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Summary An experiment in a mock-up office space gave occupants control over dimmable lighting circuits after a day working under pseudo-random lighting conditions. Data analysis indicated that the lighting experienced during the day influenced the changes in lighting made at the end of the day. Occupants chose to reduce screen glare if any existed. Even after allowing for the effect of glare, desktop illuminance at day's end varied with the illuminance experienced during the day. Regression of these end-of-day choices relative to the illuminance experienced during the day can yield a preferred illuminance, equivalent to the daytime illuminance at which no change was preferred at day's end. Using this method, preferred illuminances in the range 200 to 500 lx were derived. Preferences for luminance ratio were also derived. Interestingly, the deviation between participants' lighting preferences and the lighting they experienced during the day was a significant predictor of participant mood and satisfaction.

Lighting quality recommendations for VDT offices: A new method of derivation

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List of symbols

LC	The participant having control over lighting choices at the start of the day
NC	The participant who did not have control over lighting at the start of the day, but who got to express their preference at the end of the day
$^{VDT}G_{\%}$	Fraction of VDT screen area – when dark – occupied by visible glare image, > 40 cd/m^2 (%)
$^{VDT}G_L$	Mean luminance of visible glare image (cd/m^2)
E_D	Illuminance measured on the desktop, close to the VDT, but on the opposite side from the task light (lx)
LMM	Natural logarithm ratio of maximum to minimum luminance in the field of view; luminance values averaged over a target approx. 1° square
$^{VDT\text{-}LC}G_L$	$^{VDT}G_L$ of luminous conditions chosen by the LC participant at the start of the day, and prevailing during the day (cd/m^2)
$^{LC}E_D$	E_D of luminous conditions chosen by the LC participant at the start of the day, and prevailing during the day (lx)
$^{NC}E_D$	E_D of luminous conditions chosen by the NC participant at the end of the day (lx)
^{LC}LMM	LMM of luminous conditions chosen by the LC participant at the start of the day, and prevailing during the day
^{NC}LMM	LMM of luminous conditions chosen by the NC participant at the end of the day
ΔE_D	$^{NC}E_D$ minus $^{LC}E_D$ (lx)
ΔLMM	^{NC}LMM minus ^{LC}LMM
$\Delta^{VDT}G_{\%}$	$^{VDT}G_{\%}$ of luminous conditions chosen by the NC participant at end of day minus $^{VDT}G_{\%}$ of luminous conditions chosen by the LC participant at start of day
$\Delta^{VDT}G_L$	$^{VDT}G_L$ of luminous conditions chosen by the NC participant at end of day minus $^{VDT}G_L$ of luminous conditions chosen by the LC participant at start of day

1. Introduction

Today's lighting recommendations are based on the consensus and collected wisdom of the technical committees of professional organisations responsible for the documents. IESNA, for example, provides recommendations through consensus using rigorous procedures and committees made up of diverse representation (1). Nonetheless, the resulting recommendations are not necessarily grounded in the latest empirical research (2). This is one reason for the wide variation in illuminance recommendations between different countries and over time (3). Consensus-based procedures are a necessary means to reach practical recommendations given incomplete technical information (4), but sound empirical evidence about the effects of lighting on humans is an essential part of the information-gathering process.

Lighting recommendations have emphasised lighting for visibility during much of this century, but recently the concept of <u>lighting quality</u>, about which much less is known (5,6), has received increased attention. Lighting quality has been defined as the degree to which a lighting installation fulfils human needs within constraints such as economics, energy consumption, and maintenance (7,8).

Among the outcomes that have been suggested as targets for recommendations based on lighting quality is individual preference for luminous conditions. Baron, Rea, and Daniels hypothesised that luminous conditions that people prefer will create a state of <u>positive affect</u> (good mood) that will lead to desirable outcomes like improved cognitive task performance, increased pro-social behaviour, and more creative problem-solving (9).

A recent experiment at the Institute for Research in Construction was designed to test the hypothesis that giving individuals control over lighting will lead to improved task performance and better mood and satisfaction. Participants worked in pairs for a full-day session under lighting conditions chosen by one member of the pair at the start of the day. At the end of the day, the second participant chose the lighting conditions that they would have preferred. Extensive data on both participants' lighting choices, and satisfaction, task performance, mood, and visual performance during the working session, were collected. Parts of the data, including detailed protocols and analysis of the principal hypothesis, have been reported elsewhere (10-12).

In addition to the original hypothesis, *post-hoc* data analysis suggested a novel technique to objectively derive preferred luminous conditions. This paper reports on this novel technique.

2. Methods and procedures

2.1 The experimental space

The experiment was performed in a windowless mock-up office space, of 83 m^2 floor area. The space contained six workstations, arranged as parallel rows of three along a central spine. Each workstation was designed as a standard North American open-plan arrangement for a mid-level office worker, and measured 6 m^2 floor area. Measured room surface reflectances are reported in Table 1.

The lighting system installed in the space was not a typical real-world design, but consisted of groups of differing luminaires intended to broaden the occupants' choice of luminous environment (the office space layout and lighting system are shown in Figure 1(a)). The luminaires were connected to four independently controllable circuits:

- recessed 1'x 4' deep-cell parabolic louvered luminaires overhead, 2 x 32W lamps per luminaire (labelled 1 in Figure 1(a));
- recessed 1'x 4' deep-cell parabolic louvered luminaires (identical to those in the previous bullet) at the perimeter of the space, 2 x 32W lamps per luminaire (labelled 2 in Figure 1(a));
- partition-mounted indirect lighting, 2 x 32W lamps per 4' luminaire (labelled 3 in Figure 1(a)); and,
- under-shelf task lighting 1 x 17W lamps per 2' luminaire (labelled 4 in Figure 1(a)).

The first three circuits were continuously dimmable while the task lighting had a simple on/off control. All luminaires used electronic ballasts and 3500K T8 lamps (CRI=80).

2.2 The participants and the experimental procedure

The experiment required a total of 120 temporary office workers. On each day, two participants (matched by age and sex) were seated at the two centre workstations (labelled WS2 and WS5 in Figure 1(a)). Of each pair, one participant (randomly assigned) was designated as the lighting controller (LC), while the other was identified as having no control (NC). The participants were also randomly assigned to workstations.

At the start of the day LC was shown into the mock-up space which was lit with a standard base-case lighting design featuring the dimmers at their mid-setpoints and the task lighting on. LC was then invited to adjust the lighting system to his/her preference; NC was not in the mock-up space during this part of the procedure. LC adjusted the lighting using a dimmer panel within his/her workstation similar to a common wall-mounted architectural lighting controller. The panel had an up and down arrow for each dimmable circuit. Each circuit also had a vertical set of sixteen LEDs; when the arrows were pressed the number of LED's lit changed accordingly. Figure 1(b) shows the relationship between the dimmer setting and the relative light output for the recessed parabolic fixtures. The relationship is close to linear up to dimmer setting 12, after which there is little change in light output as the dimmer setting is increased.

Both participants were then seated in their workstations, with LC requested not to mention his/her role in choosing the lighting conditions. Because of the symmetry of the lighting design, NC received the same lighting conditions as LC, but was unaware that LC had selected the conditions. The participants then performed a day of office tasks, with appropriate breaks, during which no adjustments to the lighting were permitted.

At the end of the day, NC was given an opportunity to adjust the lighting according to his/her preferences. The starting point for these adjustments was the same base-case LC had seen at the start of the day. At the same time, and in an adjoining room, LC was asked on a questionnaire to indicate what changes he/she would have made to the original lighting set-up, given the opportunity.

2.3 Tasks performed by participants

In addition to morning and afternoon visual performance tests, the participants performed a variety of computer-based tasks designed to simulate modern office work (13). These tasks principally involved typing, proofreading, and creative writing. They also completed computer-based questionnaires (11,13) at various times of the day to assess their satisfaction with, and impressions of: lighting quality and mood; physical comfort; perceived and desired control over environmental features in general; perceived control during the session; and, lighting preferences in general.

2.4 Photometry

The lit environments chosen by the participants were recorded in detail. Spot illuminance and luminance were measured at a variety of locations in each workstation and supplemented with digital image analysis of luminance in the field of view. The fraction of each lighting circuit's maximum output (proportional to the dimmer setting) was also recorded.

The photometric measures of lighting conditions considered in this paper are desktop illuminance, luminance ratio in the field of view, and measures of VDT-screen glare. These are the most common photometric measures used in lighting research and were highly intercorrelated with other, more complex, photometric measures. Figure 2 details the photometric variables referred to in this paper.

More detail on the experiment method and procedures is provided elsewhere (10-12).

3 Data analysis method

This experiment yielded a very large data set which has been analysed both qualitatively and quantitatively elsewhere (10-12). These prior analyses looked at the effect of choice on satisfaction and performance, the choices made, how these choices compared to existing codes and standards, and the consequences for energy consumption. Further consideration suggested that these data could be re-analysed to yield objective measures of luminous preference potentially better than simple measures of central tendency and variability. This method is based on one already familiar to thermal comfort researchers (14).

