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A Revised Kruithof Graph Based on Empirical Data

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ABSTRACT Kruithof's graph identifies combinations of illuminance and correlated color temperature (CCT) alleged to yield pleasing visual conditions for interior lighting. Though in research terms the support provided by Kruithof is insufficient, it is widely cited as a design rule and has been the focus of many experimental studies despite evidence against Kruithof since at least 1990. The current article examines the trends displayed in those studies considered to provide credible evidence: these do not support Kruithof. For pleasant conditions, these data suggest only avoiding low illuminances and do not favor any CCT.

KEYWORDS CCT, illuminance, Kruithof

1. INTRODUCTION

Kruithof [1941] presented a graph that is purported to reveal preferred combinations of illuminance and correlated color temperature (CCT) for interior lighting conditions (Fig. 1). Specifically, the Kruithof graph shows lower and upper illuminance thresholds for a range of CCTs that bound the region within which the illumination is considered pleasing. Kruithof [1941] alleged that beneath the lower boundary, illumination is judged as dim at low CCT or cold at high CCT, whereas above the upper threshold, color reproduction is unpleasant and unnatural. Empirical support for these claims is, however, somewhat lacking. The aim of this article is first to discuss limitations of Kruithof's study and, second, to re-evaluate the evidence for the impact of changes in illuminance and CCT on lighting giving pleasant visual conditions.

2. REVIEW OF KRUITHOF

Before placing confidence in the predictions of Kruithof's graph, it is appropriate to critically evaluate the underlying data. Description of the experiment, what little there is, is limited to the caption for Kruithof's [1941] fig. 10 (Fig. 1). This loosely describes the light sources used—that is, a filament lamp for low CCT (<2850 K) and daylight and/or a daylight fluorescent lamp at higher CCTs—but describes little else. There is no discussion of the visual scenes examined; for example, the combinations of CCT and illuminance observed in trials. The graph shows smoothed (and extrapolated) curves without data points to identify the observed

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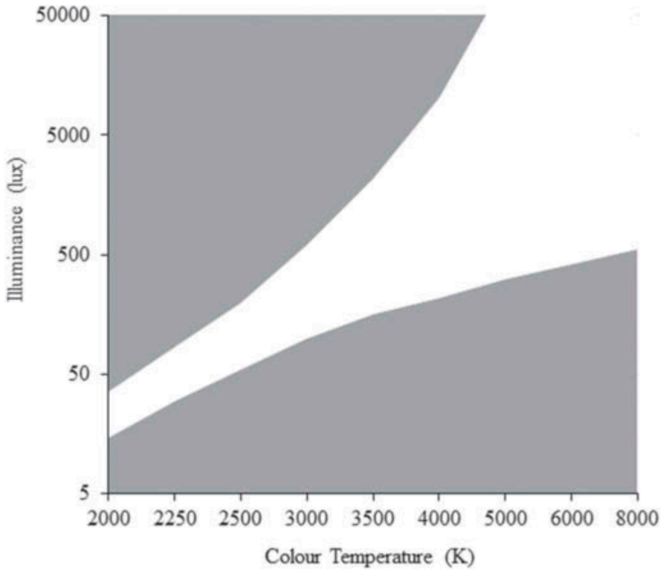

Fig. 10. For every colour temperature there exists a highest and lowest level of illumination at which the illumination is considered "pleasing": at lower levels the illumination appears dim or cold, at higher levels the colour rendering is unnatural. The left-hand part of the limiting curves, up to a colour temperature of 2850 K, is recorded by allowing electric lamps with variable (decreased) current to burn in a room, and varying the number of lamps. The illumination intensity on a table 80 cm high was here measured. In the right-hand part the lowest level which does not give the impression of coldness was determined by experiments with daylight itself and with the daylight luminescence lamps to be described below. The shape of the upper curve has been extrapolated in this region with the help of the fact that in direct sunlight (colour temperature 5000 K) even with the highest illumination intensities occurring (10^4 or 10^5 lux) the colour rendering is never found "unnatural". On the abscissa the reciprocal value of the colour temperature T_c is plotted, on the ordinate of the logarithm of the illumination intensity E, since 1/Tc and log E are measures of the physiological estimation of these quantities. In these coordinates the lower limiting curve takes on a nearly linear form. It may be mentioned that the experiments were carried out in a laboratory room. It was found, however, that in a living room with light-coloured furniture and wall coverings roughly the same limits are obtained. [Kruithof 1941]

Fig. 1 The Kruithof graph, adapted from fig. 10 of Kruithof [1941]. Also shown is the caption that appears under Kruithof's Fig. 10, which Kruithof used to describe the experiment (He stated: "In the text below the figure the experiments are described").

combinations. There is no discussion as to the method by which visual scenes were presented to observers (for example, separate or simultaneous evaluations) or the procedure with which responses were sought (for example, matching, discrimination, adjustment, or category rating). There are no data regarding the number of observers used. There are no quantitative data reported such as central tendency and variance and there is no discussion of statistical analysis.

In the caption to the graph (Fig. 1) Kruithof [1941, p. 69] stated, "On the abscissa the reciprocal value of the colour temperature *Tc* is plotted." This appears to be incorrect. The reciprocal of color temperature, commonly stated as micro reciprocal degree (mired) has the unit MK^{-1}. On Kruithof's graph the abscissa has the unit K not K^{-1}, which indicates that color temperature rather than mireds was plotted. Note also that values on the abscissa range from 2000 to 8000, which are common color temperatures for interior lighting, whereas the reciprocals for these values rage from 0.0005 to 0.000125 (or 500 to 125 mireds). Therefore, it is assumed that the abscissa shows CCT.

The absence of detail is such that the article would be unlikely to pass through peer review. Given that we are unable to determine what was done and how the findings, which are not reported, were used to produce the graph, it is ill advised to place any weight in the alleged relationship between CCT and illuminance.

These limitations are not unknown. Vienot and others [2009, p. 1433] also commented that there is "little information available about . . . the tasks proposed to the observers, as well as on the number of participants." Elsewhere it is noted that "Kruithof gave no information about the criteria for determining pleasantness or unpleasantness" [Candas and Dufour 2005, p. 34], and that "Kruithof's research has not been formally verified" [Noguchi and Sakaguchi 1999].

Several experimental studies have refuted the message of the Kruithof curve (see below). First consider two studies published in 1990, both describing experiments carried out to investigate evaluations under lighting of different combinations of CCT and illuminance [Boyce and Cuttle 1990; Davis and Ginthner 1990]. In both cases it was concluded that the results did not support Kruithof. One advantage of these two articles is that they reported sufficient data to enable repetition of the experiment and independent consideration of the findings, something lacking in Kruithof [1941] (Table 1). Recognition of this counterevidence does not hold back the faithful: for example, Zhai and others [2015] noted that results from Boyce and Cuttle's [1990] study and Davis and Ginthner's [1990, p. 796] study "do not fully agree with Kruithof's rule" but then suggest, "However, it does provide an effective method to define the comfort zone in terms of illuminance and CCT."

