A PRELIMINARY MODEL OF LIGHTING - DISPLAY INTERACTION

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ABSTRACT

Electronic displays are by now pervasive in the commercial office environment and are often the subject of complaints relating to glare, poor visibility, and bad lighting. The effects on visibility of the relevant lighting and display system parameters are complex and often poorly understood. Too often inappropriate combinations of display and lighting system are installed resulting in unnecessarily poor display visibility or over-constrained lighting system designs.

The procedures described in this paper provide a method for predicting observer responses given easily-measured parameters of the lighting and display system. Measurements of three lighting parameters are required: illuminance at the display, luminance of a source of specular reflection, and luminance of the background of this source. Four measurements of the display are required: minimum and maximum luminance, and specular and diffuse reflectance. All of the required measurements can be made using a standard luminance meter, illuminance meter, and mirror.

The proposed method of predicting observer responses was evaluated using the results of an existing human factors evaluation of glare on electronic displays. High correlations were obtained between model predictions and ratings of glare conspicuity and disturbance ($R^2 = .85$). The good fit of this preliminary model and the potential utility of the model once validated suggests that continued development should prove fruitful.

INTRODUCTION

Background

Work with electronic displays is now commonplace, and there are a number of problems associated with their use in the office environment. Three general categories of problems arise due to light reflected from displays. Previous researchers have noted that reflections can: 1) Reduce the contrast of the displayed image (CIE, 84; van Ooyen, 86; Roll, 86;

Boyce, 87; and Rea, 91); 2) compete for the attention of the user, causing distraction (CIE, 84; Boyce, 87; van Ooyen, 87; and Rea, 91); and 3) cause undesirable changes in accommodation because the displayed and the reflected images are at different focal distances (CIE, 84; Boyce, 87; Kohn, 88; and Rea, 91). All three of these problems point to the need to reduce the visibility of reflected images.

A review of the literature indicates that numerous readily-measurable attributes of lighting and display impact observer responses. Perhaps the most commonly-cited variable is the maximum luminance of a source that can be seen in specular reflection by an observer seated at a display. Additional variables shown to impact lighting - display compatibility include minimum and maximum display luminance or alternatively, display modulation (contrast) and mean luminance. For alphanumeric displays the polarity of the display has also been shown to be a strong determinant of observer responses (Isensee and Bennett, 1983; Van Ooyen, 1986; Boyce, 1987; CIE, 1987; Bernecker et. al., 1994; IESNA, 1989).

Other variables shown to influence visibility include the illumination incident on the display and the degree of specularity of the display surface. Increasing illumination on the display leads to higher veiling luminance which reduces the modulation of the displayed image. Highly specular display surfaces lead to sharp reflected images of glare sources which can mask the displayed information more effectively.

In summarizing the existing literature on lighting - display interaction two general conclusions can be drawn: 1) The lighting and display parameters which have the strongest impact on lighting - display compatibility have been identified; and 2) A consistent picture of the direction of the influence of each of these variables has emerged. These variables and their directions of influence are:

Luminance of sources of specular reflections:	Lower is better
Modulation (contrast) of sources of specular reflections:	Lower is better
Illumination on display:	Lower is better
Luminance of display:	Higher is better
Modulation (contrast) of display:	Higher is better
Display polarity:	Light background is better
Specularity of display:	Lower is better
Diffuse reflectance of display:	Lower is better
Modulation (contrast) of the reflected image:	Lower is better

While much has been accomplished to clarify our understanding of the relationship between lighting and display, we are still without a means for making *quantitative* predictions of lighting - display system performance. The present evaluation can be distinguished from previous research efforts in that we attempt to provide a quantitative model of this interaction. If successful, this model can be used to indicate the ***magnitude*** of influence of each of the variables listed above in addition to the direction of influence. Most importantly, a valid model of this interaction could be used to make precise predictions regarding the appropriateness of a wide range of combinations of lighting and display systems.

General Approach

With the goal of complexity reduction the problem of quantifying lighting - display interaction has been partitioned into two distinct but related problems:

1) Identification of a minimum set of variables, attributes, or features of the stimulus which explain a great proportion of the variance (e.g., > 80%) in observer responses. This small set of variables can be thought of as the most "perceptually relevant" variables. That portion of the proposed model which relates the perceptually relevant variables to observer responses will be called the "observer response" model (see Results section below).

2) Identification and development of the means for measuring these perceptually relevant variables. If it is found that the perceptually relevant variables are difficult to measure directly, then a means for calculating the levels of these variables from the results of less complex measurements must be identified and developed. That portion of the proposed model which relates measurements of lighting and display to the perceptually relevant variables will be called the "lighting-display" model (see Appendices 1, 2, and 3).