Consider the NC participants: they were exposed for a six-hour period to pseudo-random lighting conditions (those lighting conditions chosen by the LC participants). The lighting conditions the NC participants chose for themselves at the end of the day – specifically, the deviations from the conditions they were exposed to during the day – can be taken as an measure of their satisfaction with the lighting chosen by their LC partner, or as a measure of their preference for change. The daytime lighting conditions for which the NC participants, on average, preferred no change may define recommended luminous conditions for VDT spaces. These conditions can be derived by regression of preference for change against the lighting conditions experienced during the workday. To the authors' knowledge, lighting data have not been analysed in this way before.

4 Results

For reasons detailed elsewhere (10), 13 pairs of participants were dropped from the data set prior to analysis, leaving a sample size for all analyses of n=47 NC participants, (21 men and 26 women ranging in age from 18 to 58). Age and sex were previously established as having no effect on lighting choices in this experiment (12).

4.1 Derivation of preferred desktop illuminance

Figure 3 shows a raw plot of ΔE_D vs. $^{LC}E_D$. The linear regression[#] is statistically significant ($F_{1,45}$=29.72, p<0.01), and shows that, given a linear relationship, the desktop illuminance experienced during the day explains 40 % of the variance in the change in illuminance chosen by the NC participants at the end of the day (r^2 = 0.40). The regression line crosses the x-axis at 392 lx and has a negative slope: those who experienced high illuminances during the day tended to want lower illuminances, and vice versa.

[#] The assumption of a linear relationship between variables is the common starting point in behavioural research, unless there is a strong theoretical reason to assume otherwise. At this point, the goal is to establish relationships between variables, not to calculate the best possible curve fit. We explore other curve fits later in the paper.

However, the post-experiment data indicated that many participants adjusted the lighting (NC), or would have adjusted it if they had had the chance (LC), to reduce glare on the VDT screen from overhead luminaires (10,11). With our lighting design, as with the majority of real-world lighting designs, it was impossible to vary desktop illuminance and VDT glare conditions independently. Therefore, it is likely that end-of-day changes in desktop illuminance are not only a function of desktop illuminance experienced during the day and illuminance preferences, but also occur as a consequence of glare reduction strategies.

To separate these effects graphically a statistical technique called “partialling out” was used. We made the conservative assumption that glare control was the primary cause of end-of-day illuminance changes. Two measures of glare were available, ${}^{VDT}G_{\%}$ and ${}^{VDT}G_L$, having been derived in prior work (10). ${}^{VDT}G_{\%}$ has intuitive appeal as a driver of glare reduction strategies, however, $\Delta^{VDT}G_L$ correlated significantly with a subjective measure of glare (r=-0.31, t=-2.17, p<0.05)[∀], whereas $\Delta^{VDT}G_{\%}$ did not. Therefore, ${}^{VDT}G_L$ was the glare measure pursued in this analysis[*].

The next step is to regress ΔE_D vs. $\Delta^{VDT}G_L$, and to produce a regression equation. Next take the <u>residual</u>, which is the difference between the actual value of ΔE_D and that predicted by the regression equation. The residual is that part of ΔE_D not explained by changes in VDT-screen glare. Finally, the residual of ΔE_D was regressed

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[∀] Note, the significant correlation is negative, as expected: the greater the occupant’s rating of glare during the day, the more they reduced glare image luminance at the end of the day, on average.

[*] In fact, the analyses reported in this paper were repeated using ${}^{VDT}G_{\%}$, but ${}^{VDT}G_{\%}$ proved to be a worse predictor of outcomes than ${}^{VDT}G_L$.

vs. ${}^{LC}E_D$. This final step generated an equation illustrating how end-of-day desktop illuminance was influenced by illuminance experienced during the day, independent of changes made to affect VDT-screen glare changes. Figure 4 shows the graphs generated by this process.

Figure 4(a) shows ΔE_D vs. $\Delta^{VDT}G_L$. The linear regression is statistically significant ($F_{1,45}$=34.61, p<0.01, r^2=0.44), confirming that, as expected, changing VDT-screen glare conditions has a strong effect on desktop illuminance. The regression line has a positive slope: if glarespot luminance increases so does desktop illuminance. Figure 4(b) shows the residual of ΔE_D after the effect of $\Delta^{VDT}G_L$ is removed vs. ${}^{LC}E_D$. The linear regression is statistically significant ($F_{1,44}$=19.86, p<0.01, ΔR^2=0.18)[α], confirming that, even with the effect of glare-driven lighting changes partialled out, end-of-day desktop illuminances still correlate to daytime illuminance experience. Knowing ${}^{LC}E_D$ explains 18 % more of the variance in ΔE_D than does knowing $\Delta^{VDT}G_L$ alone, if the relationship is linear. The linear regression line crosses the x-axis at 458 lx and has a negative slope. Therefore, 458 lx could be considered the preferred illuminance for the sample (independent of the effect of glare). It is the illuminance at which, on average, the NC participants would want no change from the conditions they experienced during the day.

[α] ΔR^2 is used here to indicate the additional variance in ΔE_D explained by ${}^{LC}E_D$ after accounting for the effect of $\Delta^{VDT}G_L$. This is calculated using stepwise regression. Step 1: regress ΔE_D vs. $\Delta^{VDT}G_L$ alone (r^2=0.44); Step 2: regress ΔE_D vs. $\Delta^{VDT}G_L$ and ${}^{LC}E_D$ together (R^2=0.61), the difference is the variance explained by ${}^{LC}E_D$, =0.18. Similarly, the F-test ($F_{1,44}$) refers only to that part of the variance in ΔE_D due to ${}^{LC}E_D$ alone, after the inclusion of $\Delta^{VDT}G_L$.

Figure 4(b) also shows the 3rd-order polynomial regression on the same data. The shape of this curve is more appealing theoretically. Rather than specifying a single preferred illuminance, the 3rd-order curve provides a broad plateau close to $\Delta E_D = 0$. This plateau indicates a range of preferred illuminances. The 3rd-order polynomial regression is statistically significant ($F_{3,42}$=15.62, p<0.01, ΔR^2=0.30)[β]. So, using ${}^{LC}E_D$ plus its square and cube explains 30 % more of the variance in ΔE_D than $\Delta^{VDT}G_L$ alone explains. The range of experienced illuminances over which no change in illuminance was preferred is 200 to 500 lx.

More detail on these predictive models is provided in tabular format in the Appendix.

4.2 Derivation of preferred luminance ratio

The analysis of dependent outcomes was not limited to illuminance. Luminance data were also considered. Mean luminance in the field of view was, however, highly correlated with desktop illuminance (r=0.98) and was not pursued independently. Luminance ratio (LMM) was less strongly related to desktop illuminance (r=-0.76) (12). Figure 5(a) shows ΔLMM vs. ^{LC}LMM. The linear regression is statistically significant ($F_{1,45}$=15.83, p<0.01, r^2=0.26), indicating that the luminance ratio experienced during the day had an effect on end-of-day luminance ratio choice. The linear regression line crosses the x-axis at 3.07, translating into a maximum-to-minimum luminance ratio of

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[β] Step 3: regress ΔE_D vs. $\Delta^{VDT}G_L$ and ${}^{LC}E_D$, ${}^{LC}E_D{}^2$, ${}^{LC}E_D{}^3$ together (R^2=0.73), therefore the variance explained by ${}^{LC}E_D$, ${}^{LC}E_D{}^2$, ${}^{LC}E_D{}^3$ together, =0.73-0.44. Similarly, the F-test ($F_{3,42}$) refers only to that part of the variance in ΔE_D due to ${}^{LC}E_D$, ${}^{LC}E_D{}^2$, ${}^{LC}E_D{}^3$ together, after the inclusion of $\Delta^{VDT}G_L$

21.5. The regression line has a negative slope: those who experienced high luminance ratios during the day tended to want lower luminance ratios, and vice versa.

As with desktop illuminance, the effect of glare avoidance strategies on luminance ratio choice must be considered. Figure 5(b) shows ΔLMM vs. $\Delta^{VDT}G_L$. The linear regression is statistically significant ($F_{1,45}$=14.28, p<0.01, r^2=0.24), indicating that changing VDT-screen glare conditions has an effect on luminance ratios. The regression line has a negative slope: if glarespot luminance increases maximum-to-minimum luminance ratio decreases. Figure 5(c) shows the residual of ΔLMM after the effect of $\Delta^{VDT}G_L$ is removed vs. ^{LC}LMM. The linear regression is statistically significant ($F_{1,44}$=15.38, p<0.01, ΔR^2=0.20)[γ], again confirming that, even with the effect of glare-driven lighting changes partialled out, end-of-day luminance ratios still correlate to daytime experience. Knowing ^{LC}LMM explains 20 % more of the variance in ΔE_D than does knowing $\Delta^{VDT}G_L$ alone. The linear regression line crosses the x-axis at 2.98, translating into a preferred maximum-to-minimum luminance ratio of 19.6; the regression line has a negative slope. No 3rd-order polynomial solution is shown, because it did not substantially improve predictive power over the simple linear model.