TABLE 1 Summary of the reports of three studies carried out to examine the relationship between illuminance and CCT

Data required	Kruithof [1941]	Boyce and Cuttle [1990]	Davis and Ginthner [1990]
Test procedure	Not reported	Category rating	Category rating
Test environment	Room	Room	Room
Variations in lighting	Not reported	4 × CCT 4 × illuminance	2 × CCT 3 × illuminance
Sample	Not reported[a]	15 (experiment 1) 10 (experiment 2)	40
Statistical analysis	Not reported	Yes	Yes
Published in a peer-reviewed journal	No	Yes	Yes

[a]Suggested to be a sample of two, Kruithof and his assistant [Cuttle 2015].

The Kruithof graph is "probably the most reproduced diagram in the history of lighting" [Cuttle 2015] and has been a feature of lighting recommendations for many years despite the failure of several attempts to validate the curve [Han and Boyce 2003]. It is quoted as factual in papers discussing other aspects of lighting [Davis and others 2011; Wainscoat and others 2015] and in texts for architecture [Lam 1977]. It was included in the eighth edition of the Illuminating Engineering Society of North America *Lighting Handbook* [Illuminating Engineering Society of North America 1993], although with the caution that the relationship should be regarded as tentative, and was not included in later editions. Texts from Boyce [2014] and Cuttle [2015] include the graph but with acknowledgement of limitations.

It is concerning that Kruithof's [1941] work has become a textbook axiom, but equally concerning is the lack of recognition of conflicting studies in subsequent work. In studies carried out to examine Kruithof it is not uncommon for the report to ignore limitations of Kruithof and to ignore those studies that do not support Kruithof [Boyce and Cuttle 1990; Davis and Ginthner 1990]. Where such counterevidence is considered it is suggested to be offset by findings that do support Kruithof and therefore a new experiment is carried out: this does little more than add to the confusion. What is lacking is an analysis of why different studies led to different conclusions; for example, by a critical review of the procedures and variables used in different studies. Perhaps one reason why so many Kruithof experiments are carried out is that—with just two easily controlled variables, illuminance and CCT—the experiments appear to be relatively easy, with the promise to find an apparently interesting result. For example, the recent study by Kakitsuba [2015] used test conditions and a procedure that was destined to demonstrate a Kruithof-like relationship between CCT and illuminance [Fotios 2016].

The majority of Kruithof studies have used a category rating procedure, about which there are many questions regarding best practise [Atli and Fotios 2011; Fotios and Atli 2012; Fotios and Houser 2009; Poulton 1989]. These questions include the need to define to observers the meaning of the items being rated and giving consideration to the nature of the response range employed. Given these questions it would be useful to include a null condition or control condition within the experimental design, but this has been done rarely if at all. Internal validation could also be gained by employing a second procedure in parallel to category rating; for example, using discrimination with simultaneous evaluation of two scenes but, again, this has been done rarely, if at all, in Kruithof studies.

In summary, Kruithof's [1941] article does not provide sufficient evidence to support the alleged combinations of illuminance and CCT that lead to pleasing conditions, and validation in subsequent studies is not consistent. The current article therefore presents a further analysis carried out using the data from those studies considered to provide credible evidence. This article is not intended to be a criticism of Kruithof. Anecdotal comments suggest that he did not intend for his work to be used as an overarching guide to pleasing, preferred, or comfortable combinations of CCT and illuminance for each and every light source. Kruithof may also have considered it to be only a pilot study [Cuttle 2015]. Rather, this article is intended to be a criticism of those studies that investigate a Kruithof-type effect but have not carried out a proper and critical review of the original work nor of the many subsequent experiments carried out to verify the findings.

3. COMPARING TRENDS ACROSS STUDIES

3.1. Collated Data

A literature search revealed 29 studies in which a Kruithof-type relationship was investigated. The methods used in these studies were evaluated against recommended best practice [CIE 2014]; for example, that in a repeated measures design the different scenes were observed in a random order, that data were statistically analyzed, and that sufficient details of the work are reported to understand what was done. Following this approach it was concluded that nine of the 29 studies presented credible evidence [Ao-Thongthip and others 2013; Boyce and Cuttle 1990; Davis RG and Ginthner 1990; Dikel and others 2014; Han and Boyce 2003; Islam and others 2015; Park and Farr 2007; Vienot and others 2009; Wei and others 2014] but that the remaining 20 did not [Bodman 1967; Hseih 2015; Hwang and others 2012; Ishida and others 2007; Ju and others 2012; Juslén 2006; Kakitsuba 2015; Kanaya and others 1979; Lin and others 2007, 2015; Nakamura and Karasawa 1999; Oi and Takahashi 2007, 2013; Park and others 2010; Takahashi and others 2014; Talotte and others 2011; Tralau and Schierz 2014; Wake and others 1977; Yoshida and others 2015; Zhan and others 2003].

Of the nine credible studies, shown in Table 2, in only one case is the effect of illuminance on ratings of brightness or pleasantness not suggested to be significant [Wei and others 2014: brightness]. In five studies, CCT was found to have significant effect on ratings of brightness [Boyce and Cuttle 1990; Dikel and others 2014; Han and Boyce 2003; Vienot and others 2003; Wei and others 2014]. CCT was found to have a significant effect on ratings of pleasantness in all but two studies [Boyce and Cuttle 1990; Davis and Ginthner 1990].

Five conclude that they do not support Kruithof [Boyce and Cuttle 1990; Davis and Ginthner 1990; Dikel and others 2014; Han and Boyce 2003; Vienot and others 2009]. Ao-Thongthip and others [2013] give partial support for Kruithof: there is a tendency for the most frequently preferred CCT to increase in two of their three activity classes (reading and cooking; not sleeping), but even in these two classes there is some disagreement from elderly males.

Vienot and others [2009, p. 1445] stated that with their results "Kruithof's rule has been only partially validated" but also that "there is no indication that high colour temperature is judged more pleasant than low colour temperature at higher illuminance levels." Though they stated that "in one sense, we have validated Kruithof's statement that high CCT at low illuminance is unpleasant" [Vienot and others 2009, p. 1444] the 6500 K lighting (their highest CCT) receives the lower pleasantness rating of all three CCTs at 150 and 600 lux (but not at 300 lux). Here the mean ratings are 3.30 (150 lux) and 3.79 (600 lux), only slightly below the neutral point (4) on their 7-point unpleasant–pleasant scale, suggesting a lower level of pleasantness than other conditions but not necessarily an unpleasant situation. Hence, it is concluded in the current work that the data of Vienot and others do not support Kruithof's proposal.

