Published paper

Logadottir, A., Christoffersen, J. and Fotios, S.A. (2011) *Investigating the use of an adjustment task to set the preferred illuminance in a workplace environment*. Lighting Research and Technology, 43 (4). 403 - 422. ISSN 1477-1535
http://dx.doi.org/10.1177/1477153511400971

Investigating the use of an adjustment task to set preferred illuminance in a workplace environment

Short title: Investigating preferred illuminance adjustment

Logadóttir Á. MSc[1], Christoffersen J. PhD[1], Fotios SA. PhD[2].

[1] Danish Building Research Institute, Aalborg University, DK

[2] School of Architecture, University of Sheffield, UK

Note: Christoffersen J is now located at VELUX A/S, DK

Corresponding author:
Ásta Logadóttir
Dr. Neergaards Vej 15
2970 Hørsholm - DK
Telephone number: +45 3054 6056
e-mail: asl@sbi.dk

Abstract

An experiment was carried out to examine user preferences for light level using the method of adjustment. The study sought preferred illuminances under lighting from fluorescent lamps of different CCT. It was proposed that the preferred levels of illuminance would be influenced by variables of the experimental design including the available stimulus range, the anchor (initial setting before adjustment) and adaptation time before onset of adjustment action. The experiment included three different sized stimulus ranges (21-482 lux, 38-906 lux and 72 to 1307 lux) and these lead to significantly different preferred illuminances (337 lux, 523 lux and 645 lux). The experimental results confirmed that stimulus range and anchor have significant effect on the adjustment task, confirming the importance of considering and reporting these variables when determining user preference with an adjustment task.

Logadóttir Á, Christoffersen J and Fotios SA. Investigating the use of an adjustment task to set preferred illuminance in a workplace environment. Lighting Research & Technology, 2011; 43(4); 403-422.

1. Introduction

Previous studies have determined user preferences for illuminance in the workplace by providing subjects with a range of light levels and asking them to adjust to their preference; this is the method of adjustment. For example Juslén et al[1] investigated task lighting in an industrial setting (luminaire assembly) where occupants were able to add up to 3000 lux of task lighting to the general lighting of 0 to 380 lux, depending on location, to obtain their preferred illuminance for the task. The mean preferred illuminance was 1752 lux, prompting Juslén et al to suggest that "*Industrial assembly workers … prefer to have significantly higher illuminances than the minimum required by norms and standards.*"

In the method of adjustment the test subject is given control over the stimulus, usually involving variation in illuminance and sometimes correlated colour temperature (CCT), and is instructed to set the illuminance and/or CCT to their preferred level. There are many limitations of the adjustment method, a critical problem being that the range of illuminances that can be set by the test subject is limited by the upper and lower end of the stimulus range and a subject's ideal preference may lie outside of this range. Veitch and Newsham[2] recorded preferred illuminances set by people in an office where the maximum illuminance available on the desktop was 725 lux and reported a mean preferred desktop illuminance of 423 lux (median 413 lux): this upper limit is not as high as the mean set in the Juslén et al study, so if these subjects would have preferred such a high illuminance, they were not able to choose it.

Fotios and Cheal[3] examined previous studies using the method of adjustment to determine preferred illuminances. Some studies failed to report the range of illuminances available to test participants, a critical omission of reporting. Of the seven studies[1,2,4,5,6,7,8] where the range was reported, or could be estimated from other data, a consistent bias was noted – the reported mean preferred illuminance tended to lie near the centre of the available stimulus range. This is a case of stimulus range bias: experiments offering test subjects a range of illuminances with a high upper value would report a higher preferred illuminance than studies offering a lower range. Fotios and Cheal[3] confirmed this using an adjustment task in which the test subjects were instructed to set their preferred illuminance using a rotary dial but were unaware that the experimenter changed the range of illuminances available in successive trials.

In a preliminary study carried out by Logadóttir and Christoffersen,[9] subjects in a daylit laboratory furnished to simulate an office were asked to adjust the lighting to establish their preference for light level and CCT. These findings were reviewed following Fotios and Cheal[3] and it was found that these results also exhibited stimulus range bias within settings of preferred illuminance and CCT. As shown in Table 1, the mean preferred illuminance and CCT are near the middle of the available ranges.

It was therefore decided to repeat the study but with greater attention being paid to experimental bias associated with the adjustment task. This article reports on experimental bias in the adjustment task, in particular the effect of stimulus range, anchors, internal consistency and adaptation time. This extends previous work[3] by carrying out the adjustment task in full size rooms rather than a scale model, by using light sources of different CCT, by considering an intermediate anchor point, and by examining the effect of adaptation time prior to making the adjustment.

2. Experimental Bias

In the context of a psychophysical measurement such as brightness, bias means an unfair assessment of the stimulus magnitude. It is a systematic distortion of a response that most commonly results from the experimental methodology. An experimental bias pollutes the data by being confounded with the lighting effects under study. There are many causes of bias in psychophysical studies of lighting including those induced by the experimenter (e.g. dissimilar visual fields and inaccurate physical measurement of the stimulus), unintentional manipulation of subjects' behaviour, and changes in the subject's psychophysical criterion due to sequence effects and the degree of adaptation to the intensity and colour of the stimulus. Poulton[10,11] provides a comprehensive analysis of bias in subjective evaluations.

In the adjustment task the test subject uses a control device, for example a rotary dial or a linear slide, to set a preferred or optimum level of the variable stimulus. Potential sources of bias in this particular task include the stimulus range available (i.e. minimum and maximum values) through control action; the illuminance provided by, and the initial setting of, the control device before the task is attempted; and the time elapsed between onset of the stimulus and the control action.

2.1 Stimulus range

Fotios and Cheal[3] suggested that illuminance adjustments were characterised by a centering bias, with mean preferred illuminances tending to lie near the centre of the available stimulus range. Within visual brightness tasks this may be associated with adaptation, with the lower and upper ends of the available range of luminance, for example, appearing to be respectively too dim or too bright in comparison with the remainder of the range. Centering biases are also produced by a symmetric distribution of responses; if people use responses above the centre of the range of responses about as often as they use responses below the centre of the range, then this centres the range of responses on the midpoint of the range of stimuli.[11] The reported central tendency (e.g. mean preferred illuminance) will thus fall near the centre of the stimulus range. This would suggest that the mean is an inappropriate way to characterise population preference and is why other studies have instead reported a range of preferences[9] or the percentage of people satisfied by a particular value.[12]

An illustration of stimulus range bias is given by Poulton[10] with reference to subjective judgements of noise levels. If acoustic stimuli in the range of 80 to 100dB are judged on a category scale of very quiet to very noisy, then the

100dB stimulus will be rated to be very noisy and the 80db to be very quiet. If a second test used instead a 70 to 90dB range, the 90db stimulus would be rated as very noisy and 70dB very quiet. The same subjective rating of noisiness would thus be attributed to two different noise levels dependant on the stimulus range: 80db in the first test would be rated as very quiet but this same stimulus would fall on the quiet/noisy borderline in the second test. In general, the available range of a stimulus range is judged according to its limits, with the lower limit of a range being perceived as low or little and the higher limit of the range as high or much.[13]

To confirm the presence of stimulus range bias in the current study the adjustment task was repeated using different stimulus ranges

2.2 Anchors

LeBouef and Shafir[14] used the term anchor when referring to a starting point or stimuli encountered before judgement. In the current context anchoring refers to the initial value (or starting point) of the variable stimulus dimension (illuminance) before the test subject is instructed to carry out the adjustment task. Different starting points yield different estimates and these estimates are biased toward the initial values, a systematic and predictable error.[15] Hunt and Wolkmann[16] reported that anchoring affects judgment of the pleasantness of colours and significant anchor effects have been detected within psychophysics by different stimuli.[17]

A clear anchor effect can be seen in the glare adjustments reported by Osterhaus and Bailey.[18] In their study test subjects adjusted the brightness of a light source surrounding a PC screen to identify the borderline between different glare thresholds, and this was carried out using a range of initial presentation luminances immediately preceding the adjustment. The results show that higher anchors lead to higher estimates of the threshold luminance.