[γ] ΔR^2 is used here to indicate the additional variance in ΔLMM explained by ^{LC}LMM after accounting for the effect of $\Delta^{VDT}G_L$. This is calculated using stepwise regression. Step 1: regress ΔLMM vs. $\Delta^{VDT}G_L$ alone (r^2=0.24); Step 2: regress ΔLMM vs. $\Delta^{VDT}G_L$ and ^{LC}LMM together (R^2=0.44), the difference is the variance explained by ^{LC}LMM, =0.20. Similarly, the F-test ($F_{1,44}$) refers only to that part of the variance in ΔLMM due to ^{LC}LMM alone, after the inclusion of $\Delta^{VDT}G_L$.

4.3 Occupant satisfaction and performance data

Prior analyses of the occupant satisfaction and performance data have been detailed elsewhere (10-12). The prior analyses looked at the effect of having choice (LC vs. NC), or the effect of the absolute values of various photometric variables (LC and NC grouped on desktop illuminance, mean luminance etc.), as independent variables. These analyses yielded few significant effects. However, the method presented in this paper suggested another approach to analysing the satisfaction and performance data. In this analysis, only data from the 47 NC participants were considered. These data were then grouped according to the magnitude and direction of the change in desktop illuminance, glare and luminance ratio at the end of the day. Thus, this analysis used as independent variables not the absolute values of photometric variables, but rather the desire for change in those variables. For example, consider two participants who both indicated no change in desktop illuminance at the end of the day, one who experienced 200 lx during the day, and the other who experienced 700 lx. If the absolute values were used as independent variables these two participants would populate very different groups, but if the demonstrated desire for change is used as an independent variable then they both populate the same group.

A large set of dependent variables was available for this analysis. Where variables were measured several times during the day afternoon measurements were analysed, because these reflected the longer experience of the environment and tasks. Remember, these dependent variables were all measured prior to the NC participants making their lighting choices. As in previous analyses (10-12), variables were grouped into conceptually related sets. These sets comprised:

- ratings of mood;
- ratings of lighting quality and environmental satisfaction;
- ratings of physical sensations;
- ratings of perceived control;
- typing and proofreading performance scores;
- creative writing performance scores;
- objective measures of work rate; and,
- visual acuity test scores.

Independent multivariate analysis of variance tests (MANOVAs) were run on each of these sets of variables; only if the multivariate test was statistically significant were the univariate effects examined.

Three different categorical independent variables were chosen, each based on the photometric variables discussed earlier: ΔE_D, $\Delta^{VDT}G_L$, and ΔLMM. Each variable contained three categories labelled “MORE”, “SAME”, and “LESS”; the assignment to these variables is shown in Table 2. Also shown in Table 2 is the size of each category, and relevant mean luminous conditions prevailing during the day for each category. Note that these categories, inevitably, are not independent of absolute photometric variables; for example, those who chose an illuminance 100 lx or more higher than that which they experienced during the day (“MORE” category) also experienced the lowest illuminance during the day, on average.

The effect of each independent variable on each set of dependent variables was addressed in a separate MANOVA. Within each MANOVA two contrasts were of interest:

1. Comparing those participants who wanted a substantial change ("MORE" and "LESS" together) vs. those who did not ("SAME"). It was expected that this contrast would show strong effects on satisfaction and related outcomes.
2. Comparing those who wanted a substantial reduction ("LESS") vs. those who did not ("MORE" and "SAME" together). It was expected that this contrast would show the strongest effects on outcomes influenced by glare.

Only those MANOVAs related to mood, ratings of the lit environment and environmental satisfaction were statistically significant and only in relation to ΔE_D and $\Delta^{VDT}G_L$. The results of the significant MANOVAs are shown in Tables 3 and 4. Graphs of the mean ratings associated with the univariate effects are shown in Figures 6(a)-(d). Within the MANOVA related to mood there was a significant univariate effect of Pleasure in Contrast 1 on ΔE_D ($\eta^2_{partial}$=0.13); those who experienced lighting conditions closest to their own choices had a significantly higher Pleasure rating. Within the MANOVA related to the lit environment and environmental satisfaction there were significant univariate effects of Lighting Quality ($\eta^2_{partial}$ =0.15) and Overall Environmental Satisfaction ($\eta^2_{partial}$ =0.13) in Contrast 1 on ΔE_D. Those who experienced lighting conditions closest to their own choices had significantly higher ratings of Lighting Quality and general Environmental Satisfaction. There was also a significant univariate effect of Lighting Quality ($\eta^2_{partial}$ =0.15) in Contrast 2 on $\Delta^{VDT}G_L$.

Those who substantially lowered the VDT screen glare image luminance at the end of the day had a significantly lower rating of Lighting Quality.

5 Discussion

Figures 3, 4 and 5 clearly show that occupants do respond to the lighting conditions they experience, and will express a desire for change if the prevailing conditions are not to their liking. Although we know that people adapt well to the lighting conditions they experience and will report satisfaction over a wide range (4,7), this does not mean that they do not express a preference for something different when offered the chance. If people were perfectly adaptive (or insensitive, or habituated) the regression lines in Figures 3, 4 and 5 would have been horizontal lines at y = 0.

5.1 Regressions for preferred illuminance

As described earlier, the regression-type analysis used here can be used to derive a preferred (or "ideal") illuminance for the sample population studied. Discussion will first focus on the linear regressions in Figures 3 and 4(b). In Figure 3 the regression line crosses the x-axis at 392 lx. In other words, given a linear relationship, the average respondent would not want any change in E_D if they had experienced an E_D of 392 lx during the day. Recall, however, that it was strongly suspected that this illuminance selection was not the result of illuminance preference alone, but primarily the result of lighting choices to reduce VDT-screen glare. The regression shown in Figure 4(b) is after the effect of glare has been removed. In this case the point at which the linear regression line crosses the x-axis is 458 lx. This analysis provides values for preferred E_D independent of glare preferences. Therefore, it appears that although the preferred E_D is around 460 lx (Figure 4(b)) people will lower this to around 400 lx to avoid glare (Figure 3). Interestingly, 460 lux is close to the mean value of $^{LC}E_D$ (actual value = 445 lx (10-12)). There were no systematic differences between the LC and NC groups on important demographic variables (10,12) (age and sex were controlled by matching the pairs) and therefore one would expect the illuminance preferences of the two groups to be the similar. One interpretation of this observation is that the LC participants were also trying to achieve 460 lx on the desktop, but, because they lacked prolonged experience of the space, did it in a way that created some VDT-screen glare.

Despite the appeal of a single preferred illuminance as provided by a linear regression, experience suggests occupant satisfaction is high over a range of illuminances. Further, when designing for illuminance in a large space for a large number of occupants, a single illuminance target would clearly be impractical to achieve. Even for a regular array of luminaires there is considerable variation in illuminance between locations below luminaires and locations between luminaires. In addition, differences in workstation furniture lead to even greater local variations in illuminance. The 3rd-order polynomial regression in Figure 4(b) provides a more practical range of preferred luminances (and also fits the data better than the linear regressions). For the 3rd-order regression, preferred E_D is indicated not by the point at which the curve crosses the x-axis, but by the range of illuminances over which the curve is horizontal and close to zero. The range of preferred E_D is 200 to 500 lx for the 3rd-order curve in Figure 4(b). This range conforms well with the 200 to 500 lx range recommended for most office work in the IESNA Handbook (15) and the CIBSE Code for Interior Lighting (16), and the recommendations in IES RP-1 (17) and CIBSE LG7 (18) that desktop illuminance be less than 500 lx in VDT spaces.

5.2 Regressions for preferred luminance ratio

Figure 5(c) suggests a preferred maximum-to-minimium luminance ratio of 19.6. At first sight this number appears very high compared to values in standards and recommended practices (17,18), yet the lighting choices made by the participants were not, in general, anything out of the ordinary (12). Although standards and recommended practices do not explicitly state how these luminance ratios are to be measured (15-18), the implication is that they are derived from spot luminances at the centre of easily-defined surfaces (e.g., partitions, desktop, computer screen). This method severely restricts the range of measured luminances, leading to relatively low luminance ratios (of the order of 3:1). For the measurements in this experiment a digitial video photometer was used to look at a grid of squares of approximately 1° (15 x 15 pixels) in size. We took the mean luminance of each square in the field of view, and compared the maximum square to the minimum square. This method will clearly yield a much greater range of luminance values and luminance ratios.