Selection of Perceptually-Relevant Variables

Examination of the list of relevant parameters provided above reveals strong dependencies among most of these parameters. For example, it is well known that modulation of the displayed image is strongly dependent on display luminance and modulation, illumination incident on the display, specular and diffuse reflectance of the display, as well as the luminance of sources seen in specular reflection. With these dependencies in mind three variables were selected which are estimated to be the variables of most relevance to the observer and which are independent of one another. These variables selected are:

M_s Modulation of the reflected image of glare source
M_{da} Modulation of displayed image in ambient lighting environment
W_b Width of blur function (degree to which display blurs reflected images)

Each of these variables is defined by the method of calculation or measurement described in Appendices 1-3.

Calculation of Modulation

For this modeling effort it was decided that modulation would be calculated rather than directly measured due to the expense and training required for the direct measurement approach. For example, with text images the sizes of the critical features making up individual characters (e.g., stroke width) is on the order of .02 to .05 degrees. Direct measurement of the modulation of the displayed image (as well as images reflected from the display) would require a meter which can measure features at least an order of magnitude smaller than the one degree spot size of the common hand-held luminance meter.

In order to calculate M_{da} and M_s three measurements of the lighting environment are required:

L_{smax} Luminance of source of specular glare (cd/m^2)
L_{smin} Luminance of background of source of specular glare (cd/m^2)
E_d Illumination incident on display surface (lx)

Additionally, four measurements of the display system are required:

L_{dmax} Maximum luminance of display as measured in zero ambient (cd/m^2)
L_{dmin} Minimum luminance of the display as measured in zero ambient (cd/m^2)
R_d Diffuse reflectance of display
R_s Specular reflectance of display

The formula relating each of these attributes of lighting and display to the perceptually relevant variables are provided in Appendix 2.

Constraints on Applicability

In this paper we are assuming the use of displays for which the amount of light reflected from the display is independent of the image content of the display. An alternative way of stating this assumption is to state that the display system forms an image using only emitted (or transmitted) light (not reflected light). It is suspected that the great majority of displays in the installed base in the commercial office environment (e.g., high information content CRTs and LCDs) meet these assumptions.

HUMAN FACTORS EVALUATION

Observers

Twenty one persons (13 male and 8 female) volunteered for participation in this evaluation. Observers were recruited from among the students and staff of the Lighting Research Center at Rensselaer Polytechnic Institute. The observers ranged from 22 to 41 years of age. Ten of the observers wore glasses.

Observer Responses

Four response variables were recorded from each observer for each of the evaluation conditions employed: Detection Proportion, Conspicuity Rating, Disturbance Rating, and Preference Proportion. However, due to the restricted length of this paper, only those results pertaining to the Conspicuity and Disturbance ratings are presented. The reader is referred to Lloyd, Mizukami, and Boyce (1995) for a full technical report.

Observers rated the Conspicuity and Disturbance of reflections of the specular glare source using seven-point rating scales ranging from 0 to 6. Three verbal anchors were printed on the response sheet with "not at all" printed below the number 0, "moderately" printed below the number 3, and "very" printed below the number 6. A preliminary analysis of the response data revealed no meaningful difference between the Conspicuity and Disturbance ratings ($R^2 = .98$). Thus, these two variables were combined (mean) to form a new variable called "Conspicuity or Disturbance Rating".

Procedure

Figure 1 shows the overall layout of the room in which the evaluation took place. Volunteers participated in the evaluation one at a time. Upon arrival at the room where the evaluation took place the evaluator briefly described the evaluation procedure and pointed out the equipment that would be used. After viewing each condition for 30 to 40 seconds, observers made ratings of conspicuity and disturbance. Each observer was presented the evaluation conditions in a different random order. Ratings were obtained for all combinations of the following three variables for a total of 24 total evaluation conditions:

Display (6 levels)
Display polarity (2 levels)
Luminance of specular glare source (2 levels)

Lighting Conditions

A uniform source of specular glare was produced by placing an integrating sphere (23 cm. diameter) on a tripod behind the observer seated at each display. The sphere contained a 40 watt incandescent lamp (R-14) and the luminance of this lamp was controlled using a standard electronic dimmer. The sphere had an exit port of 5.5 cm which had a uniform luminance distribution. The position of the source with respect to the display and observer can be seen in Figure 1. The (center of the) image of the specular glare source appeared approximately 10 cm. from the center of the display active area. This positioned the image just to the right of the reflected image of the observer making the entire image of the specular glare source visible. The mean luminance on the displays was 120 lx. which was provided primarily by overhead fluorescent luminaires fitted with parabolic louvers.