In the remaining three studies [Islam and others 2015; Park and Farr 2007; Wei and others 2014] it is not possible to draw a clear conclusion regarding whether or not a Kruithof-type relationship is supported, in part because these studies did not set out to directly test the Kruithof range. The four combinations of CCT and illuminance presented by Wei and his colleagues [2014] were within Kruithof's pleasing zone. Participants responded more strongly to differences in CCT from 3500 and 5000 K triphosphor fluorescent lamps than to differences in illuminance resulting from lamps with either 3000 or 2330 lumens. Satisfaction and visual comfort was unaffected by illuminance (within the limits of this study) but was worse under 5000 K office lighting than under 3500 K.

In the studies examined here it is apparent that observers made judgments regarding an illuminated scene rather than looking directly at light sources or at specific objects. For this review a further four Kruithof-type studies looking at viewing of art [Chen and others 2015; Chou and others 2014; Pinto and others 2008; Zhai and others 2015] were ignored, because visual attention was directed toward an object rather than the illuminated scene.

Four studies used a 7-point rating scale to capture responses, in which a rating of 1 was a low rating (for example, low brightness) and 7 a high rating (for example, high preference) [Davis and Ginthner 1990; Dikel and others 2014; Vienot and others 2009; Wei and others 2014]. Results from the other studies were translated to this same range to enable comparison. Ao-Thongthip and others [2013] used a 6-point scale, with 6 being the highest rating, and this was stretched to a 7-point scale. Boyce and Cuttle [1990] used a 5-point scale in which, for the items considered here, a rating of 1 denoted the highest brightness and pleasantness. Hence, these results were estimated for a reversed polarity and stretched to a 7-point scale.

TABLE 2 Summary of studies suggested to provide credible evidence of the relationship between illuminance and CCT for preferred conditions

	Independent variables					Pleasantness		Brightness		
Study	Illuminance (lux)	CCT (K)	Other?	Adaptation time	Sample size	Illuminance	CCT	illuminance	CCT	Kruithof
Ao-Thongthip and others [2013]	50, 200, 800	2700, 4200, 6500	×	15 s	120	$P < 0.001$	$P < 0.001$	n/a	n/a	Partial support (see text)[a]
Boyce and Cuttle [1990], experiment 1	30, 90,2 25, 600	2700, 3500, 4200, 6300	With/without flora	15–20 min	15	$P < 0.01$	n.s.	$P < 0.01$	n.s.[b]	Does not support Kruithof[c]
Boyce and Cuttle [1990], experiment 2	225	2700, 3500, 6300	Wall color (2)	15–20 min	10	n/a	n.s.	n/a	$P < 0.05$	Does not support Kruithof[c]
Davis and Ginther [1990]	269, 592, 1345 (25, 55, 125 fc)	2750, 5000	×	60 s	40	$P = 0.001$	n.s	$P = 0.001$	n.s.	Does not support Kruithof[c]
Dikel and others [2014]	500 lux	2855, 3728, 3750, 4751, 5769, 6507,	×	2 min	37	n/a	$P = 0.01$	n/a	$P < 0.01$	Results do not support Kruithof[a]
Han and Boyce [2003]	100, 500, 1000	3000, 4100, 6500	Room décor (3)	Not known	21	$P < 0.001$	$P < 0.03$	$P < 0.001$	$P < 0.003$	Does not support Kruithof[c]
Islam and others [2015]	300, 500	4000, 6500	LED and fluorescent sources	Just under 30 min (final task in each session)	40	$P < 0.001$	$P < 0.05$	$P < 0.01$	n.s.	No clear message[a]
Park and Farr [2007]	500	3000, 4100	CRI (R_a 75, 85)	2–15 min	82	n/a	$P < 0.001$	n/a	n.s.	Cannot determine
Vienot and others [2009]	150, 300, 600	2700, 4000, 6500	×	10–15 min	20	$P < 0.01$	$P < 0.01$	$P < 0.001$	$P < 0.001$	Does not support Kruithof (see text)[c]
Wei and others [2014]	2330, 3000 lumens[d]	3500, 5000	×	Long term: multiple responses over 3 months	26	n.s. (web4)	$P < 0.01$ (web4)	$P < 0.01$ (web7)	$P = 0.056$ (web7)	Results do not support Kruithof[a]

Note: Repeated measures category rating used in every study. Four studies conducted tests in rooms [Boyce and Cuttle 1990; Davis and Ginthner 1990; Islam and others 2015; Wei and others 2014]; the others used a scale model environment. The two experiments reported by Boyce and Cuttle [1990] are listed here separately following the suggestion [Fotios and Houser 2009] that the first experiment may include a grouping bias, specifically that there were too few response range points for number of test conditions examined. n/a: This variable was not explored. n.s.: Effect of variable is suggested to be not significant.

[a]Conclusion inferred from reported data.

[b]In Boyce and Cuttle experiment 1 there was no significant effect of CCT on bright but there was a significant effect ($P < 0.05$) on ratings of dim: that this one item of 19 evaluated suggests a significant effect may be capitalizing on chance.

[c]Conclusion stated by original author.

[d]Wei and others defined quantity of light by lamp lumens rather than illuminance but report some spot illuminances (their table 5).

Islam and others [2015] coded responses using a −3 to +3 scale; these data here transformed to a 1 to 7 scale.

Han and Boyce [2003] stated that responses were recorded by marking a point on an 8.4-cm line with ends marked by opposing adjectives. They then reported (their fig. 2) results along an axis labeled "Rating" with labels for integers 1.0 to 7.0. In the current analysis the data from these figures are used as reported.

Kruithof [1941] refers to combinations of illuminance and CCT that may be perceived to be "dim" and "cold," "pleasant," or "unnatural" and "unpleasant" and hence the current article considers ratings of brightness and pleasantness. Note that one study [Ao-Thongthip and others 2013] sought ratings for an item labeled preference rather than pleasantness; for the current analysis ratings of pleasantness and preference are assumed to be sufficiently similar. Note also that Ao-Thongthip and others [2013] recorded ratings of preference only; they did not measure brightness. Davis and Ginthner [1990] reported a preference response derived from original ratings of pleasantness, color naturalness, and likeness.

