# Perceived room brightness: Pilot study on the effect of luminance distribution

**D K Tiller DPhil and J A Veitch PhD**
Institute for Research in Construction
National Research Council of Canada
Ottawa, Ontario K1A OR6

*A version of this paper was published in*
*Lighting Research & Technology, Vol. 27, No. 2, 1995, pp. 93 – 101*

**Summary**

This paper describes an experiment to investigate the influence of luminance distribution on perceived brightness in interiors. Thirty subjects matched the brightness of mock offices using a dimmer. Two of the four mock offices used in the experiment had relatively uniform luminance distributions, created by ceiling fluorescent lighting equipped with K-12 acrylic lenses. The other two offices had a nonuniform luminance distribution created by substituting parabolic louvres for the acrylic lenses. In control comparisons subjects matched two rooms having the same luminance distribution. In experimental comparisons subjects matched two rooms having different luminance distributions. The rooms with the nonuniform luminance distribution required between five and ten percent less working plane illuminance to match the brightness of the rooms with the uniform luminance distribution. This raises the possibility of modest energy savings through lighting design.

**Résumé**

Ce document décrit une expérience visant à étudier l’influence de la répartition de la luminance lumineuse sur la perception de la brillance des intérieurs. Trente sujets ont comparé, à l’aide d’un gradateur, la brillance de bureaux simulés. Dans deux des quatre bureaux, la répartition de la luminance, créée par des plafonniers fluorescents munis de diffuseurs en acrylique K-12, était relativement uniforme. Dans les deux autres bureaux, la répartition de la luminance était non uniforme, les plafonniers fluorescents étant pourvus d’écrans-paralumes paraboliques. Lors d’un exercice de référence, les sujets ont comparé deux pièces où la répartition de la luminance était la même. Lors d’un exercice expérimental, ils ont comparé deux pièces où la répartition de la luminance était non uniforme. Par rapport au plan de travail des deux premières pièces, celui des deux dernières exigeait entre cinq et dix pour cent moins d’éclairement lumineux. Cela montre qu’il est possible de réaliser de modestes économies d’énergie grâce à l’aménagement lumineux.

## 1 Introduction

Lighting codes and standards prescribe the quantity of illumination required to perform different visual tasks. Ensuring that designed spaces are pleasant and facilitate occupant behaviour, however, remains outside the purview of codes and standards, because our understanding of the relations between subjective reactions – and which aspects of the physical environment cue them – remains primitive. Consequently, lighting for subjective impact is more an art than an engineering discipline. Not only is this true for complicated and subtle subjective effects that might be cued or enhanced by lighting, such as using the lighting in a restaurant to enhance feelings of intimacy, it is also the case for other subjective reactions that relate to more basic perceptual processes, like apparent brightness.

Indeed, brightness perception has a long history of research, both in illuminating engineering, and especially in that branch of psychology known as psychophysics (see e.g. Reference 1 for a review). Illuminating engineers and lighting designers share this interest, because knowing what factors mediate brightness judgments could help in the more effective and efficient illumination of spaces: 'correct design attention to several "non-quantitative" lighting factors (might) compensate in some degree for reduction in overall quantity of light'[(2)]. Extrapolating the psychophysical findings to the more applied arena has been difficult, however, because the visual stimuli of interest to illuminating engineers are more complex than the simple stimuli used in the laboratory. In addition, limitations in photometry and heavy reliance on subjective assessment techniques, have slowed the development of comprehensive brightness-luminance specifications by the illuminating engineering community, and even produced conflicting and inconsistent findings.
This paper will briefly review past research and describe a pilot experiment investigating the influence of luminance distribution on perceived brightness in interiors. Evidence about what makes spaces appear bright or dim comes from several different and largely independent lines of research. Early investigators employed psychophysical methods to gain an understanding of the relationships between luminous intensity and perceived brightness. Many other studies addressing issues that fall under the broader mandate of 'psychological aspects of lighting' also describe relevant findings.

### *1.1 Psychophysics*

Psychophysics is the measurement of the perceived physical characteristics of a carefully measured stimulus, using well-defined behavioral responses from human observers. It has been exemplary in establishing predictive functional relationships between physical measures of simple light fields and quantitative perceptual effects.

In his extensive review of psychophysical studies Marsden[(3)] concluded that the perceived brightness of simple visual fields was a power function of luminance, thereby confirming the so-called 'psychophysical power law' expounded by Stevens[(1)] and his colleagues. In reviewing his own research, Stevens[(1)] concluded that the power function exponents relating perceived brightness to luminance ranged from 0.33 to 1.0, depending on the temporal and spatial characteristics of the visual stimulus.

Relating these findings to the more complex visual fields that make up room interiors was problematic. Although Marsden[3] described a number of temporal and spatial factors that could moderate the slope of the power functions relating perceived brightness to luminance, specifying general functions was virtually impossible. In fact, he concluded his review by stating that 'from the current literature all that can be predicted at the moment is a somewhat anarchical situation'[3]. This is hardly useful advice to the design community!

The problems in relating the psychophysical findings to interior applications stemmed from several factors. First, the stimuli judged by subjects in psychophysical studies were simpler than the complex visual fields presented by room interiors. Second, the problem of specifying visual adaptation for complex fields has prevented investigators from accurately characterising the visual impact of different spatial and temporal luminance patterns. Finally, limitations in photometry allow for only a rough and approximate characterisation of the physical stimulus. Without an accurate specification of the stimulus, it is difficult to determine what aspects of the visual environment are influencing the perceptual or subjective response of observers.

### *1.2 Psychological aspects of lighting*

Investigators working within the 'psychological aspects' tradition have adopted a different approach to identifying what aspects of lighting are responsible for different subjective effects. Rather than concentrating on painstaking definition of the physical stimulus, as had been the case with psychophysics, these investigators used a variety of subjective rating techniques to characterise the psychological responses that could be cued by illuminated interiors. By more accurately characterising psychological effects, they believe it should then be possible to work backwards, and identify what aspects of illuminated spaces cued the observed psychological effects.

