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Tuning the Spectrum of Lighting to Enhance Spatial Brightness: Investigations of Research Methods

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ABSTRACT
In this paper we describe research of spatial brightness at photopic levels and how this is affected by the spectral power distribution of the light source. Our research of experimental methods has identified strategies for best practice in experimental design; ignoring these leads to results which can give a misleading estimate of the effect of lamp spectral distribution on spatial brightness. This article reports the on-going meta-analysis of previous work and new experimental data pertinent to research methods. A preliminary set of reliable data are proposed for use with modelling to extrapolate the relationship between SPD and spatial brightness.

Keywords
Spatial brightness, spectral power distribution, research methods, evaluation mode, visual field.

INTRODUCTION
Spectral power distribution (SPD), along with spatial distribution, temporal modulation, and illuminance, is one of the fundamental variables available to the lighting designer. This article discusses the effect of SPD on impressions of spatial brightness at photopic levels typical of interior lighting.

The term *spatial brightness* is used to imply a subjective evaluation of the amount of light in a space. It is distinct from object brightness - the brightness of an illuminated surface or object - although brightness may be the term used by naïve observers, and may be considered akin to the visual clarity judgements investigated in some previous work [1-4]. Spatial brightness is a dominant perceptual attribute. Boyce and Cuttle asked test participants to describe the lighting in a room in their own words and found that they used mainly terms of brightness and clarity; pleasantness and colourfulness were among those also mentioned, but these very infrequently [5].

Interior electric lighting is a significant energy consumer. Within the EU, lighting in the commercial sector consumes 30% of total electricity consumption [6]; lighting accounts for up to 40% of energy costs in a typical UK office [7] and an average of 39% of the energy use in US office buildings [8]. Lighting recommendations are based almost entirely on ensuring visibility and the data on which these recommendations are based have not taken into account any possible effects of the spectral content of the light source. Visual performance models [e.g. 9] imply that virtually all tasks done in offices and schools could be done just as well at much lower illuminances than those currently used. However, illuminances have not been reduced because people like an interior to appear bright. Dim, gloomy lighting can induce a sense of visual discomfort which may change the observer's mood and motivation to carry out a task, particularly if the work is prolonged [10]. Thus, if a perception of brightness could be maintained at a lower illuminance, energy consumption and carbon emissions could be reduced.

There is evidence that light source SPD affects the perception of spatial brightness [e.g 11,12] and this provides a means for reducing illuminances whilst maintaining the same perception of brightness. To do this requires a tool for predicting how lamp SPD affects spatial brightness and hence reliable and appropriate evidence with which to develop the tool.

There is much ongoing work to investigate effects of SPD within the lighting community. The Illuminating Engineering Society of North America (IESNA) has established the Visual Effects of Lamp Spectral Distribution committee to investigate SPD effects on spatial brightness and visual effort at photopic levels, and new research was presented by several groups at the 26th Session of the CIE in Beijing, 2007.

The spatial brightness section of the IESNA committee has two stages of work. The first stage is to identify reliable empirical evidence that demonstrates an effect of lamp spectrum on spatial brightness at photopic levels; the objective of this article is to provide evidence to support decisions necessary when identifying reliable evidence. *Reliable* is here intended to mean data which are unbiased by the experimental procedure and through this are more consistent. Through experimentation, critical analysis of experimental data and literature survey, the authors have identified features of experimental design that might be considered best practise for research of subjective evaluations of lighting. The second stage is to identify a method for predicting the magnitude of the lamp SPD effect on spatial brightness, hence using the set of reliable data to test and develop prediction tools.

Around sixty studies have previously investigated lamp SPD effects on spatial brightness (or visual evaluations considered similar to spatial brightness), some reporting a significant effect while others report a negligible effect. The problem encountered when comparing the outcomes of these different studies is that each has tended to use a unique combination of independent variables and methods - lamp SPD, response task, stimulus size, illuminance and evaluation mode [13]. A first step in interpreting these data is an exploration of research methodologies to identify how these differences in methodology matter, hence to identify those methods giving reliable and appropriate estimates of lamp SPD effects on spatial brightness.

A problem within the body of previous work is that much of it must be considered unreliable, frequently because of incomplete reporting. There are three reasons for considering work to be unreliable. Firstly, the published work either reveals an experimental or subjective bias, or does not present sufficient data to check whether an expected bias has been successfully countered. Secondly, there are insufficient data to allow the results to be analysed; one common problem is that the mean value of the dependent variable is reported but without a measure of dispersion, and there are no raw data or references to further publications. Finally, descriptions of the apparatus and methodology are insufficient.

RESPONSE TASKS

The assessment of brightness is a psychophysical task that requires the test participant to make sensory responses to physical stimuli. These assessment tasks are usually one of three types:

- *adjustment*, where the participant is required to adjust the magnitude of one dimension of a stimulus (e.g. illuminance) toward a given sensation, such as matching the visual sensation of a reference stimulus;
- *discrimination*, where the test participant is required to make simple ordinal discrimination judgements of stimuli, e.g. which of two stimuli is brighter; and
- *category rating*, where the participant is required to assign numbers to stimuli to represent the sensation magnitude.

