacles, for those participants who wore them. Experimenter 1 instructed the participant to begin at either row A or row B and to call out the direction of the gap in each ring, beginning with column 1 and continuing through column 13. If the participant reported being uncertain, the experimenter strongly encouraged the individual to continue and to guess if necessary. The order of presentation of the equivalent rows of the task was counterbalanced (half of the participants did rows ACEGIK for the first conditions, and half started with rows BDFHJL).

Between visual task presentations, the dome together with the task was moved physically from one luminaire to the other by Experimenter 2. During this time participants verbally answered the demographic questions and rested their eyes by looking into the distance while sitting facing Experimenter 1 at the desk.

Results

The general analytic strategy for this set of experiments was multivariate analysis of variance (MANOVA). The dependent variables were the number of correctly-identified ring gaps for each row of the VALiD chart. Thus, there were 6 dependent variables for each person on each visual performance task. Over all the subexperiments, the data show the predicted pattern of poorer performance as the luminance contrast reduced.

Preliminary examination of the data revealed that the frequency distributions were negatively skewed (most individuals had high scores, and few had low scores). The data were transformed by squaring each value, in order to obtain more normally-shaped distributions. The MANOVA tests reported below were conducted on the transformed data.

Visual performance is known to decline with age. Age was therefore a potential confounding variable in the between-groups comparisons in experiments 2A and 2B (for example, if the low-illuminance group had more younger people than the high-illuminance group, it could have masked the illuminance main effect in that experiment). Examination of the age distribution between the groups in each experiment revealed no significant differences that could have biased the outcomes.

Experiment 2A. For this subexperiment, the independent variables were ballast type (between-subjects) and light source (within-subjects) in a 2 x 2 factorial design. The MANOVA analysis examined main effects for the two independent variables and their interaction. Table 7 displays the means and standard deviations for each experimental condition and the marginal values (collapsed across ballast types or light sources). It is evident that visual performance under all four lighting conditions was very similar.

Table 8 displays the summary of the MANOVA analysis. None of the multivariate tests achieved statistical significance; therefore, none of the univariate tests for effects on individual rows of the VALiD task were examined. In addition, the main effects and interaction were all very small effects (R^2 is the indicator of this); that is, very little of the variance in visual performance scores was associated with these variables or their interaction.

Experiment 2B. Illuminance level and light source were the variables in this sub-experiment. Table 9 displays the means and standard deviations for the light conditions and the marginal means collapsed across the independent variables. As expected, the performance for 100 lx is clearly lower than for 1000 lx. The means for the two light source conditions (filtered and unfiltered T8 4100 K lamps) are very similar to one another.

The MANOVA analysis for this subexperiment is shown in Table 10. The main effect for Illuminance was significant at the $p<.05$ level, as were five of the six associated univariate tests; only for the highest luminance contrast were participants able to maintain equivalent visual performance for the two illuminance levels. For all of the significant tests, visual performance was better under higher illuminance, and these effects explain large amounts of variance.

There were no statistically significant multivariate tests for light source nor for the interaction of illuminance X light source.

Experiment 2C. This subexperiment had one independent variable: filter type. Table 11 shows the means and standard deviations for visual performance in the two conditions, and collapsed across them. Table 12 shows the results of the MANOVA analysis of these scores. The multivariate test of the filter type effect was not statistically significant and therefore no univariate tests were examined.

Discussion

Fluorescent lighting filter effects. The results of the three subexperiments provide no evidence that adding a magenta filter to a 4100 K fluorescent lamp will aid visual performance, nor that one filter causes effects different to another. Indeed, these results provide no evidence that light source spectral composition will influence visual performance. The differences in spectral quality were greatest for the two light source conditions in experiment 2A, and yet there was no effect on visual performance. Smaller differences between light source conditions were present in experiments 2B and 2C, and these too had no effect on visual performance.

These findings are intriguing when one considers the literature concerning spectral influences on visual performance. Berman's scotopic sensitivity theory predicts better visual performance for scotopically rich lamps (such as the 5000 K, 90 CRI lamp) over scotopically poor lamps (such as the filtered 4100 K lamps).[11-13] Berman and Benson[15] criticised earlier work by Veitch and McColl[14] for having failed to find this effect through having too little statistical power, among other methodological criticisms. The present experiment (2A) was designed to address this question directly, using a within-subjects comparison of two light sources with widely different ratios of scotopic to photopic luminance (as wide as the widest pair in the Veitch & McColl experiment). Despite the added statistical power (power > .90), there was no effect of light source spectral composition on visual performance. Although it is possible that other methodological limitations might have obscured a true effect, it is worth nothing that this finding is consistent with several other investigations that have used widely varying methods of measuring visual performance and a wide variety of light sources, but have not found effects of light source spectral composition on visual performance or visual acuity.[6, 19-22]

Illuminance effects. There can be no question that the task was sensitive to changes in visual performance. The results for changing illuminance levels in experiment 2B demonstrate this. Visual performance was better under higher illuminance than lower, exactly as predicted by the literature.[23] Moreover, the effect was greater for lower-contrast task rows, which is also consistent with existing knowledge.

Ballast type effects. The absence of a ballast type effect in experiment 2A is not consistent with the literature, where there have been several reports of improved visual performance under electronic ballasts[14,24-25] The most likely explanation for the findings in this experiment is the lack of statistical power in the between-groups comparison. We examined this possibility using the statistical power analysis tools developed by Cohen.[26]

Given the sample size of 16 participants per ballast type, the statistical power of the between-groups comparison to detect a large effect (a mean difference of 0.8 SD) was 0.59. This means that the experiment had a 59% chance of rejecting the null hypothesis (no effect) even if a large effect existed. Our decision to include the ballast type variable, despite the low statistical power for this comparison, was based in part on a desire to achieve a higher sample size for the comparison between light sources in experiment 2A, the contrast testing Berman's scotopic sensitivity hypothesis[13]. It would have required 26 participants for each ballast type to have obtained a statistical power of 0.80 for a large effect. Such an increase was not possible, given the time available to collect data for this project.

In any case, even an increase of 10 people per condition (20 in total) might not have been enough. Sensitivity to flicker appears to decline with age[27], which might lead one to expect a smaller effect size in this experiment than in earlier work, given the wider age range of participants here. In that case (a mean difference of 0.2 SD), given a sample size of 16, statistical power was .09; 394 participants per ballast type would have been required to achieve a statistical power of .80.

General Discussion and Conclusions

This project set out to test two claims about the effects of fluorescent lighting filters on people: that a magenta filter added to common fluorescent lamps improves skin colour appearance, and that the filter also improves visual performance. Manufacturers have used these claims, along with product testimonials, to market such filters as beneficial lighting retrofits for improving working conditions.

The results of these two experiments, together with other evidence from the scientific literature, provide mixed support for these claims.

The visual performance experiments provide no support for the claim that adding a magenta filter to a common fluorescent lamp will improve visual performance. At least with the short-term viewing conditions used in this experiment, the visual performance claims made for such filters are not supported.

The skin colour appearance experiment, consistent with other investigations, demonstrates that people prefer the skin colour provided by light sources that are relatively poorer in green than in red wavelengths. As compared to common fluorescent lamps at 3500 K and 4100 K, adding a magenta filter can improve skin colour appearance. However, it is possible that any light source having a suitable $x:y$ ratio of CIE chromaticity co-ordinates would prove equally acceptable. Further investigation might provide valuable insights into preferred colour characteristics of light sources that manufacturers could use in modifying their products. Such investigations should include participants with a wider variety of skin tones, to ensure results that are widely generalisable.

In the absence of such products, it is possible that adding a filter to existing lamps might be an effective way to improve colour appearance of people where it is judged to be a problem. However, adding filters to fluorescent lighting systems, either as a flat insert on a lens, or directly around a lamp, comes at a cost in illuminance and lighting system performance that the facilities manager should take into account in making a retrofit decision.