The method of adjustment presents a variable stimulus that is adjusted by test subjects to identify the threshold value, or their preferred value, for this stimulus: it is recommended that the variable stimulus is set initially to values far above and far below the expected threshold value on successive trials, and that the absolute value is taken as the mean of these settings.[19] Fotios and Cheal[3] used high and low anchors in successive trials and found that these lead to significantly different illuminances, with the low anchor (i.e. low initial illuminance) leading to lower settings of preferred illuminance than did the high anchor. Boyce et al[8] used an alternative approach; their dimming control was set initially to the 50 percent position. Thus in the current work the adjustment task was repeated using a 50% starting position in addition to the low and high initial illuminances to compare results from these different approaches.

2.3 Adaptation

Adaptation means adjusting to, or getting used to, some kind of situation.[20] The human visual system has mechanisms for adapting to the prevalent illumination. The main observable attributes of light are its brightness and colour[21,22] and the human visual system has the ability to adapt to both of these attributes, with the capacity to adjust sensitivity as the illuminance rises or falls and with changes in the spectral power distribution (SPD) of the illumination. Consequently there is a tendency to experience all illumination as white, neutral or colourless in colour and normal or medium in intensity.[21] Consideration of adaptation suggests two implications. Firstly, that if the test subject commences an illuminance adjustment trial when adapted to an anchor, that any adjustment to a significantly higher or lower level would be considered too bright or too dim respectively, regardless of the absolute value. Secondly, adaptation suggests that given sufficient time a wide range of illuminances would be considered acceptable. Therefore, in the current work, the adjustment task was carried out using immediate and delayed responses to investigate the effect of adaptation.

2.4 Internal consistency

Previous work has revealed a high degree of variance in the preferred illuminance adjustment task.[1,3,9] One reason for such variance is that individuals do not have a consistent preference for illuminance (or, that the illuminance adjustment task does not allow subjects to express such preference with consistency) and this would result in test subjects giving different responses on successive trials under the same conditions. Therefore, the current experiment included a repeated condition within each stimulus range to provide a measure of internal consistency.

2.5 Correlated Colour Temperature (CCT)

The test results of Kruithof[23] have been used to suggest a relationship between light level and preferred CCT, with warmer lighting being preferred at low illuminances and cooler lighting being preferred at high illuminances, but the evidence presented was far from convincing[†]. Boyce and Cuttle[24] investigated CCT, illuminance and subjective impressions of lighting in a room to clarify the alleged Kruithof effect. They report that CCT had no significant effects on subjective impressions including brightness and this is intriguing because they used a wide variation in CCT (2700K, 3500K, 4200K and 6300K) and other studies have reported that lamp spectrum does affect brightness.[25] It may be that CCT is an inappropriate metric for characterising the brightness effects of a spectrum[26] or that the large number of stimuli (22) compared with the small number of response categories (5) did not enable test subjects to distinguish between the different CCT.[27] It was therefore decided to include CCT as a variable in the current tests to present further evidence of the relationship between preferred illuminances and CCT. The illuminance adjustment task was therefore carried out using lamps of different CCT to investigate interaction between CCT and illuminance.

3. Method

[†] Anecdotal comments suggest Kruithof did not intend for his data to be interpreted in this manner.

An adjustment task was carried out to determine user preferences for illuminance in an office setting. The test was designed to investigate the effects of stimulus range, pre-adjustment anchor, CCT, adaptation time and internal consistency.

The test was carried out in two identical, side-by-side experimental rooms (width 3.5m, length 6m and height 3m), each being furnished as an office for one occupant (Figure 1). Daylight was excluded by shielding the windows. Table 2 summarises the materials and reflectances of the furnishings. The walls were painted light grey, the carpet was dark grey, and the wooden shelf and desk were dark brown. A computer screen and a task lamp were placed on the desk but neither of these was switched on during trials. The reading task and control dial used by subjects were placed on the desk.

The lighting systems in each room were identical and consisted of three ceiling mounted direct luminaires, with each luminaire containing three 54W tubular fluorescent lamps. The voltage of the electricity supply to these lamps was stabilized (to 230V) throughout the study. The lamps operated on electronic dimming ballasts by a commercial lighting control system.[28] Three different stimulus ranges were created by varying the number of active lamps in each luminaire, i.e. one lamp (range R1, the central tube), two lamps (range R2, the outer two tubes), or all three lamps simultaneously (range R3). As shown in Table 3, range R1 provided 21 to 482 lux on desktop, range R2 provided 38 to 906 lux and range R3 provided 72 to 1307 lux. The experimenter was able to change the stimulus range (i.e. the number of tubes being adjusted) through the lighting control software.[28]

Three different levels of CCT were achieved by changing the type of fluorescent lamp used. These were nominally 3000K, 4000K and 6500K, with each type of lamp having a general colour rendering index of R_a 85. However, measurements carried out using an Ocean Optics HR4000 spectrometer in the test room suggest CCT of 2500K, 3100K and 4500K at the task location.

To adjust the illuminance, test subjects used a rotary dial placed on the desk in front of them. The rotary dial provided an illuminance range of 3% to 100% in one complete turn but was open ended so that there were no obvious physical limits to the range.

Three anchors were used within each stimulus range: in the current study an anchor is the illuminance set by the experimenter prior to each trial. Table 3 shows that the lowest anchor (A1) was set at approximately 70 lux for all three ranges. Anchor A2 was fixed to 300 lux for range one, 609 lux for range two and 882 lux for range three: these were the illuminances in each range with the control dial set to the middle of its range, the anchor used by Boyce et al.[8] The highest anchor (A3) was fixed for range one at 469 lux, for range two at 880 lux and range three at 1287 lux: these are the illuminances gained in each range with the control dial set to 90%. This was done so as not to give an immediate cue to test subjects that a downward adjustment was the only option. To check for internal consistency trials using anchor A2 were repeated within each combination of stimulus range and CCT.

The spatial distribution of luminance was examined using a CCD camera (TechnoTeam, LMK Mobile) with a Nikon FCE8 lens, field of view 183˚. The camera is equipped with software for control of the camera and analysing the luminance data of the whole recorded scene. Luminances, with range R3 at the maximum control setting, measured on the task, the immediate surround and vertical partition wall facing the test subject, are reported in Figure 2. The paper based reading task on the desktop had a mean luminance of 7.6 cd/m^2 with anchor A1, the lowest initial value presented to test subjects, reduced to 2.3 cd/m^2 at the lowest possible setting of the subject's dimming control in range R1; the maximum luminance on the reading task was 179 cd/m^2 (range R3, maximum control setting). The uniformity of luminance between the task and the immediate surround was approximately 1.0 to 3.3.