In the 1970s John Flynn in the US initiated a research program that was to establish a series of design recommendations which are still followed[4], and which have even received the imprimatur of the Illuminating Engineering Society of North America[5]. Flynn consistently and repeatedly concluded that the apparent brightness of interiors was determined by 'the perceived intensity of light on the horizontal activity plane'[6], a somewhat vague and perhaps different conclusion than that drawn by the psychophysicists. This might suggest that for extremely complex visual fields, such as might be observed in interior spaces, the function relating luminance to perceived brightness was linear. If true, problems with photometry and the specification of visual adaptation, could be ignored by designers since the apparent brightness of a room would depend solely on the amount of light falling on the horizontal surfaces in the space.
This idea was difficult to reconcile with the results from psychophysics, and contradicted other earlier and contemporary work on psychological aspects of lighting. Other studies had demonstrated that the apparent brightness of spaces could also be influenced by light source colour [7-11], and lamp colour rendering[11-14]. However, while these other studies

showed that perceived brightness was not always a simple function of illuminance, they sometimes produced inconsistent results[7,9,10].

More recently, other investigators have extended the list of factors that can influence the perceived brightness of interiors. Rowlands *et al*[15] studied the relations between subjective reactions to lighting and the luminous environment in a full scale model office, and in real offices. They found brightness could be achieved either by manipulating horizontal and vertical illuminance, or the average luminances within the field of view. Further, they contended that luminances of vertical surfaces were more important to brightness perception than were the luminances of actual luminaires. This was in contrast to Bernecker and Mier's[16] finding that the presence of a bright element in a luminaire could increase the perceived brightness of interiors.

Several other investigators have attempted to relate what is perhaps the opposite of brightness, namely gloom, to measures of ambient lighting. Rothwell and Campbell's[17] subjects reported that the light was 'getting dim' when the luminances on a simple visual acuity task ranged from 110 to 28 cd $m^{-2}$; luminances between 28 and 3.6 cd $m^{-2}$ were judged as 'gloomy'. Shepherd, Julian and Purcell[18] studied subjective judgments of three different ambient lighting levels in a complex realistic visual field. These investigators found ambient lighting was described as 'gloomy' only when the adaptation luminance in the field of view ranged from 5 to 9 cd $m^{-2}$. The two other adaptation luminance conditions used in the experiment (6-11 and 38-60 cd $m^{-2}$) were not judged as gloomy.
Perry, Campbell and Rothwell[19] speculated that nonuniformities in the distribution of luminances within a space could lead to the perception of gloom, which they attributed to visual adaptation levels falling below the lower limit of the rod saturation region. Collins, Fisher, Gillette and Marans[20] also speculated that the distribution of luminances within a space was responsible for differences in rated satisfaction and brightness for several different lighting systems studied in a post-occupancy evaluation project.

Although the psychological aspects work has provided tantalising clues about what aspects of ambient lighting can influence perceived brightness (and gloom), the design utility of this information has been limited by at least three important factors. First, different studies have sometimes produced contradictory results. For example, Kruithof's[7] often-cited work was recently contested by Cuttle and Boyce[9], and by Davis and Ginthner[10]. Rowlands et al.[15] claimed that the appearance of a luminaire is unimportant, whereas Bernecker and Mier[16] show that the appearance of a bright element on a luminaire can have an effect on perceived brightness. While these contradictions probably stem from the impossibility of simultaneously studying all the factors that might influence perceived brightness, they have slowed the transfer of research findings to design practice, which needs well-established and clearly formulated principles.

Second, as with psychophysical experiments, the inability to specify precisely visual adaptation and limitations with photometry have frustrated researchers. Traditional spot luminance meters provide an incomplete specification of the visual parameters believed to be important in brightness perception in interiors. If, as recently suggested, the distribution of luminances within a space will influence perceived brightness, then the range and variation in luminances within a space are of interest. Accurate measures of range and variation require more luminance data than are practical to collect using a spot luminance meter.

Finally, investigators working within the tradition of psychological aspects of lighting research have relied on subjective rating data to draw conclusions about what makes spaces appear bright or gloomy. This is problematic if the eventual goal is a set of recommendations that specify perceived brightness-luminance relationships; subjective ratings only give information about the rank ordering of a set of stimulus conditions, not the magnitude of the difference that exists between them. Although it is interesting to know that subjects will rate one space as brighter than another, designers and illuminating engineers also need to know how much brighter, since without this information it is difficult to balance the costs of different design decisions with the return in subjective effect.

### *1.3 Overview*

In sum, psychophysics has succeeded in establishing predictive functional relationships between physical measures of simple light fields and quantitative perceptual effects; relating these findings to the more complex visual fields that make up room interiors has been problematic. Psychological aspects research establishes that spatial distribution of light(15,16,19,20) and intensity — measured as either luminance or illuminance(6,17,18) will reliably affect perceived brightness more than either lamp source colour or lamp colour rendering. However, the nature and magnitude of these effects in realistic interiors have been difficult to characterise.

In the experiment reported in this paper we used experimental design to examine the effects of intensity and spatial distribution of light on perceived room brightness. This paradigm is more complex and rigorous than the quasi-experimental procedures(6,15), or very simple experimental designs(18) used in previous studies. We also used digital image processing to characterise the luminance distributions studied in the experiment. The results of the experiment provide a first step towards establishing the direction and magnitude of luminance distribution effects on perceived brightness, and will help designers and illuminating engineers evaluate the utility of varying luminance distribution to achieve variations in perceived brightness. We also hope the experimental paradigm we describe will be useful to other researchers interested in evaluating hypotheses about how other variables affect perceived brightness.

## 2 Methods and procedure

We used a psychophysical matching paradigm to test the effects of illuminance level, and luminance distribution, on perceived brightness. In a matching experiment, the brightness of one object is adjusted until it matches the brightness of another object. Subjects in our experiment viewed one office, and then were asked to adjust the lighting in a second office so it appeared as bright as the first. The dependent measure was the working plane illuminance required to achieve an impression of equivalent brightness. All factors in the two offices were held constant except the illuminance at the working plane, and the luminance distribution on the walls. Rooms having the same working plane illuminance but different luminance distributions nevertheless had the same average luminance from the subject's point of view. Therefore in this experiment the working plane illuminance required to achieve an impression of equivalent brightness actually serves as an indirect measure of the overall luminance required to match brightness. We expect an effect for illuminance: more light will be required to match brightness for rooms with 700 lux on the working plane than for rooms with only 300 lux on the working plane. If luminance distribution also has an effect on perceived brightness then more or less illuminance will be needed in one room to achieve an impression of equivalent brightness as in a second room with a different luminance distribution.