For Dikel and others [2014] the data used here are their composite rating of pleasantness, which is the average of ratings recorded for unpleasant–pleasant, cramped–spacious, uninteresting–interesting, and satisfaction with visual comfort. Brightness was a single rating along a dim–bright scale. Wei and others [2014] employed two data gathering methods, each with multiple questions: the analysis here uses their pleasantness response (web4: "the lighting in my work area is pleasant to work under) and their brightness response (web7: "the quantity of electric lighting of the work that I do is [1: too dim; 2: just barely adequate; 3: just right; 4: too much; 5: too bright]"), and for both it is their "without daylight access" data.

The data examined here are the reported average ratings for each combination of illuminance and CCT examined. In three studies these values are reported [Dikel and others 2014; Han and Boyce 2003; Vienot and others 2009]; for one study the data used are the mean of reported values split by age and gender [Ao-Thongthip and others 2013], and for two studies the values were estimated by measuring from figures presenting the results [Boyce and Cuttle 1990; Davis and Ginthner 1990]. Note that Boyce and Cuttle [1990] reported trends averaged across other variables; for example, the results of variations in CCT are those averaged across the four levels of illuminance. This means that the data from their experiment 1 cannot be used. In experiment 2 they included only one level of illuminance, which permits the data for variations in CCT to be used.

For Islam and others [2015] the brightness data used here are the mean of three separate ratings: for the computer task, desk reading task, and table reading task. For pleasant the data are for "light colour pleasantness." For their two levels of CCT (4000 and 6500 K) there were four variations in spectral power distribution (SPD), each providing a similar CCT but with differences in other SPD-based characteristics: the data used here are SPD1 and SPD4 to represent 4000 and 6500 K, respectively. Analysis of trends from their other SPDs did not change conclusions drawn in the current article.

Wei and others [2014] reported light quantity as lumen output rather than illuminance, and hence these data not used here to examine the effect of light level. N.-K. Park and Farr [2007] do not report results for individual cases and hence cannot be used here.

3.2. Results

Figures 2 and 3, show mean ratings plotted against CCT for ratings of brightness and pleasantness, respectively. These figures show similar trends across all studies and test conditions. Brightness ratings are more widely spread across the response scale than are pleasantness ratings, the latter being clustered around the central point of the response range. These data do not indicate a strong or consistent effect of CCT on ratings of either brightness or pleasantness.

Figures 4 and 5, Figure 5 show mean ratings plotted against illuminance for brightness and pleasantness, respectively. These figures again show similar trends across all studies and test conditions and that brightness ratings are more widely spread than are pleasantness ratings. There is a consistent trend for ratings of brightness to increases with higher illuminance (Fig. 4). Ratings of pleasantness increase from low to middle levels of illuminance but then tend to remain constant (Fig. 5). The transition lies in the range of approximately 300 to 500 lux. In other words, low illuminance (less than approximately 300 lux) leads to a feeling of unpleasantness, but once a certain threshold is reached (approximately 500 lux), a further increase in illuminance brings a negligible change in perceived pleasantness.

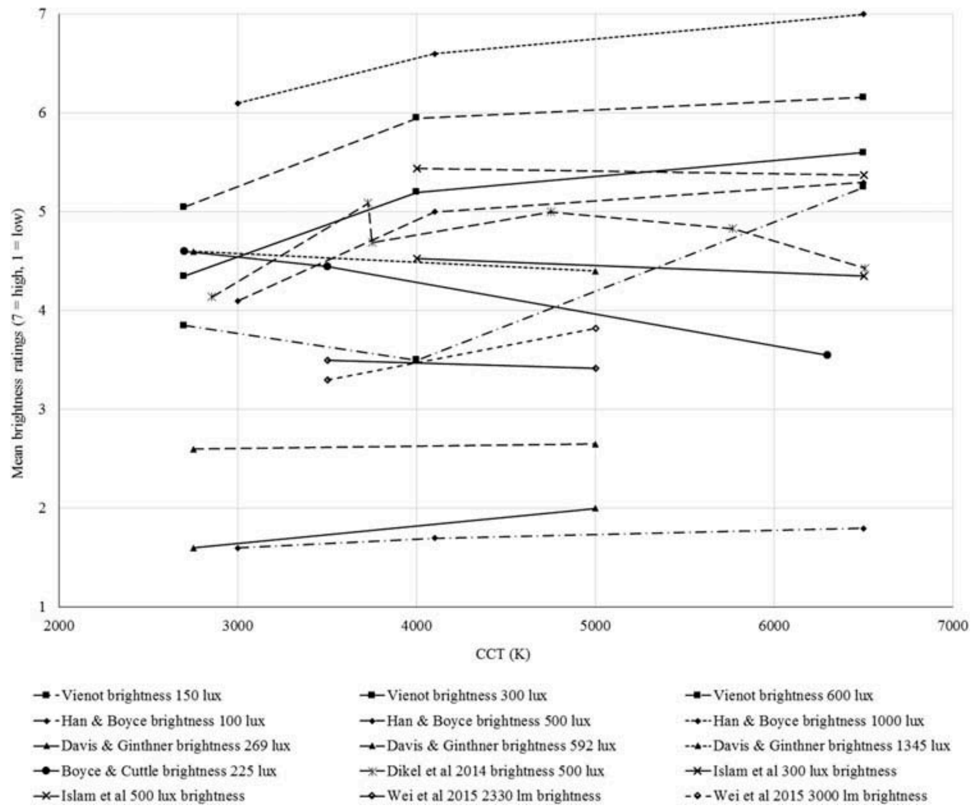

Fig. 2 Ratings of brightness plotted against CCT. The legend identifies the study and illuminance at which tests were carried out.