Tests used one room at a time: the advantage of two rooms was that fewer changes of fluorescent tubes (to set different CCT) were needed within a test session. To verify that the two rooms offered similar spatial distributions of light, horizontal illuminances were measured (using a Hagner E4-X illuminance meter) at three locations on the desk surface and four locations about the room, 0.85 m above the floor, with identical light settings in each room. Figure 1 shows the locations of these measurements. The illuminances recorded at these locations did not suggest a trend for one room to have a higher illuminance than the other. The maximum difference in illuminance between the two rooms at any one point was 6.8%. Similarly, spectral power distributions in the two rooms were measured using an Ocean Optics HR4000 spectrometer focussed on a reference white placed on the desk surface. For lamps of nominally the same CCT, the maximum difference in CCT between the two rooms was 2%.

4. Procedure

Test subjects were informed that they were participating in a study on user preferences for light levels in office environment. After entering the first test room and sitting at the desk they were given instructions regarding the task and use of the eye mask between trials, and were given the opportunity to try the dimming control device. The light setting at this time was the first experimental setting for that test subject and was therefore balanced across subjects.

Subjects were instructed to adjust the amount of light in the test room to the level they would prefer while reading a text placed flat on the desk surface and this was done using the rotary control device placed on the desk. The text was printed in black on white paper, using Arial font, point size 10, and a 1.5 line spacing. Five different texts were used, these being newspaper articles used in a former study[29] where they were judged as being "not exciting" and "not boring”. Test subjects read through all five texts in a random order, although the non adapted subjects (see below) barely got through one text.

This was a repeated measures design; all test subjects were presented with the 36 combinations of stimulus range (3), CCT (3), anchor (4; three anchors plus A2 repeated). The apparatus did not enable variation of CCT other than by changing the fluorescent tubes. Therefore, when a test subject entered a room it was lit by only one CCT, and tests using all combinations of stimulus range and anchor were completed for that CCT before moving to the adjacent room set up with a different CCT. For the ‘adapted’ subjects (see below) it took approximately 70 minutes to complete all trials under one level of CCT. For the 'non adapted' subjects (see also below) it took approximately 10 minutes to compare all trials under one level of CCT. The order in which the three CCT were experienced and their allocation to the two test rooms (see figure 1) was balanced across subjects.

From completion of one set of trials, five minutes was allowed to move to the second room and prepare to repeat the trials under the new CCT. The corridor between the two rooms was approximately 3.5m long; for safe transit the corridor was lit, and this was done using daylight, with the window shading adjusted to allow an illuminance of approximately 200 to 400 lux as measured horizontally 0.85m above the floor level.

Illuminance adjustments for the four trials anchors within one illuminance range (i.e. three anchors plus one repeat) were carried out in a balanced order, and this was repeated for the other two illuminance ranges, these being experienced in a balanced order. Test subjects covered their eyes with a mask while the experimenter reset the anchor and/or stimulus range, which took approximately 20 seconds. Subjects were not informed that the ranges or anchors were being changed.

Two levels of adaptation were used, and this was examined between subjects. Half of the test subjects (luminance adapted subjects) were instructed to wait for five minutes after removal of the eye mask before attempting the adjustment task. The other half of the test subjects (non adapted subjects) were instructed to carry out the adjustment immediately after removal of the mask.

After tests with the second level of CCT a break was taken. For the luminance adapted subjects this was a lunch break of 30 minutes; for the non adapted subjects this was a break of 15 minutes. Trials for the adapted subjects required attendance for a whole day, so the break for these subjects was used as a lunch period. Trials for the non-adapted subjects took less time to complete and were scheduled to fit into a half-day, either before or after lunch. During this time the experimenter changed the lamps in one room to the third level of CCT, allowing the lamps to warm up before the adjustment task, and test subjects were asked to complete a questionnaire to record personal details including age and gender.

36 subjects took part in the study. These were 16 males and 20 females, aged 20 to 67 years old (mean 27.7 years, std dev 9.9) and were either university students or office workers. All subjects reported normal colour vision except one who reported red-green colour deficiency. Subjects were instructed to wear vision correcting lenses if these were normally worn in office work situations. All subjects were naïve as to the purpose of the study.

5. Results

The results are summarised in Table 4 and Figure 3, which show the mean and median illuminance within each combination of range, anchor, and CCT. These results include both the adapted and non-adapted subjects and exclude the repeat trial carried out with anchor A2. Three trends are apparent in these data. Firstly, within a given stimulus range, preferred illuminance tends to increase with higher anchors. For example, in range R1 with the 3000K lamp, the 70 lux, 300 lux and 469 lux anchors lead to median illuminances of 170 lux, 370 lux and 471 lux respectively. Secondly, as the maximum limit of the stimulus range increases then so does the mean preferred illuminance. Note however that the lower anchor was the same for all three ranges (70 lux) and results for trials using the lower anchor do not suggest an effect of stimulus range. Thirdly, there appears to be no effect of CCT.

Normality of the data distributions were assessed through consideration of measures of dispersion, graphical representation and statistical analysis. Where data were considered to be drawn from a normally distributed population, the differences between levels of a variable were examined using parametric tests, ANOVA and the *t*-test; where data were not considered to be drawn from a normally distributed population, the differences were examined using non-parametric tests, Friedman's test and the Wilcoxon test for related data, and the Kruskal-Wallis test and Mann-Whitney test for unrelated data. Non parametric tests are less powerful than parametric tests at revealing differences and therefore these analyses were repeated using parametric versions for confirmation. Unless otherwise stated, identical conclusions were drawn using parametric tests as with non-parametric tests. The effect of a variable having more than two levels was initially examined using tests for multiple levels (i.e. ANOVA, Friedman or Kruskal-Wallis) and if these suggested a significant effect then the differences between all pairs of that variable were subsequently examined (*t*-test, Wilcoxon test or Mann-Whitney test). Data analyses were performed using SPSS version 18.

5.1 Internal Consistency

To examine internal consistency in the adjustment task subjects carried out two trials using anchor A2 within every combination of stimulus range and CCT. These data were not considered to be drawn from a normally distributed population. Table 5 shows the median illuminances found in these trials. There is no obvious trend in these data; in four of the nine cases the median illuminance found in the first trial is lower than in the second trial. The median illuminances from the first and second trials tend to lie close to each other and Friedman's test does not suggest the values to be different. This suggests that test subjects displayed a reasonable degree of consistency in their preferred illuminance adjustments within a particular stimulus range, anchor and CCT. Results of the second trial with anchor A2 were excluded from further analyses.

5.2 Anchors

Preferred illuminances gained from the different anchors were not found to be drawn from normally distributed populations. Table 4 suggests that the higher the anchor provided, the higher the median preferred illuminance, and this can also be seen in Figure 3. Friedman's test suggests that the three different anchors provided significantly different results within each stimulus range ($p<0.01$) and between pairs of anchors using Wilcoxon signed rank test ($p<0.01$). This demonstrates that the illuminance immediately preceding the adjustment task is of importance.