Display Characteristics
Six different displays with widely varying characteristics were used in the evaluation. The displays carried brand names of Apple, CTX, NEC, Seiko, and Zenith (in alphabetical order). The ordering of this list does not correspond with the display IDs used in this paper. Note that each of these manufacturers sells displays with widely varying luminance and reflectance characteristics and that no endorsement of any particular manufacturer or display technology is implied. The most relevant parameters describing each display are provided in Table 1. On each display the words "Lighting Research Center" were presented. This word string was repeated over and over so as to fill the entire screen.

Calculation of Perceptually Relevant Variables
In this evaluation it was expected that the observer response data can be predicted using some combination of the variables M_s, M_{da}, and W_b. In order to make these predictions the levels of these variables were calculated using the equations presented in Appendix 2. The levels of the lighting and display parameters required for making these calculations were those levels found in Table 1. Table 2 lists the results of these calculations for each of the 24 evaluation conditions for which observer responses were measured.

RESULTS

The ratings of Conspicuity or Distraction (means across 21 observers) obtained for each of the 24 evaluation conditions are provided in Column 9 of Table 2.

In all of the regression analyses that follow only three independent variables were used: M_{da}, M_s, and W_b. In preliminary analyses it was noticed that the relationship between the dependent variables and these three independent variables was generally non-linear. In the analyses that follow several non-linear transforms of these variables (inverse, square, and square-root) were considered. Thus many combinations of the un-transformed variables, the three nonlinear transforms of each variable, and many cross-products among these variables were included as potential regressors.

Stepwise regression analyses were conducted using this pool of potential regressors using the SPSS software package running on a Macintosh Quadra 630 computer. The stepwise procedure was used to identify a number of candidate models which were then examined in more detail. Three basic criterion were used to select the "best" model from among the candidate models identified using the stepwise procedure:

- Maximize the goodness of fit criterion R^2
- Minimize the number of parameters
- Eliminate models with unreasonable performance in extrapolated regions

The third criterion was used to eliminate some models for which predictions did not increase monotonically with increasing M_{da} or decreasing M_s. Transformations of the dependent variables were not employed in the analyses reported here.

For the dependent variable Conspicuity or Disturbance ratings the SPSS stepwise procedure produced 12 candidate models with adjusted R^2 values ranging from .81 to .91. These models included from 3 to 5 parameters. The response surface for each of these 12 models was plotted and examined to determine the behavior of each model, especially for the extreme regions covered by each model.

The model considered to be best by the three criteria listed above contained four terms. The goodness of fit criterion for the selected model was $R^2 = .849$ (adjusted $R^2 = .817$). An analysis of the residuals produced for this model indicated normality of variance and no statistically significant outliers ($Z_{max} < 3$). The general behavior of this model can be seen by examining Figure 2. In this figure predicted Conspicuity or Disturbance ratings are shown as a function of M_s and M_{da} with the variable W_b fixed at three different levels (110, 150, and 190). From this figure it can be seen that ratings improve (decrease) as M_s decreases, M_{da} increases, and W_b increases. Additionally, this plot shows that changes in M_s affect ratings more strongly than do changes in M_{da}. Finally it can be seen that modulation of the reflected image has a much larger impact (steeper slope) on ratings when the width of the blur function is narrow (sharp) than when it is broad (blurry).

SUMMARY

A great proportion of the variance in the observer response data collected here can be explained using the three proposed most "perceptually relevant" variables M_{da}, M_s, and W_b. The mathematical relationships between these variables and easily-measured lighting and display parameters are provided.

Caveats and Recommended Improvements

The modeling results presented above suggests that accurate predictions of lighting-display interaction can be made given relatively few and simple measurements of lighting and display. It is necessary to point out, however, several important reasons why the model reported here should be treated as preliminary:

1) In this evaluation three free parameters have been fit to the data, thus, these data do not provide a powerful test of the validity of the model. It is strongly recommended that the model be tested by attempting prediction (with no free parameters) of an *independent* set of data in which the perceptually relevant variables are varied over a similar range of values.

2) The variables *display resolution*, *line spacing*, and *character size* may have co-varied with the variable *display*. These variables were not measured or held constant across displays. It is recommended that in future work these potential confounds be held constant or explicitly accounted for in the model.