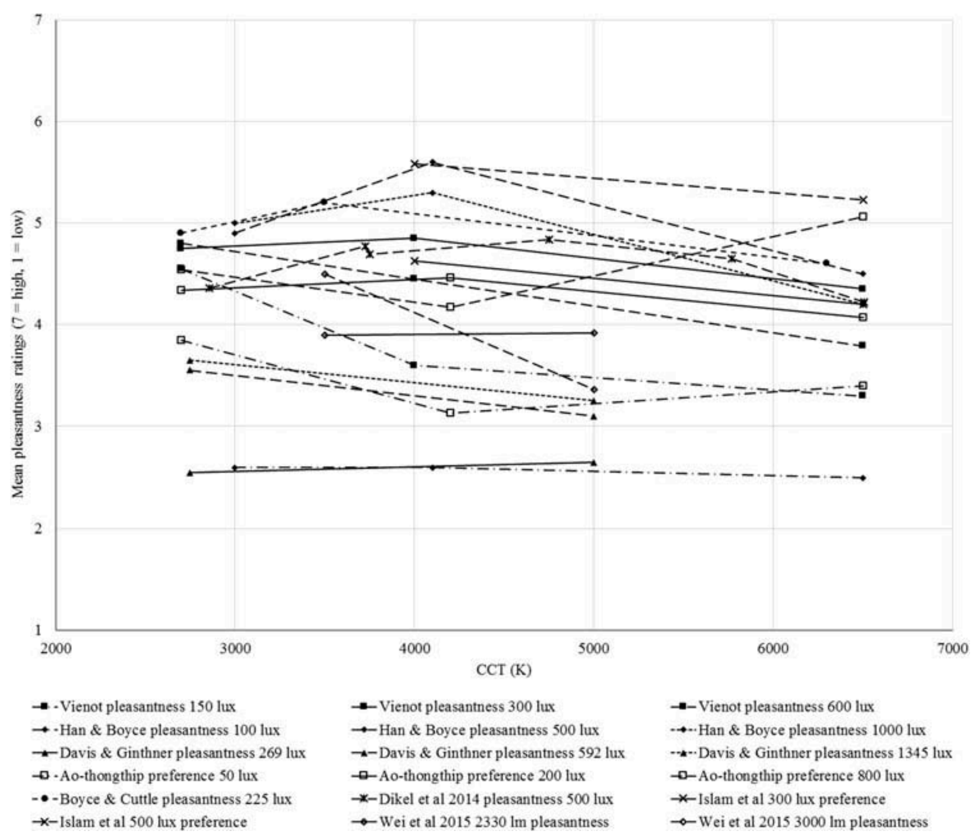

Fig. 3 Ratings of pleasantness and preference plotted against CCT. The legend identifies the study and illuminance at which tests were carried out.

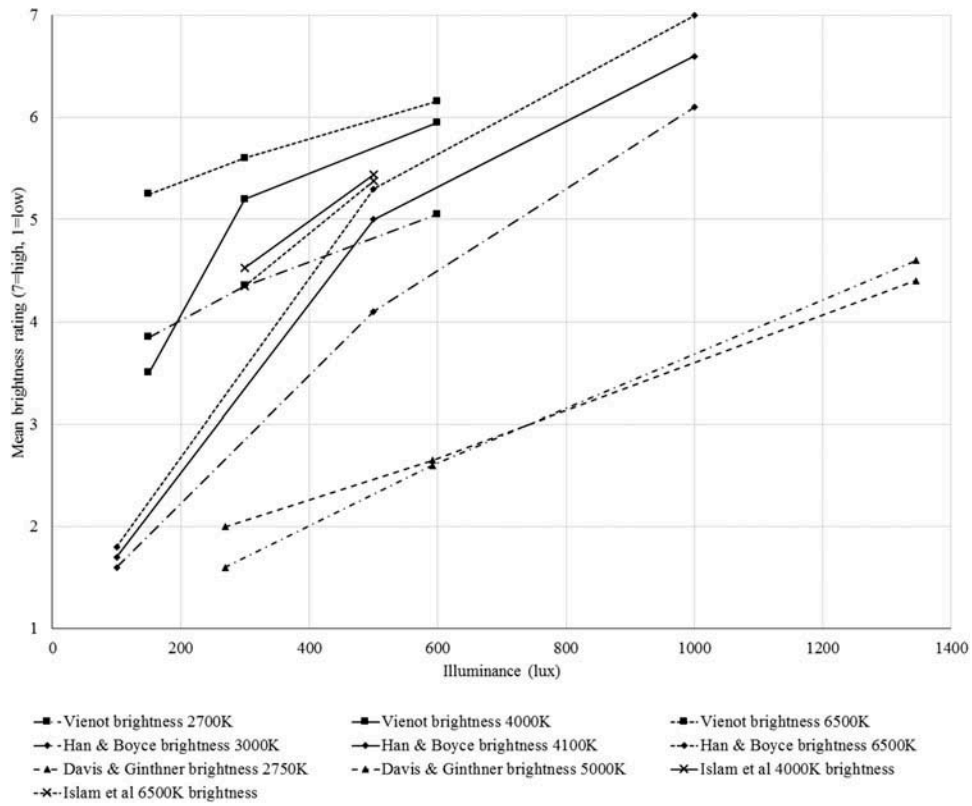

Fig. 4 Ratings of brightness plotted against illuminance. The legend identifies the study and CCT at which tests were carried out.

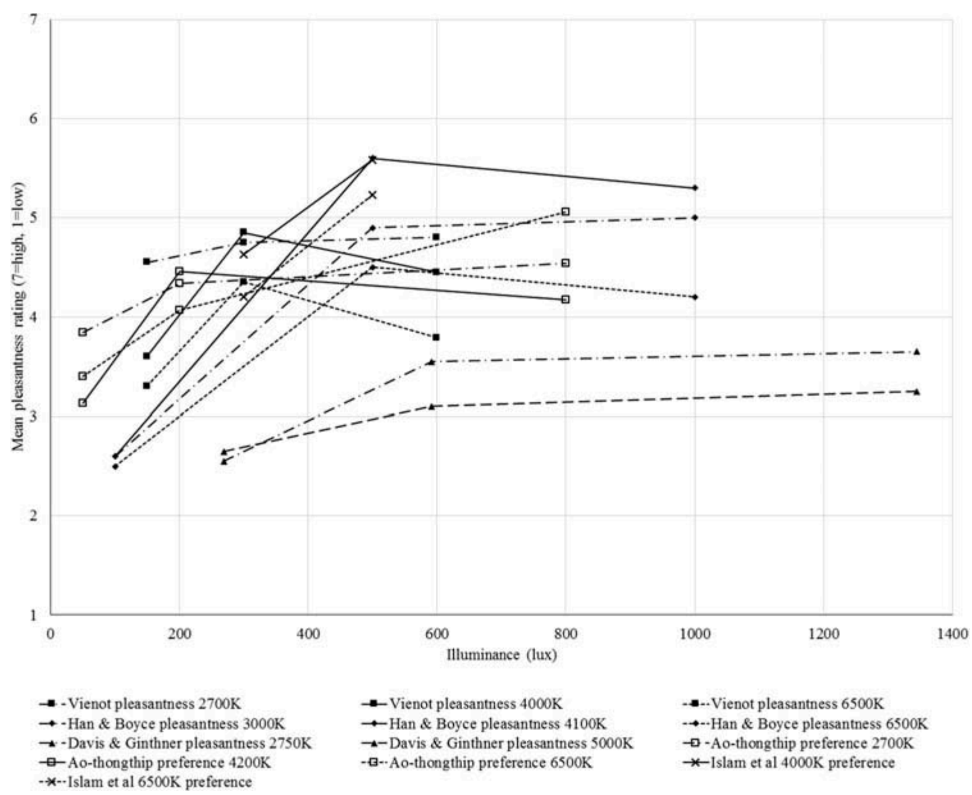

Fig. 5 Ratings of pleasantness plotted against illuminance. The legend identifies the study and CCT at which tests were carried out.