Following Gescheider[19] an estimate of a subject's preferred illuminance may be found by taking the mean of the results gained using upper and lower anchors. An alternative approach was used by Boyce et al[8] who set the control to 50% prior to adjustments. The current study employed three different anchors and the mean of all three may be considered the best estimate because it comprises the most amount of data. These transformed data were again not considered to be drawn from a normally distributed population. Table 6 presents the median and mean[‡] preferred illuminance in each stimulus range and CCT for the three different anchor treatments; the mean of anchors A1 and A3, anchor A2, and the mean of anchors A1, A2 and A3.

The estimate of preferred illuminance derived from anchors A1 and A3 provides the lowest median illuminance in all cases, and the estimates derived using A2 and the mean of A1, A2 and A3 are reasonably similar. Friedman's test suggests that, for each combination of stimulus range and CCT, preferred illuminances estimated using these three approaches to anchoring are significantly different ($p<0.01$) and the Wilcoxon test also suggests that the

[‡] Although the data are suggested to be non-normal, the mean and standard deviation are reported in Table 6 in addition to the median to assist comparison with other experimental data and further independent statistical analysis

preferred illuminances are significantly different ($p<0.01$) for all three anchor treatments.

One reason for these differences may be the non-linearity of the relationship between control setting and illuminance. As shown in Figure 4, the illuminance obtained at the 50% control setting was greater than the central value of the illuminance range. For example stimulus range R2 had a range of 38 to 906 lux giving a central value of 472 lux, but the centre of the control range (anchor 2, the 50% setting) provided an illuminance of 609 lux. This means that any estimate of preferred illuminance using anchor A2 is inflated. For consistency with standard practise[19] subsequent analyses were carried out assuming that the mean of anchors A1 and A3, the lower and upper ends of the illuminance ranges, gives the best estimate of preferred illuminance. The single middle anchor (50% control setting) may work if the relationship between control position and illuminance is linear, and this should be examined in further work.

5.3 CCT and preferred illuminance

The data in Table 6 (data rows for the mean of anchors A1 and A3) do not suggest any consistent effect of CCT on preferred illuminance. Within each stimulus range, Friedman's test does not suggest a difference due to CCT. The comparisons are made between all three CCTs between ranges R1, R2 and R3 respectively. The Wilcoxon test suggested a significant effect only in range R3 between 3000K and 4000K ($p<0.05$); the *t*-test does not suggest any differences between CCT pairs to be significant.

The electronic dimming control caused a change in CCT alongside the intended variation in illuminance. Figure 5 shows that the CCT of the fluorescent lamps did increase at when the dimming control was set to positions below 10% for the 4000K and 6500K lamps and 30% for the 3000K lamp. For control settings above approximately 30% the CCT were reasonable stable, but below 10% (30% for 3000K) there are considerable changes, an increase of approximately 73K, 750K and 1249K for the 6500K, 4000K and 3000K lamps respectively.

This may influence the light level preference results to some degree. Thus the effect of CCT was further analysed by using the data only from anchor A3 where only one value was below the control setting of 20% (and this was here treated as a missing value). Friedman’s test still does not suggest a significant effect of CCT within all ranges.

This analysis suggests that the CCT tested in this study did not affect preferred illuminances set in the adjustment task. Thus when analysing the effect of stimulus range the preferred illuminance for a test subject was estimated as the mean of their settings made for all three CCT.

5.4 Stimulus Range

The effect of stimulus range on preferred illuminances as set using the adjustment task was determined assuming that the best estimate of preferred illuminance for each subject is the mean of their settings made from anchors A1 and A3, the upper and lower anchors, and also the mean of settings made with lamps of different CCT. These data were considered to be normally distributed. Table 8 shows the mean preferred illuminances in each stimulus range. ANOVA suggests that, different stimulus ranges lead to significantly different preferred illuminances ($p<0.001$). In each case, the higher stimulus range (i.e. higher maximum value available) lead to the higher preferred illuminance: the t-tests suggest these differences are significant ($p<0.001$).

Figure 3 shows a clear stimulus range bias within the raw data. For anchors A2 and A3 the median preferred illuminance lies toward the upper end of the available range and thus increases for the higher ranges; anchor A1 does not suggest a stimulus range bias but suggests similar preferred illuminance for all three ranges, probably because it was the same anchor for each range (in Fotios and Cheal[3] the three ranges had different anchors). Figure 6 shows the mean of anchors A1 and A3 averaged across the three CCT, which is the proposed best estimate of preference: while the effect of stimulus range for all trials data is less obvious there is still a trend for preferred illuminance to change with stimulus range.

5.5 Adaptation

Table 7 shows the preferred illuminances broken down according to whether the test subjects were adapted for five minutes following exposure to the stimulus before adjustment was carried out or were not-adapted and provided an immediate adjustment. The data sets are considered to be normally distributed. In ranges R1 and R2 the mean preferred illuminance set by the adapted subjects is lower than that of the non-adapted subjects, while in range R3 the non-adapted subjects set a slightly lower preferred illuminance than did adapted subjects. ANOVA does not suggest the effect of adaptation time to be significant but the interaction of range and adaptation time is significant ($p<0.01$). One thing that does appear to be different between these two groups is the standard deviation, with results from the adapted subjects having a standard deviation nearly half that of the non-adapted subjects.

5.6 First response

Poulton[11] suggests one method for reducing experimental bias is to ask test subjects to respond to only one condition. When providing their first response, test subjects are unaware of the overall range of stimulus magnitudes and are therefore less affected by stimulus range bias. Therefore, Table 8 and Figure 6 compare preferred illuminances determined only from very first trials carried out by test subjects with preferred illuminances determined from exposure to all stimulus magnitudes. The first-trial data is that for only the first condition to which each test subject was exposed, this being balanced across subjects so that there are 12 data points in each stimulus range, and these were balanced across anchors and CCT. These data were not considered to be drawn from a normally distributed population. The all-trials results include data for the 36 subjects within every range and three trials for each due to the different CCTs.

Figure 6 shows that with the first-trial data the median preferred illuminances in ranges R2 and R3 are very similar; the median preferred illuminance in R1 is lower than these and in all three ranges the median preference is above the mid-point of the range. The all-trials suggest a mean preferred illuminance that is close to the range mid-point in R2 and R3, while for range R1 it is higher than the midpoint and coincides with the median preferred illuminance of the first-trial data.

Analysis of the first-trial data using Kruskal-Wallis test suggests significant difference between the three ranges ($p<0.01$). The Mann-Whitney test shows significant difference ($p<0.01$) between ranges R1 and R2, and between ranges R1 and R3, but does not suggest a difference between ranges R2 and R3 ($p=0.488$), the same as was reported by Fotios & Cheal.[3] Thus a difference between the first-trial data and the all-trials data is that the difference between R2 and R3 is suggested to be significant for the all-trials data but not for the first-trial data. Both sets of data suggest that stimulus range can have a significant effect on the estimate of preferred illuminance.

6. Discussion

This article reports on experimental bias in the adjustment task due to the effects of stimulus range, pre-adjustment anchors, lamp CCT and adaptation time. The experimental results show that both stimulus range and pre-adjustment anchor have significant influence on preffered illuminance set by adjustment, confirming the previous results of Fotios and Cheal.[3] Stimulus ranges with a higher maximum limit yield higher estimates of preferred illuminance: within a given range, an anchor of higher illuminance leads to a higher setting of preferred illuminance.