### *2.1 Experimental rooms and apparatus*

The experiment was conducted at the IRC/NRC subjective reactions laboratory. The laboratory consists of four rooms finished to represent 'typical' North American middle management office stock. The entrance to the laboratory suite is through a waiting room. Each room is located off a central corridor. Each room is nominally 3.6 m X 4.5 m, with a 2.4 m high ceiling. An Armstrong concealed spline non-chamfered ceiling was installed throughout the four rooms and corridor. Achromatic shades of grey were used on the interior finishes and furnishings throughout, to prevent any changes in apparent brightness that might occur as a function of colour.

The facility was furnished from the Steelcase Series 9000 range. The furniture interior surface finishes are described in Table 1. Art prints for each of the four rooms were purchased from the National Gallery of Canada, and framed by a local commercial gallery. Each print was mounted in a custom frame, using special low reflectance glass to minimise reflected glare from luminaires. Wall clocks were mounted in each room on the wall opposite the door. All clocks were set at 10.30 for the duration of the experiment.

**Table 1** Furniture and interior surfaces finish specifications

| Item | | Manufacturer | No. | colour | Reflectance |
|---|---|---|---|---|---|
| 1 | Carpet (pattern: Manchester) | Stratton Canada | 6300/72 | Laurel Griege | 0.11 |
| 2 | Base board (100 mm high) | Johnsonite | | Silver grey | 0.36 |
| 3 | Paint finish for door | Sico Paint | 3209-21 | | 0.75 |
| 4 | Paint finish for door trim | Sico Paint | 3209-41 | | 0.442 |
| 5 | Vinyl wall cavering (pattern: Espere) | BF Goodrich Koroseal | 0824-92 | Pearl | 0.58 |
| 6 | Work surface laminate | Steelcase | 2782 | Grey value 1 | 0.48 |
| 7 | Workstation paint trim | Steelcase | 4654 | Grey value 2 | 0.33 |
| 8 | Desk chair fabric | Steelcase | B376 | Violet value 3 | 0.19 |
| 9 | Desk chair outer shell and trim | Steelcase | 6250 | Red value 5 | 0.02 |
| 10 | Guest chair fabric (pattern Coarsweave) | Steelcase | 5953 | Grey value 3 | 0.12 |
| 11 | Guest chair outer shell and trim | Steelcase | 6212 | Grey value 2 | |

Working plane illuminance was continuously monitored using illuminance cells placed on the floor, behind the desk. Calibration factors were established before the experiment to relate measured floor illuminance to working plane illuminance. Output from every meter was displayed on a digital voltmeter, mounted at the experimenter's station located at the end of the central corridor. This allowed the experimenter to easily set and monitor the light levels in the four rooms. The light level in each room was controlled by a variac transformer, which gave a range of working plane illuminance of about 650 lux (minimum about 150 lux - maximum about 800 lux). During the experimental trials, the variac dials were covered to prevent cues to subjects about equivalent brightness from dial position; the change in illuminance as dial position was varied also differed slightly for each variac, preventing inferences about equivalent brightness due to tactile feedback from dial position.

Subjects viewed every room through a viewport, positioned approximately 138 cm from the floor. The viewport was mounted in a grey plywood panel (r about 0.3) that covered most of the door opening (a 82.5 cm space from the floor to the bottom of the panel allowed air circulation). A painted metal partition was positioned parallel to the floor on the room side of the grey plywood panel, just above the viewport. This prevented subjects from seeing the real ceiling of the room viewed, so that differences in luminaire brightness would not affect judgments. From the subject's viewing position the metal partition appeared about the same reflectance as the real ceiling in the space. No subjects commented on being unable to see the real ceiling, or complained about the appearance of this 'false ceiling'. Figure 1 depicts actual views into two of the four rooms.

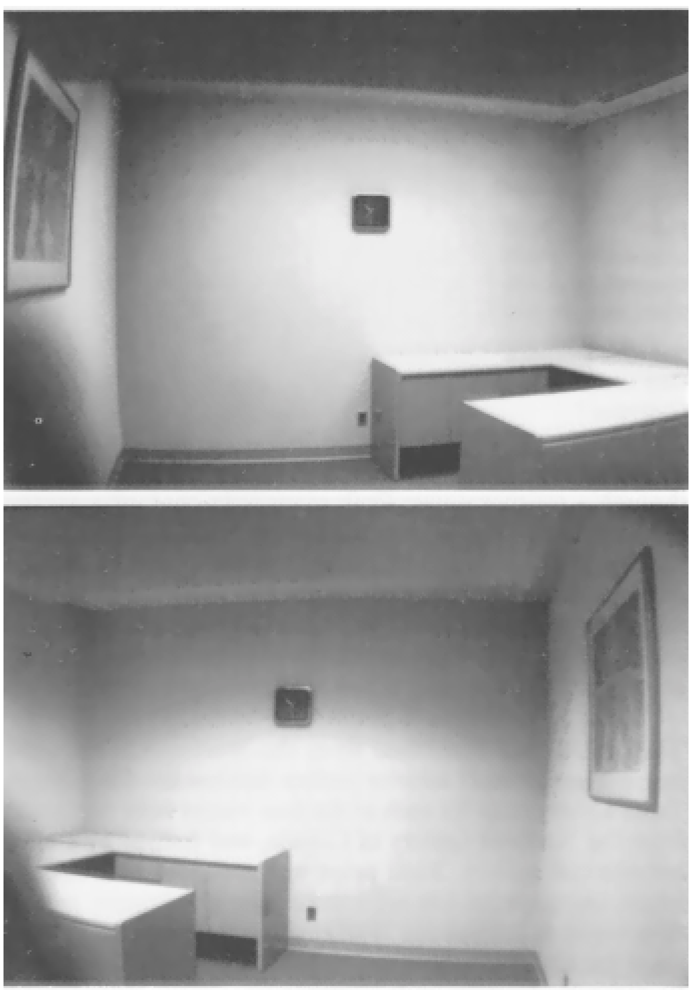


**Figure 1** Photographic images of two rooms used in the experiment: Top, a room having a relatively uniform distribution of luminance over the field of view; bottom, a room with a nonuniform distribution of luminance over the field of view

### *2.2 Ambient lighting*

Two of the four rooms had ambient lighting that produced a relatively uniform distribution of luminance over the interior walls of the room, while two rooms had lighting that produced a more nonuniform distribution of luminance over the interior walls of the room (see Figure 1). Although the distribution of luminance was different, all rooms had the same average luminance across the subject's field of view when the working plane illuminance was the same, as verified by digital image processing. Mean pixel counts from digital images of the complete field of view in all rooms were equivalent, when the working plane illuminance was the same. Three levels of working plane illuminance (300 lux, 500 lux, 700 lux) were used in the experiment.

