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Commission Internationale de l'Eclairage  
Internationale Beleuchtungskommission

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# TECHNICAL REPORT

## Guidance towards Best Practice in Psychophysical Procedures Used when Measuring Relative Spatial Brightness

**CIE 212:2014**

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UDC: 612.84  
159.931

Descriptor: Physiological optics. vision  
Vision, psychology



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This Technical Report has been prepared by CIE Technical Committee 1-80 of Division 1 "Vision and Colour" and has been approved by the Board of Administration as well as by Division 1 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-80 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau et Division 1 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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## **GUIDANCE TOWARDS BEST PRACTICE IN PSYCHOPHYSICAL PROCEDURES USED WHEN MEASURING RELATIVE SPATIAL BRIGHTNESS**

### **Summary**

This report reviews evidence for the procedures and other factors of experiments carried out to investigate relative spatial brightness, making recommendations of those aspects that ought to be considered as essential, or at least desirable, for best practice. These factors include the size and complexity of the visual field employed in trials, evaluation mode (separate, simultaneous, sequential or successive) and experimental biases associated with selection of stimulus range and response mode. Some of the issues raised will be considered, by some, to be obvious and already standard practice: unfortunately such awareness is not widespread. This report hence serves as a guide for those planning experiments to investigate spatial brightness. The proposals are presented as recommendations and not as compulsory. The report identifies those issues for which further research is desirable.

## **GUIDE DE BONNES PRATIQUES CONCERNANT LES PROCEDURES PSYCHOPHYSIOLOGIQUES UTILISÉES LORS DE LA MESURE DE LA LUMINOSITÉ SPATIALE RELATIVE**

### **Résumé**

Ce rapport examine les procédures et autres facteurs expérimentaux pratiqués lors de l'investigation de la luminosité spatiale afin d'en tirer des recommandations quant aux aspects essentiels, ou tout du moins désirables, aptent à constituer la meilleure des pratiques. Ces facteurs incluent la taille et la complexité des champs de vision employés dans les items expérimentaux, les modes d'évaluation (séparé, simultané, séquentiel ou successif) et les biais expérimentaux associés à la sélection de l'étendue des stimuli et le mode de réponse. Certains des problèmes abordés pourront paraître triviaux, mais, malheureusement, ce savoir n'est pas encore diffusé de manière optimale. Ce rapport sert donc de guide à tous ceux qui projettent d'expérimenter dans le domaine de la luminosité spatiale. Il donne un ensemble de recommandations dont le caractère n'est pas obligatoire, et il identifie les problèmes qui mériteraient davantage de recherche.

## **LEITFADEN ZUR OPTIMALEN VORGEHENSWEISE BEI PSYCHOPHYSISCHEN VERFAHREN ZUR MESSUNG RELATIVER RÄUMLICHER HELLIGKEIT**

### **Zusammenfassung**

Dieser Bericht gibt Einsicht in Verfahren und andere Einflussgrößen bei Experimenten zur Untersuchung relativer räumlicher Helligkeit, und gibt Empfehlungen hinsichtlich jener Gesichtspunkte, die als wesentlich oder zumindest wünschenswert angesehen werden sollten. Diese Einflussgrößen schließen die Größe und Komplexität des in Versuchen verwendeten Sehfeldes, die Bewertungsmethode (separat, simultan, sequentiell oder sukzessiv), sowie experimentelle Tendenzen, die mit der Auswahl des Reizbereichs und der Antwortmethode zusammenhängen, ein. Einige der aufgeworfenen Sachverhalte werden von einigen Lesern als offensichtlich und als gegenwärtige Standardpraxis betrachtet werden, aber leider ist solche Erkenntnis nicht weit verbreitet. Dieser Bericht dient deshalb als Leitfaden für jene, die Experimente zur Untersuchung räumlicher Helligkeit planen. Die Vorschläge sind als Empfehlungen anzusehen und nicht verpflichtend. Der Bericht stellt die Themen heraus, für die weitere Forschung wünschenswert ist.

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## Recommendations

This report presents recommended guidance for procedures used to compare spatial brightness under different sources of light. Some of these items are essential, others may be considered desirable. The body of this report describes the reasons for making these recommendations.

### i) Recommended requirements

| Procedure      | Recommended requirements                                                                                                                                                                                                                                                                                                                                                                                           |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Matching       | <ul style="list-style-type: none"> <li>• counterbalance position of the visual scenes (e.g. left and right)</li> <li>• counterbalance application of luminance adjustment</li> <li>• commence luminance adjustment from high and low initial settings</li> <li>• include null-condition trials</li> <li>• present visual scenes in all-possible-pairs</li> </ul>                                                   |
| Discrimination | <ul style="list-style-type: none"> <li>• counterbalance position</li> <li>• present visual scenes in all-possible-pairs</li> <li>• include null-condition trials</li> </ul>                                                                                                                                                                                                                                        |
| Adjustment     | <ul style="list-style-type: none"> <li>• use multiple stimulus ranges</li> <li>• use high and low anchors (initial illuminance settings)</li> <li>• use repeated trials to check internal consistency</li> </ul> <p>Note: further work is required to clarify best practice for using this procedure – see 7.2</p>                                                                                                 |
| Rating         | <ul style="list-style-type: none"> <li>• consider the number of response points – two issues are the presence / absence of a neutral point (i.e. odd vs even ranges) and that the number of response points and number of stimulus magnitudes should be similar</li> <li>• use repeated trials to check internal consistency</li> <li>• present pre-experimental standards to anchor the response range</li> </ul> |

### ii) Data to be collected and reported

Characteristics of test participants:

- Sample size and summary of age, gender and ethnicity.
- Normal colour vision (screened using the Ishihara Test under daylight or a daylight simulating source). If classification of colour deficiency is required then a further test is required such as the Farnsworth-Munsell 100 hue test.
- Whether the test participants were naïve or expert.

