A Metric for Judging Acceptability of Direct Luminaires in Computer Offices

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THIS PAPER RECEIVED THE 2001 TAYLOR TECHNICAL TALENT AWARD, WHICH HONORS A PAPER DETAILING RESEARCH WORK THAT FURTHERS THE APPLICATION KNOWLEDGE OF LIGHTING PRACTICE.

Computers are now ubiquitous in North American offices. Unfortunately, so is poor computer screen visibility. This research looked at subjective responses to combinations of three computer screen types and 10 recessed parabolic luminaires, at two typical angles of reflection. Analysis of the data shows that the subjective response is strongly related to the type of screen viewed and luminous intensity of a luminaire at angles that would create a specular reflection on the computer screen. The result of this research is a recommendation to the Office Lighting Committee of the Illuminating Engineering Society of North America (IESNA) that luminous intensity limits can be used to predict acceptability of a recessed interior lighting system for use in offices with computer screens.

The Problem/Question

Background of the computer screen glare issue

North American offices have become increasingly more reliant on computers and the Visual Display Terminal (VDT) has become almost ubiquitous. Unfortunately, computer screens have the potential of reflecting high luminance sources. Bright screen reflections interfere with task performance because they

1. reduce task contrast (the luminance patch superimposed on the surface of the computer screen reduces the luminance difference between the character and its background),
2. present a visual distraction for the office worker, especially if the reflection is sharp edged, and
3. create additional images on the screen which are at a different focal distance than the displayed text or graphics. The eye is trying to focus on the task detail at a distance of nominally 0.4-0.6 m (16-24 in.), and a luminaire image at a focal distance of 2.5-4.5 m (8-15 ft). The eye can do both, but not at the same time. Thus, as the eye shifts focus, fatigue and eyestrain may result.

Disturbing reflections are typically caused by luminaires, windows or lighted surfaces having a higher luminance than their surrounding ceiling or wall surfaces, and having a discrete edge. Direct luminaires are likely culprits for this reflection problem because the luminaires are usually recessed in ceilings that are significantly darker than the luminaire.

Response to the problem by the lighting industry, and current practice

Leibig and Roll studied the screen reflection problem with a variety of luminaires and computer screens.[1] A wide range of average luminaire luminances proved to be acceptable (130-500 cd/m^2), depending on the specularity and polarity of the screen. They recommended a maximum of 200 cd/m^2 for luminaires or indirectly lighted surfaces if disturbing reflections were to be avoided. This study was used to develop other European standards limiting luminaire luminance, including CIBSE's LG-3-1995.[2]

In 1989, the Office Lighting Committee of the IESNA developed average luminance values to identify luminaires whose reflections hinder the VDT viewing task. The average luminaire luminance was used because it was recognized that the reflection of the ceiling in the computer screen would include many luminaire reflections. It was assumed at the time that all of the reflections would hinder view of the whole screen and that glare from large luminaires would be mitigated because there would be fewer of them. A table of limits for direct lighting systems was published in *Recommended Practice 24* and in *RP-1* as a guide to lighting designers and engineers.[3,4] There were two levels of compliance: "Preferred," for intensive VDT use applications, and "Basic," for offices with mixed paper tasks and less critical screen tasks.

The average luminance limits effectively favor wider luminaires because the average luminance is defined as the luminous intensity at a given angle divided by the projected area of the luminaire. The reality, however, is that the surface of the luminaire is non-uniform, and the luminance of the patch of bare lamp poses the same

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reflection potential whether produced by a 2x4 ft luminaire or a 1x4 ft luminaire. The larger luminaire has a lower calculated average luminance, and is therefore more likely to comply with published luminance limits than the smaller luminaire.

Research and observation now point to the fact that the eye is only impeded by a reflection superimposed directly over the immediate task. Xin Wang showed that the number of reflected images of luminaires on a computer screen is much less important to the subjective disturbance rating than the luminance of each luminaire.[5] Thus, the Office Lighting Committee recognizes that it should consider the potential effect of one luminaire on the visual task and adapt a revised metric. A model exists which examines the lighting/display interaction, using the maximum patch luminance from a luminaire and other parameters of the computer screen and room.[6] This model was a substantial first step in producing a predictive index of acceptability for a VDT office lighting system, especially since it included parameters of the VDT screen and its software-driven display. However, it is complex to use and requires input data that is difficult to gather during design stages.

The hypotheses

This experiment examined whether objective measures could be used to predict the subjective response to VDT reflections, and the acceptability of the direct luminaire causing the reflections.

1. The type of VDT screen affects the acceptability of the lighting system. Specifically, high luminance displays are better than low luminance displays; negative contrast is better than positive contrast; low specular reflectance is better than high specular reflectance; and low diffuse reflectance is better than high diffuse reflectance.

2. The type of direct luminaire affects the acceptability of VDT screen viewing. The following luminaire photometric characteristics were tested:
   - 2a. Average luminance of the luminaire in the direction of the VDT screen (using information derived from the luminaire's standard far-field photometric report).
   - 2b. Maximum luminaire luminance toward the screen.
   - 2c. The ratio between maximum luminaire patch luminance and the surrounding ceiling in the direction of the VDT screen (i.e., the ratio of bright patches of lamp relative to darker sur rounding patches of ceiling.
   - 2d. Luminous intensity of the luminaire in the direction of the VDT screen (as derived from the standard far-field photometric report).

The acceptability of a luminaire for VDT screen viewing may not correspond to acceptability of the same luminaire for general office use.

Experiment

Description

The Office Lighting Committee of the IESNA organized a workshop/experiment at a facility in Chicago in September 1999. The intent was to examine the interaction between three different types of computer screens and 10 recessed parabolic luminaires with varying sizes, numbers of lamps, and louver finishes. Fourteen subjects were exposed to more than 39 combinations of computer screen, luminaire, and reflection angle (55 degrees and 65 degrees) and completed questionnaires on the acceptability of the conditions for office work. Two naïve subjects were run on a smaller subset of combinations so that responses from experienced and naïve subjects could be compared.

Figure 1—Photograph of experiment room.

Setup – Room

The room was 6.8 m x 12.4 m x 2.9 m ceiling (22 ft x 40.5 ft x 9.4 ft) with reflectances of 0.73 (acoustical ceiling tile), 0.42-0.69 wall and shades, and 0.13 floor. No daylight was admitted. (See **Figure 1**) Ten new parabolic luminaires of different sizes, numbers of lamps, louver types, and manufacturing were installed, near the center of the room, so that they could be evaluated separately from the pattern they produced on the walls. Ceiling obstructions necessitated installing them in the irregular pattern shown in **Figure 2**.

A row of recessed MR16 downlights spaced 3 ft on center along the two long walls were left on during the experiment in order to provide typical office wall luminance (10-28 cd/m^2).