Matching

In the side-by-side matching task, two stimuli differing in illuminance and SPD are presented simultaneously, illuminating adjacent, identical spatial locations (Figure 1). The illuminance of one stimulus is adjusted by the test participant until the two appear, as near as possible, equally bright. If the ratio of the illuminances of these stimuli is different from unity then the brightness judgement must in some way be affected by differences in light source SPD. The authors recently reported on sources of experimental bias in the matching task [14] and these tend to exaggerate apparent differences between stimuli.

Figure1. Identical side-by-side rooms used in a matching task. This is a simultaneous evaluation.

There are three elements of the matching procedure that can affect the results. The first relates to the process of adjustment itself. There is a tendency toward conservative adjustment, whereby the variable stimulus is set to a lower level than expected [15]. This can most easily be seen in null condition data (matching using stimuli of identical SPD), where the mean illuminance of the variable stimulus is significantly less than that of the fixed stimulus at equal brightness, but is also evident in matches made between different types of lamp. When matching tests are carried out at a range of reference illuminances, there is a tendency for response contraction bias [16]; matches made at the higher illuminances are set to a lower than expected illuminance, whilst matches made at the lower illuminances are set to a higher than expected illuminance. Bias due to dimming can be countered by applying the dimming action to alternate stimuli on successive trials.

The second bias in the matching task relates to the stimulus position; whether a particular stimulus is located in the left-hand (LH) or right-hand (RH) field. Thornton & Chen [4] used side-by-side matching to compare visual clarity under different lamps. Their trials included four null conditions for which an illuminance ratio (RH/LH) of unity would be expected at equal clarity if there were no positional bias. Subsequent analysis [17] of these null condition data suggested a mean illuminance ratio (RH/LH) of 1.145 at equal clarity, although there are insufficient data to determine whether this is a statistically significant departure from unity. A positional bias has also been reported when using smaller fields; this was an observer who consistently reported the top half of a horizontally split field to be brighter than the bottom half, even when the top and bottom stimuli were reversed [18]. Positional bias can be countered by using lamps to illuminate alternate spatial locations in successive trials. Some studies do analyse their data for positional bias and in these it has been shown to have negligible effect [e.g. 19], but the majority of studies do not make this analysis, do not employ counterbalancing, and a positional bias must therefore be considered possible.

In many matching studies, possible effects of conservative adjustment bias and positional bias are compounded. Table 1 shows the results from Aston & Bellchambers' matching tests [1]. In these tests, *Kolor-rite* lamps illuminated the left-hand booth and three test lamp types alternately illuminated the right-hand booth. Test participants adjusted the illuminance of the *Kolor-rite* booth until the visual clarity of the two booths appeared equal, the test lamps being set to one of three reference illuminances. Neither dimming application nor spatial location were counterbalanced. In every case, the median illuminance of the *Kolor-rite* lamp is lower than the illuminance of the test lamp; it is not possible to say whether these differences in illuminance is due to lamp SPD or to experimental bias.

Illuminance of test lamps (lux)	**Median illuminance (lux) of Kolor-rite lamp at equal visual clarity with three test lamps**		
	Daylight	Warm White	White
200	170	130	145
400	270	230	270
800	560	460	435

Table 1. Results of Aston & Bellchambers' side-by-side matching test [1]. In every case the variable stimulus (Kolor-rite) in the left-hand booth was set to the lower illuminance.

The third bias relates to the initial illuminance of the variable stimulus, as set by the experimenter prior to each trial. This can be set to an illuminance either higher or lower than that of the reference stimulus, which may modify the observer's internal brightness reference. An effect of initial illuminance can be seen when an adjustment task is used for preference judgements, an absolute judgement carried out in the absence of a reference stimulus. Ray asked observers to adjust the illuminance of lighting to a level clear and comfortable to read at [20]. This was carried out under two types of tungsten filament (GLS) lamp, having either a clear-glass or blue-glass envelope. Eighteen observers repeated this twice for each type of lamp, once each starting from a high illuminance and a low illuminance. The results are shown in Table 2. It can be seen that the lamps were set to a higher illuminance when the initial illuminance was high than when the initial illuminance was low, and these differences are statistically significant ($p<0.05$, t-test).

	Clear-glass GLS lamp		**Blue- glass GLS lamp**	
Initial illuminance of stimulus	high	low	high	low
Mean preferred illuminance (lux)	1123	645	806	419

Table 2. Mean illuminances of lamps set to a level clear and comfortable to read at [20]. Note: unpublished undergraduate thesis, raw data analysed by Fotios [17].