3) The measurement procedures used at the time the observer responses were collected were not well developed and some of the measurements required for the predictive model (e.g., L_{dmin}, L_{dmax}, and R_d) were made some time after the observer response data were collected. Thus the predictive models presented here probably reflect some additional variance that can be avoided with more tightly controlled measurements.

4) The source of specular glare used in this evaluation was designed to be easy to construct and characterize. It is recommended that future evaluations incorporate sources of specular reflection which contain multiple light sources covering more of the offending zone of the display.

Uses for a Validated Lighting - Display Model

Assuming that observer responses can be accurately predicted, it seems possible to develop a computational tool that can be used by lighting and display systems designers to optimize lighting-display systems. Such a tool could be used to evaluate:

Problems which may occur in a proposed installation
Effects of changes to an existing installation
"Optimal" trade-offs among the seven relevant lighting and display parameters

In addition to the assessment of specific lighting-display combinations, a validated model of lighting-display interaction could be used as the basis of quality criteria. Given the lighting-display interaction model and data describing "typical" lighting systems, a display susceptibility index could be generated which correlates strongly with the incidence of visibility problems occurring in those typical lighting environments. On the other hand, the lighting-display interaction model used in conjunction with data describing the typical *display* system could be used as the basis of a glare production index (describing lighting systems) which correlates strongly with the incidence of visibility problems occurring with those typical displays. However, the development of these indices is considered premature until the proposed model has been independently validated and sufficient data describing typical lighting and display systems have been collected.

Given the success in fitting this initial model and the potential utility of the model once validated, two additional evaluations are currently being conducted at the LRC to continue this work.

REFERENCES

Bernecker, C. A., Sanders, P. A., and Mistrick, R. G. (1994) Reflected luminance patterns in visual display units. Proceedings of the IESNA Annual Conference, Miami, FL. pp. 481-499.

Boyce, P. R. (1987) Lighting the display or displaying the lighting. *Work with display units 86,* B. Knave and P. G. Wideback, editors, Elsevier Science Publishers, New York. pp. 340-349.

Commission Interationale de L'Eclairage (1984) Vision and the visual display unit work station, CIE No. 60. Paris: Bureau Central de la CIE.

Illuminating Engineering Society of North America (1989) *Lighting offices containing computer visual display terminals (VDTs),* RP-24-89, New York, IESNA.

Isensee, S. H. and Bennett, C. A. (1983) The perception of flicker and glare on computer CRT displays. *Human Factors, 25(2),* pp. 177-184.

Kohn, M. (1988) Lighting offices containing VDTs. *Lighting Design and Application, December.* pp. 9-11.

Lloyd, C. J. C., Mizumaki, M., and Boyce, P. R. (1995) A preliminary model of lighting - display interaction. Technical Report 3-95, Lighting Research Center, Troy, NY.

van Ooyen, M. H. F, and Begemann, S. H. A. (1986) Lighting the electronic office. *Work with display units 86,* B. Knave and P. G. Wideback, editors, Elsevier Science Publishers, New York. pp. 350-356.

Rea, M. S. (1991) Solving the problem of VDT reflections. *Progressive Architecture,* Oct. pp. 35-40.

Roll, K. F. (1986) Recent results on the Illumination of VDU and CAD workstations. *Work with display units 86,* B. Knave and P. G. Wideback, editors, Elsevier Science Publishers, New York. pp. 368-375.

Society of Automotive Engineers (1989) *Aerospace Recommended Practice: Photometric and Colorimetric Measurement Procedures for Airborne Direct View CRT Displays (ARP 1782),* Society of Automotive Engineers, Warrendale, PA.

US Air Force (1993) *US Air Force Guide Specification: Displays, Airborne, Electronically/Optically Generated (AFGS-87213B),* US Air Force, Wright-Patterson Air Force Base, OH.

TABLES

Table 1. Relevant physical parameters of each of the six displays used in the evaluation. The parameters L_{dmax}, L_{dmin}, R_s, and R_d are defined in Appendix 1.

ID	Tech	Shape	L_{dmax}	L_{dmin}	R_s	R_d	W_b
1	CRT	Cylinder	111.0	0.7	.0063	.17	110
2	CRT	Sphere	115.0	0.3	.030	.021	140
3	CRT	Sphere	125.0	91.0	.0145	.0051	90
4	LCD	Flat	5.8	3.6	.0048	.0087	174
5	LCD	Flat	45.0	5.6	.0032	.0132	210
6	LCD	Flat	45.0	14.0	.031	.0130*	118

*The diffuse reflectance for display 6 could not be measured because the display was unavailable after the evaluation. This value has been estimated using the mean of the other five displays.