Ambient lighting in all four rooms was provided by 40 W cool white lamps installed in commercially available luminaires. The luminaires in the two rooms that had a uniform luminance distribution were equipped with plastic prismatic diffusers, while those in rooms with the nonuniform luminance distribution were equipped with deep-cell parabolic louvres. To achieve the same range of working plane illuminances the lamps mounted in luminaires with plastic diffusers were wrapped with spirals of black electricians tape, while the undersides of the lamps in luminaires with deepcell parabolic louvres were painted black.

There was no overhead lighting in the central corridor for the duration of the experiment; ambient light spilled into the
central corridor from the four test rooms. This was sufficient for subjects to see as they completed the experiment.

### *2.3 Subjects and protocol*

Thirty subjects (four females, 26 males; 22-62 years, mean age 41 years) participated in the experiment. All were drawn from the staff of the Institute for Research in Construction. When subjects reported for the experiment, they were given the following instructions to read.

*'This experiment is concerned with how lighting can influence the appearance of rooms. Your task will be to match the brightness of the lighting in two different rooms. The experimenter will adjust the lighting in one room, and then ask you to adjust the lighting in the second room, using the control located next to the door, until the second room appears as bright as the first.*

*On each trial the experimenter will indicate which room you are to adjust and which room to use as the standard. Look in the standard room first, and then begin to adjust the lighting in the second room. In making your adjustments you will be allowed to view both rooms as many times as you wish. Once you are satisfied the two rooms are the same brightness, inform the experimenter you have completed the trial.*

*You will be given several practice trials before the experiment begins. Any questions or problems you are having should be mentioned at this time.*

*Before we begin the experiment you will be given a test to assess your vision. This is a general test that examines a number of different aspects of vision. This test is used to ensure that all of our subjects meet the minimal visual requirements for the experiment.'*

After reading the instructions, subjects completed the Keystone Ophthalmic Telebinocular visual screening test, and were then escorted into the test facility central corridor where the general procedure was explained to them and a series of five practice trials was administered. The practice trials presented the range of conditions subjects could expect in the experiment, ensured subjects understood the task before data collection started, and allowed 15-20 minutes visual adaptation. The procedure followed during the practice trials was identical to the procedure used during the experiment. If subjects experienced any difficulties these were corrected during the practice trials.

Once the practice trials had been completed and any questions answered, the experiment began. In every trial, the subject was asked to match the brightness of two rooms, first viewing a standard room and then adjusting the light level in a second room, the comparison room. The light level in the comparison room was set at maximum on half the trials, and at minimum on the remaining half of the trials. Subjects were allowed to view the standard and comparison rooms as many times as they needed to ensure an accurate brightness match. Every subject compared six unique lighting configurations in all (three levels of working-plane illuminance (300 lux, 500 lux, 700 lux), crossed with two luminance distributions). Over the course of the complete experiment subjects saw every unique lighting condition four times. By including this trials factor, we can check whether subjects get better at the brightness matching task with repeated exposure to the same stimulus condition.

In the control comparisons, subjects matched the brightness of two rooms having the same luminance distribution (matching the brightness of a room having a [non]uniform luminance distribution to a room with a [non]uniform luminance distribution). In the experimental condition, subjects matched the brightness of two rooms having different luminance distributions (matching the brightness of a room having a uniform luminance distribution to a room with a nonuniform luminance distribution, and *vice-versa).* Experimental and control comparisons were presented in counterbalanced order. In half of the experimental trials subjects viewed the room with the uniform luminance distribution first, to avoid order of presentation biases. It took about 1.5 to 2 hours for subjects to complete all 48 comparisons (3 illuminance levels X 4 distribution comparisons X 4 trials).

## 3 Results

Table 2 shows the working plane illuminance required to achieve impressions of equivalent brightness, for both the control and experimental conditions. In the control comparisons, subjects matched the brightness of two rooms having the same luminance distribution, and were remarkably consistent in their settings for rooms with both uniform and nonuniform luminance distributions. As expected, subjects required more light to match brightness for rooms with 700 lux on the working plane than for rooms with only 300 lux on the working plane. However, when comparing rooms with the same luminance distribution, subjects needed slightly less working plane illuminance than the nominal setting in the standard room to achieve equivalent brightness at 500 and 700 lux. That is, they became less accurate as illuminance increased.

**Table 2** Mean working plane illuminance (lux) required to achieve equivalent brightness in comparison room.

| Working plane Illuminance (lux) | Control comparison | | Experimental comparisons | |
|---|---|---|---|---|
| | Unif.-Unif. | Nonunif.-Nonunif. | Nonunif.-Unif. | Unif.-Nonunif. |
| 300 | 310 | 302 | 344 | 277 |
| 500 | 475 | 471 | 530 | 443 |
| 700 | 642 | 642 | 688 | 609 |
| Mean | 476 | 472 | 521 | 443 |

In the experimental comparisons, subjects matched the brightness of two rooms having different luminance distributions. The results are clear and consistent. The room with the nonuniform luminance distribution appeared brighter. So, for example, subjects needed more working plane illuminance than the nominal level in the standard room, when adjusting lighting in the room with the uniform luminance distribution (and *vice-versa).* These results are summarised in Figure 2.

These conclusions were verified using a repeated measures analysis of variance. This analysis showed statistically significant main effects for working plane illuminance [$F(2,58) = 1335.84, p < 0.01$] luminance distribution [$F(3,87) = 49.41, p < 0.01$], and trial [$F(3,87) = 3.05, p < 0.05$]. There was also a statistically significant interaction between luminance distribution and trial [$F(9,261) = 2.14, p < 0.03$]. The variance explained ($\eta^2$; see Cohen[21]) by the statistically significant main ($\eta^2 = 0.006$ [Cohen's $f = 0.08$]) and interaction effects ($\eta^2 = 0.013$ [Cohen's $f = 0.11$]) involving trial are very small, whereas the statistically significant main effects for both illuminance ($\eta^2 = 0.6498$ [Cohen's $f = 1.362$) and luminance distribution ($\eta^2 = 0.1399$ [Cohen's $f = 0.403$) are bigger. The proportions of variance explained by the different independent variables is especially important here because it establishes that working plane illuminance only accounted for about 65% of the variability in the illuminance settings made by subjects. Therefore, at least 35% of the variability in these settings was due to other factors.