Nevertheless, the two methods are not necessarily inconsistent. Standards and recommended practices (17,18) do allow for small areas of higher luminance away from the traditional spot measurement locations. Such small areas can create accents and interest, whereas larger areas of the same luminance may be bothersome. Loe et al.(19) carried out an experiment in which participants assessed a variety of lighting installations in a mock-up office. The photometric measurements taken in Loe et al.'s experiment with respect to luminance and luminance ratio were very similar to the measurements made in this paper. From their results, Loe et al. suggested that the maximum-to-minimum luminance ratio in the field of view be between 10 and 50. They plotted a composite subjective rating factor related to "Visual Interest" vs. luminance ratio and found a strong relationship. As maximum-to-minimum luminance ratio increased so did visual interest, but with diminishing returns. It is interesting to note that Loe et al.'s curve starts to level off at a ratio of about 20, similar to optimum value suggested in this paper.

5.3 Satisfaction and performance analyses

There were four significant univariate effects associated with significant MANOVAs. They are entirely consistent, and in the expected direction. Pleasure (mood), Lighting Quality rating, and Overall Environmental Satisfaction rating were all higher for those participants whose daytime desktop illuminance was within 100 lux of their own preferred choice at the end of the day, compared to those whose preferred choice differed from what they experienced during the day by more than ±100 lux. In other words, those participants who experienced conditions closest to what they would have chosen for themselves had higher ratings.

Lighting Quality rating was lower for those participants who experienced a glare image with a luminance more than 20 cd/m^2 greater than their own preferred choice, compared to those whose preferred choice differed from what they experienced during the day by less than 20 cd/m^2 or those who expressed a preference for a higher luminance. The inference is that those participants who judged the glare image bothersome (irrespective of its absolute value) – and expressed this by lowering screen glare when they had the opportunity – had lower ratings of lighting quality.

In previously-reported analyses, the opportunity to choose luminous conditions at the start of the day did not lead to improved mood, satisfaction, or task performance in the LC participants, as had been expected (10,11). However, the analyses reported here show that experiencing the luminous conditions that one prefers improves satisfaction and increases pleasure. This finding provides some support to the theory that preferred luminous conditions can increase positive affect (9). The size of the mood and satisfaction effects reported here is large, according to commonly-accepted standards (20), and is larger than subjective effects of this kind typically reported in the lighting literature.

The categorical analysis of luminous conditions relative to preference that produced these results is potentially confounded by absolute luminous conditions. However, this potential confound is somewhat allayed by the fact that previous analyses of the same dependent variables vs. absolute photometric variables found little(10).

Focussing now on E_D, the results of this analysis indicate that there is a satisfaction benefit to be gained by providing occupants with an illuminance within 100 lx of the illuminance they would choose for themselves. Such a satisfaction benefit should be considered important in VDT offices, where employees represent around 90% of the cost of running a building – there are few that would argue that a more satisfied employee is not an asset to his/her organisation. With this in mind, we returned to our data to derive the fraction of participants at any given E_D who would have been within 100 lx of their own chosen illuminance; this is shown in Figure 7. There is a peak around 475 lx and a roughly-defined plateau between 275 lx and 600 lx. This could also be used as a basis for deriving recommended illuminance conditions for VDT offices. It is also interesting to note that no more than 40-50% of occupants can ever be within 100 lx of their preferred condition, with its associated satisfaction benefit, no matter what fixed illuminance is chosen. Here is a reason for providing individual control over lighting conditions.

5.4 Advantages of this Method

One can derive preferred luminous conditions by simply recording the choices people make when they have the choice and taking the mean or median. These data were recorded in this experiment for both LC and NC participants. However, the method described in this paper has three advantages:

1. Using regression one can separate preference effects, e.g., the effect of glare preference from illuminance preference;
2. The desire for change when the luminous conditions are not at preferred levels can be predicted; and,
3. Desire for change in luminous conditions appears to be a better predictor of mood and satisfaction than absolute measures of luminous conditions. Therefore this method may offer a more sensitive approach for investigating subjective effects of lighting quality.

5.5 Future work

This paper introduces a promising new method to objectively determine preferred photometric conditions. Although this paper focuses on desktop illuminance and maximum-to-minimum luminance ratio because of their widespread use, this same technique could be applied to other photometric variables of interest. However, despite the promise of the technique, it needs to be examined further before being considered as the basis for formal recommendations. This experiment was not designed with this analysis method in mind, and it therefore has its limitations.

The lighting conditions created by the LC participants were not evenly distributed across the range of interest. For example, there were few illuminance choices below 300 lux, and therefore few low illuminances experienced by NC participants (see Figure 3). This places some doubt on the reliability of the regression equations at low illuminances. Future work should fill in this gap, exposing a greater number of participants to low illuminance conditions.

Also, it is not clear that in making their choices at the end of the day, the NC participants reacted principally to illuminance or glare preferences. For this paper it was assumed, based on the comments of participants, that glare was the main driving photometric variable, and therefore its effect was partialled out first. Nevertheless, there remains a significant, although smaller, effect independent of screen glare that appears to be illuminance driven. A future experiment should separate the glare and illuminance influences not just statistically, but physically. It should be possible to create a variety of lit environments in which desktop illuminance, screen glare, and partition luminance are more independent than they were in this experiment.

Further, the data described in this paper were obtained from a single, windowless space with a specific collection of lighting equipment. Similar data need to be collected in different spaces with different lighting designs.

Related to this latter point, all lighting choices were made from a fixed starting point, which featured the dimmers at about half their maximum settings and the task light on, generating about 500 lux on the desktop. Although participants were introduced to a wide variety of possibilities when the lighting control system was being demonstrated to them, it is still possible that the choices made were influenced by this initial setting; in psychology this phenomenon is known as anchoring. This effect can easily be investigated in the future, by exposing independent groups of participants to different starting points. Any effect can then be statistically removed from the data prior to examining illuminance and luminance preferences.

In the analysis of satisfaction data, we created new independent categorical variables based on deviation from preferred luminous conditions. However, this assignment was not independent of the absolute luminous conditions experienced during the day. Independence in this experiment was not possible, given the experimental design and the sample size. A future experiment could achieve such independence by exposing a large sample to the same luminous conditions before allowing them to choose their own lighting.

Finally, the possibility that end of day lighting choices were tempered by habituation cannot be discounted. That is, end of day lighting choices were not entirely driven by lighting preferences, but also by becoming accustomed to conditions experienced during the day. This might also explain why the preferred illuminance for the NC participants derived by linear regression is close to the mean illuminance during the day. Habituation will act to reduce the slope of the linear regressions, perfect habituation would reduce the slope to zero. Shortening exposure to initial lighting conditions prior to making a lighting preference choice should reduce habituation effects (though it would also reduce the experience from which occupants could make an informed choice) – this could be examined in a future experiment.

The experimental methods suggested by this approach can be extended to provide a strong test of the positive affect theory of lighting-behavioural effects. The effect size observed in this study is large enough to warrant such attention. Despite this size, the degree of change in mood and satisfaction achieved by the discrepancy between preferred and experienced lighting conditions was insufficient to cause statistically-significant changes in other dependent variables, such as complex task performance, that other researchers have observed with other ways of changing positive affect (21, 22). A replication with a larger range of luminous conditions (and more discrepancy between preferred and experienced luminous conditions), more sensitive tasks, and a larger sample size would advance our understanding of this potentially important psychological mechanism.

Conclusions

Bearing in mind the limitations on this work described in the previous section, the following conclusions can be drawn from this experiment:

- Preference for a change in lighting at the end of the day is correlated to the lighting condition experienced during the day.
- Preference for change is driven by VDT screen glare experienced, by desktop illuminance experienced, and by luminance ratio experienced.
- Using a regression method, the preferred desktop illuminance range for a population in a VDT office is around 200 to 500 lux.
- The preferred maximum-to-minimum luminance ratio in the field of view is around 20 to 1.
- Participants experiencing lit environments substantially different from their preferred lit environment have significantly lower ratings of Pleasure (mood), Lighting Quality, and Overall Environmental Satisfaction.
- By maximising the number of occupants receiving within 100 lx of their own preferred illuminance, the recommended range in a VDT office is 275 to 600 lx. Note, however, that no more than 40-50% of occupants will be within 100 lx of their preference no matter what fixed illuminance is chosen.

These points provide the designer with some interesting information. Firstly, the research provides empirical evidence to support the recommendations for illuminance and luminance in guides for office lighting(15-18). The lighting preferences of the participants in this experiment, as a group, tended to match the current recommendations quite well. Nevertheless, the behavioural data suggests intriguing supplementary information. A close match between an individual's own lighting preferences and the lit environment they experience correlates with increased environmental satisfaction. For the majority who believe that an organisation benefits from employees who are more satisfied with their environment this is an important finding. However, the data also suggests that no fixed lit environment can match the illuminance preferences of more than around 50% of occupants. Only some form of individual control would allow all occupants to match local lighting conditions to their own preferences.