For the side-by-side matching task, this suggests a trend for the variable stimulus to be set to a higher level at the matched condition when starting from a high initial illuminance and a lower level when starting from a low initial illuminance. This trend can be seen in the results from two studies [21,22] although it is not always a significant trend, but a significant effect in the opposite direction has also been found [23], i.e. the variable stimulus was set to a higher level when starting from the lower initial illuminance. It is clear that the initial illuminance of the variable stimulus can affect the outcome of a matching task, although the evidence is not conclusive as to the direction of the effect, but this is sufficient to warrant the precaution of counterbalancing the initial illuminance of the variable stimulus.

Many studies have not employed sufficient steps of counterbalancing, and did not include null condition trials with which to quantify the magnitude of any bias effects. Thus, of 18 brightness matching studies carried out at photopic levels only five were considered to be reliable [4,19,22,24,25]: nine were suggested to be unreliable due to lack of counterbalancing and four studies failed to provide sufficient data with which to make this analysis [14]. It has been shown that in the matching task there is negligible difference in outcome (illuminance ratio) when using different visual objectives (e.g. equal brightness, equal clarity or equal appearance) [26] and this conclusion enables the findings from the five reliable studies to be collated.

Discrimination

In the discrimination task, two stimuli of different SPD are presented at a range of different illuminances; at each presentation, the test participant reports which is the brighter. Previous work has used rapid sequential presentation of the two stimuli at the same spatial location (Figure 2) [e.g. 12,27] or simultaneous evaluations (Figure 1) [28]. Whilst judgement of the brighter of a pair of stimuli is a more precise and repeatable task than is adjustment for equal brightness, the discrimination task can be biased through the range of stimulus magnitudes selected. Identification of relative illuminances for equal brightness demands the discrimination task is repeated at a range of illuminances, and two studies have shown stimulus range bias is sufficient to affect the outcome of discrimination tasks [29,30].

Figure 2. A single spatial location illuminated using two different sources of light in rapid succession. This is a sequential evaluation.

Fotios & Cheal examined stimulus frequency bias, the distribution of illuminances above and below that which produces the same brightness as the reference stimulus [29]. *Biased* here means there are, for example, more cases when the test stimulus is dimmer than the reference than when it is brighter. Consider the observation of two lamps of different SPD at the illuminances at which they are expected (perhaps as according to parallel studies) to appear equally bright; a biased stimulus frequency causes identification of *brighter stimulus* to be unfairly biased toward the stimulus which has been less frequently identified as brighter in preceding trials. This can suggest a statistically significant difference between two stimuli when none exists. This may arise from subjects' preconceptions of chance, that each of a pair of stimuli must be correct (brighter) on an equal number of trials. To counter stimulus frequency bias, the number of stimulus magnitudes should be equally divided about that giving equal brightness.

Teller, Pereverzeva & Civan [30] sought brightness judgments of small red and blue targets presented on a white monitor screen. For each colour, a range of targets varying in luminance were presented in random order, and observers reported whether the target was brighter or dimmer than the surround. Three ranges of target luminance were used in successive trials – for the red target these ranges had mid-point values of -0.6, -0.3 and 0.1 log luminance relative to the white surround. Typically 11 target stimuli were used in each range, increasing in steps of 0.05 log units. It was found that a stimulus judged brighter than the surround on 100% of trials with a target range of lower mid-point luminance, was also judged dimmer than the (identical) surround on 100% of trials with a higher mid-point range of luminances. Thus, the stimulus range affected the brightness judgment; a stimulus was made to appear brighter or dimmer than the reference by changing the range of luminances in which it was presented.

Investigation of the discrimination task in research of lamp SPD and spatial brightness is on-going. It has been used in only a few studies, and these have not tended to use null-condition trials (stimuli of identical SPD and illuminance) which would otherwise provide evidence to validate the method.

Category Rating

In the category rating task different lighting conditions are evaluated separately (Figure 3) and attributes of the visual environment are rated using a scale that gives only a limited range of fixed numbers. Poulton [31] discusses many potential causes of bias within this task. A recent review applied Poulton's ideas to research using the category rating method, and found that this method can understate the effect of lamp spectrum [32].

Figure 3. A single space is illuminated by one type of lamp. Judgements are made of this in isolation before proceeding to the next stimulus. This is a separate evaluation.

Previous lighting studies have tended to use seven-point rating scales, for example a scale ranging from 1 (dim) to 7 (bright). There is some evidence that test participants are able to reliably distinguish between approximately seven categories of a uni-dimensional stimulus, and this is apparent for a broad range of sensory judgements, but with more than seven categories confusions become more frequent [33]. Green and Rao [34] demonstrated that a response range of around seven categories is able to adequately represent intended responses; fewer categories (2 or 3) lead to poor recovery and there are diminishing returns beyond six categories. The seven-point response range has commonly been used to define the semantic differential rating task, e.g.;

– *The semantic differential consists of a set of bipolar, seven-category rating scales* [35].
– *Semantic differential rating scales – a seven category range between the extremes* [36].