Table 2. Independent and observer response variables for each combination of display, polarity, and luminance level of the specular source.

Disp ID	Pol	Spec lum	M_{da}	M_s	W_b	Disturb Rating	Conspic Rating	Dist or Cnsp Rating
1	+	850	.8815	.1683	110	1.762	2.619	2.191
1	+	200	.9434	.0456	110	.333	.762	.5475
1	-	850	.8815	.0255	110	.190	.524	.3570
1	-	200	.9434	.0061	110	0	0	0
2	+	850	.6773	.4774	140	2.81	3.333	3.072
2	+	200	.8781	.1790	140	.952	1.429	1.191
2	-	850	.6773	.1062	140	.524	.857	.6905
2	-	200	.8781	.0273	140	0	.048	.0240
3	+	850	.1411	.0606	90	4.524	4.905	4.715
3	+	200	.1531	.0150	90	2.619	3.095	2.857
3	-	850	.1411	.0477	90	3.667	3.762	3.715
3	-	200	.1531	.0117	90	1.286	1.429	1.358
4	+	850	.1152	.2916	174	2.381	2.810	2.596
4	+	200	.1685	.0888	174	.619	.810	.7145
4	-	850	.1152	.2310	174	1.857	2.190	2.024
4	-	200	.1685	.0663	174	.238	.524	.3810
5	+	850	.6493	.1029	210	1.095	1.381	1.238
5	+	200	.6976	.0263	210	.238	.286	.2620
5	-	850	.6493	.0304	210	.190	.571	.3805
5	-	200	.6976	.0073	210	0	0	0
6	+	850	.2637	.3992	118	4.429	4.619	4.524
6	+	200	.4043	.1364	118	2.524	2.952	2.738
6	-	850	.2637	.2284	118	3.381	3.857	3.619
6	-	200	.4043	.0654	118	1.381	1.952	1.666

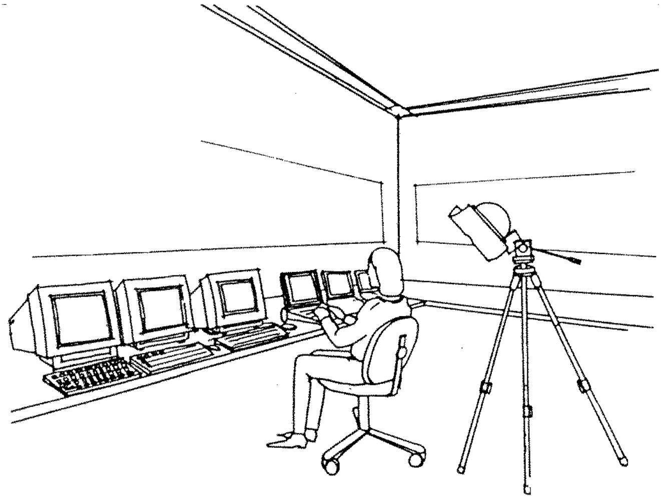
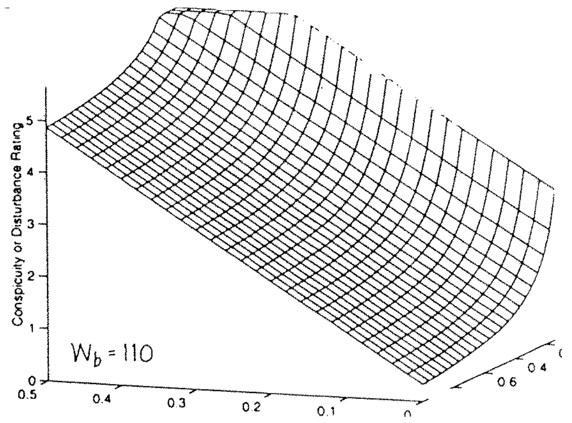
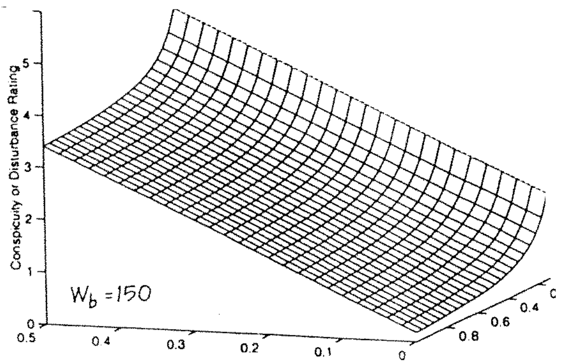


Figure 1. Sketch of room where observers evaluated lighting-display conditions.