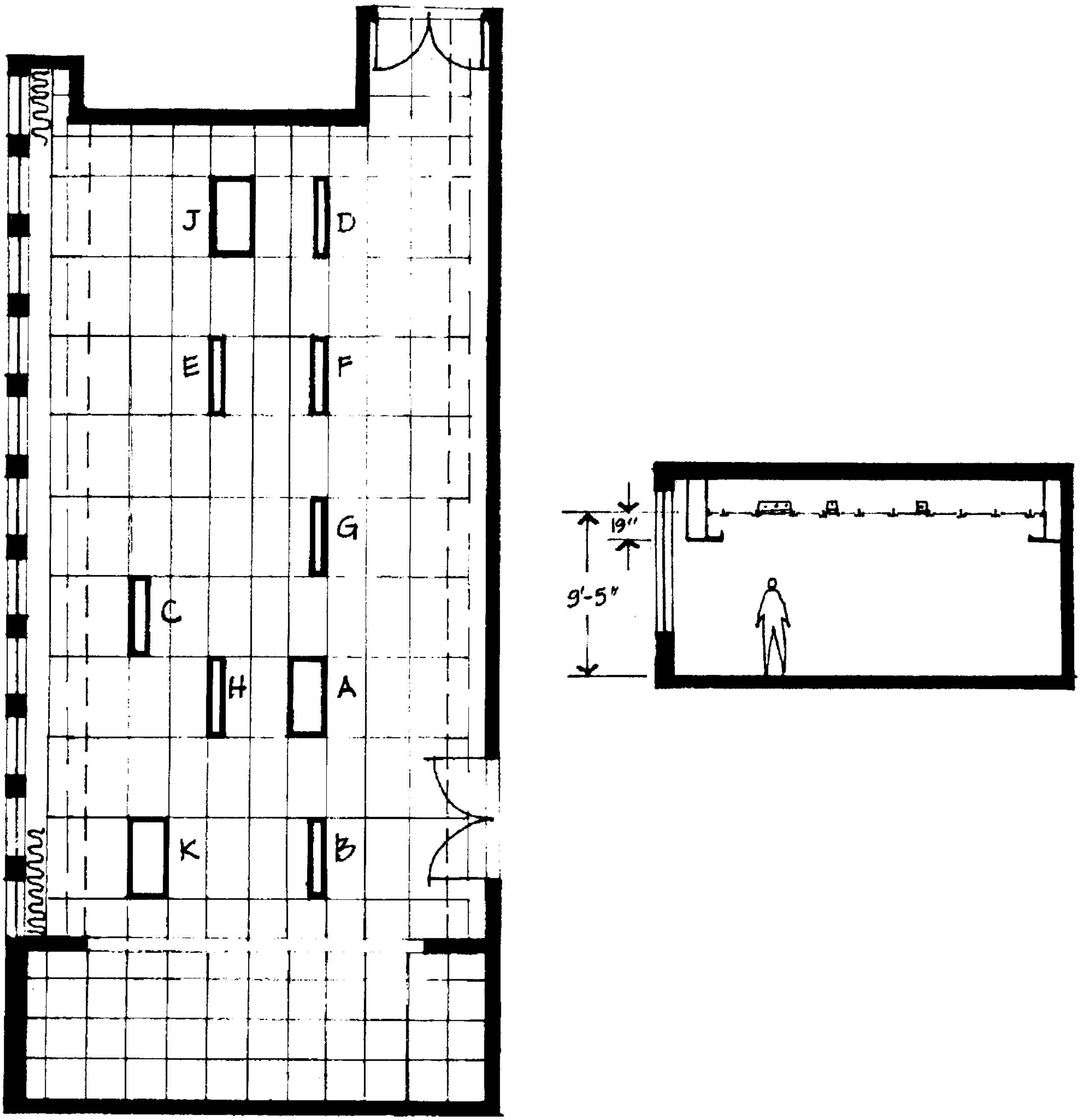


Figure 2—Plan and section of experiment room.

Setup – Lamps, luminaires, and ballasts

All luminaires used one or three seasoned T8 fluorescent lamps from a single production run. On site, the lamps were carefully marked with their location so that after the experiment they could be shipped to a laboratory for photometry and calibration. (This allowed their surface luminance and lumen output under reference conditions to be known so that the luminaire's ballast factor and thermal factors could be calculated as an application factor.)

The luminaires, labeled A through K, were selected to reflect a wide variation in available parabolic louver products. (See **Appendix 1** for more detailed luminaire data). All ballasts in the experiment luminaires were electronic, but their manufacturers and ballast factors were unknown.

Setup – Computer screens

There were three computer screens representing a range of color screen technologies and polarities mounted on movable tables for use in the experiment. All screens displayed the same text and font, and were adjusted for maximum luminance while maintaining maximum contrast. One was an IBM 380ED laptop with a Dual-scan Super-Twisted Nematic (DSTN) liquid crystal display (LCD) screen used in positive contrast mode (labeled LP for "Laptop, Positive contrast"). The second was an IBM 570 laptop with a 13 in. Thin Film Transistor (TFT) active matrix LCD screen used in negative contrast mode (labeled LN for "Laptop, Negative contrast"). The third screen was an Impression 5 Plus Model DA-1565, specular-finish cathode ray tube (CRT) used in negative contrast (labeled CN for "CRT, Negative contrast").

The shiny finish of the CRT screen reflected sharp-edged images of the luminaires. (Diffuse finishes on CRTs can help reduce the sharpness and conspicuity of the reflections, and anti-reflection coatings are available which reduce the luminance of the reflected image. Although widely available, these features increase screen cost.) The LCD screens both had a diffuse screen finish to reduce sharp-edge reflections, and featured excellent image clarity. The TFT screen exhibited the higher luminance display and best resolution of the two. Although positive contrast displays are more subject to distracting reflections,[6] the DSTN LCD screen was put in this mode because this is still commonly used in some types of software. See **Figures 3-5**.

Setup – Locations of computers and tables

Tables were positioned during the course of the experiment so that the computers "viewed" each of the luminaires from the 45 degree azimuth, potentially the worst-case position because it sees across the diagonal opening of the louver cell. The first set of observations was done at the 55 degree elevation angle from the luminaire; the second set from the 65 degree angle.

Setup – subjects

Fourteen subjects with some lighting background participated in the 55 degree trials; two additional subjects with no lighting background were added to the 65 degree trials. Of the experienced subjects, eight worked for lighting manufacturers, three were lighting designers, one was a manufacturers' representative, one worked for a lighting distributor, and one was an ergonomist. Seven of these were members of the Office Lighting Committee. The experience level with office lighting and *RP-1* compliance issues varied widely. The two "naïve" subjects were support staff from the facility in which the experiment was run.

The experienced subjects ranged in age from 30-60. Seven subjects wore glasses, two wore contact lenses. Three subjects were female; eleven were male. The naïve subjects were 36 and 58, one male and one female, with one wearing glasses and the other, contact lenses.

Experimental procedure

Instructions to subjects

Subjects were given no information about the installed luminaires. They were instructed not to discuss VDT lighting issues or their reactions to luminaires during the experiment, so that they would not influence another subjects' response. They adjusted their eye heights to 48 in. above the floor, and were told that if they could not see the relevant luminaire reflection from this position, to adjust their head position slightly so that they could. They were forbidden to touch the screen's brightness settings.

Presentation - First set of trials

The subjects were divided into three groups. Each group "toured" the 10 luminaires carrying a single table with one of the three VDT screens secured to it, following a preset randomized order of luminaires. One at a time, each member of the group viewed the combination of computer screen and luminaire, then completed the following questions using a 7-point unipolar rating scale:

1. How conspicuous is the computer screen reflection? 1 = very conspicuous, 4 = moderately conspicuous, 7 = not at all conspicuous.
2. Judging from the screen, how acceptable would this luminaire be for VDT office use? 1 = never acceptable, 4 = sometimes acceptable, 7 = always acceptable.
3. Ignoring the screen and looking at the luminaire directly, how acceptable would this luminaire be for VDT office use? And then, please check the reason why. 1 = never acceptable, 4 = sometimes acceptable, 7 = always acceptable.

   ___Louver brightness too high, overall
   ___Louver too bright in spots
   ___Transient flashing of louver is distracting
   ___Would be uncomfortable to sit beneath
   ___Bare lamps too easily seen
   ___Louver brightness too low, overall
   ___Other ______________________
4. Write down your observations/reactions to this luminaire and its reflected image.

When all group members were finished viewing the first luminaire, they moved the table to the next of 10 luminaire locations and followed the same procedure. When all 10 luminaires had been viewed, the groups all moved to a different computer screen and table, and the procedure was repeated. They were exposed to 30 combinations of screen type and luminaire. The order of computer screen types was counterbalanced to minimize order effects.