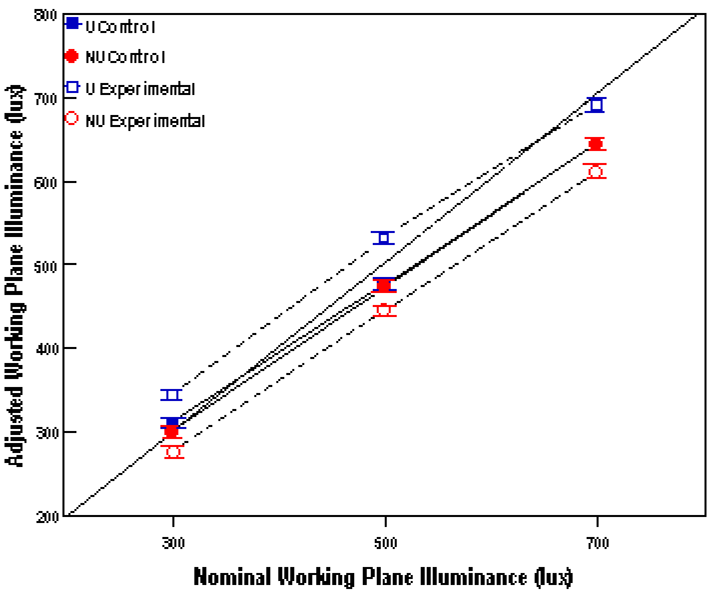



**Figure 2** Adjusted working plane illuminance as set by subjects in experimental comparison room required to achieve equivalent brightness in standard room. Error bars represent the standard error of the mean

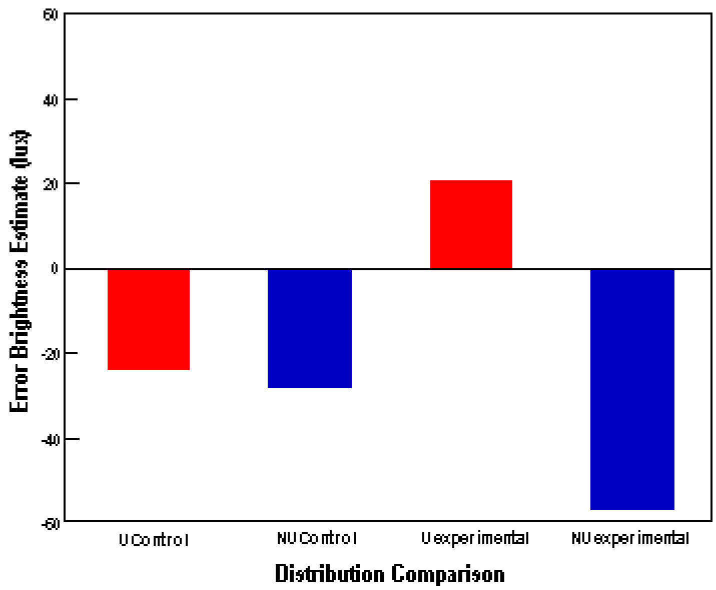
As an example of typical effect sizes, consider Cohen's analysis[21] of the data on girls' heights. The difference between the average heights of 15 and 16-year old girls is a small effect. In contrast, the average height difference between 16 and 18 year old girls is a medium sized effect: age accounts for about 5.44% of the variance in heights ($f = 0.24$). The average height difference between 14 and 18-year old girls is a large effect: age accounts for 20% of the variance ($f = 0.50$).

Using the raw illuminance values alone may distort the magnitude of variance accounted for by the different independent variables, especially the illuminance main effect because it is expressed over a range of several hundred lux. Expressing the dependent measure as a difference between the illuminance required to achieve equivalent brightness in the comparison room, from the nominal working plane illuminance set in the standard room, provides a more accurate index of the effect size. Table 3 shows the mean differences between the illuminance required to achieve equivalent brightness in the comparison rooms and the nominal working plane illuminances as set in the standard room.

Figure 3 depicts the data described in Table 3, and shows that when the luminance distribution in the two rooms was the same (U Control, NU Control), subjects needed less working plane illuminance than the nominal setting in the standard room to achieve equivalent brightness.

**Table 3** Mean difference between illuminance required to achieve equivalent brightness in comparison room and working-plane illuminance in standard room (lux)

| Working plane Illuminance (lux) | Control comparison | | Experimental comparisons | |
|---|---|---|---|---|
| | Unif.-Unif. | Nonunif.-Nonunif. | Nonunif.-Unif. | Unif.-Nonunif. |
| 300 | 10 | 2 | 44 | -24 |
| 500 | -25 | -29 | 30 | -57 |
| 700 | -58 | -58 | -12 | -91 |
| Mean | -24 | -28 | 21 | -57 |




In contrast, subjects required more working plane illuminance to achieve an impression of equivalent brightness when they were adjusting the lighting in the room with the uniform luminance distribution to make it appear as bright as the room with the nonuniform luminance distribution (U Experimental). When adjusting the lighting in the room with the nonuniform luminance distribution to make it appear as bright as the room with the uniform luminance distribution (NU Experimental), subjects required less working plane illuminance.

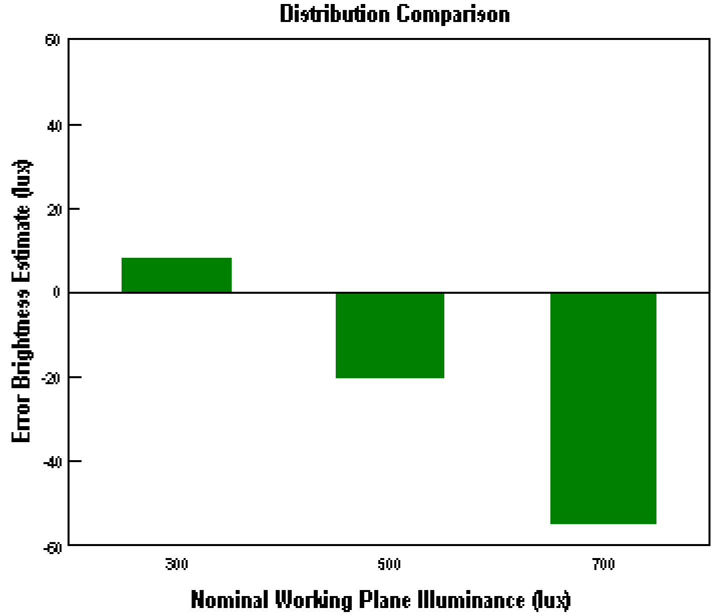



Figure 4 Mean error in working plane illuminance as adjusted by subjects in experimental comparison room required to achieve equivalent brightness at each of three nominal working plane illuminances set in comparison room.