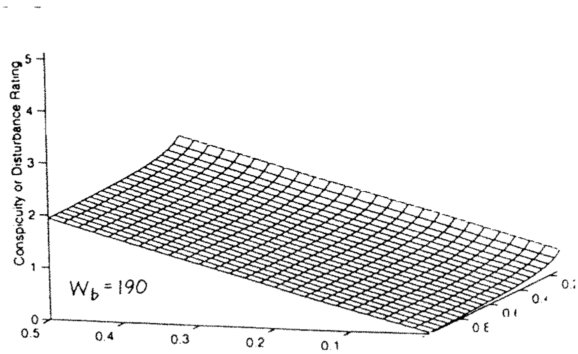


Figure 2. Three views of fitted model ($R^2 = .85$) predicting Conspicuity or Disturbance rating as a function of reflected image and display modulation (M_s and M_{da}) for three levels of blur width (W_b = 110, 150, and 190).

APPENDIX 1 - Definition of Terms and Symbols

In this paper the term "modulation" is used rather than "contrast" due to the pervasive usage of the term in the visual science and linear systems analysis literature. All luminance values are given in cd/m^2 and illumination levels are given in lx.

Lighting parameters

L_{smax}	Luminance of source of specular glare
L_{smin}	Luminance of background of source of specular glare
E_d	Illumination incident on display surface

Display parameters

L_{dmax}	Maximum luminance of display as measured in zero ambient
L_{dmin}	Minimum luminance of the display as measured in zero ambient
R_d	Diffuse reflectance of display (See Appendix 3 for measurement procedure)
R_s	Specular reflectance of display (See Appendix 3 for measurement procedure)
P_{max}	Proportion of the display active area at L_{dmax}
L_d	Space-averaged luminance of the display

Intermediate variables

L_v	Veiling luminance on display due to diffusely-reflected ambient illumination
L_{rsmax}	Luminance of reflection of source of specular glare
L_{rsmin}	Luminance of reflection of background of source of specular glare
L_{vs}	Total luminance reflected from the display (veiling + specular)
L_{vd}	Luminance of display plus veiling luminance

Perceptually relevant variables

M_{da}	Modulation of displayed image in ambient lighting environment
M_s	Modulation of image of glare source
W_b	Width (half-maximum) of the reflected image of a standard glare source

General formulas and conversions

$M = (L_{max} - L_{min}) / (L_{max} + L_{min})$ (range: 0 to 1)
$CR = L_{max} / L_{min}$ (range: 1 to infinity)
$M = (CR - 1) / (CR + 1)$
$CR = (1 + M) / (1 - M)$

APPENDIX 2 - Derivation of Lighting-Display Model

Modulation of displayed image

For self-luminous display systems the maximum luminance modulation that can be produced is given by the equation:

$$M_{dz} = (L_{dmax} - L_{dmin}) / (L_{dmax} + L_{dmin}) \quad \text{(A 2-1)}$$

where L_{dmin} and L_{dmax} represent the minimum and maximum luminance levels that can be produced simultaneously by the display. It is assumed that these luminance levels are measured in a dark room (ambient = zero).

Impact of ambient light on displayed image

The proposed method of characterizing the reflectance properties of an electronic display have been adapted from current procedures for specifying specular and diffuse reflectance of displays in the avionics and automotive industries. These two parameters are operationally defined by their methods of measurement which are described in detail in Appendix 3.

When a display is operated in an environment with illumination (E_d) incident on the display surface, a "veiling" luminance (L_v) is generally superimposed on the display which reduces the modulation of the displayed image. The level of this veiling luminance depends on the diffuse reflectance (R_s) of the display as follows:

$$L_v = (E_d * R_d) / \pi \qquad \text{(A 2-2)}$$

The luminance of the image of a source of specular glare (L_{rsmax}) can be calculated using the specular reflectance of the display (R_s) and the maximum luminance of the specular glare source (L_{smax}) as follows:

$$L_{rsmax} = R_s * L_{smax} \qquad \text{(A 2-3)}$$

The total light reflected from the display (L_{vs}) can be found by summing the contributions of the veiling luminance and the specular reflection as follows:

$$L_{vs} = L_v + L_{rsmax} = (E_d * R_d) / \pi + R_s * L_{smax} \qquad \text{(A 2-4)}$$