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Acknowledgements

The preparation of this report was supported by the National Research Council of Canada and Public Works and Government Services Canada under the NRC Project B3207, "The Effects of Fluorescent Lighting Filters on Human Vision, Perception, and Satisfaction". The authors gratefully acknowledge the assistance of the following people: Steven Elliott and Roger Marchand [NRCC/IRC] (apparatus design and construction), Guy Newsham [NRCC/IRC] (technical advice), Michael Hunter [University of Victoria, Department of Psychology] (statistical consulting), Mario Nöel and Joanne Zwinkels [NRCC/Institute for National Measurement Standards] (transmittance measurements), Joseph Zulak [Public Works and Government Services Canada] (logistics), Dean Lawrence [Client Services Manager, Public Works & Government Services Canada] (temporary laboratory facilities), and 80 volunteers from the staff of Public Works & Government Services Canada who served as research participants.

Appendix

Paired Comparisons Transformation: Experiment 1

In this technique each participant's fifteen responses are regressed onto a special paired comparison matrix which produces estimated scores representing relative preferences for the six stimulus conditions. Given Y = a data matrix (80 X 15), and X = a matrix for paired comparisons (15 X 6), then the preferences are estimated as: $YX(X'X)^{-}$ where X=

$$
\begin{bmatrix}
1 & -1 & 0 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 & 0 \\
1 & 0 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & -1 & 0 \\
1 & 0 & 0 & 0 & 0 & -1 \\
0 & 1 & -1 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 \\
0 & 1 & 0 & 0 & 0 & -1 \\
0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 & -1 & 0 \\
0 & 0 & 1 & 0 & 0 & -1 \\
0 & 0 & 0 & 1 & -1 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 & 1 & -1
\end{bmatrix}
$$

Because the X matrix is a singular matrix, it cannot be inverted in the usual way, therefore the Moore-Penrose inverse was used.

The output of this procedure is an 80 X 6 matrix of scores reflecting each participant's relative preference for the six stimulus conditions. These scores were analysed using ANOVA as described above.

Discussions

There are 2 components to this paper and these are both discussed below.

Preference for lamp color temperature based on the rendering of hand skin tone

The context for this study is unrealistic. Subjects are asked to make a comparison of lamp types based only on the singular factor-how they like the way the lighting renders the back of their hands placed against a matte black background. No other attributes of the lighting are to be considered. The authors offer no explanation of why this highly constrained condition all alone should be relevant to lighting practice given the many requirements and lighting issues that need to be balanced in a workplace environment. Nevertheless some comments are supplied here about this circumscribed and somewhat artificial study.

The authors' result in this case is essentially what would be expected based on the previous study of Rea et al[a], for a subject sample composed primarily of people of fair skin. Since 5000K lamps were used in the second part of the study it is puzzling why the authors chose to compare lamps that were so close in CCT values for experiment 1. A larger difference in the CCT values might have produced a higher level of significance and a better test.

In any case the result is probably not generalizable, even under the protocols used, to a more ethnically diverse population such as that of CA. This is born out by the paper of Quellman and Boyce, also presented at this conference, which shows different lamp preferences (based again on hands) for subjects of a variety of different complexions.

It should be noted that in real environments people do not observe their skin against matte black backgrounds. Results of preference under such conditions are interesting but unrealistic even under the singular criterion. Perhaps the authors could repeat their study under more realistic conditions thereby demonstrating that their result has more connection to real environments even for a restricted population and protocol.

It would improve the readability of the paper if the authors would list the mean results for the 15 different comparisons rather than simply averages over some of the comparisons, as is presented in Table 4. It is not possible to reconstruct these 15 values from the contents of Table 4.

Effect of lamp color temperature on Landolt ring acuity

In the second part of the study, the authors did not find any effect of color temperature differences on Landolt ring acuity. The results of the authors disagree with previous laboratory studies and also the study presented by M. Navvab at last years IES conference and published in the J.IES Summer 2001 as well as the new study of M.Navvab presented at this conference and session. There are several possible reasons for this outcome discussed below.

The proposition forwarded by Berman et al of acuity effects of lamp spectrum is based on the occurrence of pupil size changes caused by changes in the color temperature of the surround lighting. This is best accomplished in a full field of view, the situation for most interior lighting situations and for the previous laboratory studies as well as those above mentioned studies of Navvab. Restricting the size of the field of view will diminish the pupillary response, and for small fields there is little or no change in pupil size for either changes in CCT or light level once typical interior levels are achieved [b]. The 'Valid' device used by the authors for testing acuity has a substantially smaller field than occurs in natural viewing.

Although the size of the visual field in the 'Valid' is not provided, it is possible from additional information to determine the size of its field of view. That field of view (taking account of the dome and eyepiece dimensions) is approximately 0.28 stearadians or about 5% of the solid angle covered in a full field of view. Given the relatively small differences in the S/P ratios compared and the small size of visual field, it is not surprising that the authors did not find a pupillary related color temperature effect. This problem of field size of the 'Valid' apparatus has been previously remarked to the authors and it is specifically mentioned in their reference 15.

The 'Valid' apparatus also provides a secondary confound and that is the effect on pupil size of having subjects press their face into the eyepiece. Studies on the psychological aspects of pupilometry have shown that such facial and viewing constraints effect pupil size in an unpredictable manner and could further reduce the sensitivity of the authors' study.

The authors' claim that experiment 2b, comparing acuity at 2 light levels a factor of 10 different, shows that their measures are sensitive. On the other hand, the hypotheses of the effects of different S/P values on vision have never claimed comparable vision with an order of magnitude in light level difference but typically equality of vision with some 30% to 40 % differences of light level or energy. They cannot claim experiment 2b has the relevant sensitivity to draw their conclusions about the S/P hypothesis.

A further examination of the results of exp. 2b shown in Table 9 demonstrates areas of lack of sensitivity even over the large range of luminance difference used by the authors. For the 2 highest contrast levels the difference in ring acuity at 100 lux and 1000 lux is not significant, contrary to well known results in vision. This lack of a difference is somewhat surprising given that the mean age of the participants appears to be in forties. Perhaps this might be due to a large spread in individual acuities. The significant effect demonstrated for exp.2b is entirely due to the low contrast results. It is difficult to understand why the authors would invoke a between-subjects protocol as a means to normalize the intrinsically higher sensitivity possible for a within-subjects protocol.

In view of the various protocol limitations discussed above, the authors' claim that "these results provide no evidence that light source spectral composition will influence visual performance" has limited context and on the basis of the present study cannot be generalized to apply for interior lighting practice.

The authors also claim that their study is consistent with a number of other studies that do not show effects of light spectrum on visual performance and provide 5 references of which only 2 are actually papers in peer review journals. Reference 6 was presented as a conference poster and tested spectral changes with a small field of view even smaller than the 'Valid' apparatus. The limitations of this protocol have already been discussed above. Of the journal papers, reference 19 did not perform a detailed study of vision and although reference 22 did examine vision, the conditions were not sensitive. (A thorough critique of the sensitivity issue for ref 22 has been provided by me and is published as a discussion appended to the referenced article.) The conference papers refs 20&21 are extremely crude studies lacking the necessary protocols to test the concept of S/P values on vision.

On the other hand the authors have chosen not to reference other studies in the published literature (besides the study of Navvab mentioned above) that do show spectral effects on vision, 4 of which are listed below [c,d,e,f]. These 4 have been referenced in papers that the authors have referenced. In each of these 4 references noted below, a sensitive measure of vision has been applied and those references listed here indeed find spectral effects on vision entirely consistent with the S/P concept. The authors should be concerned with the appearance of a possible referencing bias as this has also been commented on previously by Salares[g].