Appendix

This Appendix contains tables detailing the final models for predicting ΔE_D. The information given here in tabular format complements that shown in graphical format in Figure 4. Each table gives the additional variance in ΔE_D explained (ΔR^2) when a variable (or block of variables) is added to the model. In all cases, the first predictor entered into the model accounts for changes in screen glare conditions at the end of the day (consistent with the "partialling out" process described in the main body of the paper). Models with a both a linear (Table A1) and cubic (Table A2) relationship to ${}^{LC}E_D$ are shown. In the case of the cubic relationship, ${}^{LC}E_D$, ${}^{LC}E_D{}^2$, ${}^{LC}E_D{}^3$, are added to the model at the same time; i.e., the best linear combination of ${}^{LC}E_D$, ${}^{LC}E_D{}^2$, ${}^{LC}E_D{}^3$ is used as a single predictor.

At the bottom of each Table is the total variance in ΔE_D explained by the model (ΣR^2). Also shown is ΣR^2_{adj}, which compensates for the number of predictors used in the model; when comparing the success of various models one should compare ΣR^2_{adj}.

Table A1. Model predicting ΔE_D from $\Delta^{VDT}G_L$ and linear components of $^{LC}E_D$.

Variables added (in order)	Standard. coefficient	*df*	*p*	ΔR^2
$\Delta^{VDT}G_L$	0.495	1, 44	<0.01	0.44
$^{LC}E_D$	-0.450	1, 44	<0.01	0.18
			ΣR^2	0.61
			ΣR^2_{adj}	0.59

Table A2. Model predicting ΔE_D from $\Delta^{VDT}G_L$ and cubic components of $^{LC}E_D$.

Variables added (in order)	Standard. coefficient	*df*	*p*	ΔR^2
$\Delta^{VDT}G_L$	0.445	1, 42	<0.01	0.44
$^{LC}E_D$, $^{LC}E_D^2$, $^{LC}E_D^3$,	-2.205, 6.167, -4.568	3, 42	<0.01	0.30
			ΣR^2	0.73
			ΣR^2_{adj}	0.71

Acknowledgements

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Table 1 Measured room surface reflectances

Room Surface	Material	Colour	Reflectance
ceiling	acoustic tile	matte white	.89
partition	fabric	matte light grey	.46
partition frame	enamel paint	low gloss light grey	.47
VDT screen (off)	specular glass	black	.12
desk top	Formica	low gloss light grey	.50
binder bin	Formica	low gloss maroon	.07
floor	carpet tile	matte multi-colour (dark grey base)	.12

Note. From Houser *et al*.(23) The space these authors modelled was the same space, and included the same furnishings, as was used in this study.

Table 2. Conditions for assigning the individual values of each independent variable to categories, with sample sizes and relevant mean luminous conditions during the day for each category.

Variable		MORE	SAME	LESS
ΔE_D, lx				
	criterion	≥ 100	> -100 AND < 100	≤ -100
	n	13	18	16
	Mean $^{LC}E_D$	341	416	562
$\Delta^{VDT}G_L$, cd/m^2				
	criterion	≥ 20	> -20 AND < 20	≤ -20
	n	3	32	12
	Mean $^{VDT\text{-}LC}G_L$	0*	45.1	51.8
ΔLMM				
	criterion	≥ 0.25	> -0.25 AND < 0.25	≤ -0.25
	n	14	25	8
	Mean ^{LC}LMM	2.81	2.95	3.36

* Note, there was no glare image in the VDT screen for this subsample.

Table 3. Results of significant MANOVAs related to ΔE_D. Each significant MANOVA is followed by each of its univariate tests, significant or not. Cells associated with univariate tests show group means, with standard deviations in parentheses. Notes below the table refer to letters in the Contrasts columns; there is a letter if the test associated with that contrast is significant.

Independent Variable = ΔE_D					
	Assignment to groups (units = lx)			Contrasts	
	LESS ($\leq$ -100)	SAME (> -100 and < 100)	MORE ($\geq$ 100)	1 (SAME vs. OTHER)	2 (LESS vs. OTHER)
n	16	18	13		
Mood MANOVA				*(a)*	
Pleasure	4.23 (1.53)	5.71 (1.54)	4.55 (2.09)	*(b)*	
Arousal	3.26 (1.34)	3.36 (1.33)	3.43 (1.43)		
Dominance	3.74 (1.35)	4.65 (1.24)	4.15 (1.14)		
LQ & Satis. MANOVA				*(c)*	
Ltg. Qual.	3.80 (0.77)	4.37 (0.53)	3.65 (0.98)	*(d)*	
Glare	2.19 (1.09)	1.56 (0.78)	1.65 (1.01)		
Env. Satis.	2.44 (0.80)	3.08 (0.60)	2.54 (0.92)	*(e)*	

Notes: *(a)* Overall MANOVA: Wilks' Λ=0.797, $F_{3,42}=3.56$, $p<0.05$, $\eta^2_{ave}=0.07$; *(b)* Pleasure: $F_{1,44}=6.66$, $p<0.05$, $\eta^2_{partial} = 0.13$; *(c)* Overall MANOVA: Wilks' Λ=0.805, $F_{3,42}=3.36$, $p<0.05$, $\eta^2_{partial}=0.11$; *(d)* Lighting Quality: $F_{1,44}=7.99$, $p<0.01$, $\eta^2_{partial}$ = 0.15; *(e)* Environmental Satisfaction: $F_{1,44}=6.66$, $p<0.05$, $\eta^2_{partial}$ = 0.13

Table 4. Results of significant MANOVAs related to $\Delta^{VDT}G_L$. Each significant MANOVA is followed by each of its univariate tests, significant or not. Cells associated with univariate tests show group means, with standard deviations in parentheses. Notes below the table refer to letters in the Contrasts columns; there is a letter if the test associated with that contrast is significant.

Independent Variable = $\Delta^{VDT}G_L$					
	Assignment to groups (units = cd/m^2)			Contrasts	
	LESS (≤ -20)	SAME (> -20 and < 20)	MORE (≥ 20)	1 (SAME vs. OTHER)	2 (LESS vs. OTHER)
n	12	32	3		
LQ & Satis. MANOVA					*(a)*
Ltg. Qual.	3.52 (0.75)	4.08 (0.78)	4.73 (0.31)		*(b)*
Glare	2.29 (1.18)	1.61 (0.82)	1.83 (1.44)		
Env. Satis.	2.35 (0.71)	2.82 (0.76)	3.00 (1.52)		

Notes: *(a)* Overall MANOVA: Wilks' Λ=0.832, $F_{3,42}$=2.82, p=0.05, $\eta^2_{partial}$=0.09; *(b)* Lighting Quality: $F_{1,44}$=7.84, p<0.01, $\eta^2_{partial}$ = 0.15

Figure Captions

Figure 1(a). Layout of furniture and reflected ceiling in mock-up office. Numbers indicate the individual circuits described in text.

Figure 1(b). Relationship between dimmer setting (number of LEDs lit) and relative light output, for the recessed parabolic fixtures .

Figure 2. Key photometric variables referred to in this paper. LMM, ${}^{VDT}G_{\%}$, ${}^{VDT}G_L$, were determined using a video photometer. LMM did not include the VDT screen.

Figure 3. Change in desktop illuminance chosen by NC participants (ΔE_D) vs. desktop illuminance they experienced during the day (${}^{LC}E_D$).

Figure 4(a). Change in desktop illuminance chosen by NC participants (ΔE_D) vs. change in glarespot luminance chosen ($\Delta{}^{VDT}G_L$). (b) Residual of change in desktop illuminance chosen by NC participants after effect of glarespot luminance change is removed vs desktop illuminance experienced during the day (${}^{LC}E_D$). Linear and 3rd-order polynomial regressions are shown.

Figure 5(a). Change in log of luminance ratio chosen by NC participants (ΔLMM) vs. log of luminance ratio they experienced during the day (^{LC}LMM). (b) Change in log of luminance ratio chosen by NC participants (ΔLMM) vs. change in glarespot luminance chosen ($\Delta^{VDT}G_L$). (c) Residual of change in log of luminance ratio chosen by NC participants after effect of glarespot luminance change is removed vs log of luminance ratio experienced during the day ($^{LC}\Delta$LMM). Linear regression is shown.

Figure 6. Graphs of significant univariate effects when mood, satisfaction and performance outcomes were analysed with respect to end-of-day changes in photometric variables.

Figure 7. Fraction of participants who would be within 100 lx of their chosen desktop illuminance (E_D), for any given E_D.