Apparatus characteristics:

- Procedure and apparatus.
- Lamp characteristics: spectral power distribution (SPD) in the form of numeric data or graphs, an indicator of the colour of the light source (e.g. correlated colour temperature (CCT) and/or chromaticity) and of the colour appearance of objects viewed under the light source (e.g. colour rendering index (CRI) or some other metric that may be proposed in the future), and other proposed metrics such as S/P-ratio.
- Characteristics of the visual scene (e.g. types and reflectances of surfaces and/or objects).
- Luminances in addition to illuminances where horizontal illuminance is the target variable.
- Luminance/illuminance uniformity if using homogeneous scenes. If using complex scenes (such as a room for example) report the highest contrast or luminance range or show pseudo colour scene luminance image.

- Type of photometric meters used and confirmation of calibration to national standard.
- Practice trials (number of trials and scenes observed).
- Unintended variations of light settings during the experiment, e.g. the range of CCT variation or MacAdam ellipses. This may be particularly necessary when using LEDs.
- Instructions/information given to test subjects (verbal and/or written).
- Original language version of rating scales (i.e. if reported in English but experiment carried out using native language).

Results:

- Mean and standard deviation are reported (or median and inter-quartile range for non-normal distribution). If the raw data were made available (e.g. on a website) this would allow subsequent independent analysis.
- Results of null-condition trials.
- Statistical tests used to analyse data.
- Correlation: report the numbers of pairs of observations on which a correlation coefficient is based.

# 1 Introduction

## 1.1 Aim

The purpose of the TC 1-80 work was to provide guidance to aid the successful implementation of the experimental procedures commonly used to measure spatial brightness. This was done through a review of the procedures and conditions under which these experiments have been carried out.

*Spatial Brightness* describes a visual sensation to the magnitude of the ambient lighting within an environment, such as a room or lighted street. Generally the ambient lighting creates atmosphere and facilitates larger visual tasks such as safe circulation and visual communication. This brightness percept encompasses the overall sensation based on the response of a large part of the visual field extending beyond the fovea. It may be sensed or perceived while immersed within a space or when a space is observed remotely but fills a large part of the visual field. Spatial brightness does not necessarily relate to the brightness of any individual objects or surfaces in the environment, but may be influenced by the brightness of these individual items (Fotios & Atli, 2012).

Evaluation of spatial brightness is a subjective assessment and experimenters need to be aware of the limitations of such assessments as can be observed through two statements:

*Quantitative subjective assessments are almost always biased, sometimes completely misleading.*

[Source: Poulton, E.C., British Journal of Psychology, 1977; 68; 409-425]

*In the study of perception, I think we get caught up a little in thinking that much has to do with what people see. Sometimes the procedural matter is more about influences on what people say, rather than what they see.*

[Source: Niall, K., TC1-80 member, June 2011; feedback on an early draft]

## 1.2 Procedures For Brightness Measurement

This report deals with quantitative methods for investigating relative spatial brightness. For a single trial involving an explicit<sup>1</sup> measurement of a specific perceptual attribute of a given visual scene, there are four basic types of procedures: adjustment, matching, discrimination and category rating. All four procedures have been used in past studies of spatial brightness and are therefore discussed in this report. The relationship between these is shown in Figure 1.

Relative spatial brightness implies the brightness of one scene compared with that of another scene. The procedures may employ relative or absolute measurements. Relative measurement involves a direct comparison between two light settings. Absolute measurement involves comparison between an observed light setting and a reference – such as an internal standard or memory – of what that scene would look like when lit by a different light setting or how it should appear under ideal conditions.

<sup>1</sup> An *explicit* measurement indicates that observers are given a task in which they explicitly respond to the visual scene under investigation. *Implicit* measurements are also possible (e.g. physiological measurements such as skin conductance or brain activity, eye-movements, and behavioural measurements such as task performance or approach-avoidance tendencies) but these are not within the scope of this report.

|                                                        | Absolute measurement<br>No external reference present | Relative measurement<br>Presence of an external reference |
|--------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------|
| <b>Passive</b><br>No interaction with the visual scene | <i>Rating</i>                                         | <i>Discrimination</i>                                     |
| <b>Active</b><br>Interaction with the visual scene     | <i>Adjustment</i>                                     | <i>Matching</i>                                           |

NOTE *External reference*: a second relevant visual scene is presented whilst assessment of the test scene is made, although not necessarily simultaneously.

*Interaction*: within the trial, the visual scene itself can be changed by the actions of the participant. In brightness studies this interaction is limited to one dimension – variation in quantity, such as luminance or illuminance, at a calibration point.