There is a tendency for respondents to avoid using the ends of a scale, to underestimate large sizes and overestimate small sizes, and this response contraction is enhanced if the response range has an obvious middle value such as with the seven-point scale [31]. Such an outcome can be observed in the findings of previous lighting research: Wake et al [37] used 7-point scales, and for their brightness rating they concluded "*the differences among lamps are extremely small*"; Akashi & Boyce [11] used 5-point scales (-2 to +2) with a middle neutral point marked '0' and found "*The mean ratings ... do not indicate any strong opinions, i.e. all mean responses are around neutral*". Because of potential response contraction bias it is not clear whether there really is no difference of brightness between the lamps used in these studies, under the particular conditions used, or if the mid-point value in the response range contributed to the test failing to reveal a difference. This bias can be countered by using a response range with an even number of response points.

The rating task is affected by the relative numbers of response categories and stimulus magnitudes [31]. If the response scale has fewer categories than there are stimuli, several stimuli will need to be grouped within each category, and this may hide the difference between two stimuli when this difference may be small but is nonetheless real. Consider the study by Boyce & Cuttle (their Experiment 1) which used 22 stimulus conditions, including four types of lamp and four illuminances, and a five-point response range [5]. Their participants would thus need to group several of the 22 stimuli within each response category. Their results reveal that only one of the 19 rating items (dim) was found to be significantly affected by lamp type, and this at $p<0.05$ may be a Type I error (i.e. erroneous rejection of the null hypothesis). Differences in brightness due to illuminance were significant; these may be more prominent than differences due to SPD and would thus dominate the response category decision. The use of too few response categories does not give observers the opportunity to report whether two SPDs are differently bright. This response grouping bias can be countered by using similar numbers of stimulus magnitudes as there are response categories.

Response contraction in the category rating task can also be induced by failure to randomise or balance the order in which stimuli are presented and by failure to anchor the response range to the stimulus range by visual demonstration [32].

In a recent review of 17 studies using category rating at photopic levels to compare brightness effects of lamp spectrum, only three were considered to provide reliable data, the remainder having suspected experimental bias or provided insufficient data to check for such bias [32].

STIMULUS SIZE

Three further aspects of experimental design pertinent to all psychophysical methods in lighting research are discussed below: stimulus size, evaluation mode and design of the illuminated field.

Previous studies have used visual stimuli of a wide range of sizes, from remote viewing of a bipartite field subtending 2° at the eye [38] or booths subtending around 40° at the eye [4], to tests placing subjects within lit rooms [5] and thus giving stimulation of the whole retina - full-field stimulation. Stimulus size is expected to matter because the relative distribution of the long, medium and short-wavelength sensitive photoreceptors varies with retinal location [10]. Whilst full fields are representative of most real world conditions, it is often easier to set up and characterise smaller fields in laboratory trials.

Experimental evidence demonstrates that a 10° field produces different colour matching judgement to a field of size 102° wide and 50° high [39]; that the difference in sensitivity between fields of size 9° and 64° is small relative to the difference between 3° and 9° fields [40]; and that the average luminance of the horizontal band 40° wide centred at normal eye height relates well to subjective ratings of spatial brightness [41]. These data suggest that subjective evaluations of lighting for full field vision can be made using scale models, and that the minimum size is somewhere in the region of 10° to 40°. This proposal will be examined in further work.

EVALUATION MODE

There are two primary modes of evaluation, joint and separate [42]. In the separate mode (Figure 3) stimuli are presented individually, whilst in the joint mode two or more stimuli are presented in juxtaposition. The joint mode can be subdivided into simultaneous and successive modes. In the simultaneous mode (Figure 1), two stimuli are presented at the same time in adjacent spatial locations; in the successive mode (Figure 2) the two stimuli are presented in temporal juxtaposition at the same spatial location.

Chromatic adaptation

Joint and separate modes of evaluation lead to different degrees of chromatic adaptation. Chromatic adaptation is the neutralisation of activity in the opponent colour channels as the eyes acclimatise to the stimulus. Activity in the opponent colour channels contributes to brightness [43] and thus the degree of chromatic adaptation will affect the size of this contribution.

The time course of chromatic adaptation has been measured using colour appearance judgements following a change in adaptation. The data suggest two stages of adaptation. The initial rapid stage gives approximately 60% chromatic adaptation in the first five seconds, and is followed by the slower stage where approximately 90% chromatic adaptation is reached after 60 seconds; it takes almost two minutes to reach 100% chromatic adaptation [44,45].

In separate evaluations which allow adaptation to a single stimulus for two minutes or more, an observer's white point becomes the chromaticity of the stimulus. This complete chromatic adaptation reduces the chromatic contribution to brightness although experimental results suggest it does not completely eliminate any effect of SPD [32,46].