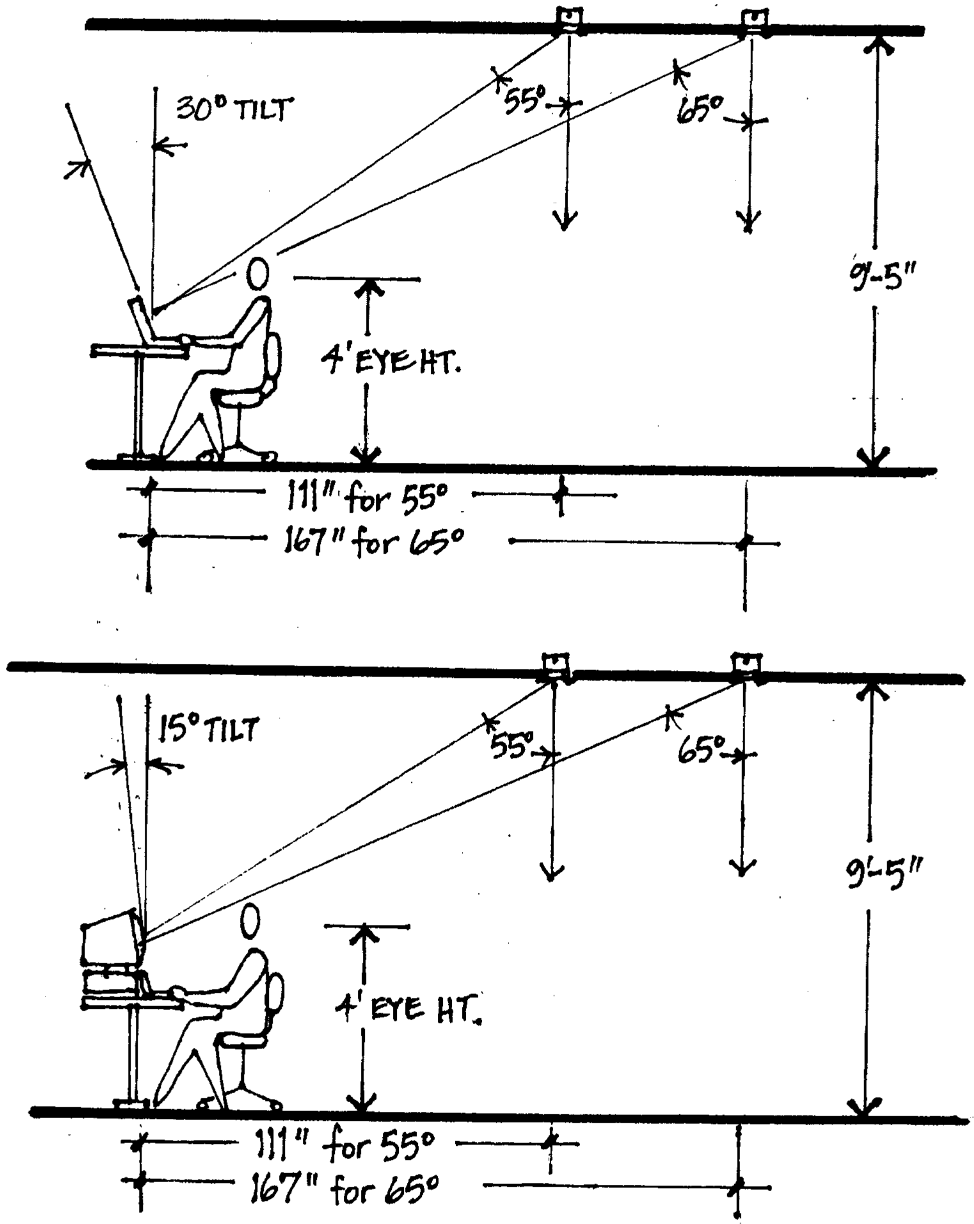


Figure 3—Sketched illustrations of laptop and CRT setup for experiment.

Presentation – Second set of trials

One inexperienced subject was added to each of two groups. The procedure was repeated, but the computer tables positioned to receive light from the 65 degree angle. Only three luminaires, A through C, were used, for a total of nine combinations of screen type and luminaire. These were pre-selected from the full 10 to represent three widely different size and parabolic louver types.

Computer screen and table under trial conditions

The following data were collected for each combination of computer screen, angle and luminaire.

Horizontal illuminance on tabletop near keyboard.

Maximum patch luminance of luminaire, measured from the 55 degree or 65 degree elevation angle.

Luminance of ceiling near edge of luminaire.

Luminances were measured with a 1/3 degree luminance meter.

Luminaire, and adjustments to luminaire photometric data

A method was developed to determine the luminaire's in situ luminous intensity and average luminance, knowing that the surface luminance of a T8 lamp is proportional to its actual lumen output, reflecting the effect of

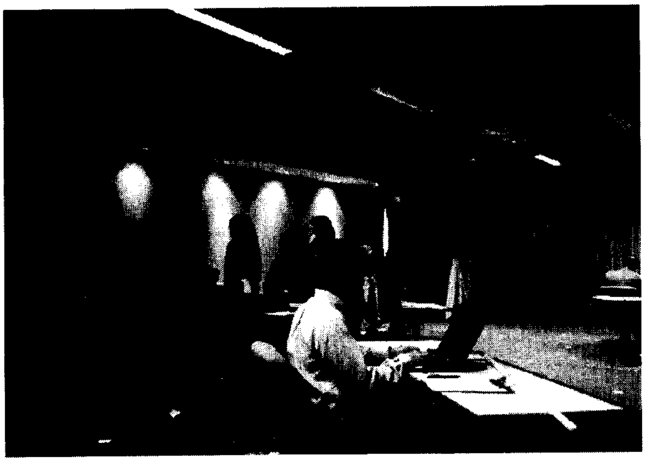


Figure 4—Photograph showing subjects using Laptop (LP) screen during experiment.

Figure 5—Photograph showing subjects using CRT (CN) screen during experiment.

the ballast factor and thermal factor. The surface luminance of each lamp (SL1) was measured inside the luminaire, isolated by a large black cloth draped over the lamp so that surrounding surfaces did not contributing to its luminance. The lamp's lumen output (LO1) was determined by sending the lamp to a photometric laboratory after the experiment, where it was photometered under standard conditions to determine its full lumen output (LO2) when operated on a reference ballast. Its surface luminance was also measured under these conditions (SL2). The luminaire's application factor (AF), used to determine its actual intensity distribution during the experiment was calculated as follows, knowing the lumen output (LOP) of the lamp listed in the luminaire's relative photometric report:

$$AF = \frac{LO_1}{LO_P} = \frac{SL_1}{SL_2} \times \frac{LO_2}{LO_P}$$

The *in situ* lamp data was collected after luminaires had stabilized for 6+ hours. The resulting application factors are listed in the Luminaire Data Tables of **Appendix 1**.

Results

Correlation between questions

The bulk of the statistical analysis was performed on the more extensive 55 degree trials. The data from the 65 degree trials allowed comparing the response of experience and inexperienced subjects, and also provided additional data points. Except where noted, the analysis is for the 55 degree data.

Questions 1 (conspicuity) and 2 (acceptability for VDT use) are very strongly correlated (r^2=0.929), so it was concluded that the responses could be considered identical, and the rest of the analysis was done using Question 1 responses only. See **Figure 6**.

A plot of the means of the subjective responses, differentiated by luminaire type and screen type, is shown in **Figure 7** for all three questions. The type of screen makes a substantial difference in the conspicuity of reflections (Question 1). Screen type LN produces higher ratings that correspond to lower conspicuity of reflections, while screens LP and CN track very closely together at a lower end of the scale. Note also that the luminaire type clearly affects subjective response to Question 1. Luminaires B, E, J and K produce less favorable responses.

Question 3 ratings (acceptability in direct view) show that luminaires E, J and K still elicit poorer ratings. Luminaire B fares better in direct view than it did in reflected view.

Main effects summary

A two-factor repeated measures ANOVA was performed on the data. For Question 1, it showed a main effect from screen type ($p < .0001$) and from luminaire type ($p < .0001$), strongly supporting hypotheses 1 and 2. There is an interaction between luminaire type and screen type ($p < .0002$). For Question 3 there is a main effect of the luminaire, ($p < .0001$) and of the screen ($p < .0001$), but the interaction between luminaire and screen is no longer significant. It appears that when the best quality screen is viewed, the type of luminaire has little effect on the subjective rating. Ratings are much more

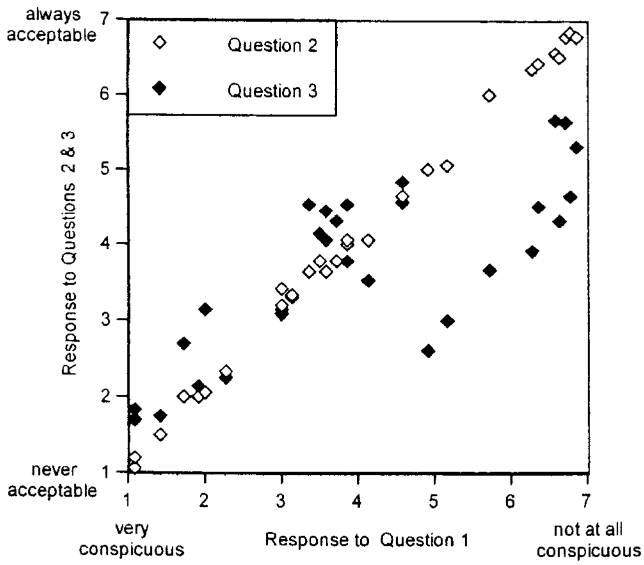


Figure 6—Plot of Correlations between Questions 1 and 2, and Questions 1 and 3. (r2=0.929 for Questions 1 and 2; r2=0.276 for Questions 1 and 3).