**Figure 1 — Basic procedures for explicit quantitative measurement of spatial brightness**

**Adjustment** is a single-interval<sup>1</sup> task. Participants are instructed to adjust the amount of light in a space to an optimum, preferred or ideal level, a magnitude production method. This may be through direct control of luminance levels (e.g. a rotary control dial) or by giving commands (e.g. higher or lower) to an experimenter who carries out the action. The output is luminance at the optimum level. Different visual scenes (e.g. lighting of different SPD) are presented individually, in succession, and the task is carried out in isolation of an external reference.

**Matching** is (usually) a two-interval adjustment task. Participants are presented with two scenes in spatial or temporal juxtaposition. One scene is the reference, and the luminance of this is held constant. Participants are instructed to vary the brightness of the second scene, by adjustment of its luminance, until it matches as near as possible the brightness of the reference scene. This action is usually carried out directly by the participant but may also be carried out by the experimenter following a command from the participant. The output is the ratio of luminances of the two scenes at equal brightness. The results of null-condition trials suggest that naïve test participants have a satisfactory understanding of the instruction to match the scenes for equal brightness.

**Discrimination** is (usually) a two-interval task. Participants are presented with two visual scenes in spatial or temporal juxtaposition. The luminances of both are fixed and the participant is instructed to report which scene is brighter. This is usually (but not necessarily) a forced choice task, where the response ‘equally bright’ is not allowed\*. The output is the frequency of responses by which a particular scene is considered to be the brighter. To enable subsequent estimation of the illuminance ratio for equal brightness the discrimination task is repeated with the illuminance of one or both of the visual scenes varied through several steps.

\*NOTE In null-condition trials where the response of equal brightness would be appropriate if allowed, the forced-choice procedure assumes that test participants will use one of the two available options (e.g. left or right) with equal frequency. Analysis of such data allows investigation of propensity to unfairly favour one of the two alternatives.

**Category Rating** is a single-interval task. A participant is presented with an illuminated scene and instructed to use rating scales to describe the appearance of the scene, e.g. a 4-point response scale representing a bright-dim axis with intervals labelled *very bright* (1), *bright* (2),

<sup>1</sup> A single-interval task is one in which only a single visual scene is observed; judgements are made against an internal standard such as a memory. A two-interval task is one in which two visual scenes are observed, the scene being judged and a visual comparison.

*dim* (3) and *very dim* (4). These four categories are usually assumed to be an interval scale. Different visual scenes (e.g. lighting of different SPD and illuminance) are presented individually, in succession, and are usually rated in isolation from external references. The output is the rating of spatial brightness.

### 1.3 Terminology

This report is phrased in terms of **luminance and illuminance**. Horizontal illuminance is the variable reported in the majority of studies; it is easy to characterize and it directly relates to lighting design practice. It is more correct, however, to measure illuminance at the plane of the observer's eyes, or to measure average luminance over the observer's visual field. If horizontal illuminance is employed to characterize the scene, the experimenter should take care to verify through measurement that it correlates with the more direct visual sensations of illuminance at the plane of the observer's eyes or luminance within the observer's visual field. Regarding spatial variation in illuminance / luminance, if the aim of an experiment is to compare lighting from lamps of different SPD then these distributions need to be the same under different lamps.

A **stimulus** is any energy change which excites a receptor: employed loosely, it refers to any object or event which has such an effect (Drever, 1952). The International Lighting Vocabulary (ILV) defines a colour stimulus as *visible radiation entering the eye and producing a sensation of colour, either chromatic or achromatic* (<http://eilm.cie.co.at/term/229>), and thus in the current context a stimulus may be defined as *visible radiation entering the eye and producing a visual sensation* by activating the photoreceptors.

In many instances in the literature the term stimulus (or stimuli) is incorrectly used to define what it is that the observer perceives, e.g. an illuminated scene, room, scale model or object. While this might be considered irrelevant as understanding is not impaired, or because 'stimulus' is in general use in the literature as the object/source the observer perceives in addition to the energy change definition, incorrect use of terminology should be avoided because it can lead to mistakes which often pass unobserved. According to note #6 from the ILV definition 17-567: Image state, scene-referred (<http://eilm.cie.co.at/term/567>) *the scene may correspond to an actual view of the surrounding world or the experimental ambient/environment*.

### 1.4 Exclusions from the Work of TC 1-80

There are further possible procedures that could be used to evaluate spatial brightness such as magnitude estimation. Magnitude estimation is used commonly in other fields, such as colour appearance, and requires participants to assign a number to the visual scene in accordance with the perceived magnitude along a particular dimension. Such further procedures have been omitted from the TC 1-80 review because:

1. They have not been widely used (if at all) in previous experiments of spatial brightness.
2. While the psychophysics literature may suggest problems with a particular procedure, the lack of previous data pertinent to spatial brightness means it is difficult to evaluate the presence and magnitude of such problems within judgements of spatial brightness.
3. Such further procedures can probably be considered as variants of the four procedures described in Figure 1. For example, magnitude estimation is a variation of category rating but with a response scale that is defined by the test participant rather than by the experimenter.

Clause 8 of this report identifies those elements of spatial brightness evaluations considered to be important and that should be addressed in further work but which have not been included in the current report for reasons including insufficient evidence to be able to offer guidance. This further work includes discussion of alternative procedures.

This report considers only the measurement of psychophysical responses to lighting. Measurement of other responses to lighting such as physiological (Kobayashi & Sato, 1992) or mental activity (Deguchi & Sato, 1992) are not discussed.