These findings highlight the earlier conclusion that the rooms with the nonuniform luminance distribution appeared brighter than the rooms with the uniform luminance distribution. The overall tendency to underestimate required illuminance to achieve a brightness match is depicted in Figure 4; as working plane illuminance was increased, subjects needed less illuminance than the nominal setting in the standard room to achieve equivalent brightness at 500 and 700 lux.

A repeated measures analysis of variance of the difference scores showed statistically significant main effects for working plane illuminance [$F(2,58) = 46.11, p < 0.01$], luminance distribution [$F(3,87) = 49.41, p < 0.01$], and trial [$F(3,87) = 3.05, p < 0.05$]. There was also a statistically significant interaction between luminance distribution and trial [$F(9,261) = 2.14, p < 0.03$]. The variance explained by the statistically significant main ($\eta^2 = 0.006$ [Cohen's $f = 0.08$]) and interaction effects ($\eta^2 = 0.013$ [Cohen's $f = 0.12$]) involving trial remain small, whereas the statistically significant main effects for both illuminance ($\eta^2 = 0.06$ [Cohen's $f = 0.25$]) and luminance distribution ($\eta^2 = 0.09$ [Cohen's $f = 0.321$]) were moderated, but still medium-sized, when this different dependent measure is used.

The interaction effect between trial and distribution suggests that the illuminance required to achieve equivalent brightness changed slightly each time the subject saw every unique lighting condition, and that this practice effect depended on the specific comparison being made. Figure 5 depicts this interaction effect for the difference scores. For control comparisons in which subjects matched the brightness of rooms with the same luminance distribution (solid lines), mean difference scores got closer to the nominal setting in the standard room on successive trials. For experimental comparisons in which subjects matched the brightness of rooms with different luminance distributions (dashed lines), mean difference scores departed from the nominal setting in the standard room on successive trials.

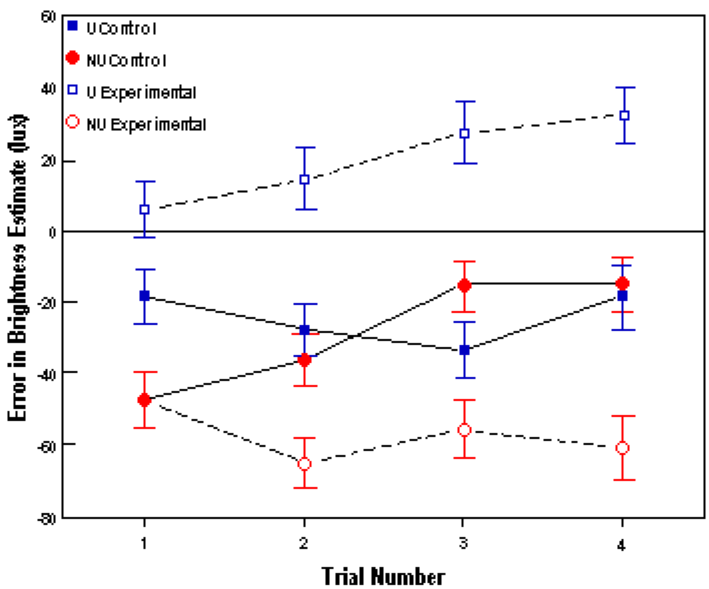
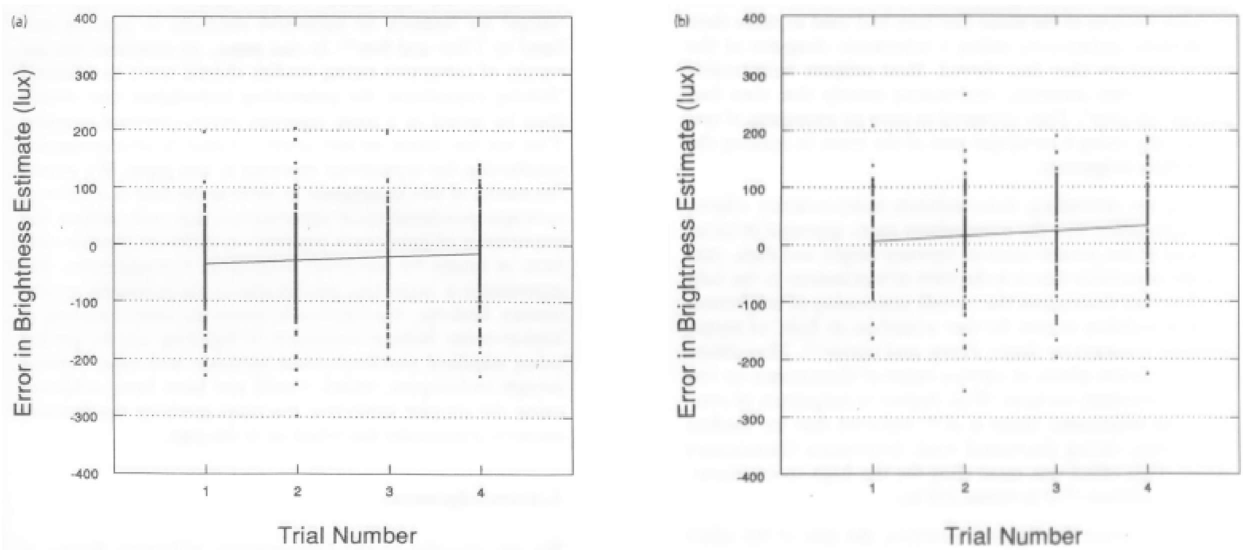



**Figure 5** Mean error in working plane illuminance as adjusted by subjects in experimental comparison room required to achieve equivalent brightness at each of four trials, for experimental and control comparisons. Error bars represent the standard error of the mean

These conclusions were verified using regression analysis. Linear regression was used to examine the relationship between difference scores and the trial number (i.e. whether a difference score had been collected from the first, second, third, or fourth time a subject made a particular comparison). The results of this analysis are depicted in Figure 6. Plot (a) shows that there was a statistically significant tendency for the difference scores to approach zero for the control comparisons [$F(1, 718) = 5.391, p < 0.021$]. This confirms that with practice, subjects got better at matching brightness in rooms with the same luminance distribution. Plot (b) shows a statistically significant tendency for the difference scores to increase for the experimental trials involving adjustments to the rooms with the uniform luminance distribution [$F(1,358) = 6.364, p < 0.012$]; plot (c) shows a slight but non-significant trend for the difference scores to decrease for experimental trials that involved adjustments to the rooms with the nonuniform luminance distributions [$F(1,358) = 0.654$, $p < 0.654$]. These analyses confirm that when comparing rooms with different luminance distributions, practice did not help, and in some cases resulted in more erroneous brightness matches.