The superimposition of the total luminance due to the ambient lighting environment is calculated by adding the total reflected luminance calculated in Equation A 2-4 to the minimum and maximum luminance emitted by the display. The modulation of the displayed image in presence of ambient light is calculated by modifying Equation A 2-1 as follows:

$$M_{da} = ([L_{dmax} + L_{vs}] - [L_{dmin} + L_{vs}]) / ([L_{dmax} + L_{vs}] + [L_{dmin} + L_{vs}]) \qquad \text{(A 2-5)}$$

By combining terms in Equation A 2-5 we get:

$$M_{da} = (L_{dmax} - L_{dmin}) / (Ldmax + L_{dmin} + 2 * L_{vs}) \qquad \text{(A 2-6)}$$

Modulation of reflected image of glare source

Calculation of the modulation of the reflected image begins with calculation of the mean luminance of the display in the ambient lighting environment. The mean luminance of the display is the sum of two components: The space-averaged luminance of the light emitted from the display, and the veiling luminance caused by diffusely-reflected ambient illumination. The formula for the veiling luminance was provided in Equation A 2-2.

The space-averaged luminance of the (text) display is calculated given three parameters as follows:

$$L_d = P_{max} * L_{dmax} + (1 - P_{max}) * L_{dmin} \qquad \text{(A 2-7)}$$

where L_{dmin} and L_{dmax} are the minimum and maximum luminance levels of the display (as measured with zero ambient) and P_{max} is the proportion of the display active area which is at the maximum luminance level.

The mean luminance of the display in the ambient lighting environment is calculated as:

$$L_{vd} = L_v + L_d = R_d * E_d + P_{max} * L_{dmax} + (1 - P_{max}) * L_{dmin} \quad \text{(A 2-8)}$$

The effect of L_{vd} on the modulation of the reflected image is calculated by adding L_{vd} to both the minimum and maximum reflected image levels as follows:

$$Ms = ([L_{rsmax} + L_{vd}] - [L_{rsmin} + L_{vd}]) / ([L_{rsmax} + L_{vd}] + [L_{rsmin} + L_{vd}]) \quad \text{(A 2-9)}$$

By combining terms in Equation A 2-9 we get:

$$M_s = (L_{rsmax} - L_{rsmin}) / (L_{rsmax} + L_{rsmin} + 2 * L_{vd}) \quad \text{(A 2-10)}$$

APPENDIX 3 - Display Measurements

The specular and diffuse reflectance measurement procedures described here have been adopted from the procedures used for the characterization of cockpit displays (US Air Force, 1993; Society of Automotive Engineers, 1989).

Diffuse Reflectance

The test setup for making measurements of diffuse reflectance are diagrammed in Figure A 3-1. The displays were turned off while making these measurements. The displays were illuminated using ceiling mounted (fluorescent) fixtures installed in the room where observer responses were made. The illumination level at the display was measured using an illuminance meter (Minolta digital illuminance meter, T-1) with cosine response profile positioned normal to the display surface at the position of measurement. The luminance of this position on the display was then measured using a luminance meter (Minolta LS-100) with a one degree spot size. The diffuse reflectance was calculated for each display using the formula:

$$R_d = \pi * L_v / E_d \quad \text{(A 3-1)}$$

where R_d is the diffuse reflectance, L_v is the luminance of the display, pi = 3.1416, and E_d is the illuminance incident on the display. The diffuse reflectance values obtained for each display are presented in Column 7 of Table 1.

Specular reflectance and Blur width

The test setup used for making measurements of specular reflectance and blur width are diagrammed in Figure A 3-2. These measurements were made in a dark room with the display turned off. The light source consisted of a heavy diffuser illuminated from behind using a 12 v, 50 w (MR-16) lamp. The source appeared as a circle of uniform luminance that subtended 3.4 degrees from the point of view of the display. The imaging photometer was aimed at the center of the reflected image and was focused on the image of the source (rather than at the display surface).

Luminance of the source was measured by placing a plane mirror normal to the display surface at the position of measurement. The mirror used had a specular reflectance of .90

and the measured luminance of the source was 6240 cd/m^2. Correcting for the reflectance of the test mirror, the luminance of the source was 6240 / .90 = 6930 cd/m^2.

Luminance profiles of the reflected images of the glare source were measured for each display using a CapCalc imaging photometer. Calculation of the specular reflectance for each display was made by dividing the mean luminance of the central one degree of the reflection luminance profile for each display by the luminance of the source. These reflectance values are provided in Column 6 of Table 1.

Calculation of the blur width for each display was made by finding the positions where the luminance was 50% of the maximum luminance of the profile. Blur width is defined as the difference in these half-max positions. The blur widths for each display are provided in Column 8 of Table 1. These blur widths are expressed in arbitrary units (e.g., number of imaging photometer pixels) but can be converted to degrees (approximately) by dividing by the factor 30 pixels/deg.