## 2 Size Subtended by the Visual Scene

'Size' refers to the angular size of the observed scene or room. The focus of TC 1-80 was on methods for measuring the effect of SPD on spatial brightness, the brightness of the ambient lighting in a space rather than lighting on a specific task. This frequently implies full field vision but smaller fields are also pertinent such as the view into a room when entering from a corridor. The full field of view, with binocular, natural viewing conditions, extends approximately 180° horizontally and 130° vertically (Hu & Houser, 2006; Boyce, 2003).

Previous studies have used different methods to enable full-field stimulation:

- Houser and colleagues had participants sit immediately in front of two adjacent rooms giving very near full-field stimulation (Houser et al., 2004b; 2009).
- Boyce had participants sit with their head inside his scale model offices (Boyce, 1977).
- Berman et al. and Houser et al. had their participants sit within the space of which illumination was being judged (Berman et al., 1990; Houser et al., 2009).

Smaller fields have been used in other studies, for example two degree (Alman, 1977) and ten degree (Houser & Hu, 2004) light patches, and booths viewed remotely giving a field of approximately 40 degrees (Fotios and Cheal, 2011a, 2011b). These stimulate areas of the retina smaller than full field. If the effect of field size is not significant, then experiments that employ smaller field sizes may simplify further experimental work. Many past studies of spatial brightness did not employ full field vision. This may have been for practical purposes: scale models are easier to set up than real rooms and it is easier to control extraneous parameters such as spatial distribution to ensure that SPD is the only variable.

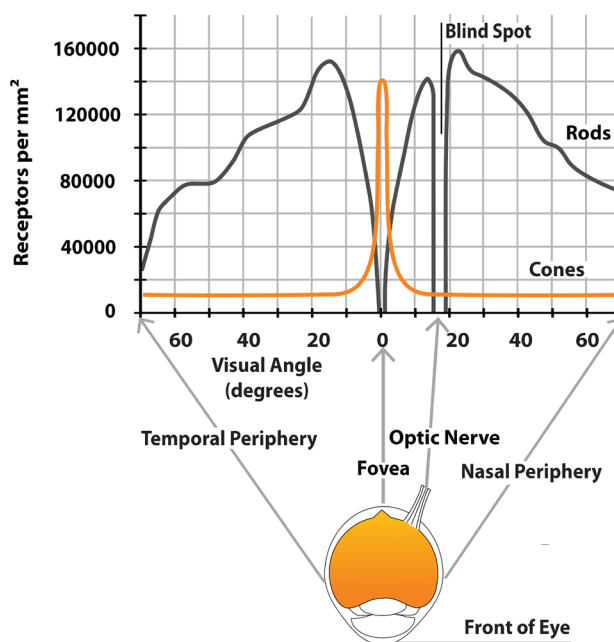
The magnitude of the difference between full field and smaller fields is open to question. It is therefore desirable to identify the minimum field size that can be employed in spatial brightness research that maintains a visual response representative of large fields including full field. If it is found that the full field response differs significantly from fields that are smaller than full field but that might also be considered large, then previous work will need to be categorized according to field size.

One reason why size of the visual scene may matter would be if there were significant changes across the retina. Rods and cones (and melanopsin cells: intrinsically photosensitive retinal ganglion cells, ipRGCs) are distributed differently across the retina (Figure 2) and similarly the proportions of the different types of cone photoreceptors vary across the retina (Boyce, 2003). The peak foveal cone density for the average retina is about 170 000 mm<sup>-2</sup> (geometric mean), but there is substantial variability both within individuals between eyes and across individuals (Curcio et al., 1990).

The ratio of the long-, medium-, and short-wavelength sensitive (LWS, MWS, and SWS) cone types in the fovea is approximately 40:20:1, with significant interpersonal variations (DeCusatis, 1997, Chapter 9). The density of the LWS and MWS cones declines with increasing eccentricity from the fovea: the SWS cones are largely absent from the fovea, reaching a maximum concentration just outside the fovea, and then declining with increasing eccentricity. Rods are absent from the fovea, but outside of the fovea they rapidly increase in density, peaking (~160 000 mm<sup>-2</sup>) at about 20° eccentricity from the fovea (Boyce, 2003). Hence, as the size of the field of view changes, there is a change in the relative proportions of the three cone types and the rods which are stimulated. The maximum density of cones occurs in the fovea; in the region surrounding the fovea the density of cones decreases as eccentricity from the fovea increases from 1° to 10° (Curcio et al., 1987). However, whilst there is a further progressive decrease in cone density beyond 10°, the rate of change is

much smaller. Osterberg's data suggests very little change of cone density in peripheral regions beyond  $20^\circ$ , being approximately  $5\,500\text{ mm}^{-2}$  at  $20^\circ$  decreasing to  $4\,500\text{ mm}^{-2}$  in the  $40^\circ$  to  $100^\circ$  region (Boyce, 2003). Viénot (2001) comments that neither macular pigment optical density nor cone optical density or cone type distribution vary considerably beyond a  $7^\circ$  diameter disk centred on the fovea.

If the distribution of photoreceptors affects spatial brightness judgements, then the distribution of cones in the human retina suggests that for field sizes up to approximately  $10^\circ$ , field size will affect brightness judgements, and similarly small ( $< 10^\circ$ ) fields will yield different brightness judgements to larger fields. However, there is little change in photoreceptor distribution between a field of size  $20^\circ$  and full field vision.