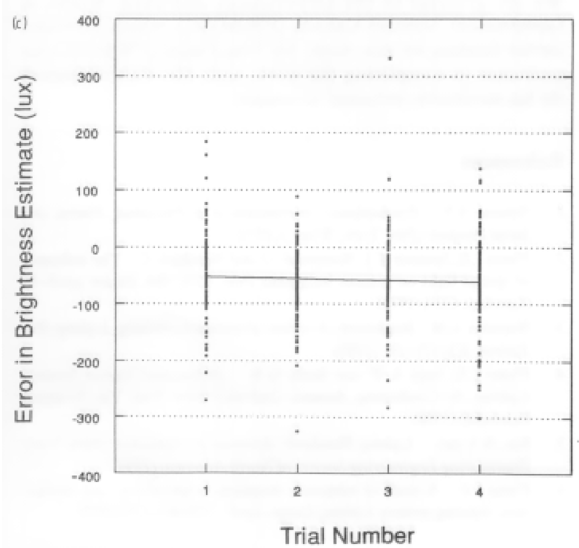




**Figure 6** Plots of residuals from linear regression analysis relating adjusted working plane illuminance required by subjects to achieve equivalent brightness and over successive trials. Plot (a) depicts results from control comparisons. Plot (b) depicts results from trials that involved adjustments to the rooms with the relatively uniform luminance distributions. Plot (c) depicts results from trials that involved adjustments to the rooms with the nonuniform luminance distributions.

## 4 Discussion

Lighting design has remained more of an art than an engineering discipline because our understanding of the relations between subjective reactions and which aspects of the physical environment cue them remains primitive. In our opinion, this imperfect understanding is largely because measurement technology that provides an accurate and comprehensive characterisation of the visual stimulus has been unavailable. Frustrated by an inability to accurately characterise the visual stimulus, investigators adopted different strategies which, although clever, did not completely fulfill the promise of subjective reactions research to provide design guidelines for comfortable and functional spaces.

We believe a clear understanding of the lighting variables that cue subjective effects will only be achieved by applying recently developed video photometry and image processing techniques[22], coupled with rigorous experimental designs for laboratory studies[23], and quasi-experimental designs for field studies[24]. Particular attention must also be paid to the dependent measures used to assess the subjective effects of interest. Our experiment applied experimental design and video image processing, along with a dependent measure used extensively in psychophysics, and produced useful results. We intend to use this paradigm to investigate the influences of other lighting variables on perceived brightness, and hope it will serve as a model for investigating other psychological effects that might be cued by lighting.

Before discussing future prospects for these methods, however, we turn to consider the results of this experiment. Our results confirm previous speculations[15,16,19,20] that the distribution of luminances within a space can influence how bright that space appears. More important, the findings of this experiment help establish the direction and magnitude of the effect. Perry, Campbell and Rothwell[19] speculated that nonuniformities in the distribution of luminances within a space could lead to the perception of gloom, whereas our results show that a nonuniform distribution of luminance made the rooms we studied appear brighter than identical rooms with uniform luminance distributions. Our results raise the interesting question: can a brighter space also appear more gloomy?

The answer depends in part upon the locations within the rooms that the subjects used to make their judgments. It is the nature of the nonuniform distribution that its brightest area is brighter than the brightest area in the uniform distribution, although the average luminances were equal. If the subjects consistently used the brightest area in the uniform distribution to determine equivalent brightness, then this would account for the outcome of this experiment without ruling out the possibility that the nonuniform room could also appear gloomy to occupants.

In a post-experimental questionnaire, the subjects were asked to mark the area of the scene that they had used to make their brightness judgments, using a schematic diagram of the office-mockups they had viewed. Most subjects were unable to answer this question, responding simply that they had looked "all over". They appeared to have no awareness of systematically using a particular part of the room in making the brightness judgments. During the debriefing, some subjects independently offered the explanation that the nonuniform room appeared brighter because of the greater contrast between bright and dark, raising the possibility that it is the ratio of luminances in the field of view that determines the overall impression of brightness. This possibility merits further attention in light of recent findings reported by Slater, Perry, and Carter[25] They examined subjective effects of varying ratios of illuminance on two desk (horizontal) surfaces. With respect to judgments of overall room brightness, Slater *et al*[25] reported that the median brightness rating decreased with decreasing illuminance ratios. This effect was most clear for the high room illuminance condition (730 lx versus 350 lx).

More important for lighting practice, the size of the effect observed in the pilot study reported here was not small, either statistically or substantively. Rooms with a nonuniform distribution of luminance were judged as requiring between five and 10% less working plane illuminance to achieve equivalent brightness than identical rooms with a uniform luminance distribution. This raises the possibility of modest energy savings through lighting design. Further experiments are planned to determine whether these figures accurately represent the magnitude of the luminance distribution effect for different variations in luminance distribution other than the small luminance distribution differences we used in this experiment.

We hope this pilot experiment will serve as a model for investigating the influences of other lighting variables on perceived brightness. Specifically, we intend to use the brightness matching paradigm developed in this experiment to evaluate the energy efficiency consequences of scotopic sensitivity. Berman and his colleagues have recently proposed that replacing standard cool white lamps with so-called scotopically enriched' narrow band light sources could significantly reduce lighting energy consumption[26-28].Scotopically enriched sources are judged as brighter, and result in smaller pupils, than other sources matched for illuminance, but less rich in 'scotopic lumens'. However, knowing that one lamp source was judged as brighter than another gives no information on the magnitude of the effect, which can be evaluated in a brightness matching experiment like the one we reported here.