In simultaneous evaluations the chromatic adaptation state of the observer is difficult to define. The observer does not adapt to the individual stimuli but to the mixed spectrum, giving a white point somewhere between the chromaticities of the two adapting conditions being considered [47]. In sequential evaluations the same spatial location is illuminated by different stimuli in rapid sequential presentations. Berman et al [12] illuminated a wall alternately by two different sources, presented for 5 seconds each, and with three alternations between the two sources. Vrabel et al [27] illuminated a room for three seconds per source, with a two second dark interval between them, this cycle being repeated as many times as required by the observer. With each stimulus presented for approximately five seconds before alternating to the second stimulus, the observer's white point would move toward the chromaticity of the first stimulus, without actually reaching it, then towards the chromaticity of the second stimulus when that is presented, again without reaching it, and so on. The white point would therefore eventually lie somewhere between the chromaticities of the two individual stimuli and the state of chromatic adaptation would be similar to that for the side-by-side presentation. Hence the simultaneous and sequential modes of evaluation will yield similar results when other parameters are also similar. Studies using joint modes of evaluation tends to exaggerate differences between stimuli compared to findings using separate evaluation [46].

Interval bias

While simultaneous evaluations may suffer from positional bias, the preference for one spatial location over another, successive evaluations may be affected by interval bias [48], the preference for one temporal interval over the other. In brightness discrimination judgements this would be a tendency to report a particular interval as being brighter when it is not. Yeshurun et al present experimental data exhibiting large interval bias in visual judgements, some favouring the first interval and some the second interval [48]. Needham defines interval bias as the overestimation (negative time-error) or underestimation (positive time-error) of the second of two stimuli presented in succession [49] and suggests that it changes with variation of the time interval, or pause, between presentations of the stimuli: intervals of up to approximately three seconds tend to result in an underestimate of the second stimulus, whilst intervals above approximately three seconds tend to result in an overestimate of second stimulus.

In their detection task, Jäkel and Wichmann [50] found a strong bias to the second interval from three of their five observers, including the expert observer, when using successive evaluation whilst the simultaneous evaluation task was virtually unbiased. In their discrimination task, Jäkel and Wichmann found similar sensitivity with simultaneous and successive tasks but each of their four naïve observers was still better at the simultaneous discrimination task than the successive discrimination task after 20,000 detection trials [50]. Uchikawa and Ikeda found that matching and discrimination tasks using side-by-side brightness comparisons gave more precise results than did successive presentations [51]. Doubts about the successive discrimination task lead a recent study to report that it should be used with caution, if at all [48].

There are two issues regarding use of sequential and simultaneous evaluation modes that need further investigation before discussions of previous lighting research can be resolved. The first relates to the dominant visual mechanism though which lamp SPD affects spatial brightness. If this is through the opponent colour channels [43] then chromatic adaptation is of interest and the sequential and simultaneous evaluation modes lead to similar states of chromatic adaptation. Alternatively, it has been suggested that the spatial brightness response is mediated by control of pupil size [12] in which case the sequential evaluation is preferable to the simultaneous mode because it would allow the pupil to respond to the SPD of the individual stimuli rather than to the mixed SPD of both. The second issue is that of interval bias in sequential evaluation tasks. It is unfortunate that previous studies of lamp SPD and brightness using discrimination between successive stimuli have tended not to include a null condition trial so there are no data with which to quantify the magnitude of any such bias.

Further research has been carried out at Sheffield University and Pennsylvania State University to compare the simultaneous and sequential modes of evaluation and preliminary results are reported below.

Experimental data: Sheffield

Fotios & Cheal previously reported the results of brightness matching and brightness discrimination tests, both using simultaneous evaluations [21]. This work is currently being repeated using sequential evaluation.

The simultaneous evaluations [21] used a pair of side-by-side booths, with separate light sources simultaneously illuminating each booth. Light was transported to the top of each booth through a light pipe, using an iris in the pipe to adjust illuminance and avoid any effect on the SPD or spatial distribution of light in the visible chamber. The sequential evaluations used only one of these booths, presenting a visual field of approximately 37° high and 36° wide. Light from two different lamps was transported to the top through separate light pipes, again using irises to adjust the illuminance. Luminance measurements show negligible differences in spatial distribution between lamps, between light from the two light pipes and between levels of dimming.

The two stimuli were presented in rapid succession: stimulus A (5s); dark interval (300ms); stimulus B (5s); dark interval (300ms); stimulus A (5s) etc. These durations were chosen to repeat the conditions used by Berman et al [12]. For the matching test this procedure was followed until the test participant was satisfied with their brightness match. For the discrimination test the number of repeats was limited to three.

Four lamps were used; a standard high pressure sodium (HPS 70W), a compact fluorescent (CFL) and two types of metal halide (MH1, MH2), as defined in Table 2, these being the lamps used in previous work [21]. Using the HPS as the reference source gave four lamp combinations including a null condition. The order in which lamp pairs were presented was balanced between subjects.

Lamp		CCT (K)	CRI
HPS	*70W/150W SON-T Pro*	2000	25
CFL	*55W PL-L*	3000	82
MH1	*70W CDO-TT*	2800	83
MH2	*70W CDM-T*	4200	92
MH3	*150W CDM-TT*	4200	92

Table 2. Lamps used by Fotios & Cheal in brightness matching and discrimination tests.