3.3. Other Data

The data used to draw Figs. 2 – 5 were those from studies considered to provide credible evidence according to recommendations for best practice in experimental design [CIE 2014]. One key item of this review was whether it was stated that different scenes were observed in a random order. If this was not stated, the data were not considered to be credible. It is possible that in some studies the experimenters did randomize the order but failed to mention this when writing up. As a check for bias in this approach to data selection, Fig. 6 shows the results from two studies that did not confirm that different conditions were observed in random order [Lin and others 2015; Nakamura and Karasawa 1999]. In both cases, there were ratings associated with pleasantness (that is, likeness and preference) but not with brightness.

The effect of illuminance on ratings of pleasantness is similar to that shown in Fig. 5: at low illuminances an increase in illuminance leads to a significant increase in ratings of pleasantness, but above approximately 500 lux any further increase in illuminance does not have significant effect.

The effect of CCT on ratings of pleasantness is mixed between the two studies: results from Lin and others [2015] suggest no change with CCT, as also shown in Fig. 3, whereas the results from Nakamura and Karasawa [1999] suggest a decrease in pleasantness with higher CCT in three of their four conditions, which does not agree with Fig. 3. Reasons for variance between studies are discussed below.

4. VARIANCE BETWEEN STUDIES

4.1. Specification of Light Source SPD

One reason for disagreement between studies is an imprecise specification of the SPD of the light sources. This specification is frequently limited to CCT. CCT is defined as the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the SPD of the light source in a specific color space [CIE e-ILV] and describes the appearance of illumination along a reddish-white to blueish-white dimension. Many different SPDs can have the same CCT, so specification of CCT alone does not pinpoint the precise SPD used in a study. It is known that as a sole metric CCT fails to predict the perceived brightness of a scene [Berman and others 1990; Boyce 1977, Fotios 2001; Fotios and Cheal 2011; Houser and others 2009; Royer and Houser 2012]. CCT may have been an internally valid correlate for some studies, but generalization to other situations is a problem. That, however, may be a correct statement when attempting to define any visual perception with a single metric. What may be an improvement is to define two metrics, as has been suggested for spatial brightness [Besenecker and Bullough 2014; Fotios and others 2015] and color rendition of illuminated objects [Guo and Houser 2004; Rea and Freyssinier-Nova 2008].

Given that CCT alone provides an insufficiently precise definition of the spectrum, it would be useful to report a range of spectrum-based metrics. A good example of this approach is Dikel and others [2014], who reported (their table 3) CCT, R_a, R_9, Q_a, Q_g, Q_f, D_{uv}, and x–y chromaticity.

Differences may arise due to errors in physical measurement—for example, the precision and location of measurements used to specify illuminances—or by relying on a manufacturer's nominal CCT rather than determination from the SPD measured in the experimental situation. This latter point is recognized by B.C. Park and others [2010].

4.2. Adaptation

Adaptation means adjusting to, or getting used to, some kind of situation [Boynton 1992], and the human visual system will tend to adapt to the brightness and color of the prevalent illumination. Consequently, there is a tendency to experience all illumination as "white" or "neutral" in color and "normal" or "medium" in intensity [Hesselgren 1967]. A significant part of this adaptation takes place in the first 60 s following exposure [Fairchild and Reniff 1995; Hunt 1950; Shevell 2001]. Therefore, one explanation for the variance between studies is the duration of exposure before evaluation.

The presence of an adaption effect on ratings can be seen in Takahashi and others [2014] who obtained category ratings of comfort after 0, 2, 4, 6, 8, and 10 min. These were ratings of comfort from six test participants for seven CCTs (2000 to 6500 K) at two illuminances (200 and 500 lux). Figure 7 shows the maximum and minimum mean ratings for the seven CCTs in each illuminance: it can be seen that there was a greater difference between the minimum and maximum mean ratings recorded immediately upon exposure than for later trials. For trials at 500 lux the decrease in range did not tend to reduce after 2 min, whereas for 200 lux there is a trend for a gradual reduction. Figure 8 shows the mean of the mean