Figure 7 shows the frequency by which the preferred illuminance setting lies within each 10% interval of the control setting for all trials within each of the three ranges. It can be seen that all parts of the range are used, mostly with equal frequency. In range R1, the illuminance range offering the lowest maximum illuminance, Figure 7 shows that 36% of the settings were in the 90-100% control range, i.e. test subjects have chosen near the maximum possible illuminance, more so than for the other ranges where 16% and 9% of settings were found in ranges R2 and R3 respectively.

The 36% of the settings in range R1 that were in the 90-100% control range account for 155 of the 432 R1 settings. Of these, 45 settings (29%) were made when R1 was the first range to be experienced, and 110 settings (71%) were made when R2 and/or R3 had been experienced before R1. Therefore this ceiling effect could arise from previous exposure within the experiment to stimulus ranges of higher illuminance where range R1 would appear dim compared to the higher stimulus ranges, and thus that some test-subjects were seeking a higher illuminance because they were aware that the experiment permitted a higher illuminance to be set, an inherent problem of an experiment using multiple levels of a variable with a repeated measures design. In studies using only one range of illuminances, which is the case for most studies using the adjustment method, this ceiling effect is less likely to occur.

The remaining 64% of settings in range R1 are distributed widely within the 10% to 89% region. All settings for ranges R2 and R3 are distributed reasonably evenly across the 3%-100% range of control settings. This even spread of settings demonstrates that within a group of subjects all parts of the response range will be used with an approximately equal frequency. This is a clear case of centering bias as defined by Poulton,[11] whereby the even distribution of settings across the entire range will lead to a mean value falling at the middle of the range. The distribution of settings calls into the doubt the value of the adjustment task for establishing preferred illuminances and the value of using the mean average to indicate population tendency.

The current study used three different anchors (illuminance set by the experimenter prior to each adjustment task) to investigate the influence of these. Primarily, this was done to compare preferred illuminance found as the mean of settings from high and low anchors, the approach described by Gescheider[19] with preferred illuminance found using only an anchor at the centre of the range, the approach used by Boyce et al.[8] The results show that anchors do have a significant effect on preferred illuminance. The preferred illuminances found using only the middle anchor were significantly higher than the mean of the low and high anchors. In the current study the middle anchor was defined as the controller set to the 50% position. Figure 4 shows that the relationship between control setting and illuminance is non-linear, meaning that at the 50% control setting illuminances were above 50% of the illuminance range. It is possible that the difference between the two approaches to anchors could be reduced by using a controller offering a linear relationship between control setting and illuminance, or by setting an anchor at the 50% point of the illuminance range rather than of the control range.

An advantage of using the middle anchor is that it may be more likely to produce data which are normally distributed, whereas using low and high anchors may skew the data distribution due to floor and ceiling effects. Figure 8 shows the frequency by which the preferred illuminance setting lies within each 10% interval of the control setting for anchors A1, A2 and A3 within range R2. It can be seen that the distribution is positively and negatively skewed for anchors A1 and A3 respectively whereas the results for anchor A2 are closer to a normal distribution.

The experimental results suggest that CCT does not affect preferred illuminances in an office setting, within the range of CCT included in the current study. This finding is consistent with previous studies which report that CCT does not influence evaluation of lighting or light levels for equal brightness[24,26] but inconsistent with other studies suggesting that lamp spectrum does affect brightness.[25] Possible reasons for this discrepancy are that CCT may be an inappropriate way to characterise the subjective quantitative evaluations of light sources of different SPD, or that the prominence of wide variation in illuminance is sufficient to outweigh any effects of SPD.

One test subject reported a red-green colour deficiency. Comparing the results of this subject to the mean of the other subjects it is evident that the colour deficient observer adjusted to somewhat lower illuminance levels for all stimulus ranges and CCTs. However, Figure 7 shows that there is a wide distribution of illuminance from all subjects so the results of this one subject do not stand out.

In the current study the preferred illuminance adjustment was made with a PC screen on the desktop but this screen was not switched on. In real situations the PC screen is likely to be switched on, and screen reflections may have affected the task. While further work may be required to determine if the presence of a screen affects settings of preferred illuminance it should also be noted that different screens have different reflectance properties[12] and thus consideration will be needed as to the types of screens used.

While the current study excluded daylight to avoid a confounding variable, a real office is likely to have daylight for some parts of the day. Results from the preliminary study[9] suggest that stimulus range bias persists despite the presence of daylight; subjects did not adjust according to the overall amount of light but only according to the stimulus range available for adjustment.

7. Conclusion

Previous studies have employed an adjustment task to identify the illuminances preferred by the occupants of a space. This article reports an illuminance adjustment task that was carried out to determine how the task was affected by experimental design.

It was found that the estimate of preferred illuminance was affected by the range of illuminances available, a stimulus range bias; as the maximum available illuminance in a range increased, then the estimate of preferred illuminance also increased. The three stimulus ranges used in the current study lead to significantly different estimates of preferred illuminance (337lux, 523lux and 645 lux). The preferred illuminances set by test subjects tend to lie across the whole range of available settings, and thus the central tendency of the data lies at the centre of the range, a centering bias. Stimulus range bias suggests the single interval adjustment task is not an appropriate research method for determination of preferred illuminance.

The illuminance immediately preceding the adjustment task (anchor) also has a significant effect on preferred illuminance, with higher anchors leading to higher settings of preferred illuminance. One approach to countering this bias is to carry out adjustments from both high and low anchors and use the mean of these two settings as the best estimate of preferred illuminance.

When considering assertions about preferred illuminances from studies using the adjustment method, designers and others should note that the results are likely to have been biased by the particular experimental design, and should take care note of two issues:

- Stimulus range: the range(s) of illuminance available to test subjects.
- Anchors: the illuminance experienced before the adjustment is carried out.

These two items should be considered and described in further work using single interval adjustment.

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Acknowledgements

This project was financed by Aalborg University Doctoral School, Faculty of Engineering and Science, the Danish Energy Agency through the R&D funding programme of the Danish Energy Association, Elforsk, the Danish Agency for Science, Technology and Innovation, and the Icelandic research fund for graduate students.

Table 1:

Results from a preliminary study of lighting preferences: mean preferred illuminances and CCT in a daylit office[9]. Note: n=22 test subjects.

		Illuminance (lux)	CCT (K)
Range	maximum	1270	5500
	minimum	57	2900
	centre	664	4200
Mean preference	Winter trials		
	Mean	627	4030
	Std Dev	178	426
	Autumn trials		
	Mean	631	4057
	Std Dev	*230*	*363*

Table 2.
Colour and reflectance of surfaces in the test rooms.

Surface	Material	Colour	Reflectance
Desktop and shelf	Wood	Dark brown	0.15
Wall	Gypsum plaster	Light grey	0.62
Floor	Nylon carpet	Dark grey	0.11
Ceiling	Acoustic tile	White	0.88

Table 3

Illuminance ranges and initial illuminances (anchors) used in preferred illuminance adjustment tests.

Range	Desktop illuminance (lux)				
	Limit of range		Anchor		
	Minimum	Maximum	A1	A2	A3
R1	21	482	70	300	469
R2	38	906	74	609	880
R3	72	1307	72	882	1287

Table 4.

Results of preferred illuminance adjustments. These are the mean and median illuminances, and the standard deviation (Std Dev), for each combination of CCT, stimulus range and anchor, and include both the adapted and non-adapted subjects. Note: the results reported for anchor A2 were derived from the first trial with this anchor from each test subject.