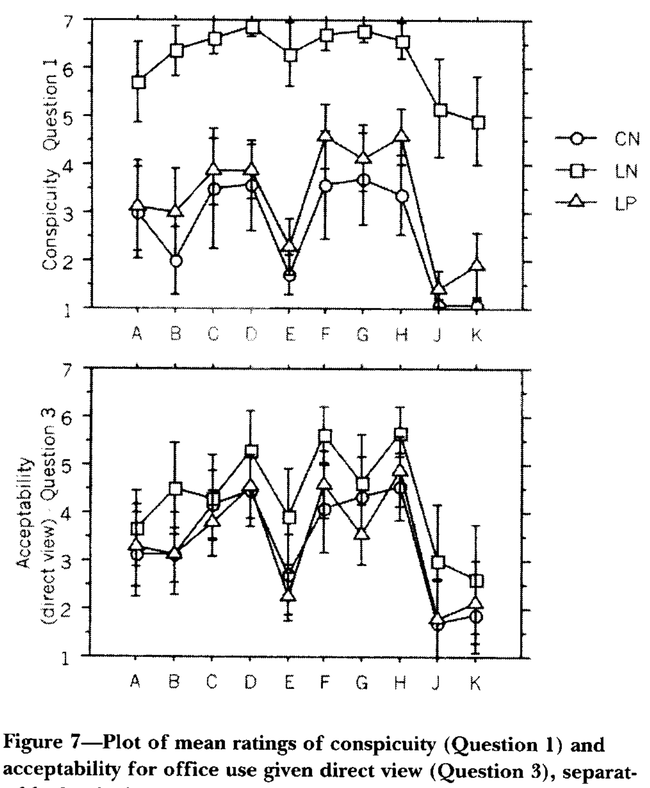


Figure 7—Plot of mean ratings of conspicuity (Question 1) and acceptability for office use given direct view (Question 3), separated by luminaire type and screen type, in the 55 degree trials. (Error bars represent the 95 percent confidence interval.).

sensitive to luminaire type when viewed in poorer screens. This effect is much less pronounced when subjects are viewing the luminaires directly, as shown in the lack of interaction for Question 3.

The results clearly show that computer screen characteristics combined with polarity of the display affect the conspicuity of screen reflections, and the acceptability of a luminaire for VDT office use. In fact, it is such an important factor that lighting practitioners need to be aware of differences in screen quality, and need to be able to communicate with their clients about evaluating and choosing screens.

The LN screen produced much higher ratings of acceptability than both the LP and CN screens, and the LP screen performed only slightly better than the CN screen. This ranking corresponds to the sum of "good" screen features of high luminance, negative display contrast, low specular reflectance, and low diffuse reflectance, as illustrated in **Figure** 8 and in **Figures 9**, **10** and **11**. (See **Appendix 2** for measured values.)

Effect of room and luminaire photometric characteristics

In order to test Hypotheses 2a, 2b, 2c and 2d, correlations between mean responses to Question 1 (conspicuity, acceptability reflected view) and the room and luminaire photometric characteristics were performed, averaging across screen types.

The luminaire's photometric characteristics can indeed be used to predict acceptability, but some explain more variance than others (see **Figure 12**). Average luminaire luminance (hypothesis 2a) and luminaire maximum luminance toward the screen (hypothesis 2b) work moderately well (r = -0.640 and r = -0.669, respectively), while the ratio of maximum luminaire luminance to the surrounding ceiling luminance (hypothesis 2c) was not a good predictor (r = -0.131). Also poorly correlated was VDT table horizontal illuminance (r < 0.013). Illuminance ranged between 124 lx and 745 lx, but both extremes of illuminance yielded high acceptability ratings. This result indicates that it is possible to have good seeing conditions for the VDT screen with a wide range of workplane illuminance.

Figures 12 and **13** show that luminaire luminous intensity (hypothesis 2d), irrespective of number of lamps in the luminaire, has great potential in predicting luminaire acceptability ratings. The luminaire's luminous intensity toward the screen has a correlation of r = -0.953 for the 55 degree data trials when averaged over screen type, and r = -0.902 when the 65 degree data is included.

Effect of luminaire luminous intensity

Examination of the data suggested that a transformation of luminous intensity might explain a great deal of

	Screen Luminance High = ✓ Low = ✗	Display Contrast Neg. = ✓ Pos. = ✗	Specular Reflectance High = ✗ Low = ✓	Diffuse Reflectance High = ✗ Low = ✓	Sum
LN	✓	✓	✓	✓	✓✓✓✓
LP	✗	✗	✓	✓	✓✓
CN	✓	✓	✗	✗	✓✓

Figure 8—Table of screen and display features for computer monitors used in experiment.

the variance in responses to different luminaires in Question 1. **Figure 13** shows the relationship between luminous intensity raised to the power of 0.4 and the mean responses to Question 1 (conspicuity and acceptability). (The best fit actually used an exponent of 0.375, but this was rounded up for simplicity.) The slope for the LN screen is more shallow than for the other two screens, indicating that a good quality screen produces good responses almost irrespective of the luminaire used. However, the luminaire luminous intensity makes a substantial difference for the lower quality and positive contrast screens. Note the correlation coefficients of r^2 = 0.875, 0.78, and 0.791 for the three screens.

Effect of luminaire physical characteristics

An attempt was made to relate the subjective ratings to physical characteristics of the experiment luminaires. The rank ordering of acceptable luminaires at 55 degrees for Question 1, from most to least acceptable is: F, G, H, D, C, A, B, E, K, J. This ranking was poorly related to luminaire size, number of lamps, and louver specularity, alone. It was better related to louver shielding angle, the angle measured from horizontal below which the louver no longer shields the direct view of the lamp. (See **Appendix 1** for a listing of shielding angles, calculated in the 0 degree plane of the luminaire. It is the arctan of (louver height/cell width along the length of the lamp).) F, G, H and D all have shielding angles of 40 degrees or greater and are rated highly. With the exception of C, all of the luminaires with shielding angles of less than 30 degrees received lower average ratings. Although louver shielding angle was the best explanation of all the examined physical characteristics, it is important to note that all of the characteristics interact and work in concert to produce the luminous intensity distribution.

Acceptability of luminaire for VDT office use

Question 3 was intended to elicit the acceptability of a luminaire for office use when the luminaires are viewed directly, and the differences in responses to Questions 1 and 3 support hypothesis 3 and demonstrate that there are many reasons why a recessed parabolic luminaire may be less acceptable for general office use than its low reflection in a VDT screen might indicate. Dark-looking specular louver parabolics can contribute towards a gloomy appearance in offices; the specular louver may be comfortable to view at high angles, but "flash" uncomfortably as an individual walks into the cone of light below its sharp cutoff point; or the luminaire may produce uncomfortable overhead glare. It is important to make it clear that there are more criteria in judging a lighting system than whether it will image in a computer screen.

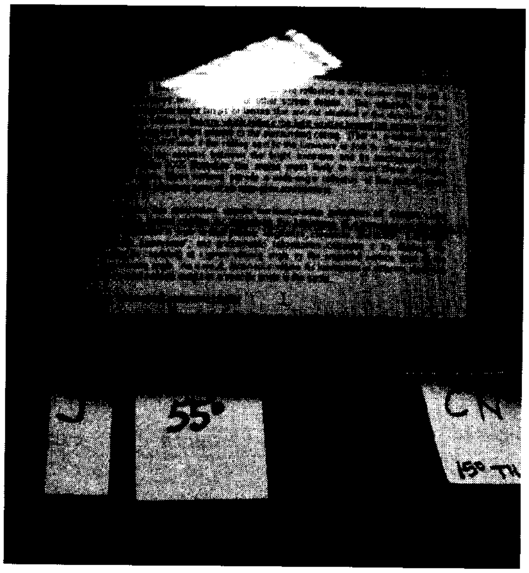
Figure 14 shows the Regression of Question 3 responses against a transformation of luminaire luminous intensity. The regression lines for the CN and LP screens plot almost right on top of each other, but the responses to Question 3 are almost a half point higher when the subject responds after viewing the best (LN) screen. The better screen seems to improve the subject's evaluation of the luminaire's acceptability for office use.