NOTE The rod density is zero at the fovea, while the cone density is maximum. There are no rods or cones at the place on the retina where the optic nerve exits the eye.

**Figure 2 — Photoreceptor density in the retina across a horizontal line that passes through the blind spot. Note that there is substantial variability both within individuals between eyes and across individuals**

(Image © Illuminating Engineering Society, The Lighting Handbook Tenth Edition: Reference and Application, used by permission)

There is some evidence that field size affects brightness judgements.

- As field size reduces from about  $2^\circ$  of visual angle the relative contribution of the y-b opponent system becomes progressively less important until, with very tiny centrally fixated fields, normal colour vision becomes tritanopic (Boynton, 1992) and this would affect brightness judgements if there is a chromatic contribution. Du Buf (1984) used two field sizes,  $2'$  and  $30'$ , and used brightness matching and magnitude estimation tasks, and there are clear differences in response between these two field sizes.
- Burnham (1952) used a colour matching task and found a significant effect of size, with a  $12^\circ$  stimulus appearing brighter than a  $2^\circ$  stimulus. Note however the potential for position bias and conservative adjustment in this work: the matching field was always a  $2^\circ$  field, always on the right-hand side and only this was varied by test participants.
- Kokoschka and Adrian (1985) carried out brightness matching using on-axis field sizes of  $3^\circ$  to  $64^\circ$ , using a 530 nm reference stimulus and test stimuli of 400 nm to 700 nm in

20 nm steps. They present results for three field sizes, 3°, 9° and 64° and their data suggest the difference between the 9° and 64° fields is small relative to the difference between the 3° and 9° fields. One caveat with these data is that a 2 mm artificial pupil was used in trials and therefore this is not representative of natural viewing.

- Hu and Houser (2006) obtained different colour matching results from a horizontally bisected circular field of diameter 10° and a larger, vertically bisected field of size 102° wide and 50° high which suggests these two field sizes would also produce different brightness responses.

There is indirect evidence that a field of size 37° produces similar brightness judgements to full field vision. Fotios and Cheal (2007) used three brightness assessment procedures, including brightness discrimination using side-by-side booths which subtended a visual field of 37° high and 71° wide, and category rating with full field vision (judgements were made within the illuminated room). The results from both tests placed the five test lamps in the same rank order of brightness at equal illuminance. Rank ordering is a very basic level of measurement and an equal interval scale is needed for a sensitive comparison, but this does suggest similarity of response from the two sizes of field. Rea et al. (2011) comment that good agreement between their results using an 18° × 18° field and an independent study suggest that “*large field sizes include those as small as 18° × 18°*”.

Loe et al. (1994) compared subjective ratings of a full-size mock conference room with a range of photometric measurements. They measured the average, maximum and minimum luminances of various field sizes, including the whole field, the ceiling, central circular fields of angular subtense 20° and 40° and horizontal bands of width 20° and 40°. Loe et al. concluded that the average luminance of the horizontal band 40° wide centred at normal eye height related well to the subjective ratings of the brightness of the scene, although there is only a slightly lower correlation with brightness ratings for the average luminance of the 20° horizontal band ( $r^2 = 0,70$ ) than for the 40° horizontal band ( $r^2 = 0,72$ )<sup>1</sup>.

DuBois (2009) raised two studies which compared visual evaluations in scale models with full size rooms. Cowdroy (1972) compared glare assessments in scale models with those obtained in full-scale rooms under real sky conditions and found that the use of large scale models (scale > 1:6) resulted in the same discomfort glare assessments as the full-scale tests. Lau (1972) compared judgements of pleasantness and gloominess in trials using a full size room (3,5 m length × 4,0 m width × 2,6 m height) and a 1/6 scale model and found that the responses were very similar – the same rank order of lighting conditions was found.

**Proposal:** a centrally fixated visual field of  $\geq 20^\circ$  adequately represents the spatial brightness response of larger fields, including full field vision. Without direct testing this is not a firm conclusion, but could be used as a first estimate for filtering previous studies of spatial brightness: studies using small fields would be omitted from analyses of spatial brightness, e.g. the studies by Alman (1977) and Alman et al. (1983) who used a 2° field, and tests using fields subtending a field of  $\geq 20^\circ$  would be considered relevant. The effect of size has not been directly tested and further work is needed to do so.

Investigation of visual field is being carried out within CIE TC 1-84: Definition of Visual Field for Conspicuity.

This discussion has identified several issues for which further research is required, not least of which is the need to confirm whether the proposed 20° field size does provide a satisfactory approximation of larger field sizes, including full field. These items are listed in Clause 8 of the current report.

<sup>1</sup> Note: consideration of  $r^2$  should include also the number of data pairs. In the Loe et al. analysis the number of data pairs is unknown: it is expected that these are the same for both cases in which case it is acceptable to draw a conclusion that  $r^2$  is similar for both cases, but not to comment on the absolute  $r^2$  value.

### 3 Complexity of the Visual Scene

Complexity is defined here as the presence of coloured surfaces and/or objects in the visual scene for a judgement of spatial brightness, and the level of this colourfulness, as these result in a scene that is more complex than a flat surface of neutral reflectance. Previous studies of spatial brightness under lighting from lamps of different SPD have been carried out using a variety of visual scenes, ranging from flat, uniform, neutral surfaces to interior spaces. They have been both achromatic and coloured, and interior spaces have tended to contain objects. Oguichi et al. (1999) purposefully placed four objects in their otherwise plain booths (sphere, cylinder, cone and cube) so that “*subjects could grasp the illumination by these solids*”.