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Sam Berman
Sausalito, CA

This paper describes a series of carefully done and expertly analyzed experiments on the effect of filtered fluorescent light on preferred skin appearance and on visual performance. However, I have two concerns, one with the skin appearance experiment and one for the visual performance experiments. The core of my concern for the skin appearance work lies in the use of the x/y ratio as a predictor of preferred skin appearance. I suspect this finding is fortuitous, the x/y ratio simply having a larger change in value for the direction of movement in chromaticity coordinates when the filters were introduced than the other photometric measures considered. Certainly, the x/y ratio cannot be a general predictor, because the locus of constant x/y ratio is a line through the chromaticity diagram so a single x/y ratio covers a wide range of light colors, not all of which can be preferred for skin. An alternative approach to finding a photometric predictor that would be more understandable would be to quantify the effect of adding the filters on the separation of the chromaticity coordinates of the lamp/filter combination from chromaticity coordinates that are known to be satisfactory for skin appearance. For example, it is notable that the effect of adding the filter to both lamps is to move the chromaticity coordinates of the lamp/filter combinations closer to the black body locus than those of the lamps alone.

As for the visual performance experiments, my concern is with the use of the rows in the VALiD chart with different contrasts as different dependent variables and then the carrying out of a multivariate analysis of variance on them. Given that an experimenter is using several different quantities to measure the same underlying effect, then multivariate analysis of variance is the correct procedure. However, in this case there is a-priori reason to believe that these dependent variables will show a systematic change in sensitivity to the independent variables, i.e., the high contrast rows will be less sensitive than the low contrast rows. In this situation it does not seem sensible to treat the different rows of the VALiD chart as separate dependent variables measuring the same underlying effect. Would it not have been better to treat the contrast of the row as another independent variable? Would the authors please comment?

Peter Boyce
Lighting Research Center
Troy, NY

The authors have done an impeccable job of reporting their experiments and results. I have only the following questions and comments:

Experiment 1: It is satisfying to hear about experimental results that confirm common sense and personal experience. Northern Europeans are used to hearing expressions such as “pale”, “sallow”, or “jaundiced” as meaning ill or sickly or “not in the pink of health”. We are used to hearing terms such as “rosy” or “ruddy” to describe healthy skin tones. So, yellow or poor red content in the skin tone equals undesirable sickliness, while red content implies health. The magenta filters subtract out some of the undesirable yellow-green while transmitting most of the desirable red wavelengths. We should remember, however, that just because the filtered lamps were “preferred”, it does not imply dissatisfaction with the unfiltered lamps.

I was surprised to see only an R^2 of 0.096 for the x:y ratio, the best photometric predictor. Is there a better photometric description of the shift in color due to the filters? Would a ratio between the radiometric power of the “long wavelengths” to the “mid-range wavelengths” yield a higher correlation value?

Experiment 2: How much does the filtering of the lamps affect their “S/P” ratios? Would it shift the ratio enough to produce a significant effect in visibility, according to Berman’s theories?
In order to achieve the improved visibility from scotopically-rich sources, it is my understanding that it is necessary to fill the full visual field with luminance. I am unfamiliar with the VALiD viewing chamber. Does it provide the subject with a full field of luminance, or does it provide a viewing aperture?

Naomi Miller
Naomi Miller Lighting Design
Troy, NY

Authors' Response

We have chosen to respond to remarks regarding each experiment in turn, for the sake of clarity, and to respond to all three reviewers together, as there is some overlap between them.

Experiment 1

Our experiment was designed principally to answer a specific, applied question, and this dictated the choice of lamps and filters, commented upon by Dr. Berman. Although we examined a limited range of experimental conditions in order to address the question posed by our client, we have attempted here to propose an explanation that other investigators might wish to explore further. The restricted variability in experimental conditions accounts for the small effect size noted by Ms Miller.

Dr. Boyce expressed reservations concerning the use of the ratio of CIE *x:y* as a predictor of preferred lamp type for skin color judgements. It is certain, as he points out, that colours exist with *x:y* ratios that would not provide acceptable skin color. His suggestion that a measure of difference from some commonly-accepted value of goodness might be more useful is well-taken, and worthy of further study.

Dr. Berman commented on limitations to the generalizability of these findings. We do not disagree that we used tight experimental control to focus attention on the target that we wished to have judged, but we view that as a strength not a weakness. It is certainly possible that in the context of a real space, relative preferences for light source colours would be different; this is an empirical question. Regarding the generalizability of the results to other populations, we do not disagree. Indeed, we explicitly limited our conclusions to the fair-skinned population that participated, and recommended that further studies include a broader range of skin tones.

Regarding Dr. Berman's request for the forced-choice preferences for the 15 pairs, we disagree concerning their usefulness; the pattern of results is far from clear to the reader from these raw data (as, in general, is the case for most raw data sets). Instead we presented the means for all participants of the relative preference scores by light source in Table 4.

Experiment 2

As was the case Experiment 1, our principal concern in this project was an applied question concerning the use of retrofit filters for office fluorescent lighting. To study this question we used a paradigm that was developed in this laboratory by Mark Rea in the 1980s - the Vision and Lighting Diagnostic Kit - as a tool to assist in determining the visual capabilities of office workers. This contributed to our choices of experimental conditions. For example, in experiment 2B we were more interested in the effects of adding the retrofit filter - an effect size we expected to be small - than in the effects of increased illuminance - an effect known to be large. We assigned the filter contrast to the within-subjects comparison because of its increased sensitivity.

This paradigm had been used in a previous experiment (Ref. 14), which Dr. Berman had criticized both for a lack of statistical power in the comparison of various spectral conditions and for a too-small visual field. Because we had been contracted to study the retrofit filters, we decided to take the opportunity to address Dr. Berman's criticism concerning the statistical power of the previous experimental design. We chose not to change the paradigm for the visual performance test because we believe this near-field visual performance task to be relevant to paper-based office tasks. The field of view for this task is suffiently large to encompass more than only foveal vision: Subsequent to receiving his prepared discussion, we measured it at 16.8 degrees vertically, and 56.46 degrees horizontally (the viewport is rectangular). There is clearly surround luminance in the field of view. We did not clearly explain this reasoning in the paper, which perhaps we ought to have done.

As we had done in the earlier work (Ref. 14), we considered the scores on various rows of the VALiD task to be separate measures of visual performance in a MANOVA design, rather than adding contrast as an additional independent variable (as Dr. Boyce suggested). Contrast is well-understood, and we did not see a need to probe it further although we could have done so. the approach we took provided the information we sought: evidence of overall effects of visual performance (if any), across all contrasts, and tests at each contrast level of the effects of the independent variable. (These would be equivalent to paired-comparison tests of contrast X independent variable interactions.)

We have elsewhere reviewed the literature related to the broad issue of spectral effects on visual performance[h], including most of the papers cited by Dr. Berman in his comments. We invite the audience to visit our WWW site, where the paper is available in PDF form (http://www.nrc.ca/irc/ie/light), read our publications, and to form their own opinions of the scholarly quality of our work. In response to his written comments, we returned to the literature to examine the question again. In Dr. Berman's experiments (Ref. 11, 12, and b [above]), and in the paper presented by Navvab today (the paper in-press in JIES (Summer, 2001) was not available to us for inclusion), task and surround illumination were carefully separated. In Ref 11 and 12, the task was presented as a mirror image of a white-screen VDT with black text; in ref b, the task was backlit with incandescent lamps. Similarly, Navvab used a light table with incandescent lamps to backlight the task separately from the surround. In ref. b, Dr. Berman and his colleagues reported that higher surround luminances, provided by a "scotopically enriched" lamp, produced smaller pupils and improved word-reading accuracy. Both Berman (Ref. 11, 12) and Navvab (today) reported that surround lighting with a higher S/P ratio improved visual performance. In these studies, the comparisons between surround spectra were wide.