On the use of a hand-held luminance meter

While an imaging photometer was used for specular reflectance measurements only the mean luminance for the central one degree of the image was used in the calculation. Thus, the equivalent measurement can be made using a hand-held luminance meter with a one degree spot size.

Similarly, the calculation of blur width can be made by scanning a one degree luminance meter across the reflected image of the specular source and noting the positions at which the luminance is at half maximum. Implementation of this procedure could involve mounting the photometer on a tripod and measuring the maximum luminance of the reflected image. The evaluator could then slowly scan the meter to the left until the measurement read one half of the maximum. The position of the left half-max point could be measured by locking the photometer/tripod at the half-max position and then looking through the photometer and placing a piece of tape on the display surface at the center of the photometer's spot. The position of the right half-max point would be measured by scanning right and marking the half-maximum position in the same way. The blur width for the display is found by measuring the distance between the (centers of) the two pieces of tape. If the distance from the display to the center of rotation of the tripod is known, the blur width can be expressed in degrees using the formula:

$$W_b = 2 * \arctan[W / (2 * d)] \qquad \text{(A 3-2)}$$

where W_b is the blur width (in degrees), W is the blur width and d is the display-to-photometer center of rotation distance.

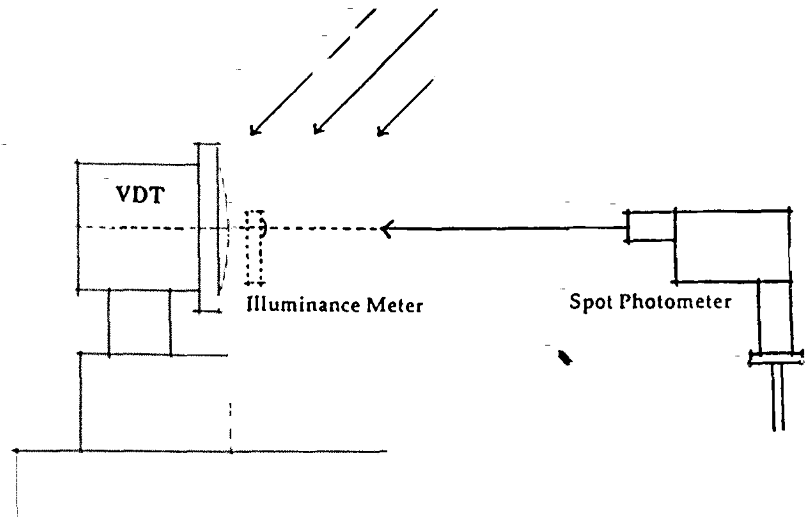


Figure A 3-1. Test setup for making measurements of diffuse reflectance.

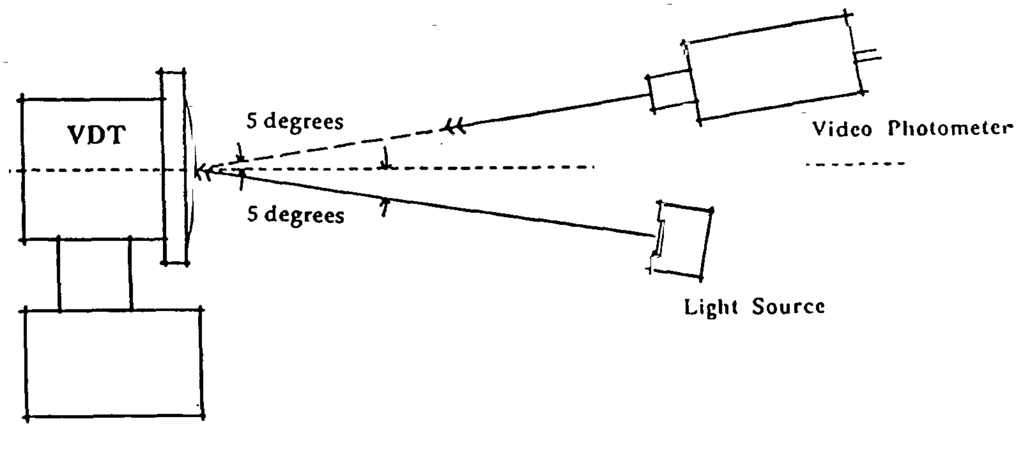


Figure A 3-2. Test setup for making measurements of specular reflectance and blur width. Angle of light source is 3.4 deg from the point of view of the display surface.