Range	**Anchor**		**3000K**	**4000K**	**6500K**
			Illuminance (lux)		
R1 [21-482lux]	A1 [70lux]	Median	170	182	228
		Mean	228	238	248
		Std Dev	*135*	*138*	*134*
	A2 [300lux]	Median	370	392	449
		Mean	372	398	407
		Std Dev	*92*	*67*	*91*
	A3 [469lux]	Median	471	477	482
		Mean	433	433	445
		Std Dev	*68*	*69*	*56*
R2 [38-906lux]	A1 [74lux]	Median	195	211	218
		Mean	249	308	267
		Std Dev	*165*	*234*	*183*
	A2 [609lux]	Median	648	635	635
		Mean	609	644	657
		Std Dev	*196*	*167*	*175*
	A3 [880lux]	Median	847	834	789
		Mean	783	776	761
		Std Dev	*128*	*150*	*141*
R3 [72-1307lux]	A1 [72lux]	Median	185	215	215
		Mean	255	250	234
		Std Dev	*191*	*214*	*119*
	A2 [882lux]	Median	869	844	870
		Mean	860	817	868
		Std Dev	*276*	*221*	*234*
	A3 [1287lux]	Median	977	1078	1040
		Mean	984	1080	1065
		Std Dev	*305*	*174*	*193*

Table 5
Median preferred illuminances found in the 1st and 2nd trials with anchor A2.

Range	CCT:	3000K		4000K		6500K	
	Trial:	1st	2nd	1st	2nd	1st	2nd
R1		370	419	392	406	449	403
R2		648	642	635	609	635	609
R3		869	857	844	869	870	921

Table 6.
Comparison of mean preferred illuminances determined according to different anchor treatments.

Range	Anchor treatment		3000K	4000K	6500K
			Illuminance (lux)		
R1 [21-482lux]	Anchors A1 and A3	Median	315	319	338
		Mean	330	335	347
		Std Dev	*81*	*85*	*83*
	Anchor A2	Median	370	392	449
		Mean	372	398	407
		Std Dev	*92*	*67*	*91*
	Anchors A1, A2 and A3	Median	370	398	453
		Mean	344	356	367
		Std Dev	*78*	*74*	*79*
R2 [38-906lux]	Anchors A1 and A3	Median	520	542	502
		Mean	516	542	514
		Std Dev	*119*	*151*	*135*
	Anchor A2	Median	648	635	635
		Mean	609	644	657
		Std Dev	*196*	*167*	*175*
	Anchors A1, A2 and A3	Median	648	645	635
		Mean	547	576	562
		Std Dev	*135*	*144*	*138*
R3 [72-1307lux]	Anchors A1 and A3	Median	627	657	636
		Mean	619	665	650
		Std Dev	*197*	*151*	*124*
	Anchor A2	Median	869	844	870
		Mean	860	817	868
		Std Dev	*276*	*221*	*234*
	Anchors A1, A2 and A3	Median	823	831	851
		Mean	700	716	722
		Std Dev	*202*	*154*	*137*

Table 7
Comparison of preferred illuminances obtained from adapted and non-adapted test subjects. Adapted here means a five minute delay between exposure and adjustment action: non-adapted means an immediate response was sought.

Range		**Preferred illuminance [lux]**	
		Non-adapted subjects	**Adapted subjects**
R1 [21-482 lux]	Mean	374	301
	Std Dev	*73*	*48*
R2 [38-906 lux]	Mean	558	490
	Std Dev	*133*	*81*
R3 [72-1307 lux]	Mean	642	647
	Std Dev	*150*	*82*

Table 8
Results of preferred illuminance adjustment: Mean preferred illuminance for first trial of the day (12 subjects within range) and mean preferred illuminance for all trials including three ranges and all three CCT's (36 subjects within range x 3 trials).

Range		**Preferred illuminance [lux]**	
		First trial	**All trials**
R1 [21-482lux]	Median	344	335
	Mean	301	337
	Std Dev	*167*	*71*
	N	12	36
R2 [38-906lux]	Median	741	507
	Mean	691	523
	Std Dev	*233*	*114*
	N	12	36
R3 [72-1307lux]	Median	802	644
	Mean	776	645
	Std Dev	*441*	*119*
	N	12	36

Figure captions

Figure 1.
Plan of the test rooms used for the illuminance adjustments. The left room shows the locations of the luminaires; the right room shows the location of the seven illuminance measurements used to compare spatial distributions. All windows were shielded and the doors closed during the study to exclude daylight and external views.

Figure 2.
Photograph in the direction of the view during the study. Mean luminances (for the maximum control setting in range 3) were 179.4cd/m^2 on the paper reading task on the desk, 51.9cd/m^2 across the surrounding desktop and 59.7cd/m^2 on the vertical wall facing the test subject.

Figure 3.
Preferred illuminances for the three types of lamp. The figures show the median illuminances for each of the three anchors and include both the adapted and non-adapted subjects. The vertical lines show the available range of illuminances placed on the x-axis according to the mid-point of each illuminance range.

Figure 4:
The relationship between control setting and the illuminance on desktop for the three stimulus ranges.

Figure 5.
Variation of CCT with adjustment of illuminance. This was measured at the location of the reading task.

Figure 6.
Results of preferred illuminance adjustment. The 1st trial data are the median preferred illuminance for the very first trial carried out by each subject (thus 12 subjects within each range). The all trials data are mean preferred illuminances of the 36 subjects, and for each subject this was estimated as the mean of anchors A1 and A3 in all three CCT.

Figure 7.
Frequency of control setting at preferred illuminance for the three stimulus ranges (R1, R2 and R3). These data include settings made under all three CCT and all three anchors including the repeat trial with anchor A2.

Figure 8.
Frequency of control setting at preferred illuminance for stimulus range R2, anchors A1, A2 and A3.