Other respected lighting investigators, using other methodologies, have reached other conclusions (Ref. 19, 20, 21, 22). (These papers would have received complete peer review: two are journal papers, one is a complete PhD thesis successfully defended, and one is a CIE paper, which would have been reviewed in full prior to acceptance.) These investigations differed from the Berman and Navvab work. In all cases, the task was lit using general room lighting, so that surround and task had the same color temperature and the task was not itself luminous. In Ref. 19, 21, and 22, the range of light sources was smaller than in either Berman's or Navvab's work (across the range of 2700 - 5000 K), although Halonen's thesis included sources of 2900, 3300, 5500, and 9500 K. These investigators did not find effects of spectral composition on visual performance. Our experiment differed yet again in allowing only a near field of view, although both the task and its surround were lit in the same way to the same level.

Several possibilities exist for this set of findings, which we view as open empirical questions: First, the null-effect studies might be flawed in ways that prevented the detection of effects. Dr. Berman clearly thinks so. Second, the effects might be real, but effective use of the pupil size mechanism might require very large S/P ratios, larger than would be expected with typical lamp types in use today, even the most "scotopically enriched" (as Ms Miller and Dr. Berman both noted, the range of S/P ratios in our experiment is quite small). Third, perhaps the use of the luminous task with the separate surround lighting influences the process, perhaps because of the colour contrast between the task and surround. There would have been a limited task:surround distinction in the other four papers if one considers the surround to include elements of the entire room.

Although our experiments did not show an effect of spectral difference on near-field visual performance during a short exposure, there are research questions that have yet to be answered. We clearly limited the generality of our conclusions to the conditions we studied. We invite others to pursue some of the other possibilities, as independent replication and extension is the best basis on which to build a *corpus* of empirically-based understanding that can be used in making policy decisions.

Reference

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Table 1 — Participant Demographic Characteristics

	Experiment 1	Experiment 2A	Experiment 2B	Experiment 2C
Sample size	N=80	N=32	N=32	N=16
Session Language				
English	75	30	31	14
French	5	2	1	2
Correction lenses				
none	21	8	8	5
reading glasses	10	5	4	1
distance glasses	27	10	11	6
bi- or trifocals	8	4	4	0
gradual or multi-focal lenses	9	3	3	3
contact lenses	5	2	2	1
Hearing impairment?	5	2	1	2
Hearing aid?	1	1	0	0
Have a cold today?	1	0	1	0
Decongestants today?	1	0	1	0
Fatigue				
very badly rested	1	1	0	0
badly rested	9	4	4	1
somewhat well rested	31	14	9	8
well rested	28	9	13	6
very well rested	11	4	6	1
Age				
18-29	7	2	3	2
30-39	18	5	12	1
40-49	39	18	11	10
50-59	16	7	6	3
60-69	0	0	0	0
70-79	0	0	0	0
Skin Colour		n/a	n/a	n/a
pale pink or ivory	41			
rose	35			
yellowy-olive	4			
browny-red	0			
yellow-brown	0			
brown-black	0			
Skin Tone		n/a	n/a	n/a
very light	9			
light	48			
medium	22			
darkish	1			
very dark	0			

Note. Participants in Experiments 2A-2C were subsets of the participants in Experiment 1.

Table 2 — Photometric Summary of Experiment 1 Light Sources

	F32T8 - 3500 K, CRI-80			F32T8 - 4100 K, CRI-80		
	Filter 1	Filter 2	Unfiltered	Filter 1	Filter 2	Unfiltered
Photopic Luminance (cd/m^2)	217.48	217.74	213.87	219.69	217.74	215.36
Scotopic Luminance (cd/m^2)	298.01	296.75	296.62	337.80	336.92	336.13
S:P ratio	1.37	1.36	1.39	1.54	1.55	1.56
CCT (K)	3269.20	3162.16	3433.76	3685.54	3720.78	3982.84
x	0.42	0.42	0.41	0.39	0.39	0.39
y	0.40	0.39	0.41	0.38	0.38	0.39
x:y ratio	1.05	1.07	1.02	1.04	1.03	0.98

Note. All light sources were measured using a calibrated Photo Research SpectraScan PR 705 Spectroradiometer. A reflectance standard was placed on a defined point on the inclined pad; measurements at this point on the left and right sides of the apparatus were averaged to obtain the values reported here. All conditions included cardboard baffles to provide equivalent illuminance (approx. 670 lux) on the inclined board where participants placed their hands.

Table 3 — Descriptive Statistics for Relative Light Source Preferences

	3500 K	4100 K	Filter *M* (*SD*)
Filter 1	.16 (.43)	.029 (.47)	.09 (.45)
Filter 2	.24 (.45)	-.031 (.52)	.10 (.50)
Unfiltered	-.16 (.53)	-.24 (.50)	-.20 (.51)
Lamp *M* (*SD*)	.08 (.50)	-.08 (.50)	

Table 4 — Summary of ANOVA of Relative Light Source Preferences

Effect	F (1,79)	p	R^2
Lamp	3.45	.07	.042
Filter 1 vs Filter 2	0.115	.74	.001
Filter (1 or 2) vs Unfiltered	31.55	.00	.285
Lamp X Filter (1 vs 2)	3.913	.05	.047
Lamp X [Filter (1 or2) vs Unfiltered]	4.398	.04	.053

Note. R^2 is the squared correlation ratio (proportion of explained variance) associated with each effect.

Table 5 — Summary of Hierarchical Linear Models of Relative Light Source Preference

Photometric Predictor	z	p	R^2
Photopic Luminance	4.69	< .001	.048
Scotopic Luminance	-1.81	> .05	.019
CCT	-5.81	< .001	.062
x	4.62	< .001	.040
y	-1.09	> .05	.003
x:y ratio	7.10	< .001	.096

Note. R^2 is the squared correlation ratio (proportion of explained variance) associated with each effect.

Table 6 — Photometric Data for Experiment 2

A. Experiment 2A	Fil-1+ 4100 K, CRI-80		5000 K, CRI 90	
	Magnetic	Electronic	Magnetic	Electronic
Photopic Luminance (cd/m^2)	56.15	56.84	54.60	56.13
Scotopic Luminance (cd/m^2)	81.25	82.51	110.67	114.42
S:P ratio	1.45	1.45	2.03	2.04
CCT (K)	3499	3486	4565	4504
x	.407	.408	.361	.363
y	.395	.396	.378	.377
x:y ratio	1.03	1.03	0.96	0.96
IESNA Flicker Index (120 Hz)	.0944	.0046	.0842	.0045
% luminous modulation (120 Hz)	33.56	1.67	38.84	1.89

B. Experiment 2B	Fil-1+ 4100 K, CRI-80		Unfiltered 4100 K, CRI 80	
	100 lx	1000 lx	100 lx	1000 lx
Photopic Luminance (cd/m^2)	28.46	283.47	28.55	283.83
Scotopic Luminance (cd/m^2)	41.48	411.10	42.42	419.84
S:P ratio	1.46	1.45	1.49	1.48
CCT (K)	3496	3478	3809	3806
x	.407	.408	.398	.398
y	.396	.395	.410	.411
x:y ratio	1.03	1.03	0.97	0.97

C. Experiment 2C	Fil-1+ 4100 K, CRI-80	Fil-2+ 4100 K, CRI-80
Photopic Luminance (cd/m^2)	56.84	54.47
Scotopic Luminance (cd/m^2)	82.51	79.52
S:P ratio	1.45	1.46
CCT (K)	3486	3537
x	.408	.406
y	.396	.398
x:y ratio	1.03	1.02

Note. All light sources were measured using a calibrated Photo Research SpectraScan PR 705 Spectroradiometer. Nominal horizontal illuminance on the VALiD task was 200 lx in experiment 2A and 2C. All lamps in Experiments 2B and 2C were run using electronic ballasts. The flicker measurements for Experiment 2A were taken with a silicon photodetector directly from the lamps (both lamps in one luminaire) connected directly to an oscilloscope.