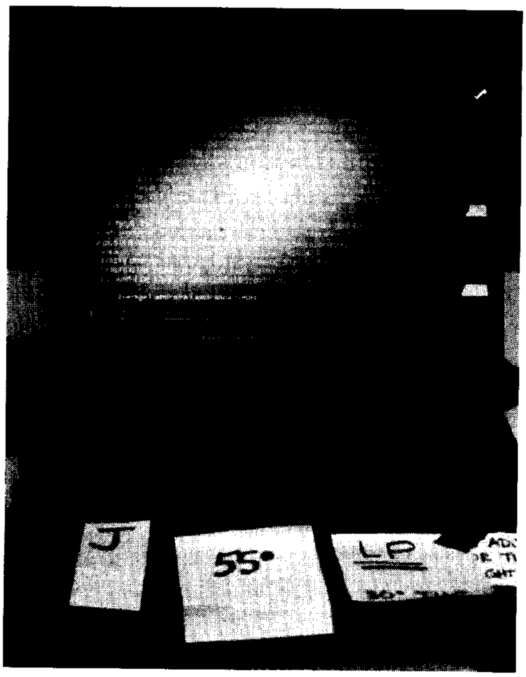
Comparison of luminaire acceptability with RP-1-1993 Recommendations

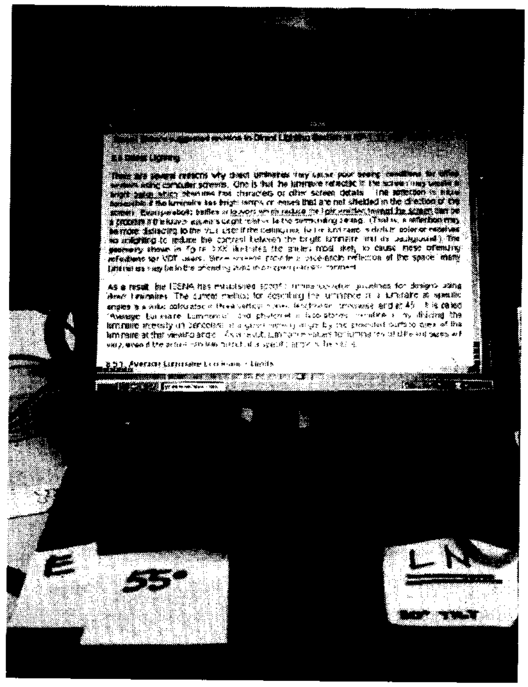
Four of the 10 luminaires studied were compliant with the RP-1-1993 "Preferred" standard: A, D, G and H. All of these performed well in this study, but so did luminaires C and F, demonstrating that high levels of acceptance are not well correlated with the current RP-1-1993 average luminance limit recommendations.

Discussion of luminaire luminous intensity

Why does this transformation of luminous intensity work, and why is the exponent 0.4? One possibility is that the subjects were responding to the "brightness" of the reflected image. Luminous intensity (I) is proportional to luminance (L) and may behave similarly to a brightness (B) function of the form







Figures 9–11—Photographs illustrating screen visibility on the three screens used in the experiment. Figure 9 shows the CN screen reflecting luminaire J; Figure 10 shows the LP screen reflecting luminaire J; and Figure 11 shows the LN screen reflecting luminaire E. (Note: Since the LN screen looked virtually the same under all luminaires, it was only photographed in this one condition.)

$$B \equiv L^{0.33}$$

Equations very similar to this one were developed by Hopkinson, Stevens and Stevens and then Marsden to fit the relationship between brightness and luminance.[7-9] The exponents each of the three models used to transform luminance to brightness ranged between 0.31-0.35. This is surprisingly close to the 0.4 used here to convert luminous intensity into a "brightness of reflected glare" function, and even closer to the 0.375 that provided the best fit. It implies that acceptability of the reflected view of the luminaire is inversely proportional to the perceived brightness of that reflection.

Why is luminaire luminous intensity so strongly correlated to acceptability for VDT viewing when average and maximum luminance are less so? In far-field photometric conditions, luminous intensity is defined as

$$I = L \times A_{proj}$$

	Luminaire luminous intensity	Max to ceiling lum. ratio	Maximum luminaire luminance	Table illuminance	Average luminaire luminance	Question 1 average	Question 3 average
Luminaire luminous intensity	1.000	.174	.716	.195	.590	-.953	-.911
Max to ceiling ratio	.174	1.000	.718	.596	.808	-.131	-.118
Maximum luminaire luminance	.716	.718	1.000	.494	.846	-.669	-.646
Table illum.	.195	.596	.494	1.000	.306	.013	.002
Average luminaire luminance	.590	.808	.846	.306	1.000	-.640	-.604
Question 1	-.953	-.131	-.669	.013	-.640	1.000	.964
Question 3	-.911	-.118	-.646	.002	-.604	.964	1.000

Figure 12—Correlation Matrix for 55 degree trial responses and Room/Luminaire Characteristics.

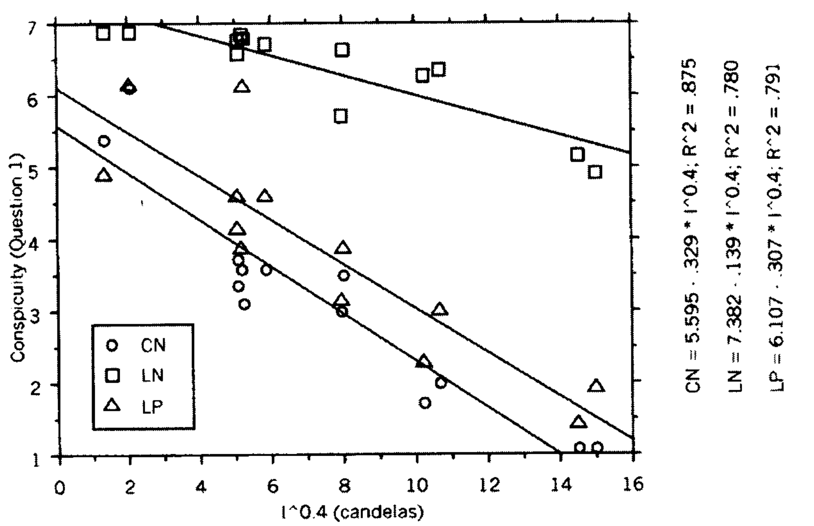


Figure 13—Regression of Question 1 responses against a transformation of luminaire luminous intensity ($I^{0.4}$) for the three screens

or the product of the luminance of a surface times its projected area in the direction of view. There is a tradeoff between luminance and area inherent in luminous intensity. A luminaire may be twice as large but have half the luminance of a second luminaire, while producing equal luminous intensity.

Conspicuity, too, is a function of luminance and area. Luminous intensity may be a simple way of describing the conspicuity of a luminaire's reflected image because it takes both the luminance and the area into account. For a non-uniform luminaire such as the parabolic louver units studied in this experiment, luminous intensity would be the sum of the luminances of small patches of luminaire multiplied by the area of each patch.

The tradeoff of luminance and area for equal conspicuity implied by the use of luminous intensity also makes intuitive sense. Imagine a very small but bright light source causing a reflection on a computer screen. If the very bright reflection were as small as a dot, the luminance would make little difference because the area would be so small it would interfere with the visibility of only a single character. For all but the most critical numerical tasks, the bright dot could be ignored, or a simple head movement could move the dot out of the way. Conversely, imagine a large area source of low luminance, such as an indirectly lighted ceiling. This source would produce a very low luminance, low contrast reflection on the screen, but it would cover a large area of the screen. It, too, is less likely to produce severe interference with the visual display.

Luminance alone is unable to predict this effect, because it ignores area. An average luminance or maximum luminance standard would tell us the small, bright source is unacceptable when we know intuitively that it would be acceptable.