There are two reasons why visual scene complexity could be expected to affect spatial brightness judgements under lamps of different SPD. Firstly, the interaction between the SPD of the light source and the spectral reflectances of the surfaces used in a particular study means that the SPD reflected to observers is unique to that study. Secondly, if the scene contains objects or details which draw the attention of observers, and thus visual fixation, then the test may be evaluating the foveal response rather than a large field response. Those methods used for measuring the spectral sensitivity of human vision that demand attention on to a target, such as minimally distinct border and Landolt C visual acuity, tend to produce a  $V(\lambda)$ -like sensitivity function (Lennie et al., 1993). Spatial brightness is a large field response and the small field or foveal response is different to that of larger fields (Hu & Houser, 2006; Kokoschka & Adrian, 1985). Therefore, different combinations of objects, surface details and colours may be expected to give different results in brightness judgements.

If there are significant effects of complexity, then to determine which visual scene is appropriate it is necessary to ask what a test is trying to measure when it compares light sources of different SPD. If it is the brightness of the light emitted by different sources, then a completely uniform environment of neutral spectral reflectance is required. This was the approach adopted by Berman et al. (1990) who had their observers facing a metal wall of few visual features and painted with a spectrally non-selective paint; the absence of colour and objects was a purposeful approach to avoid a foveal response. Alternatively, if it is the brightness of environments illuminated by the light sources that is of interest, then the objects and surfaces of test environments should be representative of those found in the real world. This was the approach used by Boyce (1977) who used a scale model office containing objects (model furniture and occupants), and the colourfulness of the surfaces was varied between trials. Boyce included an achromatic scene in his trials but suggested “*this is not likely to be of practical importance as the coloured interior is a much more realistic situation.*” (Boyce, 1977). Both studies (Berman et al., 1990; Boyce, 1977) conclude that lamp SPD affects brightness; what we do not know is how different the results from these methods would be if comparing the same set of lamps.

From a psychological point of view, any effect of complexity is explained by referring to the organization of the perceived world according to some fundamental laws, one of which is simplicity. Objects are characterized by qualities such as size, colour, movement in the simplest way to drive human behaviour. For this reason there is a tendency in perceiving objects with a single colour (colour constancy), size (size constancy), and motion (motion constancy). This is also the reason why continuous variations in luminance are coded by our visual system as not belonging to the object but to something non-relevant for the object, something which can change without the object changing, that is illumination. Therefore when luminance is varying continuously (such as with curved surfaces or flat surfaces but with an illumination gradient) it is easier to disentangle the varying component (illumination) from the uniform component (surface colour) than when the luminance is uniform. The Retinex theory of colour vision, formulated by Land (1977), exploits this principle by considering locally below-threshold variations in illumination, which then do not affect surface colours.

Something similar happens when adjacent surfaces of the same object are differently oriented in the 3D space: the luminance component of the colour change can be perceived as a change in illumination (the distinction between reflectance edges and illumination edges was introduced by Gilchrist (1977)). Of course there are natural objects whose surfaces are not

uniformly coloured: in this case variations are not only in lightness but also in hue and chroma with continuous transitions from one colour to another.

The results from five studies in which field complexity was purposefully manipulated, one at mesopic levels (Fotios & Cheal, 2011a) and four at photopic levels (Boyce, 1977; Boyce & Cuttle, 1990; Han & Boyce, 2003; Houser et al., 2004a) provide evidence for an analysis of the implications of scene complexity within the context of spatial brightness.

Fotios and Cheal (2011a) used a matching procedure with side-by-side booths and these were decorated to create four different visual targets: achromatic (interior surfaces of the test booths visible to participants were painted matt grey); coloured objects (four small pyramids made from coloured card (red, green, blue and yellow) were placed on the floor of the achromatic booth); coloured surfaces (approximately one third of the visible interior surfaces of the achromatic booth were lined with unglazed quarry tiles in three colours (red, beige and black), chosen to simulate the brick, stone and asphalt surfaces of residential streets); and uniform field (the front openings of the achromatic booths were covered with sheets of acrylic diffuser of neutral transmittance to provide a neutral and uniform field). In any trial, the same field design was used in both the left-hand and right-hand sides of the booths in a mirror image. Boyce (1977) used side-by-side booths and two procedures, matching and category rating, and varied the colour of surfaces inside the booths, representing achromatic, low colourfulness and high colourfulness. Boyce and Cuttle (1990) used category rating to judge perceptual attributes of lighting in separate evaluations; they varied the colour of surfaces in their test rooms and also examined whether the presence of an object (fresh fruit and flowers) affected judgements. Han and Boyce (2003) used a rating scale to compare judgements of brightness under three SPDs, three illuminances, and three levels of room décor, these described simply as warm, neutral or cool. Houser et al. (2004a) carried out brightness matching experiments in full-scale side-by-side rooms furnished as office interiors. The room surfaces and main furnishings were neutral grey, giving an achromatic environment; coloured items including prints on the walls, plastic plants and fruit, 3-ring binders and silk flowers were placed in the rooms to give a chromatic environment.