Table 7 — Summary of Visual Performance Descriptive Statistics: Experiment 2A

		Fil -1 + 4100 K T8 *M* (*SD*)	Unfiltered 5000 K T8 *M* (*SD*)	Ballast Type Main Effect *M* (*SD*)
Magnetic Ballasts	Row A/B	11.25 (1.53)	11.31 (1.40)	11.28 (1.44)
	Row C/D	11.19 (1.22)	11.38 (0.89)	11.28 (1.05)
	Row E/F	10.81 (1.47)	10.94 (1.00)	10.88 (1.24)
	Row G/H	10.44 (1.26)	10.50 (0.82)	10.47 (1.05)
	Row I/J	8.62 (1.67)	8.19 (1.80)	8.41 (1.72)
	Row K/L	5.94 (2.05)	6.19 (2.37)	6.06 (2.18)
Electronic Ballasts	Row A/B	11.38 (1.15)	11.31 (1.20)	11.34 (1.15)
	Row C/D	11.13 (1.20)	11.06 (1.29)	11.09 (1.23)
	Row E/F	10.81 (1.56)	10.87 (1.31)	10.84 (1.42)
	Row G/H	10.19 (1.42)	10.56 (1.03)	10.38 (1.24)
	Row I/J	8.63 (2.00)	8.50 (2.48)	8.56 (2.21)
	Row K/L	6.62 (2.53)	6.25 (2.98)	6.44 (2.72)
Light Source Main Effect	Row A/B	11.31 (1.33)	11.31 (1.28)	11.31 (1.30)
	Row C/D	11.16 (1.19)	11.22 (1.10)	11.19 (1.14)
	Row E/F	10.81 (1.49)	10.91 (1.15)	10.86 (1.32)
	Row G/H	10.31 (1.33)	10.53 (0.92)	10.42 (1.14)
	Row I/J	8.62 (1.81)	8.34 (2.13)	8.48 (1.97)
	Row K/L	6.28 (2.29)	6.22 (2.65)	6.25 (2.46)

Note. The means and standard deviations displayed here are raw values. The data were then transformed to approximate a normal distribution by squaring each value. The transformed data were used in the MANOVA analyses reported in Table 8.

Table 8 — Summary of Visual Performance Multivariate Analysis of Variance: Experiment 2A

Effect	Wilks' ?	*F*	*(df)*	*p*	R^2
Ballast Type	0.85	0.74	6, 25	.62	.006
Light Source	0.87	0.65	6,25	.69	.014
Light Source X Ballast Type	0.76	1.28	6,25	.30	.022

Note. None of the multivariate tests reached statistical significance, therefore no univariate tests (for individual rows/contrast levels) were interpreted. R^2 is the squared correlation ratio (proportion of explained variance) associated with each effect. For multivariate effects it is the average of the R^2 values for the associated univariate (VALiD row) effects.

Table 9 — Summary of Visual Performance Descriptive Statistics: Experiment 2B

Illuminance (E)		Fil -1 + 4100 K T8 *M* (*SD*)	Unfiltered 4100 K T8 *M* (*SD*)	Illuminance Effect *M* (*SD*)
100 lx	Row A/B	11.25 (0.93)	11.12 (0.62)	11.19 (0.78)
	Row C/D	10.75 (1.00)	10.81 (0.98)	10.78 (0.97)
	Row E/F	10.31 (0.95)	10.50 (1.03)	10.41 (0.98)
	Row G/H	9.81 (1.28)	10.06 (1.06)	9.94 (1.16)
	Row I/J	7.63 (1.96)	7.37 (2.19)	7.50 (2.05)
	Row K/L	4.87 (2.22)	5.31 (2.50)	5.09 (2.33)
1000 lx	Row A/B	11.69 (1.45)	11.88 (1.15)	11.78 (1.29)
	Row C/D	11.63 (1.31)	11.63 (2.31)	11.62 (1.29)
	Row E/F	11.63 (1.36)	11.44 (1.63)	11.53 (1.48)
	Row G/H	11.31 (1.20)	11.25 (1.69)	11.28 (1.44)
	Row I/J	9.56 (1.75)	9.81 (2.07)	9.69 (1.89)
	Row K/L	8.00 (2.42)	7.75 (2.79)	7.87 (2.57)
Light Source Effect	Row A/B	11.47 (1.22)	11.50 (0.98)	11.48 (1.10)
	Row C/D	11.19 (1.23)	11.22 (1.21)	11.20 (1.21)
	Row E/F	10.97 (1.33)	10.97 (1.43)	10.97 (1.37)
	Row G/H	10.56 (1.44)	10.66 (1.52)	10.61 (1.47)
	Row I/J	8.59 (2.08)	8.59 (2.43)	8.59 (2.24)
	Row K/L	6.44 (2.78)	6.53 (2.88)	6.48 (2.81)

Note. The means and standard deviations displayed here are raw values. The data were then transformed to approximate a normal distribution by squaring each value. The transformed data were used in the MANOVA analyses reported in Table 10.

Table 10 — Summary of Visual Performance Multivariate Analysis of Variance: Experiment 2B

Effect	Wilks' ?	*F*	*(df)*	*p*	R^2
Illuminance	0.59	2.84	6,25	.03	.248
A/B		3.49	1,30	.07	.104
C/D		5.79	1,30	.02	.162
E/F		8.48	1,30	.01	.283
G/H		11.88	1,30	.00	.284
I/J		13.76	1,30	.00	.314
K/L		15.55	1,30	.00	.341
Light Source	0.97	0.12	6,25	.99	.004
Light Source X Illuminance	0.85	0.76	6,25	.61	.030

Note. Of the multivariate tests, only the Illuminance main effect reached statistical significance, therefore only those univariate tests (for individual rows/contrast levels) were interpreted. R^2 (proportion of explained variance) for multivariate effects is the average of the R^2s for the associated univariate (VALiD row) effects.

Table 11 — Summary of Visual Performance Descriptive Statistics: Experiment 2C

	Fil -1 + 4100 K T8 *M* (*SD*)	Fil - 2 + 4100 K T8 *M* (*SD*)	Row (Contrast) *M* (*SD*)
Row A/B	11.38 (1.15)	11.63 (1.15)	11.50 (1.14)
Row C/D	11.44 (1.15)	11.19 (1.17)	11.31 (1.15)
Row E/F	11.06 (1.39)	11.06 (1.06)	11.06 (1.22)
Row G/H	10.81 (1.11)	10.56 (1.21)	10.69 (1.15)
Row I/J	9.00 (1.67)	8.94 (.2.21)	8.97 (1.93)
Row K/L	6.25 (2.46)	6.63 (2.33)	6.44 (2.37)

Note. The means and standard deviations displayed here are raw values. The data were then transformed to approximate a normal distribution by squaring each value. The transformed data were used in the MANOVA analyses reported in Table 12.