Our experiment had subjects match brightness of actual rooms. The utility of these methods is obviously limited if they require a suite of full-size rooms. If we can replicate the results of the experiment using scale models, then it is more likely the method will be used by other investigators. If results from scale models can be validated, then it becomes possible to investigate other subjective effects which are not so easily investigated in a full-size room. For example, impressions of spaciousness are supposedly cued by bright, uniform wall lighting[6]. While it may not be practical to build full-sized rooms with moveable walls and ceiling, it is possible to build a large model chamber with the moveable features needed to investigate the effects of wall lighting on subjective estimates and adjustments of room volume.

Finally, in this experiment we have attempted to follow the 'recipe' for research on subjective reactions to lighting outlined by Tiller and Rea[29]. In that paper, we proposed that the results of subjective rating studies should serve as a formal 'fishing expedition' for generating hypotheses that would then be tested in a more rigorous psychophysical context. This was the course we attempted to follow in developing and conducting the experiment reported in this paper. We intend the results of this experiment to serve as the first in a series of strategic psychophysical experiments that will outline the importance of luminance patterns on different interior surfaces of rooms for perceived brightness. Consequently, this experiment is important not because it has produced revolutionary findings, but because it shows an understanding of higher-order human responses to lighting can be gained using standard psychophysical methods and experimental design techniques, which would not have been achieved using the simpler subjective reactions methods the lighting research community has relied on in the past.

**Acknowledgements**

We are grateful to the Department of Public Works & Government Services Canada (PW&GSC), which provided partial funding for this work; Mr Ivan Pasini (PW&GSC) for assistance in completing the work, and; Mr. Ralston Jaekel, for his invaluable technical assistance.

**References**

1 *Stevens S S Psychophysics: Introduction to its Perceptual, Neutral, and Social Prospects (New* York: *Wiley ) (* 1976)

2 Flynn J E, Spencer T J, Martyniuk O and Hendrick C The influence of spatial light on human judgment *Proc. CIE 18th Session* pp39-46 (London: CIE)(1975)

3 Marsden A M Brightness: A review of current knowledge *Lighting Res. Technol.* 1(3)171-181 (1969)

4 Flynn J E, Segil A W and Steffy G R *Architectural Interior Systems: Lighting, Air Conditioning, Acoustics* (2nd edn) *(New* York: *Van* Nostrand Reinhold) (1988)

5 Rea M S (ed) *Lighting Handbook: Reference* & *Application* (New York: Illuminating Engineering Society of North America) (1993)

6 Flynn J E A study of subjective responses to low energy and nonuniform lighting systems *Lighting Design Applic.* 7(2) 167-179 (1977)

7 Bodmann H W Quality of interior lighting based on luminance Trans. Illum. Eng. Soc. 32(1) 22-40 (1967)

8 Bodmann H W, Sollner G and Voit E Bewertung von beleuchtungsniveaus bei verschiedenen lichtarten *Proc. CIE 15th Session* pp502-509 (Vienna: CIE) (1963)

9 Cuttle C and Boyce P R Kruithof revisited: A study of people's responses to illuminance and color temperature of lighting *Lighting in Australia* 8(6)17-28 (1988)

10 Davis R G and Ginthner D N Correlated color temperature, illuminance level, and the Kruithof curve F. *Illum. Eng. Soc19 (1)* 27-38 ( 1990)

11 Kanaya S, Hashimoto K and Kichize E Subjective balance between general color rendering index, color temperature and illuminance of interior lighting Proc. *CIE 19th Session* pp274-278 (Kyoto: CIE) (1979)

12 Aston S M and Bellchambers H E Illumination, color rendering and visual *clarity Lighting Res. Technol.* 1(4) 259-261(1969)

13 Bellchambers H E and Godby A C Illumination, color rendering and visual *clarity Lighting Res. Technol.* 4(2)104-106 (1972)

14 Boyee P R Investigation of the subjective balance between illuminance and lamp color properties *Lighting Res. Technol 4 (2)* 11-24 (1977)

15 Rowlands E, Loe D L, Mclntosh R M and Mansfield K P Lighting adequacy and quality in office interiors by consideration of subjective assessment and physical measurement *CIE 7.4(1 )* 23 37 ( 1985)

16 Bernecker C and Mier J M The effect of source luminance on the perception of environment brightness F. *Illum. Eng. Soc.* 15(1) 253-271 (1985)

17 Rothwell S E and Campbell F W The physiological basis for the sensation of gloom: Quantitative and qualitative aspects *Ophthalmology and Physiological Optics* 7(2)161-163 (1987)

18 Shepherd A J, Julian W G and Purcell A T Gloom as a psychophysical phenomenon *Lighting Res. Technol.* 21(3) 89-97 (1989)

19 Perry M J, Campbell F W and Rothwell S E A physiological phenomenon and its implications for lighting design *Lighting Res. Technol19 (1)* 1-5 (1987)

20 Collins B L, Fisher W, Gillette G L and Marans R W Second-level post-occupancy evaluation analysis F. *Illum. Eng. Soc19 (2) 21-44* (1990)

21 Cohen J *Statistical Power Analysis for the Behavioral Sciences* (Second Edition) (Hillsdale N J: Lawrence Erlbaum Associates) (1988)

22 Rea M S and Jeffrey I G A new luminance and image analysis system for lighting and vision: 1. Equipment and calibration F. *Illum. Eng. Soc. NA* 19 (1) 64-72 (1990)

23 Kirk R E *Experimental Design: Procedures for the Behavioral Sciences* (Belmont, California: Brooks/Cole) (1982)

24 Cook T D and Campbell D T *Quasi-Experimentation: Design and Analysis Issues for Field Settings* (Boston: Houghton Mifflin) (1979)

25 Slater A I, Perry M J and Carter D J Illuminance differences between desks: Limits of acceptability *Lighting Res. Technol.* 25(3) 91-103 (1993)

26 Berman S M Energy efficiency consequences of scotopic sensitivity F. *Illum. Eng. Soc.* 21(1) 3-14 (1992)

27 Berman S M, Jewett D J, Fein G, Saika G and Ashford F Photopic luminance doff not always predict perceived room brightness *Lighting Res. Technol.* 22(1) 37-41(1990)

28 Berman S M, Jewett D J, Bingham L R, Nahass R M, Perry F and Fein G Pupillary size differences under incandescent and high pressure sodium lamps F. Illum. *Eng Soc.*16(1) 3-20(1987)

29 Tiller D K and Rea M S Prospects for semantic differential scaling in lighting research *Lighting Res. Technol.* 24(1) 43-52 (1992)