Differences between experienced and inexperienced subjects

This study could easily be criticized for using biased subjects because most had experience in the lighting industry. Several steps were taken to counteract potential

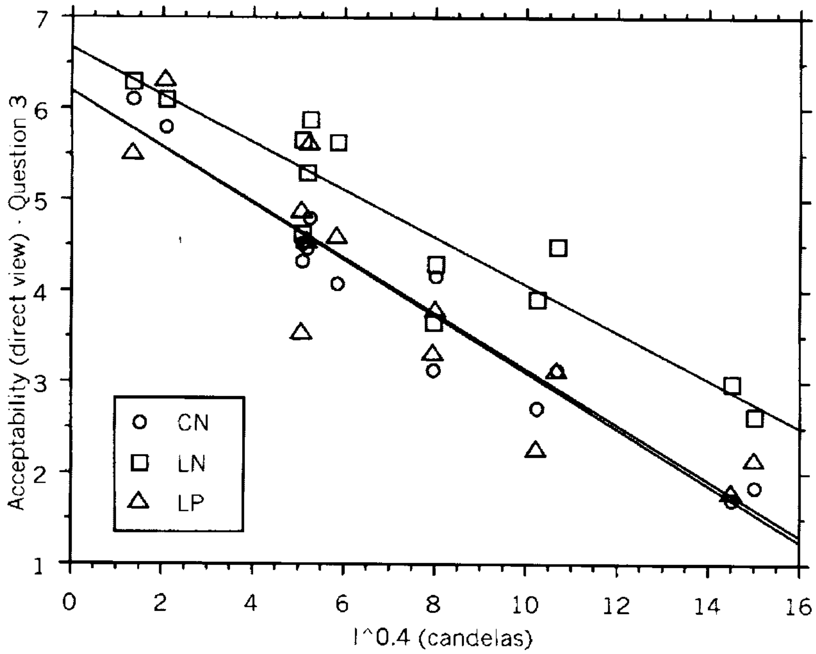


Figure 14—Regression of Question 3 responses against a transformation of luminaire luminous intensity (I0.4) for the three screens.

bias. First, the subjects were instructed to view the parabolic luminaires objectively, and not to be swayed by what they expected to discover. (The fact that the subjects rated even the poorly-shielded luminaires very highly when viewing them in the LN screen points to the fact that they were not predisposed to "trash" the bad fixtures!) Second, the luminaire manufacturers were not identified, and subjects were asked not to compare notes among themselves, so it would have been difficult for them to guess which luminaires were "supposed" to work well with VDTs. Third, two inexperienced subjects were run during the 65 degree trials in order to compare their responses with those of the larger experienced group.

Of these nine trials, only three showed differences in their means of two rating points or more. All other trial responses coincided very closely. When different, the inexperienced subjects' ratings were lower. This surprised the authors because we had assumed that experienced subjects would be more critical of screen reflections than the naïve user would be. Lower ratings occurred when subjects were observing the poorer screens (CN and LP), and/or the 2x4 three-lamp parabolic luminaire (A). The subjects responded that they disliked the bright spots on the louver and the overhead glare produced by this luminaire.

Conclusions

Applying these results to lighting design

This work has direct and immediate application to office lighting practice. It shows that the choice of computer screen is the most critical factor in VDT screen visibility. It also leads to a simpler and more reliable metric based on a luminaire's luminous intensity that will guide the designer and engineer in specifying recessed parabolic luminaires for VDT office applications.

Recommendation of luminous intensity limits for direct lighting in computer offices

How do we convert this information into a viable recommendation for office lighting specifiers? The authors suggest the recommendation be set for the poorer screens, and let designers and engineers use higher-intensity luminaires if they know their clients will have excellent screens. We further suggest that the recommendation set maximum luminous intensity values that would correspond to a subjective response of "3," or "just starting to be unacceptable." This will compensate for the conservative approach of looking at intensities that interfere with the visibility of poor screens.

Here are the intensities that correspond to an acceptability of 3 for the three screens: (Values are maintained intensities; values in square brackets are initial intensities)*

	Acceptability of 3
LN Screen (LCD, neg. contrast)	cp > 4800 [6400]
LP Screen (LCD, pos. contrast)	cp = 316 [422]
CN Screen (CRT, neg. contrast)	cp = 181 [241]

The recommendation to practitioners then becomes:

1. Determine the geometry of the VDT screens being used in the office under design. This will help you determine which angles of the luminaire are likely to cause reflection problems, and thus which angles should be considered for intensity limits.

**The luminous intensity values related to the acceptability responses are actual luminaire intensity values which include ballast factor and thermal factor. The authors suggest assuming a level of dirt, and ballast factor for parabolics of approximately 0.75. All luminous intensity shown in square brackets are values are divided by 0.75 to achieve the maximum candlepower allowed according to the relative photometry photometric report.*

2. Determine what kind of VDTs and software are used;. CRT? LCD? Anti-reflection coatings? Positive or negative contrast?
3. If the users use excellent computer screens and negative contrast software, then there are no maximum luminous intensity limits beyond those set by the designer or engineer's experience and judgment. (Certainly we know from this experiment that luminous intensities of 1000 produce acceptable visibility for good quality screens.) For very poor screens, luminous intensities <250 cd are advisable. But, if the users have unknown quality screens, then they should specify luminaires that do not exceed 300 cd in luminous intensity at the critical reflection angles.

4. These rules apply to all widths of parabolic luminaires: 6 in. x 4 ft, 1x4 ft, and 2x4 ft. An inspection of photometric reports from 2x2 ft parabolic luminaires and 7 in. diameter round compact fluorescent downlights suggests that this luminous intensity limit may be meaningful also to other sizes and types of direct luminaires. This warrants further study.

If VDT users have more horizontal screens, or if they are viewing a monitor mounted behind a horizontal glass desktop, then the geometry of the problem changes, but the principles do not. The designer or engineer simply needs to calculate the angles at which the recessed luminaires are reflected in the screen (see **Figure 15**), and make certain the luminaire's intensity is limited at those angles.

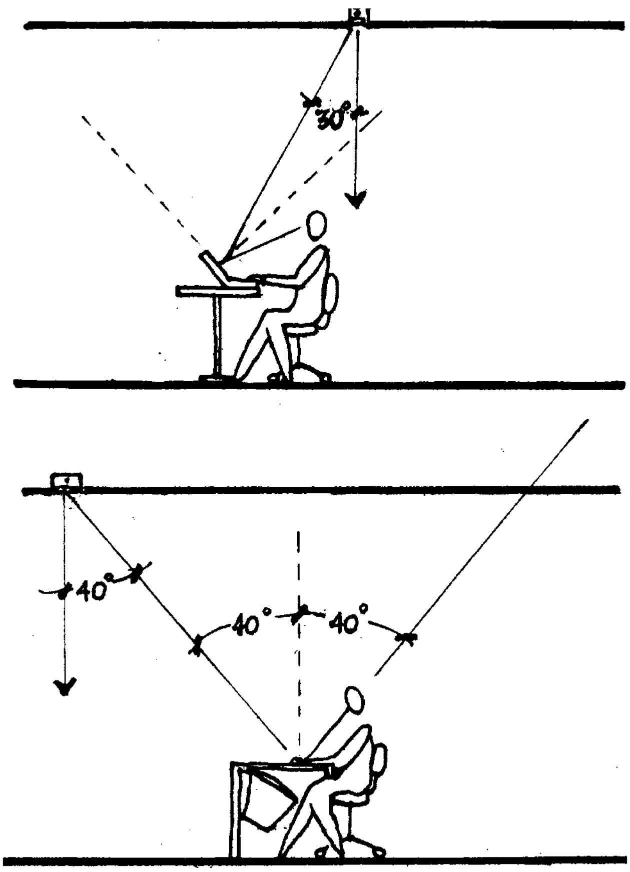


Figure 15—Alternate VDT screen geometries. Laptop screen tilted 40 degrees from vertical, and below-desk screen with horizontal glass top

Further research

There are several limitations to this experiment that warrant further research. Most subjects had lighting experience that may have made their responses unrepresentative of the larger office population. A limited range of direct lighting products was examined. Subjects had a short exposure time to each combination of luminaire, screen, and angle (approximately one minute). There was no objective measure of productivity loss from reflections. Only a narrow range of adaptation luminance was studied. Only T8 lamp luminaires were studied, and only one ceiling height was studied. Additional work is needed to validate the results of this experiment, exploring the responses of naïve subjects under a wider range of conditions.

Acknowledgments

This work would have been a struggle without help from Neil Eklund, the statistical wizard. We also had much input and help from so many folks and manufacturers: Noel Florence, Ron Caferro, Mitch Kohn, Peerless, Lightolier, Zumtobel, Lithonia, Metalux, Columbia and all the great folks at Cooper who helped us wreck their conference room for two days. Then there were the volunteer subjects who gave up their time to be subjects: Mitch Kohn, Ron Caferro, Dawn Kack, John Selander, Dennis Ankrum, Doug Paulin, Marc Pilipuf, Connie Whiteley, Gary Woodall, Ann Reo, Phil Gabriel, Bill Johnson, Maarten Mulder, Scott Ortiz, Howard Wurster, Geri Tipitino and Mike Madaj. Others who contributed photometric expertise and time include John Zhang, Conan O'Rourke, Tom Ballman, Andrew Bierman, Roy Sierlaje and Bob Levin. It was an enormous, but satisfying effort.