Table 12 — Summary of Visual Performance Multivariate Analysis of Variance: Experiment 2C

Effect	Wilks' ?	*F*	*(df)*	*p*	R^2
Light Source	0.80	0.41	6,10	.86	.042

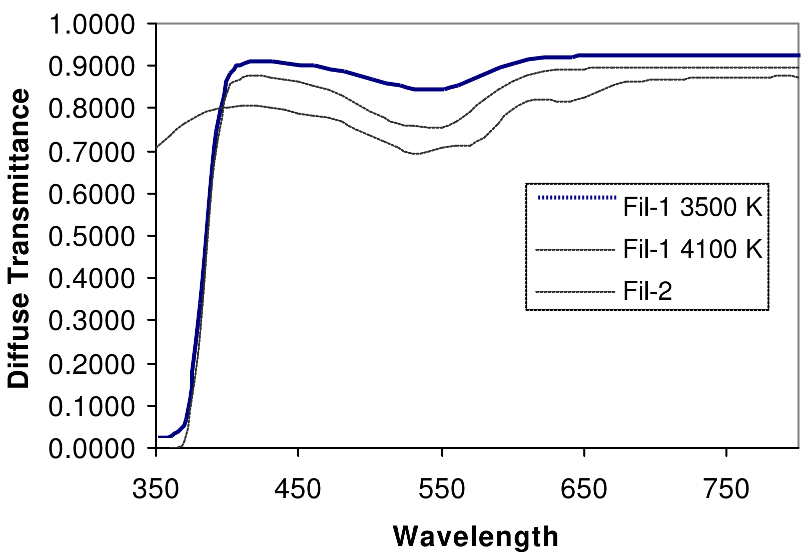
Note. The multivariate tests did not reach statistical significance, therefore no univariate tests (for individual rows/contrast levels) were interpreted. R^2 is the squared correlation ratio (proportion of explained variance) associated with each effect. For multivariate effects it is the average of the R^2 values for the associated univariate (VALiD row) effects.

Figure 1: Temporary Laboratory Facilities and Apparatus

1.A. View of Skin Appearance apparatus and writing desk

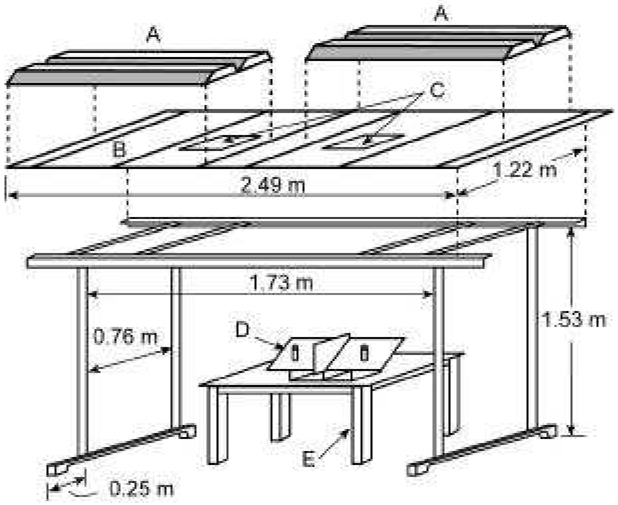
1.B. View of VALiD apparatus (90-deg left turn from view in fig. 1A)

Figure 2: Transmittance of Selected Filters



Note. By permission, from National Research Council Report of Measurement (Reference Number PO-1711). (1997).

Figure 3: Skin Appearance Apparatus



Legend. A = Luminaires (2 each, left and right, one lamp type in each luminaire), on sliding rails. B = Plywood mount for luminaires. C = Apertures for light from luminaires (filters were laid across these as necessary). D = Stand on which participants placed hands for viewing (an opaque barrier [not shown] separated the left and right sides of the booth). E = Table at which participants sat. An opaque booth surrounded the apparatus and concealed the luminaire assembly from direct view.

Figure 4: Photographs of Skin Appearance Apparatus

4.A. Participant's View

4.B. Luminaire Exchange Mechanism

Figure 5: Spectral Power Distributions of Experiment 1 Light Sources

Note. Both sides were measured, but only side A data are shown because the two were identical. All curves sum to approximately the same radiance; illuminance on the target was approx. 650 lx.