In sequential brightness matching trials one of the two lamps in a pair was set by the experimenter to the reference illuminance. The test participant used the dimming control, a three-turn rotary dial, to match the lighting as-near-as-possible for equal brightness. This procedure was repeated by each test participant to counterbalance dimming application and dimming direction. When the HPS lamp in a pair was used as the stimulus of fixed illuminance the reference illuminance was 7.5 lux, measured at the centre of the floor of the booth, this being a pilot study for further research of street lighting. When the MH and CFL lamps were used as the stimulus of fixed illuminance the reference illuminance was 5.0 lux, this expected to be approximately equally bright as the HPS at 7.5 lux and thus maintain a similar state of adaptation in both cases.

In sequential brightness discrimination trials, lighting from one lamp in each pair was set to the reference illuminance and lighting from the other lamp was set to a range of illuminances. At each presentation the test participant reported which interval appeared brighter, a forced choice task. This procedure was repeated by each test participant to counterbalance lamp nomination as reference and variable stimulus. When the HPS lamp in a pair was used as the stimulus of fixed illuminance, this being 7.5 lux, the CFL and MH lamps were presented at 2.0, 3.0, 5.0, 7.5, 10.0 lux. When the MH or CFL lamps in a pair was used as the stimulus of fixed illuminance, this being 5.0 lux, the HPS lamp was presented at 3.0, 5.0, 7.5, 10.0 and 15.0 lux. These ranges were chosen with expectation that the middle value would tend to appear equally bright as the fixed illuminance stimulus, thus avoiding a stimulus frequency bias [29].

Results from the ten test participants used to date are shown in Table 3, in comparison with results from the previous trials using simultaneous evaluation [21]. The four-parameter logistic equation was used to derive the illuminance ratio for equal brightness from the results of the discrimination tests.

Evaluation mode	Illuminance ratio at equal brightness			
	HPS/ HPS	CFL/ HPS	MH1/ HPS	MH2/ HPS
Brightness matching				
Sequential	0.99	0.68	0.74	0.70
Simultaneous	0.99	0.72	0.73	0.71
Brightness discrimination				
Sequential	1.01	0.67	0.69	0.66
Simultaneous	1.00	0.59	0.68	0.64

Table 3. Comparison of illuminance ratios for equal brightness determined using matching and discrimination tasks with simultaneous (n=21) and sequential (n=10) modes of evaluation. Simultaneous data as previous reported [21]; sequential data not previously reported.

Two observations are drawn from Table 3. Firstly, there appears to be little difference in illuminance ratio for a particular lamp pair between sequential and simultaneous evaluation modes, for both the matching and discrimination tasks, and thus that the evaluation mode does not significantly affect operation of the visual mechanism(s) responsible for SPD effects on spatial brightness. Secondly, brightness discrimination appears to suggest illuminance ratios that depart slightly further from unity than those from the matching task. Data from the null condition trials, the HPS/HPS lamp pair, suggest negligible experimental bias.

Results of the sequential brightness judgements and comparison of these with results of the simultaneous tests will be submitted for peer reviewed publication upon completion of the trials. In addition to using illuminance ratios to compare the size of any SPD effect upon spatial brightness, this analysis will also analyse precision and interval bias.

Experimental data: Penn State

Brightness judgements at photopic levels were made using side-by-side and rapid sequential discrimination tasks. The visual field in each case was one, or both, of a pair of identical empty rooms with approximate dimensions of 3.0m (wide) x 3.6m (deep) x 2.7m (height). All surfaces within the subject's field-of-view were neutral gray. The rooms were fitted with indirect luminaires, suspended about 400mm from the ceiling, and these had continuous rows of RGB LEDs. Four stimulus conditions were used, these being the four possible combinations of two correlated colour temperatures (3000K, 7500K, both on the blackbody locus) and two luminances (24 and 30 cd/m^2) as measured at eye height on the surface of the wall directly in front of the subject. The ten paired combinations of these four stimuli included four null conditions and the left/right stimulus position (simultaneous evaluations) and the first/second stimulus interval (sequential evaluations) were counterbalanced for the between-stimulus pairs, giving sixteen paired comparisons.

In the simultaneous evaluations the rooms were observed from a seated position just outside of the rooms, with the partition between the rooms aligned with the subject's sagittal plane. In the sequential evaluations the subject was seated within the left-hand room, In all cases a chin/forehead rest was used to maintain consistency in the viewing field across trials and subjects. For the simultaneous evaluations, presentation durations were not limited. For the sequential presentations each stimulus was presented for 5s with a 25ms dark interval and subjects were instructed to view at least three sets of alterations (i.e. ABABAB) before making their choice about which light setting was brighter. This is comparable to the method employed by Berman et al [12].

The tests were carried out by 47 participants using a repeated measures procedure. Full results will be submitted for publication in a peer reviewed journal and here we focus on the comparison of results from the sequential and simultaneous evaluations.