The effect of field complexity is considered here through four questions.

*1. Is there a difference in brightness judgements when using either an illuminated achromatic interior environment or a flat, uniform surface?*

Comparison of the illuminance ratios at equal brightness found with the uniform fields and the achromatic booths used by Fotios and Cheal (2011a) did not suggest a difference in brightness judgements. These two fields might also be considered as self-illuminated (the uniform field) and an illuminated surface (the achromatic field). Granzier et al. (2009) carried out colour matching using different visual fields, these being coloured patches that were either self-luminous (PC monitor) or illuminated colour samples, and their results also suggest that when the two samples being matched were of the same type, then the type of visual field does not affect the judgement.

*2. Does the insertion of (coloured) objects into an achromatic environment affect the outcome of brightness judgements?*

Fotios and Cheal's results do not suggest a difference in brightness matching between the coloured objects field and either the achromatic field or the uniform field (Fotios & Cheal, 2011a). Boyce and Cuttle (1990) introduced coloured items, in the form of fruit and flowers, into an otherwise achromatic room and this did not affect ratings of brightness or clarity (although it did increase ratings of colourfulness). Furthermore, Houser et al. performed brightness matching experiments in full-scale side-by-side rooms furnished as office interiors (Houser et al., 2004a; see Section 2.4 of Appendix C p. 46 and Table 14 on p. 99). In one session, the rooms were furnished only with neutral grey objects and in a second session colourful objects were placed in the rooms (e.g. file folders, binders, towels, wall-hung prints, plastic plants and foodstuff, and other colourful objects). See Figure 3 for photographs of the

rooms in the chromatic mode. Their results do not suggest a difference in brightness matching between the achromatic and chromatic environments.



**NOTE** During an experimental session the observer was seated in the chair in the centre of the photograph. A fabric wall placed behind the subject was removed for this photograph. The achromatic environment was created by removing all of the props (i.e. prints on the walls, plastic plants and fruit, 3-ring binders, silk flowers, towels, etc.).

**Figure 3 — Photograph of the side-by-side arrangement used by Houser et al. (2004a, 2004b) showing the chromatic environment of their experiment**

### *3. Do achromatic and chromatic environments lead to different judgements of spatial brightness?*

Boyce's (1977) matching task was carried out under five lamp combinations at two standard illuminances and in achromatic and chromatic booths, a repeated measures procedure carried out by 12 test participants. In the achromatic booth the curtains, acoustic screens and the end wall were black and white while in the chromatic booth these were coloured. Other items (e.g. model desks and chairs) were grey. Table 1 shows the results. Comparison of these data using the two-sample  $t$ -test does not suggest the mean illuminance ratios for achromatic and chromatic booths to be different in any of the ten cases.

Experiment-wise error rate is the probability of making a Type I error (concluding that there is an effect) in an experiment involving one or more statistical comparisons when the null hypothesis (no effect) is true in each case (Field, 2005). Experiment-wise error is defined by:  $1-(1-\alpha)^n$  where  $\alpha$  is the desired level of significance and  $n$  is the number of statistical tests carried out. For this analysis of Boyce's data, the ten  $t$ -tests lead to an experiment-wise error rate of 0,4, for  $\alpha = 0,05$ , i.e. a 40 % chance of making a Type I error. For this reason an ANOVA type test should be used (a single statistical method that tests the hypothesis that all group means are equal) but it is not possible to do this without access to the raw data, and these are nearly always unreported in past studies.

Applying the one-sample  $t$ -test enables the departure from unity to be determined; comparing conclusions thus drawn for the achromatic and chromatic booths for the ten lamp pair and illuminance combinations suggests the same conclusions are drawn in eight cases. In the two cases where different conclusions are drawn, in one case tests using the chromatic booth show a significant effect of lamp type whilst the achromatic booths do not, and vice versa in the second case. Note here the experiment-wise error rate ( $\alpha = 0,05$ ; 20  $t$ -tests) is 0,64.

While Table 1 does not suggest a consistent difference in the results of a matching task between booths of achromatic and chromatic interior surface colour, these particular data must be treated with caution because of the potential to make a Type I error.

**Table 1 — Comparison of mean illuminance ratios at equal satisfaction in visual appearance for lamps presented in achromatic and chromatic booths, after Boyce (1977)**