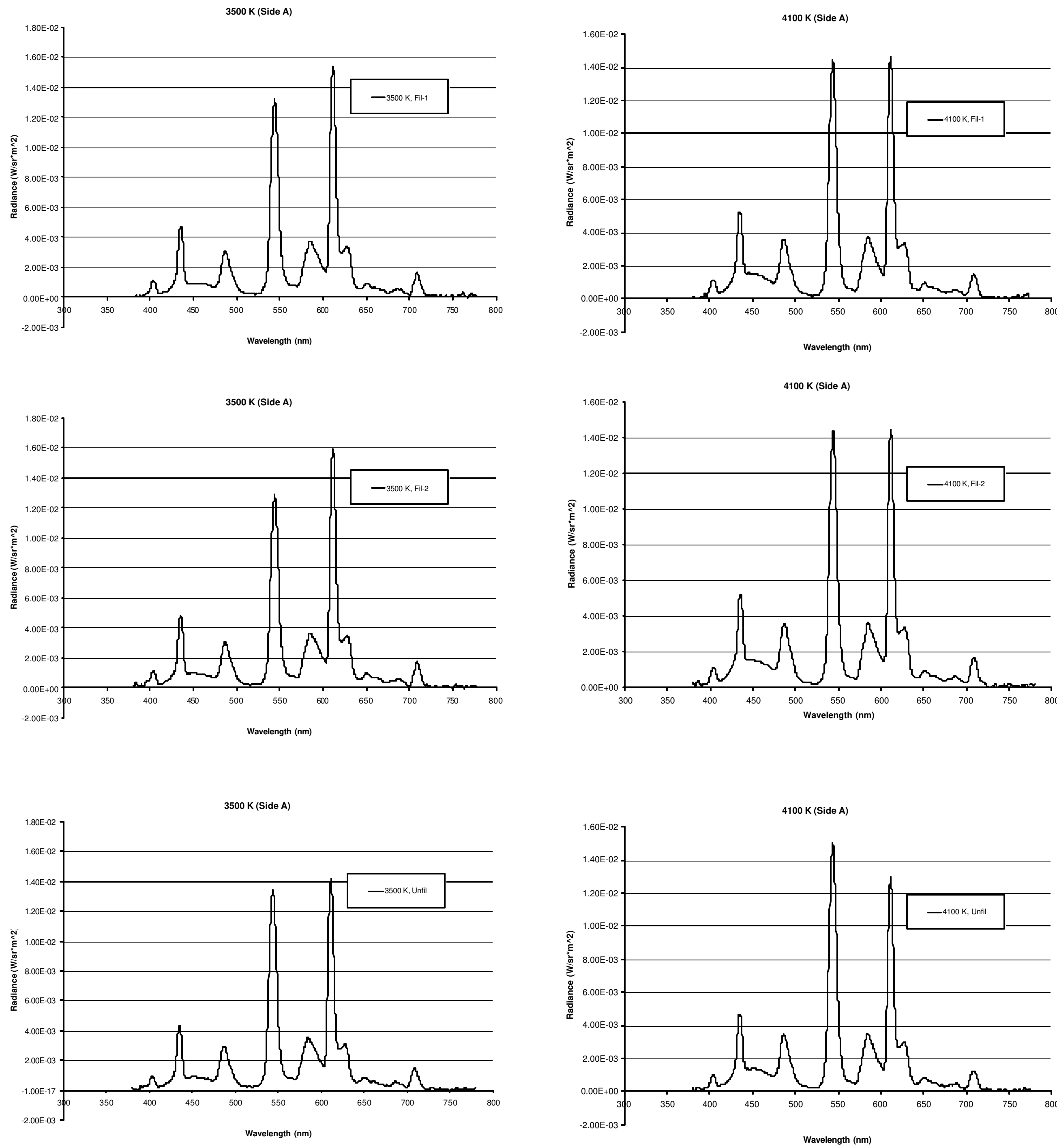


Figure 6: Interaction Effect (Lamp x Filter) on Relative Preference

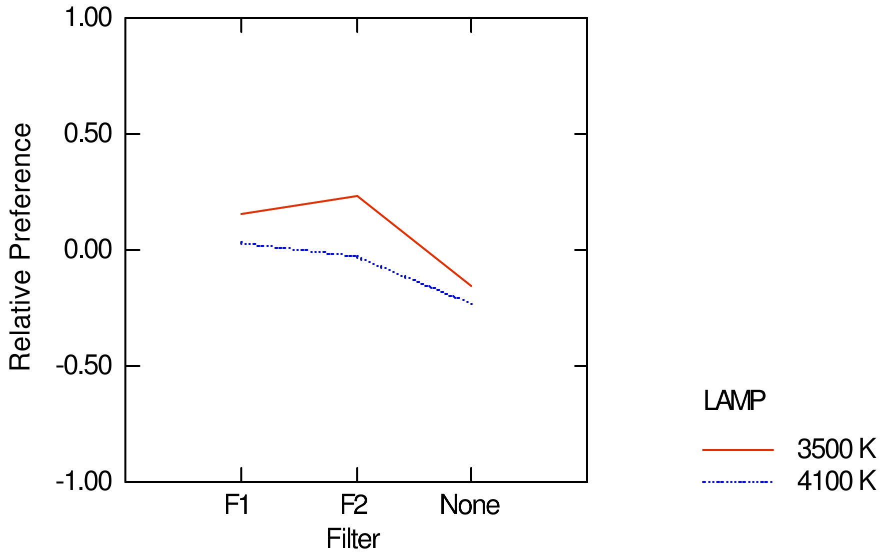
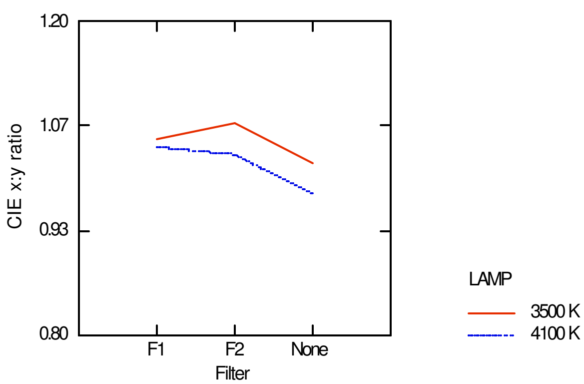
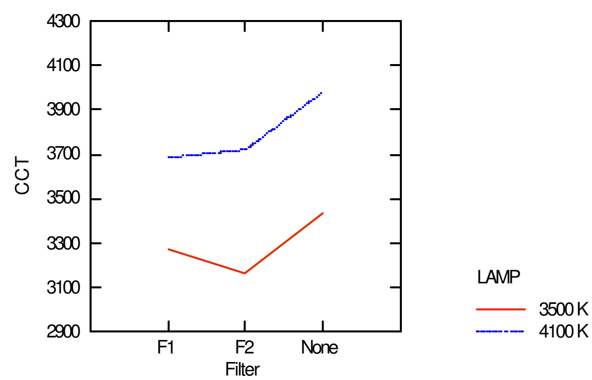


Figure 7: Photometric Values of Light Source Conditions

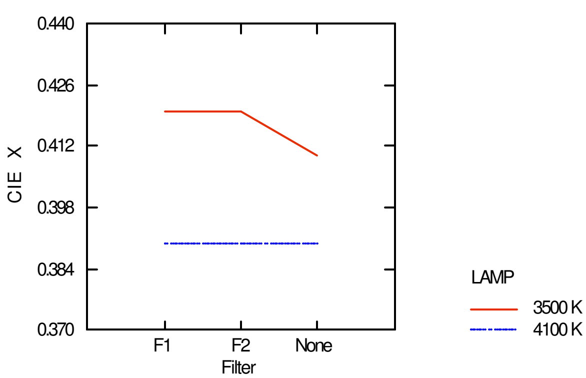
7.A. CIE x:y ratio



7.B. Correlated Colour Temperature



7.C. CIE x chromaticity coefficient



7.D. Photopic Luminance

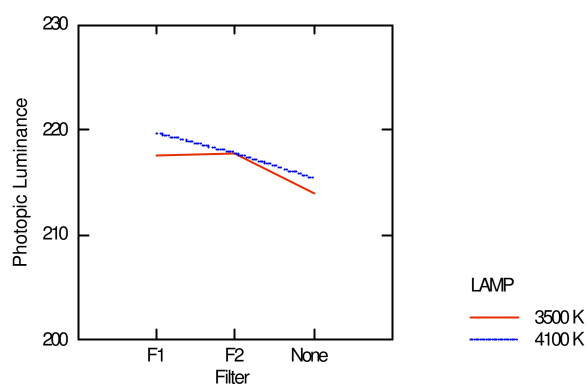
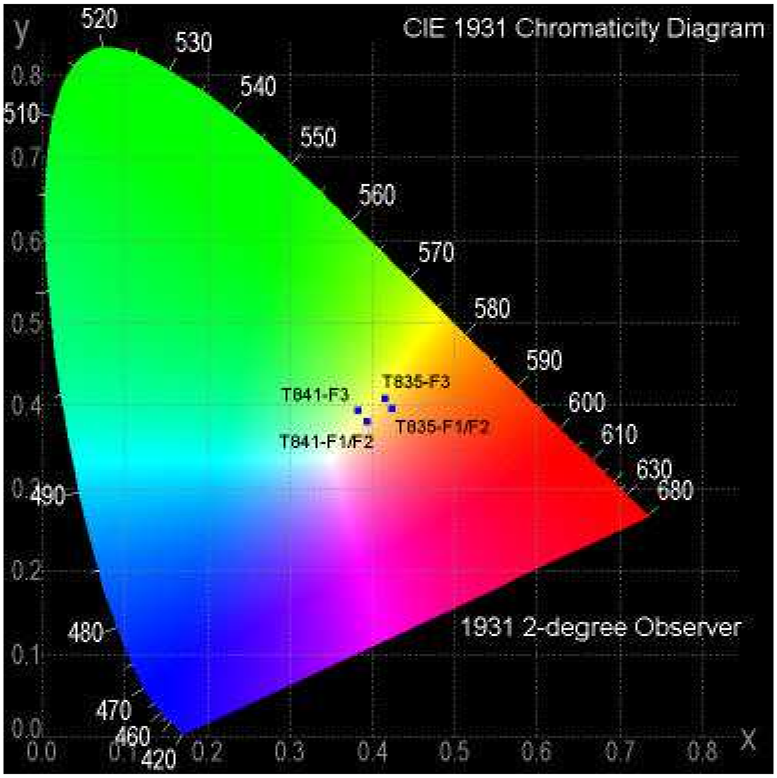
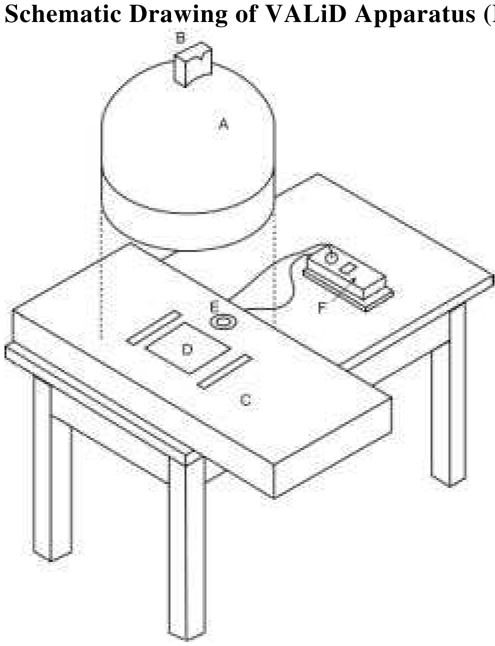


Figure 8
Chromaticity Co-ordinates for Filtered and Unfiltered Light Sources (Experiment 1)



Legend: T841-F1/F2 shows the average *x* and *y* co-ordinates for the filtered 4100 K conditions. T835-F1/F2 shows the average for the filtered 3500 L conditions. T841-F3 and T835-F3 show the values for the unfiltered 4100 K and 3500K lamps, respectively.