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Discussions

The research described in this paper is remarkable as much for its genesis as for its results. After several years of discussion in the Office Lighting Committee, a hypothesis evolved that distracting glare on a computer screen is not caused by the whole array of reflected luminaires, but rather, by the single luminaire whose reflection lies over the point of eye focus on the screen. There was also a feeling that for a single luminaire, luminous intensity might be a better predictor of screen glare than the current average luminance criterion.

The idea that we should look at some computer screen luminaire reflections quickly evolved into a full-blown research experiment designed, housed, equipped and staffed with member subjects and researchers. Naomi Miller wrote the final design of the experiment and then organized it, ran it and finally wrote this paper with help from her coauthors. Members donated their time, manufacturers donated luminaires and shipped on short notice and one provided the space in which to install them all. The basic research was completed, analyzed and reported within three months. The experiment was well designed and organized and the results were meticulously analyzed. It was a wonderful demonstration of what a lively, desperate, dedicated committee can do! We were lucky to have the expertise of the three authors and a strong chairman. But many members took part.

Luminaire luminous intensity, maximum luminaire luminance, and average luminaire luminance were compared with respect to the viewer's assessment of the degree of confusing reflected glare. Luminaire luminous intensity showed a strong correlation.

With regard to the application of light loss factors, I agree it may be useful to take into account the ballast factor. Thermal factors should not be used, however, because the photometric report measurements are taken after thermal equilibrium is reached and thus are already taken into account. Light loss factors should not be used either because we are not interested in maintaining a minimum intensity. The maximum intensity will occur when the luminaire is new and will diminish (improve) as time passes. A new luminaire should not exceed the recommended intensity limits.

The authors suggest further research topics. Because the experiment was designed around a single luminaire, I suggest adding a confirmation that in an array only a single luminaire causes distracting reflected glare on a computer screen.

As one who has for many years resisted attempts to change the average luminance recommendations originally set down in *RP-24*,[3] I am now persuaded by the research that luminaire luminous intensity is a better criterion for the effect of computer screen reflected glare.

Noel Florence, FIES
Noel Florence Associates
Savannah, GA

It would be extremely easy to use the approach of classical paper discussion by congratulating the authors and proceeding to pick every nit that could be found.

We all know that the authors are consummate professionals and from the description of the experiment design and the methods of measurement, they obtained a monumental amount of information in the time they had available (short) and the money available (zero).

If (that magical word) unlimited funds and time were available, the work would be more statistically significant. However, the correlation and relative consistency of the results do indicate that luminous intensity is the most effective metric available for determination of the suitability of a luminaire for use in a VDT environment. Intensity values are also readily available and luminaires can be easily designed to candela requirements.

Being one of the dinosaurs in the Society, I cannot resist picking a few nits. First, when using a luminance meter with any acceptance angle one must be aware of the integrating effect. The measurement distance is critical and should be noted. Second, no luminaires with lenses were considered. With unlimited funds and time I expect that they would be included in the experiment. I realize that the luminous intensity metric will apply to all luminaires regardless of shielding types, but just one piece of data would have been nice.

The author's stated need for further research should be heeded. This type of work will ensure that the lighting industry will continue to provide quality equipment to meet quality standards.

Thomas L. Ballman FIES
Hermann, MO

Few problems have been around as long as the question of how to determine the acceptability of a luminaire based on some metric of visibility. Quantitative assessment of a lighting unit's performance based on screen reflection is the latest twist, although this too has been argued for many years. It is encouraging to know that we now have a basis for a scientific approach to the subject.

I have a concern regarding the author's calibration method for checking the intensity characteristics of the luminaires used in the field test. Apparently it is based on the use of a luminance meter which views a patch of a T8 lamp, and this measurement is then correlated with laboratory testing. If I understand the calibration trail correctly, then a 10 percent error in this field luminance measurement will ultimately translate into a 10 percent error in all field data, including the derived recommended intensity limits.

The measurement of spot luminance, be it of a lamp or luminaire, is highly prone to error. Some of the reasons for this are understood while others are not. The IESNA Testing Procedures Committee has been wrestling with this problem for many years. Round Robin testing for spot luminance has been conducted between laboratories on several occasions. Reputable testing facilities, with qualified personnel and good quality, accurately calibrated equipment; produce variations in result which have exceeded 50 percent. This is the reason that the IES Guide on the measurement of maximum luminance was withdrawn many years ago.

I strongly suspect that the reason for this problem is effects of haloing or ghost images generated by the lensing of the luminance telephotometer. Luminous areas of parts of the luminaire outside of the small area being measured can produce an additional luminance on the photo-detector, due to such effects. (Such effects can easily be seen by looking through the viewfinder of a camera aimed in a general direction towards the sun, although not directly to the sun. A ghost image fills the screen.)

Did the authors screen parts of the luminaire, other than the spot being measured, from the luminance meter?

In addition, what spot on the T8 lamps was measured? Any fluorescent lamp changes its luminance across the height (diameter) of the lamp, so the luminance being measured is non-uniform. I have always felt this method of calibration is fraught with the potential for error. Could the authors comment?

I would be interested to hear how the luminaires were evaluated from the standpoint of producing acceptable office lighting, question 3. Were the viewers fixed, or allowed to evaluate the luminaire from many locations? Do the authors feel that evaluation of a single luminaire, particularly amongst a ceiling covered with many other luminaire types, is a valid method of assessing acceptability of a whole lighting system using that luminaire?

I note that intensity limits are derived by "backing out" ballast factor, thermal factor and dirt depreciation factor, in order to evaluate a luminaire directly from its photometric report. There are problems in doing this. Ballast factors for modern ballast vary greatly, both by accident and design. Thermal factors also vary, and in fact parabolic louvered luminaires may have such factors of 1.00. I do not know how an IESNA Committee can validly decide upon a single value of each of thee factors and use it for all luminaire types, to derive the limitation. Should not the intensity be taken from the test report, multiplied by the two factors, whatever they genuinely might be, and then the result compared to an agreed-upon limiting value. After all, this is a normal procedure for determining other field performance measures such as illuminance.

Regarding Light Loss Factor, I am not sure that it should appear in the calculations of intensity at all, because unlike other lighting quantities such as maintained illuminance, for example, the intensity value is a maximum limitation. The luminaire should meet the required intensity when it has new lamps and is clean, not at the end of the maintenance cycle.

Finally, let us not forget that in all of this, the very best way of controlling VDU images is by positioning. Very often VDU images can be completely eliminated if the relative locations of the luminaires and VDUs can be selected properly. This should be our first and foremost recommendation to the design practitioner.

Ian Lewin, FIES,
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The authors conclude that the subjects of this study responded to something like the brightness of the reflected image of the luminaire on the VDT, and found that the lighter that brightness the less acceptable the luminaire was for a VDT application. It would be tempting to conclude that providing dimming controls to the end users would greatly improve the acceptability of a given lighting installation and furniture arrangement. Could the authors please comment?

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Appendix 1—Luminaire data.