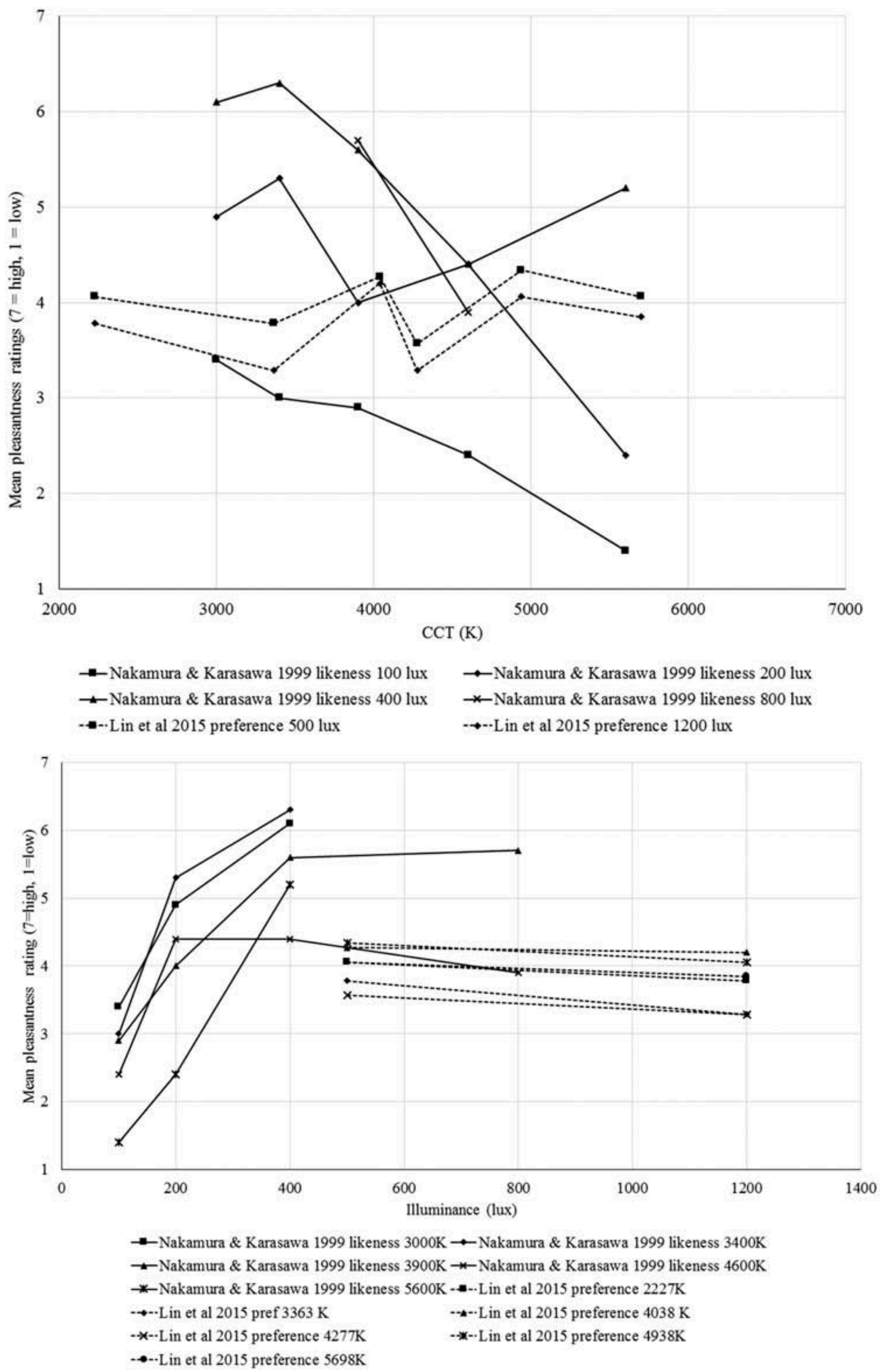

Fig. 6 **Ratings associated with pleasantness plotted against CCT (top) and illuminance (bottom) from two studies [Lin and others 2015; Nakamura and Karasawa 1999].**

ratings for the seven CCT conditions and shows that it tended to increases with elapsed time. In other words, the immediate response was to indicate a lower level of comfort than was indicated a few minutes later. For the 500 lux trials the ratings may have reached a plateau around 6 min, whereas for the 200 lux trials a plateau may not yet have been reached.

Adaptation time, however, does not offer a consistent explanation for variations between studies in Table 2. Studies with both short term adaptation (for example, 15 s

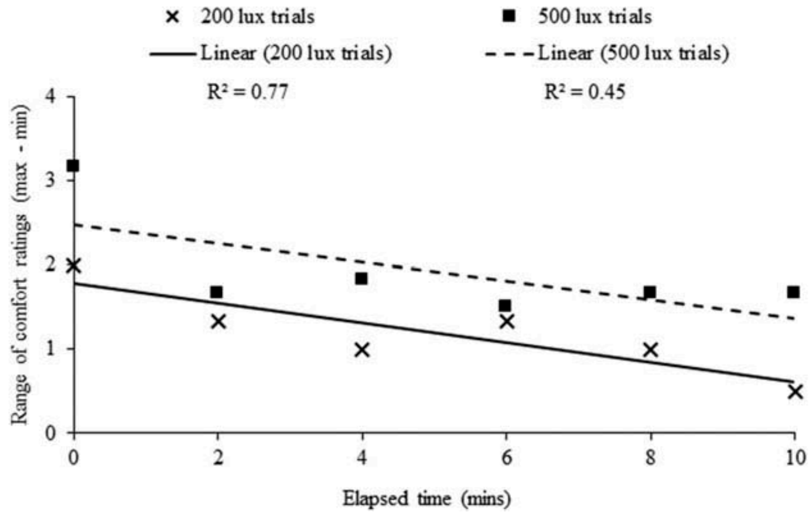

Fig. 7 **Range between minimum and maximum mean ratings of comfort plotted against time elapsed before judgments were given, after Takahashi and others [2014].**

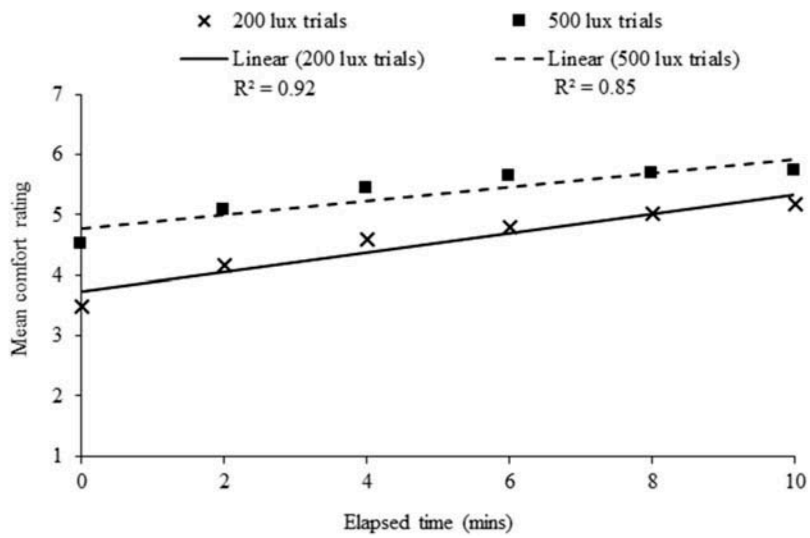

Fig. 8 **Mean ratings of comfort plotted against time elapsed before judgments were given, after Takahashi and others [2014].**

[Ao-Thongthip and others 2013]) and long-term adaptation (for example, ~30 min [Islam and others 2015] or across 3 months [Wei and others 2014]) reported significant effects of CCT on ratings of pleasantness. What can be seen in Table 2 is that the level of significance tends to decrease with adaptation.

4.3. Consistent Understanding

Though there may be a common understanding of the term brightness, this may not be the case for other terms for which evaluations are sought, such as pleasantness. There is inconsistent understanding between lighting experts (that is, the authors of published articles) regarding the meaning of the widely used term “visual clarity” [Fotios and Atli 2012], and experimenters should therefore be cautious about assumptions of how naïve test participants interpret the term [Rea 1982]. The same must be considered for judgments of pleasantness, particularly because pleasantness may not be directly related to the luminous environment [Tiller and Rea 1992]. In few, if any, studies reviewed for the current article did experimenters attempt to define the meaning of rating scales or otherwise check participants’ understanding of pleasantness: there are no data by which to evaluate whether test participants have a consistent interpretation of pleasantness or whether this agrees with the experimenter’s understanding. Therefore, one possible source of variance within and between studies is the interpretation of pleasantness as an attribute of the visual environment.

5. FURTHER WORK

5.1. Should Further Kruithof Studies Be Carried Out?

There is little need for further experimental work regarding a relationship between CCT and illuminance. Any further work would likely fit the trends shown in Figs. 2–5 but should not be expected to confirm Kruithof's zones or provide insights not already inferred from the nine credible studies summarized in this article.