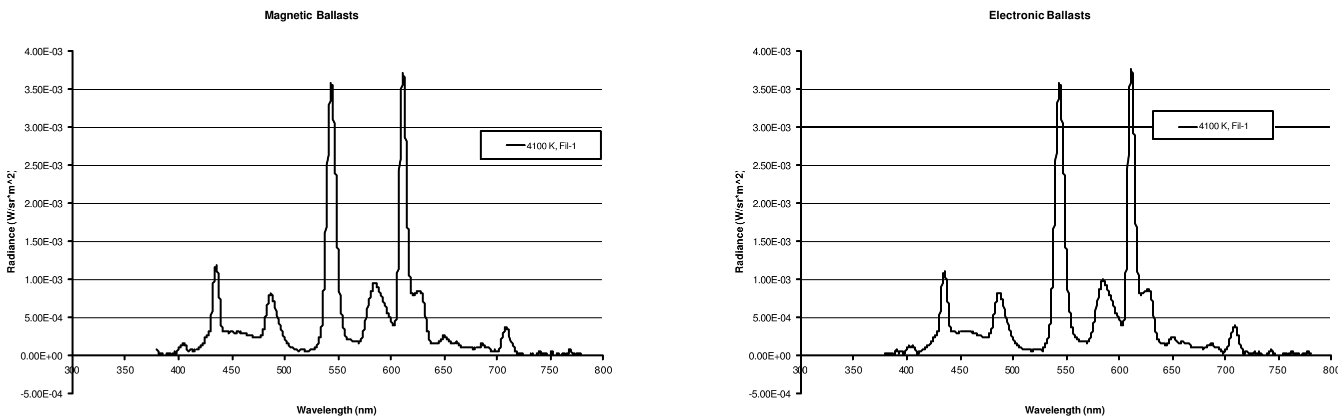
Figure 9
Schematic Drawing of VALiD Apparatus (Experiment 2)



Legend: A = hemispheric Plexiglas dome. B = view port. C = aperture for light from luminaire below. D = VALiD task. E = illuminance sensor. F = external illuminance meter.

Figure 10
Spectral Power Distributions for Experiment 2A Light Sources

Note. All sources used 200 lx on task.
A. 4100K + Fil-1, Low-frequency condition [left]. High-frequency condition [right].



B. 5000K, Low-frequency condition [left]. High-frequency condition [right].

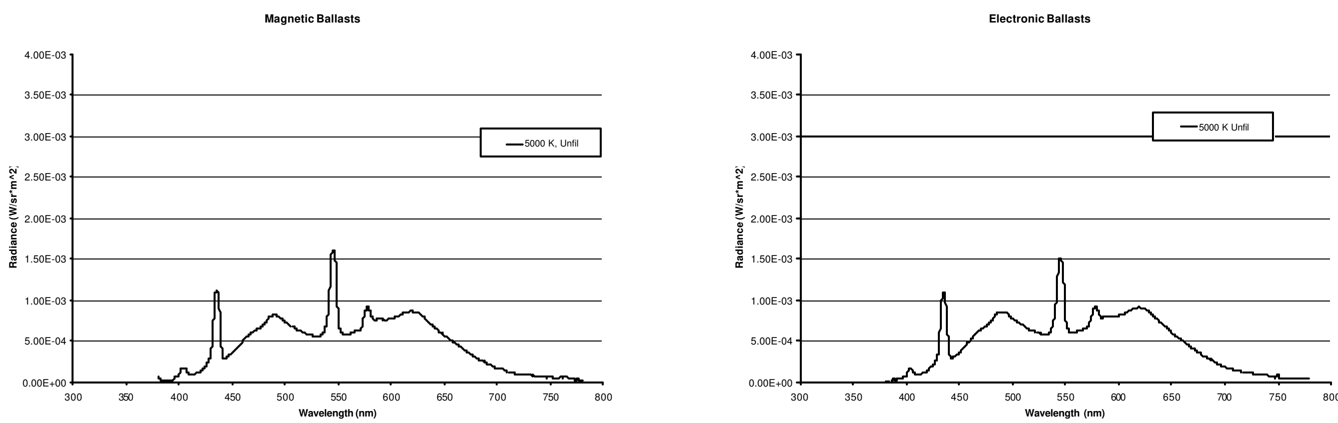
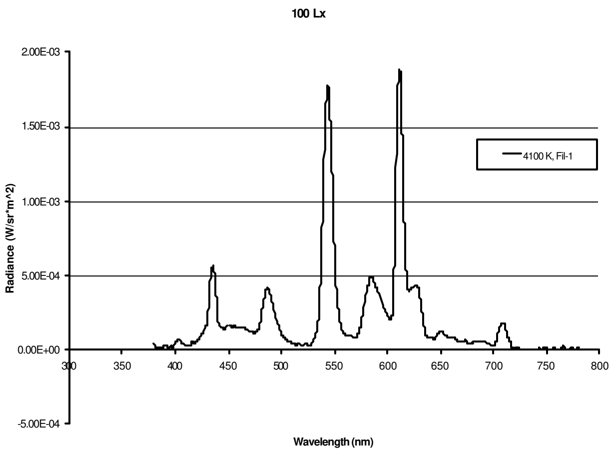
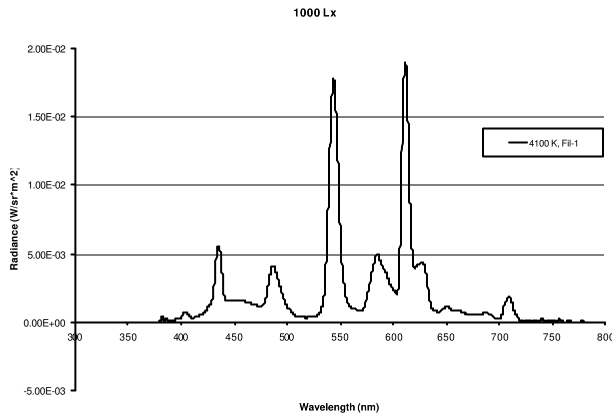


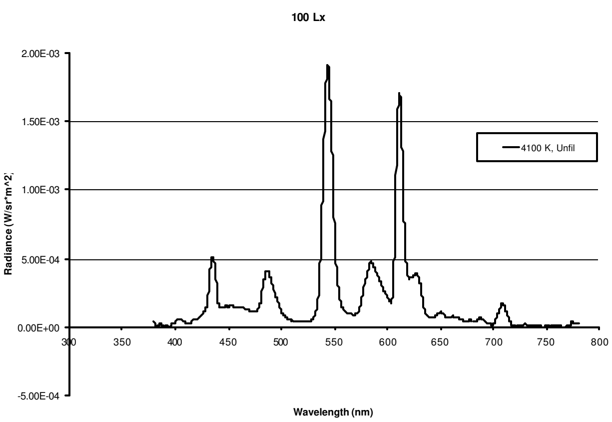
Figure 11
Spectral Power Distributions for Experiment 2B Light Sources

Note. All sources used electronic ballasts
A. 4100K + Fil-1, low and high illuminance.





B. 4100K, low and high illuminance.



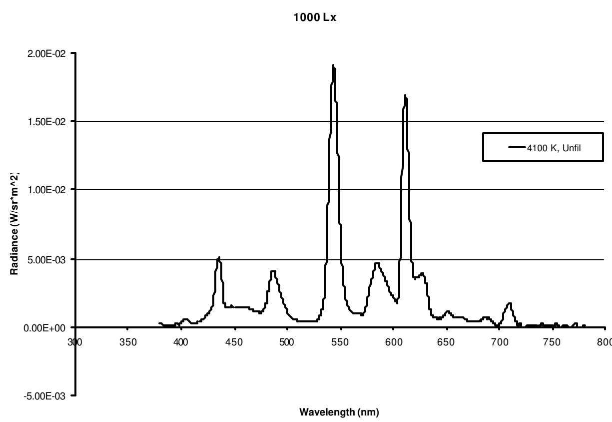


Figure 12
Spectral Power Distributions for Experiment 2C Light Sources

Note: All sources were 200 lx on task and used electronic ballasts.