Stimulus pair		**Distribution of judgements of brighter stimulus**			
		Simultaneous evaluation		**Sequential evaluation**	
1	*2*	*1*	*2*	*1*	*2*
A	D	6	88	4	90
B	C	72	22	90	4
A	C	28	66	39	55
B	D	31	63	49	45
C	D	2	92	0	94
A	B	2	92	0	94

Table 4. Comparisons of brightness discrimination judgements obtained using sequential and simultaneous modes of evaluation. (n=94). These stimuli are A (3000K, 24 cd/m^2), B(3000K, 30 cd/m^2), C(7500K, 24 cd/m^2), D (7500K, 30 cd/m^2).

Table 4 summarises the results. The frequency with which the stimulus in a pair was reported to be brighter is similar for both the sequential and simultaneous evaluations. McNemar's test suggests the difference is significant ($p<0.01$) only for the BC and BD lamp pairs. Conclusions drawn about statistical significance related to effects of SPD and luminance were identical with both methods. The room with the higher luminance was selected as brighter irrespective of CCT, and at equal luminance CCT was unrelated to brightness perception. There are subtle differences in some of the contrasts that were studied and these are presently under further investigation, but the general conclusion is that both experimental methods will lead to comparable results. This is not unexpected since both methods place the subject in a state of mixed adaptation. Preliminary analysis suggests that any bias between the right-hand and left-hand rooms in the simultaneous evaluation, or between the first and second intervals in the sequential evaluation, was negligible.

VISUAL FIELD

In previous work, visual fields have ranged from uniform, neutral surfaces, to interior spaces with coloured surfaces and containing objects. Whilst the neutral field enables analysis of brightness effects purely due to differences in SPD, the coloured environment better represents most real world interiors. Two questions are raised. Firstly, are results obtained in studies using coloured environments transferable to other settings? Secondly, are test participants attracted to objects in the observed field such that their response is dominated by foveal vision rather than full field vision? Brightness matching trials were carried out using four different field designs to explore the transferability of results from one setting to another [52]. These tests were carried out at mesopic levels, this again being a pilot study for work investigating lighting for residential streets.

Method

The four illuminated fields are shown in Figure 4. These are:

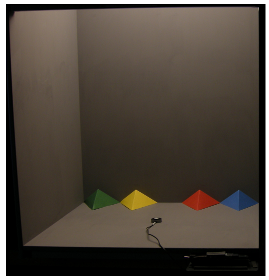
Achromatic: These are two side-by-side booths. The interior surfaces of the booth were painted matt grey (Munsell N5, r = 0.2).

Coloured Objects: Pyramids made from coloured card (red, green, blue and yellow) were placed on the floor of the achromatic environment. This is the field design used in previous work [21].

Coloured Surfaces: Approximately one third of the visible interior surfaces of the achromatic booths were lined with unglazed quarry tiles in three colours (red, beige and black) simulating brick, stone and asphalt surfaces. The proportion of colour was determined from a brief survey of residential streets in Sheffield, a city in the UK.

Uniform Field: The front openings of the achromatic booths were covered with two sheets of acrylic diffuser of neutral transmittance. This provided a neutral and uniform stimulus field.

Achromatic



Coloured Objects

Coloured Surfaces

Uniform Field

Figure 4. Visual fields used to compare effect of colour and objects on the results of brightness matching tests. Note: only the left-hand field is shown; the right-hand field was a mirror image.

The test participant's task was to adjust the illuminance in one booth to match the brightness produced by the reference illuminance (7.5 lux) in the other booth. For the uniform field design the reference illuminance was set to achieve an average luminance of the front surface of the reference field equal to the average luminance (0.38 cd/m^2) of the walls in the other field designs. In trials, both sides were of identical design, the left-hand booth being a mirror image of the right-hand booth.

Four lamps were used, these being similar to the lamps used in previous work [21]. These were high pressure sodium (HPS 150W), compact fluorescent (CFL), and two types of metal halide (MH1, MH3) as defined in Table 2. Lamp MH1 was used as the reference stimulus, and thus there were four lamp pairs including a null condition.

Each of the four lamp pairs were matched four times, counterbalancing the initial illuminance of the variable stimulus (set by the experimenter to be obviously higher or lower than the fixed stimulus) and counterbalancing the designations of fixed and variable booth. Each trial was repeated twice. The order in which the four lamp pairs were used and the booth in which the reference lamp (MH1) was located were balanced across the ten test participants (age range 25-54 years; 7 female, 3 male). Each participant saw all experimental conditions, a repeated-measures procedure, and hence made 128 brightness matches.

Results

The mean illuminance ratios for the four lamp combinations and the four field types are shown in Table 5. Within these treatments, data for each subject are the mean of the eight trials carried out per lamp pair and field design.