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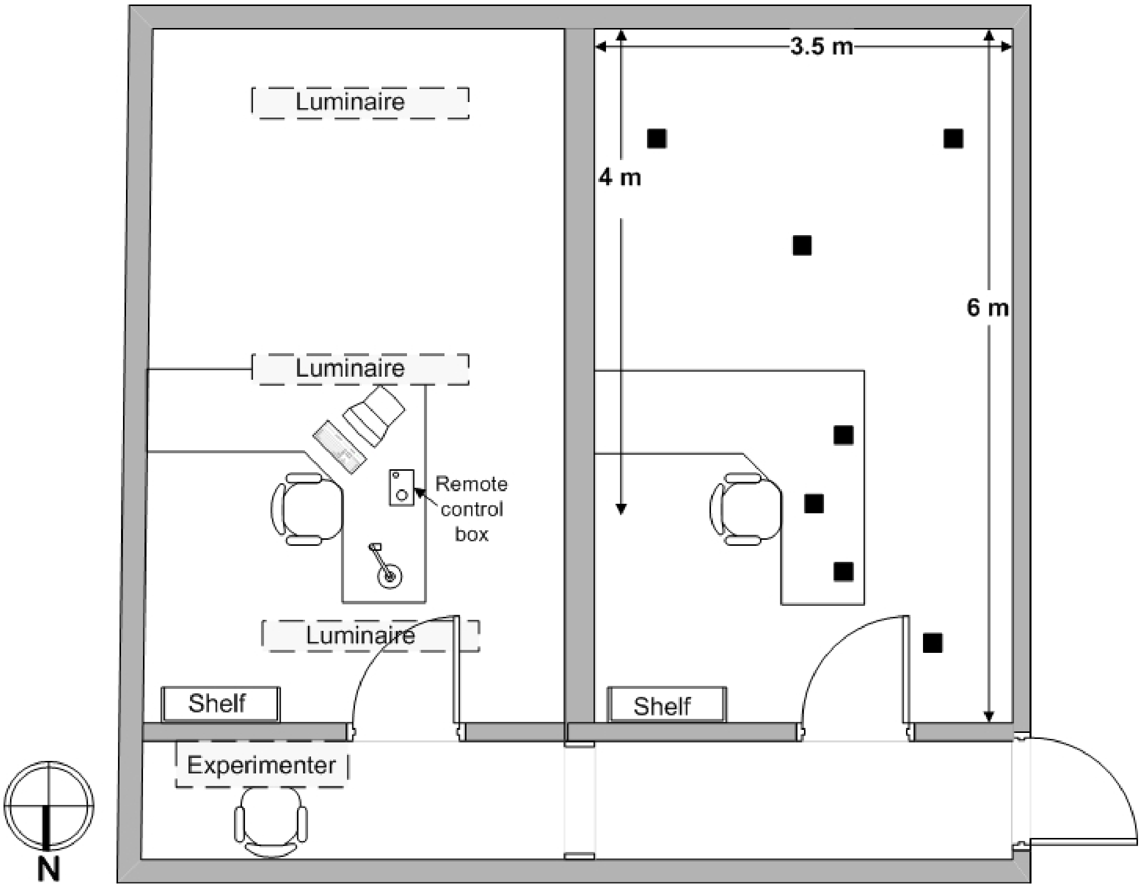
Plan of the test rooms used for the illuminance adjustments. The left room shows the locations of the luminaires; the right room shows the location of the seven illuminance measurements used to compare spatial distributions. All windows were shielded and the doors closed during the study to exclude daylight and external views.



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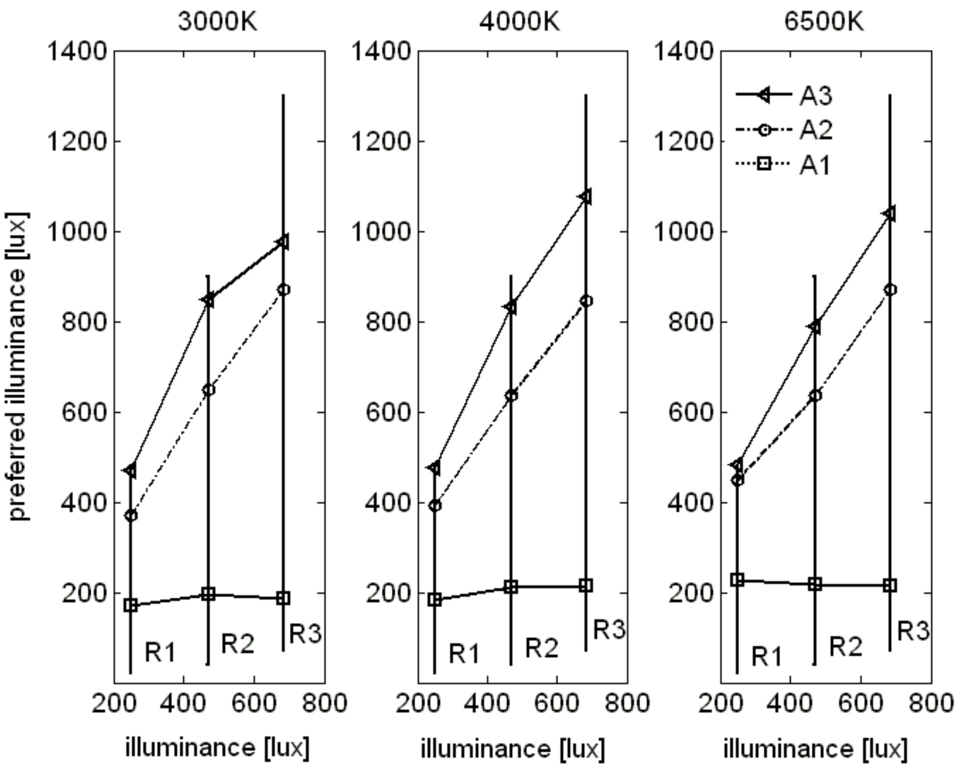

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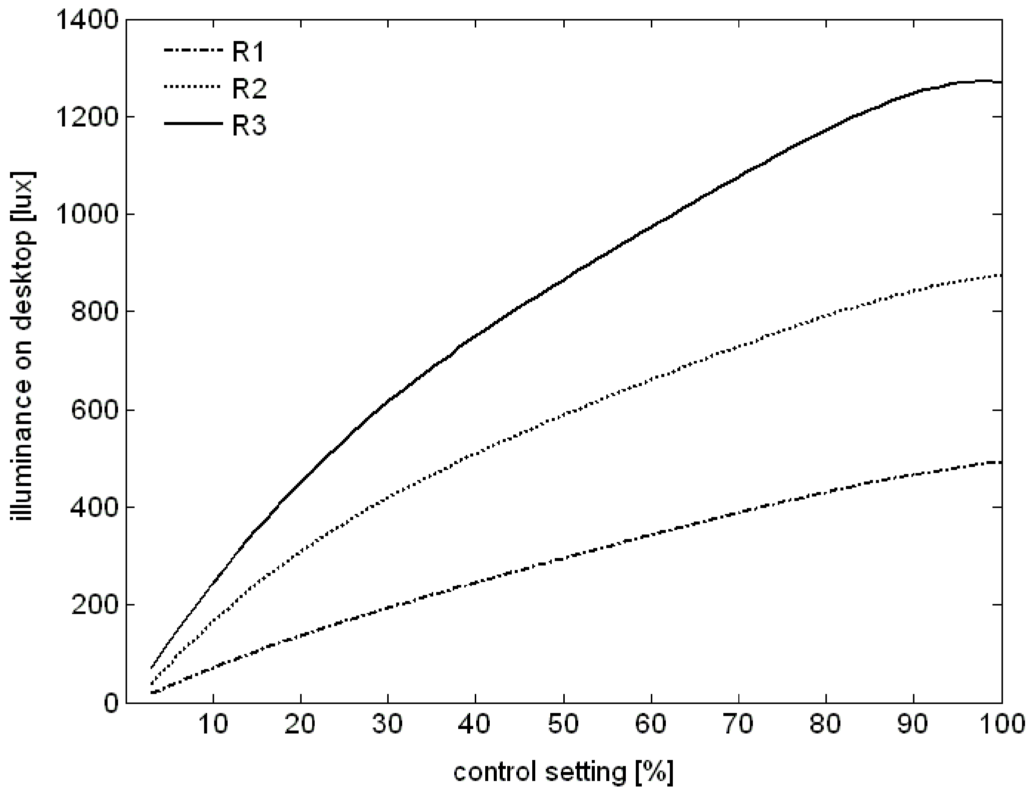