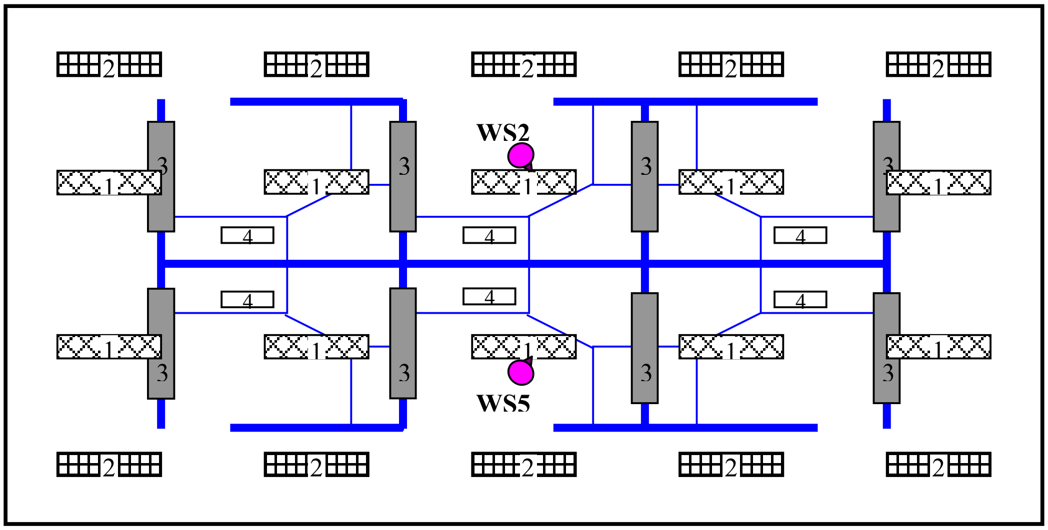


Figure 1(a)

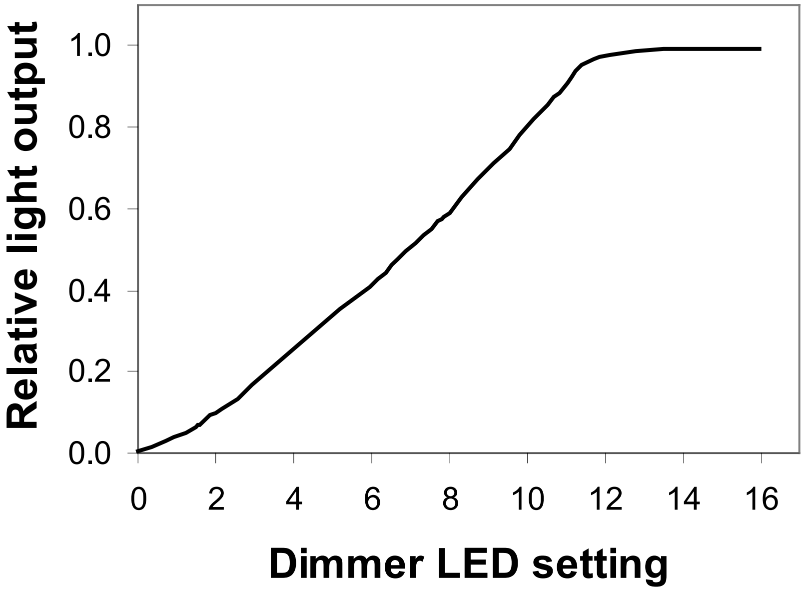
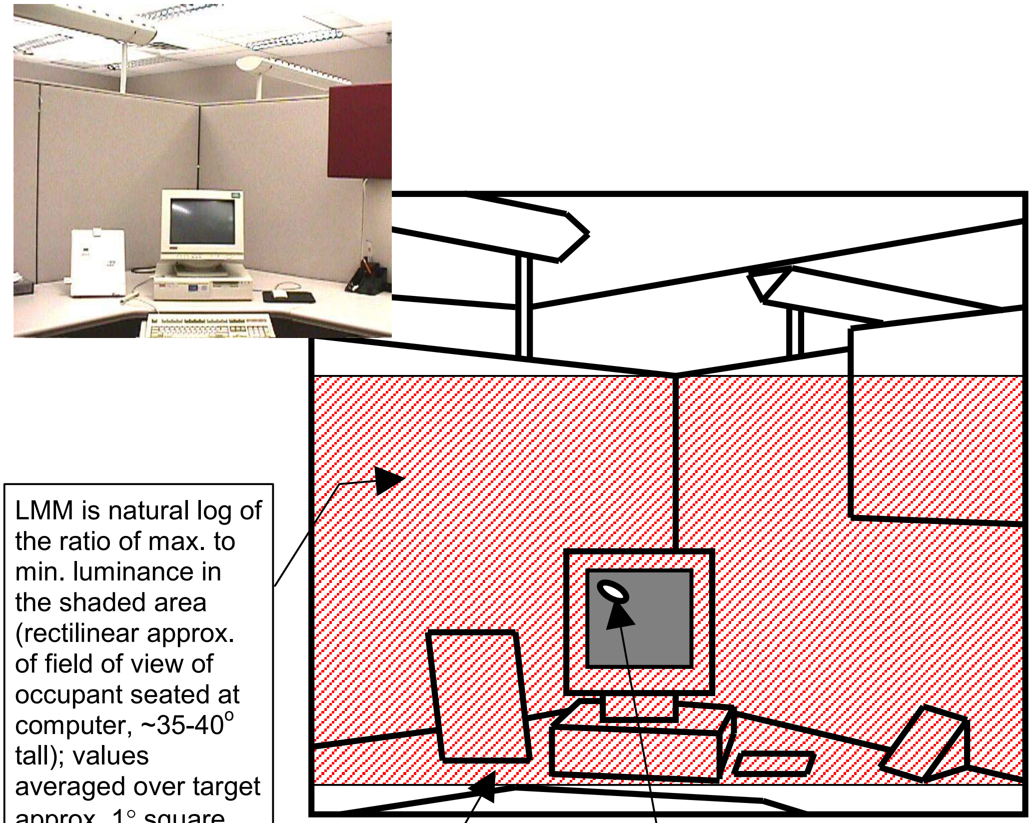


Figure 1(b)

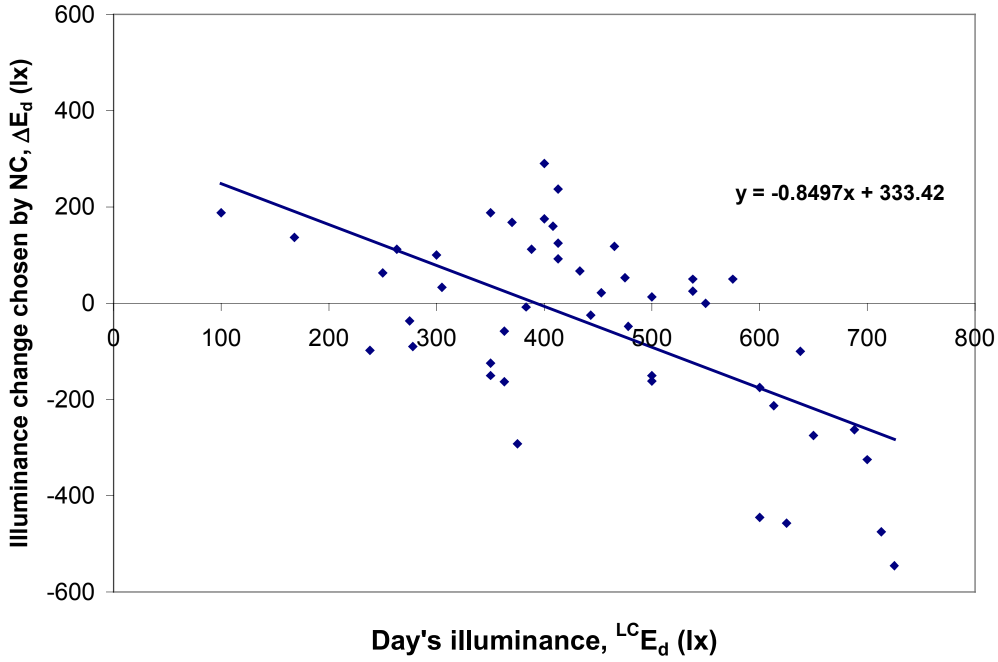


LMM is natural log of the ratio of max. to min. luminance in the shaded area (rectilinear approx. of field of view of occupant seated at computer, ~35-40^{o} tall); values averaged over target approx. 1° square

E_D is illuminance measured on the desktop, on the side opposite the task light.

$^{VDT}G_{\%}$ is percent of VDT screen area > 40 cd/m^2, when screen is off. $^{VDT}G_L$ is the mean luminance of these areas.