Lighting for VDT Offices Experiment
Appendix 1
26 March 2000

Note: All units for luminance in cd/m^2; for luminous intensity in cd

Type	Luminaire description	Avg. Lamp Luminance (cd/m2) In situ	Avg. Lamp Luminance (cd/m2) In lab**	Exper. Lamp Lumens ****	Photometric test*** Lamp Lumens	Applic. Factor AF (*)	Photometric Report*** Avg. Luminaire Luminance 55 deg.	Photometric Report*** Avg. Luminaire Luminance 65 deg.	Lumin. Intensity 55 deg	Lumin. Intensity 65 deg	Per lamp Lumin. Intensity 55 deg	Per lamp Lumin. Intensity 65 deg
A	2x4 parabolic, 3-lamp 27 cell,4"deep,spec.louver RP-1-1993 compliant Shielding angle =37.5deg PhotometricTest# LTL6872	9385	10333	8533	8550	0.906	560	27	198	7	66	2
B	7"x4' parabolic 1-lamp 18 cell,1.5"deep "matte" finish louver Shielding angle =29.9deg PhotometricTest#LTL04089	10200	10250	2835	2900	0.973	3861	892	382	65	382	65
C	8"x4' parabolic, 1-lamp 13 cell, 2" deep specular louver Shielding angle =29.0deg PhotometricTest# LSI9881	10250	10300	2839	2900	0.974	1579	18	186	2	186	2
D	7"x4' parabolic, 1-lamp 16 cell,2.5"deep,semi-spec. louver Shielding angle =40.4deg PhotometricTest# LSC3832	8595	10190	2831	3050	0.783	849	0	77	0	77	0
E	7"x4' parabolic 1-lamp 18cell,1.5" deep,specular louver Shielding angle =29.9deg PhotometricTest#LTL04090	10400	10300	2851	2900	0.993	3406	411	337	30	337	30
F	6"x4' parabolic, 1-lamp 18cell, 2.2"deep, Alcoa Reflectormatte 501louver Shielding angle =40.1deg Photo.Test# MRL173P157	8695	10200	2802	2800	0.853	1203	102	96	6	96	6
G	6"x4' Cell II" parabolic,1-lamp 18cell,2.2" deep,specular louver Shielding angle =40.1deg Photo. Test# MRL173P164	8655	10350	2835	2800	0.847	841	34	67	2	67	2
H	7"x4' parabolic, 1-lamp 16cell,2.5"deep,specular louver Shielding angle =40.4deg PhotometricTest# LSC5443	8755	10350	2843	3050	0.788	780	0	73	0	73	0
J	2'x4' 3-lamp parabolic 24cell,3"deep,semi-spec. louver Shielding angle =27.1deg PhotometricTest# LTL 5246	9227	10217	8469	8700	0.879	2566	748	908	195	303	65
K	2'x4' 3-lamp parabolic 24cell,3"deep,specular louver Shielding angle =27.1deg PhotometricTest# LTL 5245	9362	10228	8513	8700	0.896	2663	564	973	147	324	49

* *Applic.Factor=(In situ lamp luminance/lab lamp luminance)x(lab lamp lumens/rated lamp lumens in luminaire photometric test)*
** *Luminance measured in lab, with lamp operated on reference ballast (BF = 1.0)*
*** *Data taken from photometric test for luminaire*
**** *Total lamp lumens per luminaire, based on lumen output measured in lab on reference ballast for individual lamps*

Photometric Report Avg. Luminaire Luminance 55 deg.	65 deg.	Values Adjusted Lumin. Intensity 55 deg	65 deg	for AF Per lamp Lumin. Intensity 55 deg	65 deg	In situ Luminances (cd/m2) Min. on Louver 55 deg	Max. on Louver 55 deg	Avg. on Ceil.tile 55 deg	Ratios Max/min 55 deg	Max/ceil. 55 deg
508	24	179	6	60	2	48.8	2837	15.2	58.1	186.6
3756	868	372	63	372	63	1665	6617	14.6	4.0	453.2
1538	18	181	2	181	2	177	6050	16.3	34.2	371.2
665	0	60	0	60	0	26.9	2925	12.6	108.7	232.1
3381	408	335	30	335	30	360	6400	17	17.8	376.5
1026	87	82	5	82	5	560	3187	10	5.7	318.7
712	29	57	2	57	2	40.7	3704	13.7	91.0	270.4
615	0	58	0	58	0	21.7	4406	16	203.0	275.4
2256	658	798	171	266	57	1382	5770	20.6	4.2	280.1
2385	505	871	132	290	44	1279	7177	23.6	5.6	304.1

In situ Luminances (cd/m2) Min. on Louver 65 deg	Max. on Louver 65 deg	Avg. on Ceil.tile 65 deg	Ratios Max/min 65 deg	Max/ceil. 65 deg
32	32.7	13.7	1.0	2.4
409	2441	12.9	6.0	189.2
37.2	39.6	13.4	1.1	3.0

Authors' response

We are grateful to the reviewers for their careful reading of the paper and supportive comments on both the process and results. Discussers Ballman and Lewin raised the issue of lamp luminance measurements. The lamps were measured with a 1/3 degree luminance meter, from a distance of 0.5-0.7 m. All of the luminaire elements, except the length of the T8 lamp, were masked from view with a black cloth to minimize their contribution. Two measurements were taken approximately normal to each lamp, at points 0.3 m and 0.6 m from one end of the lamp, and their average was reported as the *in situ* lamp luminance. (These two lamp luminances varied less than four percent.) When the lamp was photometered, the lamp luminance was measured at three points, two outer points and one center, with less than a two percent difference among the three readings. Subsequent to receiving these discussions, the same lamps were tested on two opposite sides, and we again found the variation to be under two percent. We feel confident that the *in situ* measurements were representative of the lamps' performance.

Florence and Lewin brought up the issue of whether ballast factor, thermal factor and light loss factor should be used in deriving a maximum recommended luminous intensity value. In this paper, thermal factors were not applied separately; they would only have been inherent in the application factor that related *in situ* light output to photometric test report output. The actual ballast and thermal factors were backed out photometrically for each luminaire, and then a consistent BF of 0.88 and LLF of 0.85 were applied to derive the recommended intensity limit. We can back out the LLF of 0.85 to achieve an "Opening Day" intensity limit, and that would reduce the compliance value from 300 cd to 255 cd when the luminaire is clean and the lamps are new and perky. (We admit to a bias in favor of a "maintained" intensity limit, in an effort to avoid recommending cave-like office environments.)

Whether or not to apply a consistent ballast factor and the light loss factors is a philosophical question for the Office Lighting Committee, balancing the ease of use of this standard against a high level of precision. We have since recommended adding an equation to the proposed *RP-1* standard that shows the specifier how to adjust the compliance value if the specified lamp and ballast is more than 10 percent different in output than assumed in the derivation of the intensity limit.

In response to Lewin's question on "spot luminance," maximum luminaire luminance was measured with a luminance meter mounted on a tripod on a rolling cart, aimed at the luminaire from the 55 and 65 degree angles. The luminaire was scanned until the highest reading was captured (usually a bare lamp or where the lamp flashed on the louver). I agree it would be difficult to agree on a consistent procedure for measuring this,

Appendix 2—Collected display device data.

Display characteristics of computer screen

The following data of the three screens were collected at the LRC laboratory, or derived from collected data using the equations from the Lloyd 1996 model:[6]

	Laptop Negative	Laptop Positive	CRT Negative
	LN	**LP**	**CN**
L_{dmax}	98.65 cd/m^2	46.99 cd/m^2	76.15 cd/m^2
L_{dmin}	0.19 cd/m^2	1.54 cd/m^2	0.09 cd/m^2
L_{dmean}	60.66 cd/m^2	5.58 cd/m^2	63.8 cd/m^2
R_d	0.0040	0.0045	0.0917
Rs	0.0193	0.0310	0.0629
W_b	134 pixels	67 pixels	14 pixels

L_{dmax} (maximum luminance of the display), L_{dmin} (minimum luminance of the display), and L_{dmean} (mean luminance of the display) were all measured in a dark room with the computer screen on. Rs (specular reflectance) and W_b (blur width) were measured in a dark room with the screen off, following the instructions of the LET Commercial Lighting Toolkit.[10] R_d (diffuse reflectance) was measured in a black room with screen off with semi-direct lighting. Illuminance perpendicular to the screen was measured, as well as the luminance of the screen from the direction of the luminaire, making sure that any specular reflections from bright surfaces were minimized at the point of measurement. R_d was calculated as follows: screen luminance x π/illuminance at screen.

and fortunately maximum luminance did not turn out to be the best of the metrics tested.

Lewin asked about how luminaires were evaluated in direct view. Subjects were allowed to view the luminaire directly from a seated position, but also encouraged to walk around the space around the luminaire. We agree that a single luminaire is not a fair way to evaluate an entire lighting system, but the point of the question was to determine whether a luminaire good for screen viewing was by definition good for office lighting. The responses showed clearly that there were other criteria for judging the luminaire beyond its ability to reduce VDT screen reflections.

We agree with the discussers that this luminous intensity concept should be tested with lensed luminaires, round downlights, direct/indirect luminaires, etc., and with naïve subjects.

Hakkarainen's comment, dimming could indeed reduce the "brightness" of a luminaire to a level that would not be offensive. However, what we may want is differential dimming of the luminaire, since the luminaire that is interfering with screen visibility for one employee may be providing needed working light for another.

Lewin points out that positioning of the VDU is the best way to control VDU images. This is most often true, but, unfortunately, the positioning of the screen is seldom predictable in office spaces. There is too much change, too many individual ergonomic needs, and too many types of screens and workstations. We would suggest a change in the order of recommendations to the practitioner: First, buy a good screen and negative contrast software. Second, try to know the luminaire/screen/eye geometry in order to minimize reflected glare. Third, use a lighting system that limits the luminaire intensity at the angles at which the screens are likely to be viewed.