| Lamp pair                                                                                                                                    | Northlight / Kolor-rite |        | Northlight / Daylight |            | Kolor-rite / Daylight |        | Kolor-rite / White |            | White / White |        |
|----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|--------|-----------------------|------------|-----------------------|--------|--------------------|------------|---------------|--------|
| Reference illuminance                                                                                                                        | 300 lx                  | 600 lx | 300 lx                | 600 lx     | 300 lx                | 600 lx | 300 lx             | 600 lx     | 300 lx        | 600 lx |
| <b>Achromatic Interior</b>                                                                                                                   |                         |        |                       |            |                       |        |                    |            |               |        |
| Mean illuminance ratio                                                                                                                       | 1,17                    | 0,97   | 0,98                  | 0,83       | 1,16                  | 1,12   | 0,70               | 0,74       | 0,98          | 1,03   |
| Standard deviation $\sigma$                                                                                                                  | 0,50                    | 0,17   | 0,32                  | 0,26       | 0,19                  | 0,30   | 0,09               | 0,15       | 0,10          | 0,09   |
| Departure from unity ( <i>t</i> -test, one tailed)                                                                                           | n.s.                    | n.s.   | n.s.                  | $p < 0,05$ | $p < 0,01$            | n.s.   | $p < 0,01$         | $p < 0,01$ | n.s.          | n.s.   |
| <b>Chromatic Interior</b>                                                                                                                    |                         |        |                       |            |                       |        |                    |            |               |        |
| Mean illuminance ratio                                                                                                                       | 1,14                    | 1,07   | 0,81                  | 0,77       | 1,02                  | 0,98   | 0,73               | 0,78       | 0,97          | 0,95   |
| Standard deviation $\sigma$                                                                                                                  | 0,33                    | 0,20   | 0,22                  | 0,16       | 0,34                  | 0,33   | 0,15               | 0,25       | 0,10          | 0,13   |
| Departure from unity ( <i>t</i> -test, one tailed)                                                                                           | n.s.                    | n.s.   | $p < 0,01$            | $p < 0,01$ | n.s.                  | n.s.   | $p < 0,01$         | $p < 0,01$ | n.s.          | n.s.   |
| <b>Difference</b>                                                                                                                            |                         |        |                       |            |                       |        |                    |            |               |        |
| Statistical difference ( <i>t</i> -test, two tailed) between achromatic and chromatic interiors                                              | n.s.                    | n.s.   | n.s.                  | n.s.       | n.s.                  | n.s.   | n.s.               | n.s.       | n.s.          | n.s.   |
| Do the mean illuminance ratios for the achromatic and chromatic visual scenes lead to different conclusions regarding departure from unity?  | No                      | No     | Yes                   | No         | Yes                   | No     | No                 | No         | No            | No     |
| NOTE Number of test persons: 12 in all cases; n.s. = not significant.<br>See original article by Boyce (1977) for explanation of lamp types. |                         |        |                       |            |                       |        |                    |            |               |        |

Results from Boyce and Cuttle (1990) also do not suggest a difference in brightness judgements between tests carried out in achromatic and coloured rooms when using a category rating task. Room surfaces and objects in the 'achromatic' room were black, white or grey, other than a teak wood finish on the desk and book case. In the coloured rooms the light grey walls were repainted either pink or blue. Analysis of rating items made at only one combination of illuminance and lamp SPD (225 lx, 6 300 K) suggest no difference between rooms of different wall colours. Analysis across ratings made at three lamp SPD (225 lx; 2 700 K, 3 500 K and 6 300 K) suggested there no significant effect on ratings of brightness and clarity, although there was a significant effect on ratings of colourfulness.

Fotios and Cheal (2011a) carried out their brightness matching with an achromatic field and the same field with either coloured surfaces or coloured objects. From their four lamp pairs, in only one of these eight cases did statistical analysis suggest a difference between the achromatic and chromatic fields.

#### 4. Does the level of colourfulness affect the outcome of brightness judgements?

Boyce (1977) included three levels of colourfulness and these were achieved by varying the colours of curtains, acoustic screens and the end wall in the scale model office. For example, the curtain was coloured royal blue, kingfisher blue and light blue for the high, medium and low levels of colourfulness respectively. Other items of mock furnishing and occupants were of constant colour in all trials, and these were of a wide range of colours. The results did not suggest a significant effect of colourfulness on illuminance ratios in the matching procedure and no effect in the category rating task other than the ratings of colourfulness.

Results of brightness judgements recorded by Han and Boyce (2003) suggested significant effects of Correlated Colour Temperature (CCT) ( $p < 0,003$ ) and illuminance ( $p < 0,001$ ) but did not suggest a difference between the warm, neutral and cool levels of room décor.

### Summary

Field complexity (i.e. the presence of colour in a test environment, the level of this colourfulness, and the presence of solid objects) did not appear to affect the outcome of spatial brightness judgements in past studies, in the conditions under which these tests were carried out (Table 2).

These conclusions have been drawn from studies where parameters of scene complexity were purposefully varied, but the results did not suggest a significant effect. The conclusion of 'no difference' is always the easy option. It may be that any effect is indeed negligible, or if the effect is real then the experiments were not sufficient to reveal an effect. This could be examined in further work by establishing the magnitude of differences in colour that are needed to gain different judgements of spatial brightness.

Further work required related to field complexity is identified in Clause 8.

**Table 2 — Summary of questions raised to evaluate the effect of field complexity on judgements of spatial brightness**

| Complexity question                                                                                                                            | Response | Evidence                                                              |
|------------------------------------------------------------------------------------------------------------------------------------------------|----------|-----------------------------------------------------------------------|
| 1. Is there a difference in brightness judgements when using either an illuminated achromatic interior environment or a flat, uniform surface? | No       | Fotios & Cheal, 2011a                                                 |
| 2. Does the insertion of (coloured) objects into an achromatic environment affect the outcome of brightness judgements?                        | No       | Boyce & Cuttle, 1990<br>Fotios & Cheal, 2011a<br>Houser et al., 2004a |
| 3. Do achromatic and chromatic environments lead to different judgements of spatial brightness?                                                | No       | Boyce, 1977<br>Boyce & Cuttle, 1990<br>Fotios & Cheal, 2011a          |
| 4. Does the level of colourfulness affect the outcome of brightness judgements?                                                                | No       | Boyce, 1977<br>Han & Boyce, 2003                                      |