Figure 2



Illuminance change chosen by NC, ΔE_d (lx)
600
400
200
0
-200
-400
-600
0
100
200
300
400
500
600
700
800
y = -0.8497x + 333.42
Day's illuminance, $^{LC}E_d$ (lx)

Figure 3

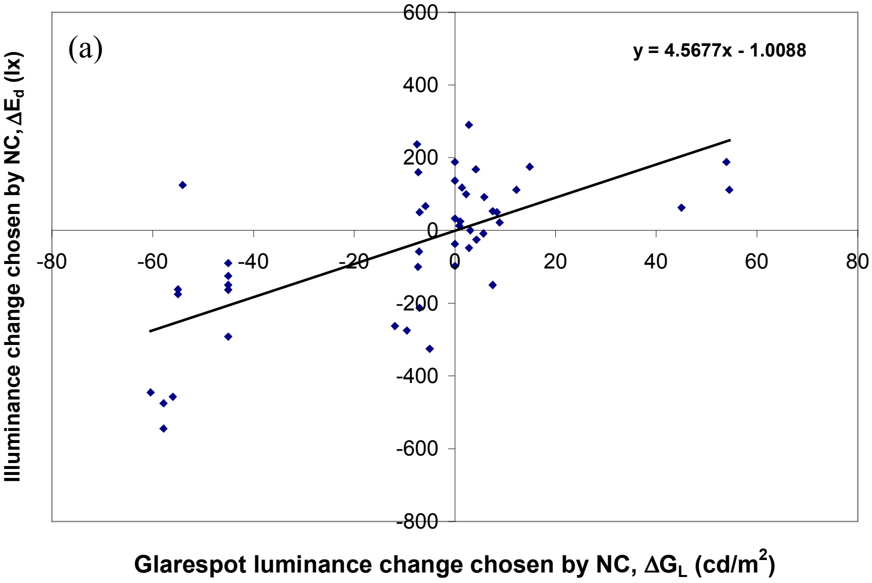


Figure 4 (a)

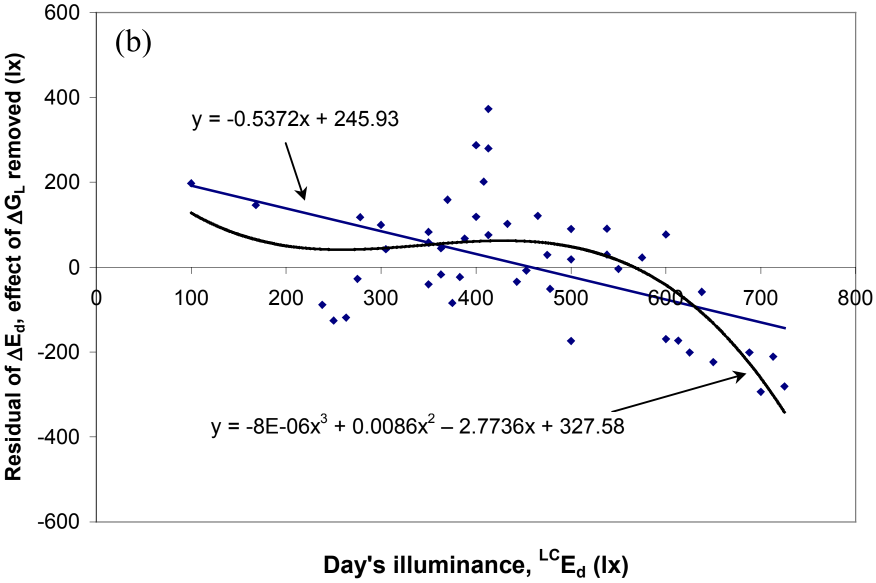


Figure 4 (b)

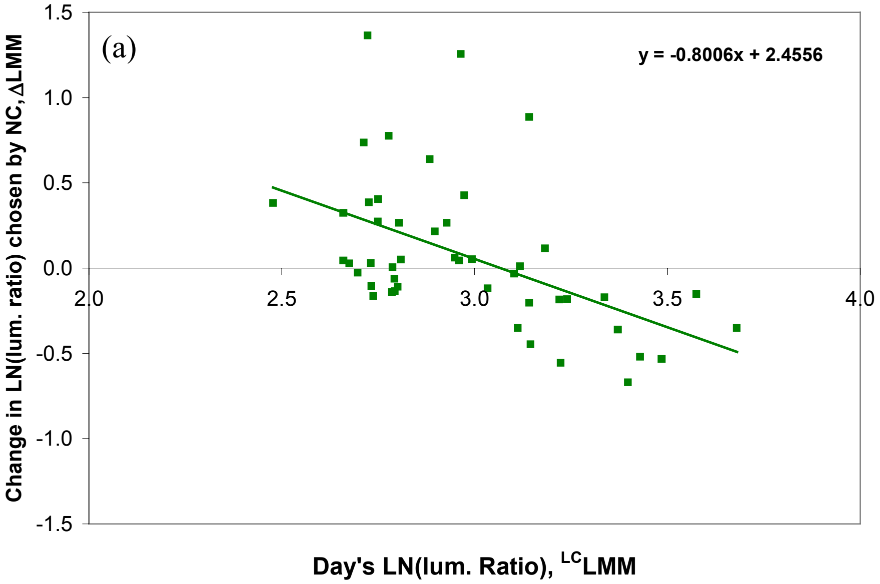


Figure 5 (a)

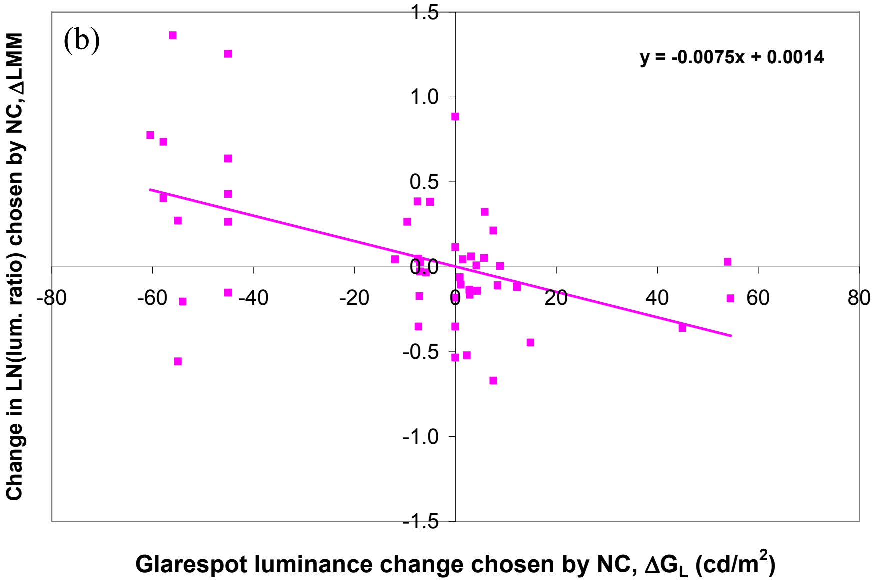


Figure 5 (b)

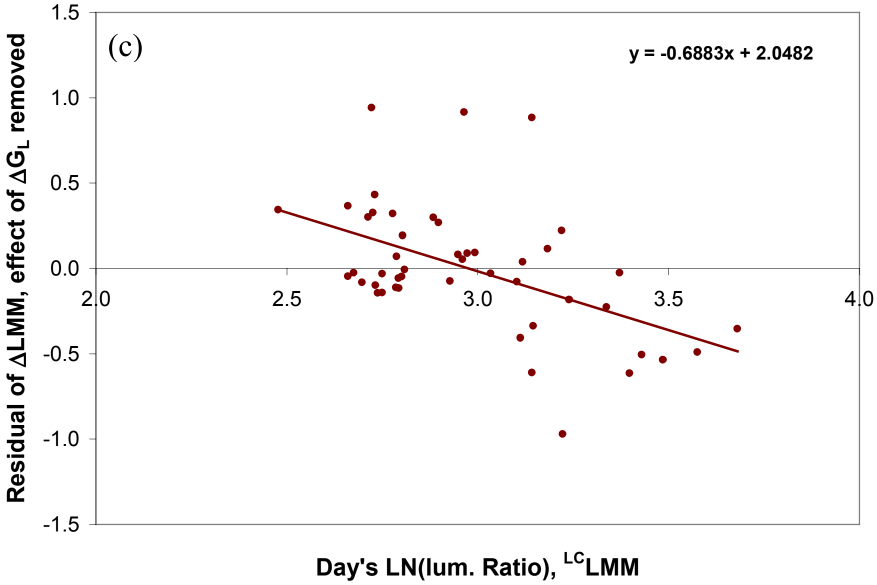

(c)
y = -0.6883x + 2.0482
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0
2.5
3.0
3.5
4.0
Residual of ΔLMM, effect of ΔG_L removed
Day's LN(lum. Ratio), ^LC LMM

Figure 5 (c)