However, "Lighting designers continue to refer to it with reverence . . . " [Cuttle 2015], which suggests that there is something regarding the interaction of SPD and illuminance still to be teased out. Further work would be interesting if it explored SPD metrics beyond CCT. It is also recommended here that alternative techniques be employed. Most Kruithof studies have used category rating; it would be useful to use in parallel matching and/or discrimination task because converging evidence from these would lead toward more robust conclusions [CIE 2014]. The experiment reported by Boyce [1977] is recommended as an example of good practice: there are a priori predictions of the likely relationship between the visual response studied and various spectrum metrics, two procedures (rating and matching) are employed to compare different conditions, and there are null conditions to provide a measure of internal validity.

Some studies have been carried out apparently in response to the introduction of light emitting diode (LED) illumination as an alternative to fluorescent lamps for general illumination [Hwang and others 2012; Islam and others 2015; Oi and Takahashi 2013; Vienot and others 2009]. One advantage of commercially available LED sources is that it is easier to independently adjust lumen output and CCT than with fluorescent and other conventional light sources. There is, however, little reason for further experiments to investigate the response to a spectrum simply because of a new technology for delivering that spectrum unless that new technology has significant effect on the spectrum. This was confirmed by Dikel and others [2014, p. 109], who carried out tests using both LED and fluorescent sources and concluded that "the comparison of judgements of the fluorescent source to the LED spectrum having approximately the same CCT showed no differences."

5.2. Nonvisual Responses

This discussion has focused on subjective evaluations of the visual environment and how these may be influenced by changes in SPD. Others have investigated the effect of changes in lighting on physiological responses. Kobayashi and Sato [1992] claimed that blood pressure increased at 7500 K compared to either 3000 or 5000 K. Heart rate variability may be affected by illuminance (200 vs. 1000 lux) [Smolders and others 2012], although the same effect was not apparent with smaller variation in illuminance (30 vs. 150 lux) [Noguchi and Sakaguchi 1999]. Other studies have measured how electrodermal response [Keil and others 2008], electromuscular activity [Wenzel and others 2006] and electroencephalogram [Park and others 2013] responses are affected by changes in lighting. Concerning task performance, Mills and others [2007] found in a field study that high CCT (17,000 K: control CCT not reported) lighting led to a significant increase in self-reported ability to concentrate. The timing, intensity, duration, and wavelength of light affect the circadian response [Brown and others 2012; Duffy and Czeisler 2009], which can increase alertness, leading to an improvement in task performance [Boyce 2014]. Holistic design requires that lighting design consider these factors in addition to visual responses, and further research should therefore be carried out to clarify the significance of changes in lighting.

6. CONCLUSION

This article examined evidence for a relationship between illuminance and CCT leading to illumination conditions likely to be considered as pleasing. It was first suggested that Kruithof's [1941] evidence for such a relationship is not credible because insufficient data were reported to know what was done. This should not be news. Two studies published approximately 25 years ago concluded that "subjective ratings of preference were influenced only by light level and not by colour temperature" [Davis and Ginthner 1990, p. 33] and that "once the subject is fully adapted to the conditions, the CCT of good colour rendering lamps in the range 2700K to 6300K has little effect on people's impressions of the lighting of the room" [Boyce and Cuttle 1990, pp. 33–34]. Despite these conclusions, there are still some researchers determined to find evidence in favor of Kruithof.

Studies carried out subsequently to verify Kruithof have mixed conclusions. However, when the mass of studies is reduced to those considered, by review of experimental design and reporting, to provide credible evidence, these tend to be more consistent and tend to reject Kruithof's proposed relationship. Of the nine studies suggested to provide credible evidence, by following best practice guidance for methodology [CIE 2014], five conclude that they do not support Kruithof, one gives partial support, and in the remaining three the message regarding Kruithof is not clear. For eight studies where results are sufficiently clear the data were redrawn. Examination of the trends in these eight studies for judgments of brightness and pleasantness suggest that

1. Variation in CCT has a negligible effect on ratings of brightness and pleasantness.
2. Low illuminances (less than approximately 300 lux) may be perceived as unpleasant; an illuminance of 500 lux is sufficient to provide a pleasant environment and a further increase in illuminance above 500 lux is of little benefit.
3. Higher illuminances are perceived to be brighter and this effect appears to be stronger than for other relationships.

This suggests that the one condition to avoid is low illuminance (these data refer to interior contexts, not exterior) and that variation in CCT (within the range of approximately 2500 to 6500 K) does not affect pleasing conditions and can be chosen by other criteria. The Kruithof graph should therefore show a single curve, a straight line ($y \approx 300$), shaded underneath to suggest likely unpleasant conditions and clear above to suggest likely acceptable conditions (Fig. 9).

Further work should consider SPD metrics beyond CCT, should seek verification using alternative procedures to category rating, and should investigate physiological responses.

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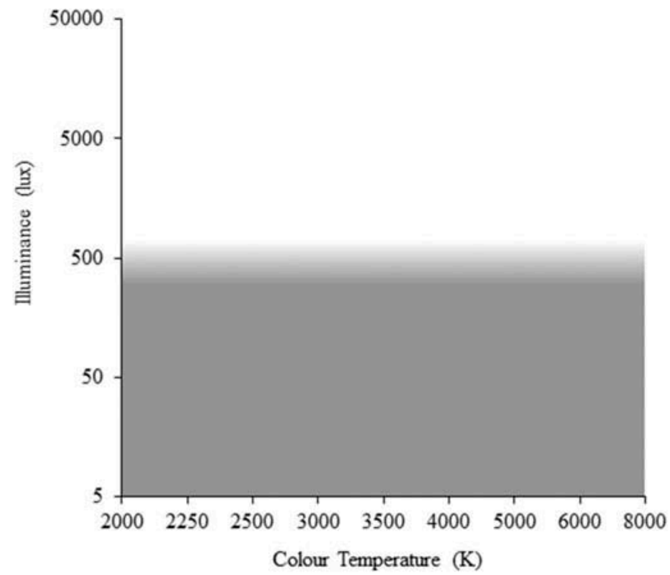

Fig. 9 **The Kruithof curve revised according to the results of credible studies. The shaded region represents conditions likely to be considered unpleasant, and the clear region above suggests conditions likely to be acceptable. The credible studies evaluated suggest that the transition from likely acceptable to likely unpleasant conditions is in the range of (approximately) 300 to 500 lx. Low illuminances (less than approximately 300 lux) may be perceived as unpleasant; an illuminance of 500 lux is sufficient to provide a pleasant environment, and further increase in illuminance above 500 lux is of little benefit.**

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