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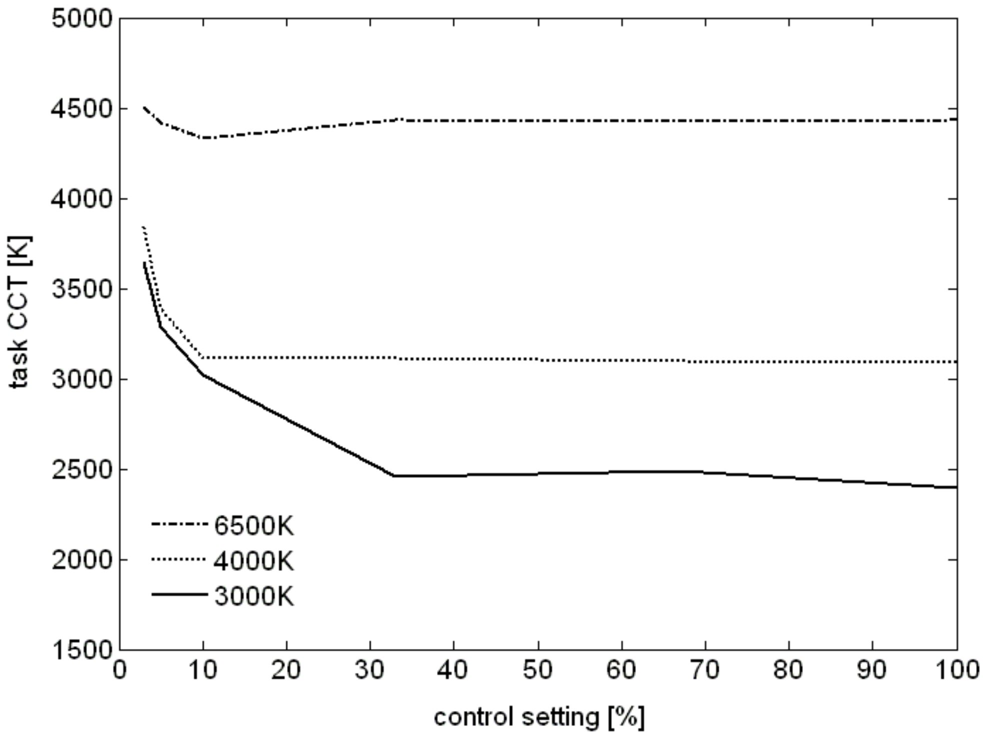

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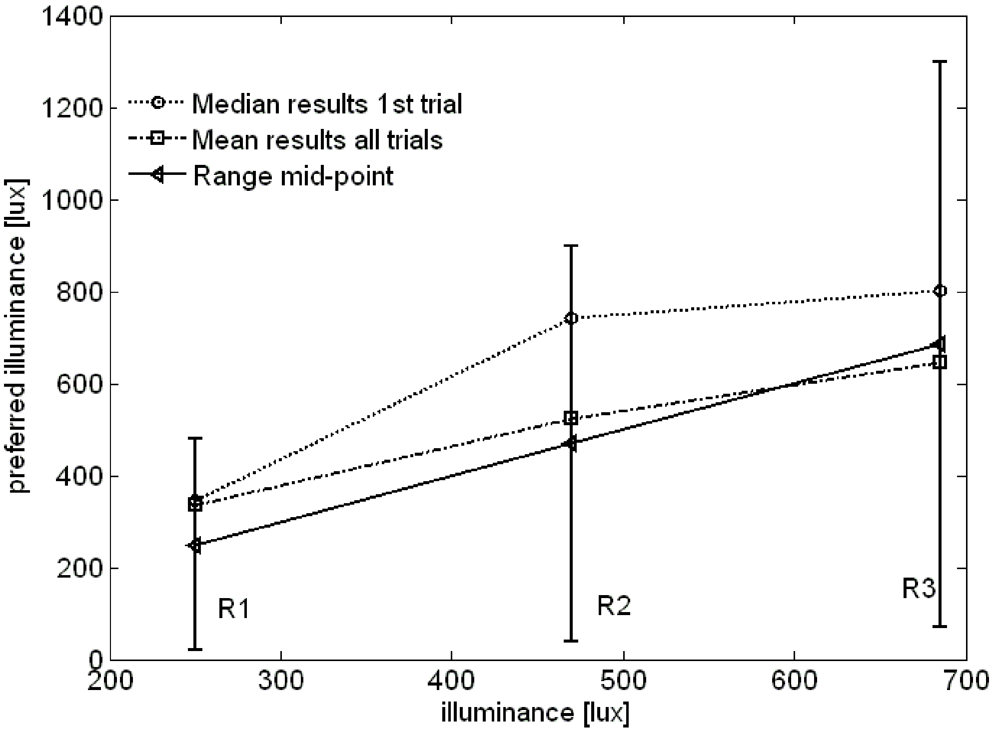

Figure 7.
Frequency of control setting at preferred illuminance for the three stimulus ranges (R1, R2 and R3). These data include settings made under all three CCT and all three anchors including the repeat trial with anchor A2.

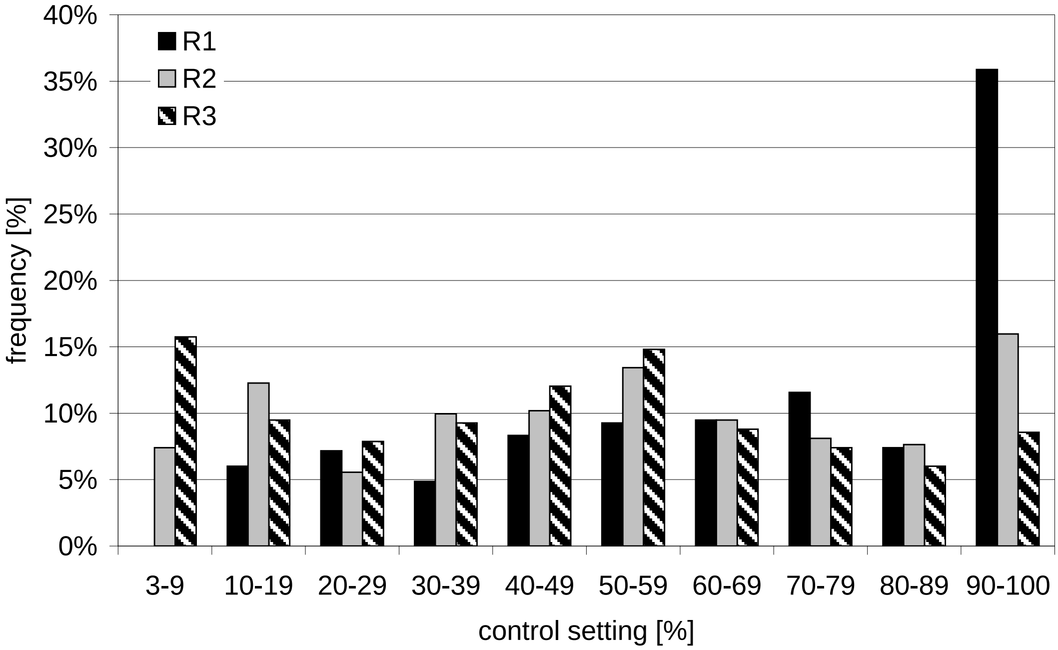

Figure 8.
Frequency of control setting at preferred illuminance for stimulus range R2, anchors A1, A2 and A3.