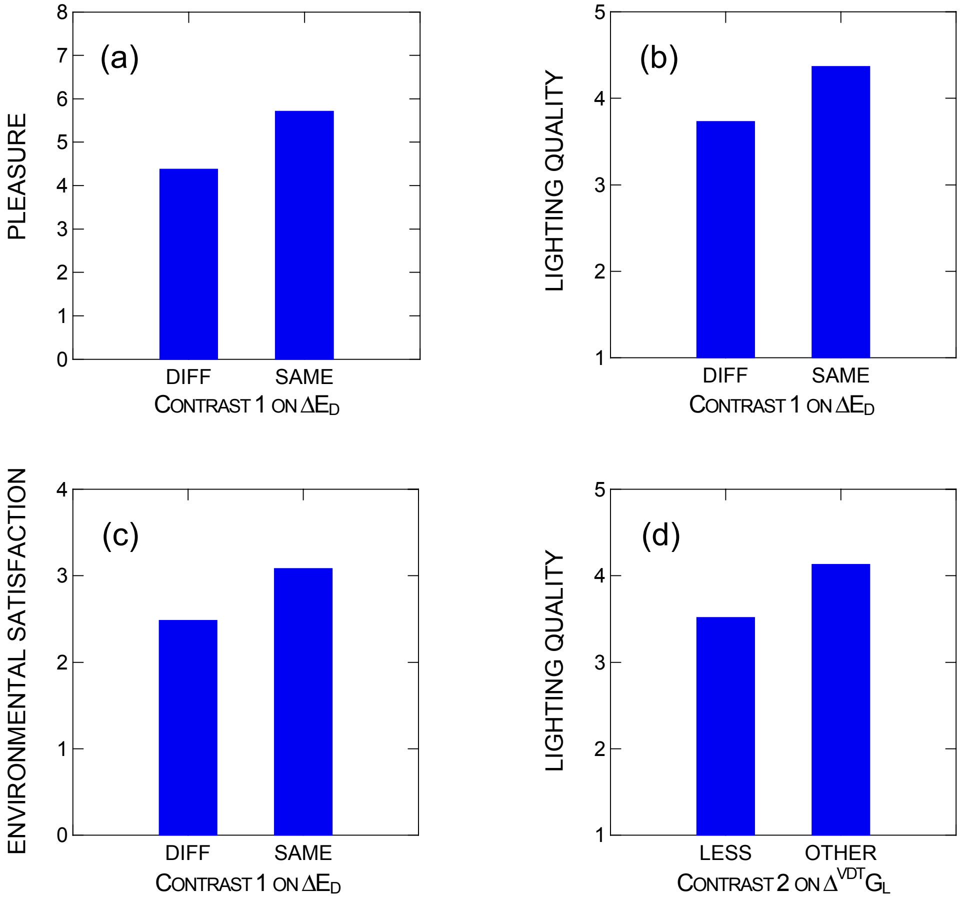
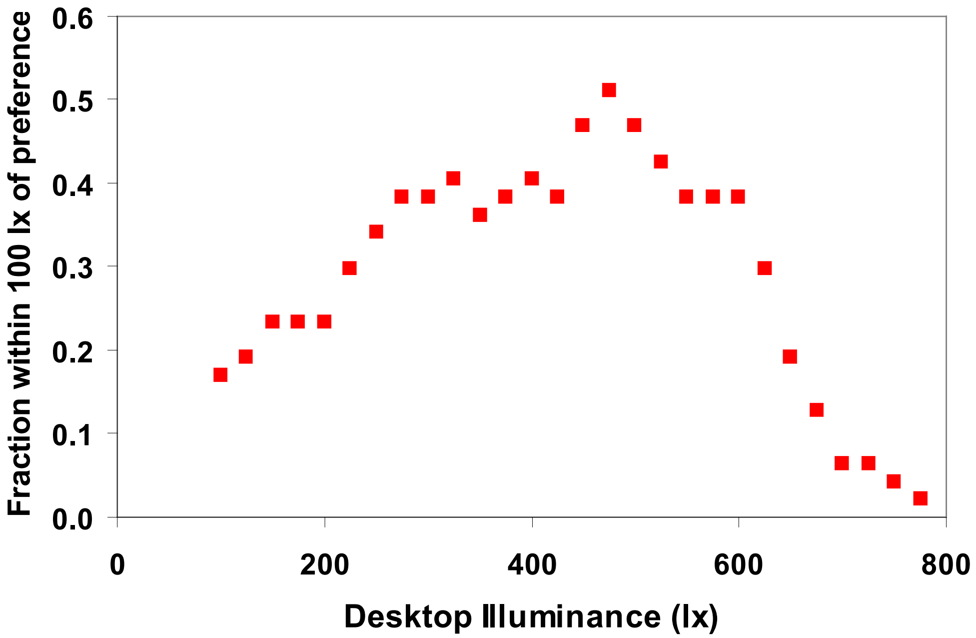

(a)
PLEASURE
0
1
2
3
4
5
6
7
8
DIFF
SAME
CONTRAST 1 ON ΔE_D
(b)
LIGHTING QUALITY
1
2
3
4
5
DIFF
SAME
CONTRAST 1 ON ΔE_D
(c)
ENVIRONMENTAL SATISFACTION
0
1
2
3
4
DIFF
SAME
CONTRAST 1 ON ΔE_D
(d)
LIGHTING QUALITY
1
2
3
4
5
LESS
OTHER
CONTRAST 2 ON $\Delta^{VDT}G_L$

Figure 6


Fraction within 100 lx of preference
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
200
400
600
800
Desktop Illuminance (lx)

Authors' Response to Dr. Carter & Dr. Boyce

We thank Drs. Boyce and Carter for their thoughtful and encouraging comments. Firstly, we will address Dr. Boyce's request for data related to the use of the different lighting systems. This information is available in Ref. 11, and is reproduced here. For the task lamp (which was on/off control only), the number in the table is the fraction of participants that switched it on. For the other three systems (which were continuously dimmable) the number in the table is the mean fraction of full light output chosen the by the participants; the standard deviation, shown in parentheses, gives an indication of the variability of choices between participants.

	LC	NC
Partition-mounted	0.72 (0.27)	0.68 (0.29)
Perimeter parabolic	0.56 (0.30)	0.35 (0.34)
Centre parabolic	0.54 (0.32)	0.51 (0.37)
Task lamp	0.94	0.83

The statistical analysis described in Ref. 11 shows that only the use of the perimeter parabolic system differed significantly between the two groups. One explanation for this, again described in Ref. 11, is that one of the perimeter parabolic luminaires caused a reflected glare image in the participants' VDT screens. This might not have been apparent when luminous conditions were initially chosen at the start of the day, but the NC participants, after a day's experience in the space, reduced the output from those fixtures, on average. Interestingly, when we asked the LC participants what changes they would have made to the lighting during the day had they had the chance, several indicated that they too would have reduced the output from the perimeter parabolic luminaires. The fact that the NC participants were able to identify an unpleasant aspect of their luminous environment and correct it when they had the chance argues against simple habituation to conditions.

Dr. Boyce suggests that "lighting conditions in the working area are what matters, and how they are achieved does not matter". Certainly, the current structure of numerical lighting recommendations is largely predicated on the assumption that preferred luminous conditions are independent of the lighting system used to produce them. As researchers, we have a vested interest in this assumption in that it broadens the applicability of our findings. However, although this study adds to a body of research on preferred luminous conditions, we still believe more studies are needed before we can draw firm conclusions. In this study we used a particular combination of lighting fixtures in a particular space with participants performing a particular set of tasks. This set limits on the possible range of luminous conditions that participants could create. It remains to be seen whether repetition of our methods in a different set of circumstances will produce similar results.

Dr. Carter wonders whether the results from a non-daylit space with a North American furniture design would be applicable in a European setting. The answer is that we do not know; again, only repetition of the experiment in different settings can address this very valid question.

He also invites our comment on the applicability of our method in a field study setting. The method requires that we obtain an occupant's preferred luminous conditions while also measuring their satisfaction under conditions potentially far-removed from those preferred conditions. In any real field installation of individual control occupants would presumably act to maintain their preferred conditions, and artificially imposing non-preferred conditions for a period of time would destroy the realism that is the very benefit that the field situation offers. (Though it would be interesting to observe how far conditions would have to deviate before a control action was triggered). Nevertheless, it might be possible to obtain useful data through observations over a period when individual controls were phased in. A similar analysis to the one in our study could be performed by comparing luminous conditions and satisfaction after the installation of controls, when the occupants have created their preferred conditions, to the luminous conditions and satisfaction before the installation of controls, when the luminous conditions for some individuals would be quite different from their preferred conditions. Perhaps a "passive" method in a daylit space with fixed electric lighting might also work. One could administer regular lighting satisfaction questionnaires while simultaneously measuring ambient lighting conditions. With daylight one could expect a wide variation in ambient lighting conditions. It would be interesting to observe whether higher satisfaction votes are associated with a consistent set of luminous conditions in such a setting, and whether ambient conditions far from this preferred set result in significantly lower satisfaction.

We hope that others are encouraged by our findings to use our method in their own experiments. We believe that a focus on deviation from individual preferred conditions, rather than on absolute photometric values, has promise, but only repetition in other experiments will prove if this is the case.

Figure 7