Field design	**Mean illuminance ratio for each lamp combination**			
	HPS/ MH1	**CFL/ MH1**	**MH1/ MH1**	**MH3/ MH1**
Coloured surfaces	1.35	0.93	0.99	0.92
	(0.13)	*(0.09)*	*(0.08)*	*(0.08)*
Coloured objects	1.24	0.90	0.96	0.92
	(0.11)	*(0.09)*	*(0.07)*	*(0.07)*
Achromatic	1.24	0.88	0.98	0.93
	(0.14)	*(0.12)*	*(0.06)*	*(0.14)*
Uniform field	1.22	0.90	0.96	0.90
	(0.27)	*(0.08)*	*(0.08)*	*(0.12)*

Table 5. Mean illuminance ratios (and standard deviations) from side-by-side brightness matching trials (n = 10) using four different visual fields.

The effect of field design can be seen by comparing illuminance ratios for the four field designs under each lamp combination. The mean illuminance ratios in Table 5 suggest all four field designs yield similar illuminance ratios under the MH1/MH1, MH3/MH1 and CFL/MH1 lamp pairs; under the HPS/MH1 lamp pair there appears to be a difference between the coloured surfaces field and the other three field designs. Two-way repeated measures ANOVA (lamp pairs x field design) suggests that the effect of field design is not statistically significant, although it is close ($p=0.082$). Differences between field-designs were examined using paired t-tests on all combinations of field design within each lamp pair. Of these 24 analyses, only two differences are significant, and both of these are for the HPS/MH1 lamp pair; coloured surfaces vs. coloured objects ($p=0.003$), and coloured surfaces vs. achromatic ($p=0.008$).

Effects of field design on brightness judgements were considered using the current results and also the results from two previous studies at photopic levels [5,19] in which surface colour and the presence of an object were varied. Three conclusions were drawn:

1. Brightness matching using illuminated achromatic interior environments produces the same outcome (illuminance ratio at equal brightness) as brightness matching using illuminated flat surfaces of neutral spectral reflectance.

2. The insertion of coloured objects into an achromatic environment does not affect the outcome.

3. An environment with coloured surfaces produces the same outcome as an achromatic environment, and there is no significant effect with the level of colourfulness.

These findings will be submitted to a peer reviewed journal for publication.

SUMMARY

All experimental methods contain bias. This is not necessarily a problem if there are data, such as null-condition data, that enable bias effects to be estimated. Robust conclusions demand the same stimuli are compared using a variety of psychophysical methods and if these tend to agree then greater confidence can be placed in the results. Whilst a few studies have done this [11,19,24,27], most do not, hence the meta analysis being carried out by the authors.

The consideration of research methods discussed in this article suggests that much of the previous work provides an unreliable estimate of lamp SPD effects on brightness. Frequently, this is because the reported method reveals experimental error, or because there are insufficient data reported to determine whether a potential experimental error has been countered. At present, the analysis suggests that data from only 14 of 60 previous studies are reliable; these are shown in Table 6.

The next stage of this research is to develop a tool to enable prediction of lamp SPD effects on spatial brightness, hence to guide the selection of lamp type and illuminance. A common limitation of the experimental work is that lamps are selected from those commercially available using coarse indicators of lamp spectral characteristics, such as Colour Rendering Index, Correlated Colour Temperature or the ratio of scotopic to photopic lumens (S/P). It is less common for researchers to create custom illuminants that have spectra intentionally designed to manipulate an underlying mechanism of vision; only two studies appear to have done so [12,28].

Three categories of prediction tool are colour appearance models; the S/P ratio, e.g. consideration of the intrinsically photoreceptive retinal ganglion cell (ipRGC); and lamp colour characteristics, e.g. relative values of CCT, CRI, and gamut area. Allied discussions include consideration of how the effect of lamp SPD might be applied in practice and comparison with effects on visual effort and circadian response.

Study	Response task	Field size	Evaluation mode
Akashi & Boyce, 2006 [11]	Yes/No response to statements.	Full field	Separate
Berman et al, 1990 [12]	Discrimination	Full field	Sequential
Boyce, 1977 [19]	Matching	Full field	Simultaneous
Boyce, Akashi, Hunter & Bullough, 2003 [53]	Yes/No response to statements.	Full field	Separate
Boyce & Cuttle, 1990 (Experiment 2) [5]	Category rating	Full field	Separate
Flynn & Spencer, 1977 [54]	Category rating	Full field	Separate
Fotios & Gado, 2005 [26]	Matching	40^o high, 72^o wide	Simultaneous
Fotios & Levermore, 1997 [22]	Side-by-side Matching	22^o high, 38^o wide	Simultaneous
Houser, Tiller & Hu, 2004 [28]	Discrimination	Full field	Simultaneous
Hu, Houser & Tiller, 2006 [24]	Matching	Full field	Simultaneous
Ray, 1989 [20]	Adjust to preferred illuminance	Full field	Separate
Thornton & Chen, 1978 [4]	Matching	30^o high x 50^o wide	Simultaneous
Vrabel, Bernecker & Mistrick, 1998 [27]	Discrimination	Full field	Sequential
Vrabel, Bernecker & Mistrick, 1998 [27]	Category rating	Full field	Separate

Table 6. Tests suggested to give reliable demonstration of SPD effect on brightness at photopic levels

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