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Interlaboratory Comparison of Contrast Measurement

by M.S. Rea, M.J. Ouellette and I. Pasini

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Interlaboratory Comparison of Contrast Measurement

M.S. Rea (1), M.J. Ouellette (1), I. Pasini (2)

Introduction

Luminance contrast is one of the fundamental variables of vision. Although repeatedly a subject for discussion, there have been no systematic studies to determine whether contrast can be measured accurately by either laboratories involved in lighting research or practitioners in the field. This report focuses on the measurement of contrast* under controlled conditions in the laboratory and in simulated, realistic environments. Three tasks were performed by each of four laboratories: the National Research Council Canada, Institute for Research in Construction, Ottawa, Canada; the National Bureau of Standards, Center for Building Technology, Gaithersburg, MD, USA; the Building Research Establishment, Watford, England; the Electricity Council Research Centre, Capenhurst, England.** Problems in contrast measurement under laboratory and simulated field conditions are identified and recommendations proposed.

Task 1 examines the influence of stray light from surrounding luminous areas under controlled laboratory conditions. Task 2 is an investigation of consistency in making photometric measurements under more realistic conditions. Finally, Task 3 examines whether inexperienced people could make consistent photometric measurements with a luminance photometer and brightness matches in a side-by-side comparison technique of printed materials in realistic environments.

Statistical tests were performed on the data obtained for each task. The actual data are less important than the conclusions drawn from these tests, but summary data tables of each task are presented for the benefit of those interested in the numerical values.

Since this report deals mainly with the results of several statistical tests, it is necessary to describe the context within which the statistically significant results were obtained. Under laboratory conditions it is possible to detect small effects that might not be noticed in less controlled, more realistic settings. Consequently, the importance of the statistical findings must be understood in the context within which the data were obtained. An attempt will be made to describe the importance of each finding as well as its statistical significance.

Task 1

Description

The purpose of Task 1 was to assess the influence of stray light from surrounding luminous regions, and to

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****Although there are several alternative forms of contrast the computation of the contrast of printed materials always involves a ratio of luminances at a luminous border. In this report contrast is defined simply as the ratio of the luminance of the darker zone to that of of the lighter zone, except where noted. By this definition, contrasts range from unity for very faint luminous border to approximately zero for such prominent borders as black ink on white paper.***

*****Each Laboratory will be referred to by numbers 1-4; these numbers do not correspond to the order given in this sentence.***

Table 1—Description of laboratory photometers and hemispheres.

Laboratory number	Photometer	Measuring field, deg	Hemisphere	Light source
1	Hagner Model S2	1	Non standard box, 0.16m × 0.23m × 0.76m	"white" fluorescent
2	Spectra-Pritchard Model 1980A	⅓	Opaque cover, 0.61 m dia*	"Tri-phosphor" fluorescent
3	Spectrascan Spot Spectoradiometer Model PR-710	½	Opaque cover, 0.29m dia	Cool-white fluorescent
4	Spectra-Pritchard Model 1980A	⅓	Translucent cover 0.52 m dia.	Warm-white fluorescent

**Laboratory 2 used a 0.3 m dia hemisphere for Task 2.*

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Table 2—Photometric samples.

Sample	Nominal description	Darker Card		Lighter Card	
		Munsell notation[2]	Luminous reflect.*	Munsell notation[2]	Luminous reflect.*
A	Low luminance ratio	N 2.5/	4.6	N 8.5/	68.4
B	Medium luminance ratio	N 4.0/	12.0	N 6.0/	30.0
C	High luminance ratio	N 5.25/	22.1	N 5.5/	24.6

**Luminous reflectance, in percent, relative to MgO (Table 1 of reference 2,).*

determine whether the measured contrast of printed materials can be reproduced by different lighting laboratories under controlled conditions. Each laboratory was instructed to make all measurements with its best calibrated photometer under standard, hemisphere lighting conditions.[1] Each had a different photometer and hemisphere or facsimile, (**Table 1**), but all four used the same sample materials.

Three samples were prepared from juxtaposed pairs of matte, achromatic Munsell cards (**Table 2**); all six cards were 76 × 89 mm. Achromatic cards were employed to minimize the impact that different light source spectral emissions and different photometer spectral sensitivities might have on the photometric measurements. Each sample was mounted on a (210 mm × 210 mm), white, opaque plate; and, when not in use, each was individually protected in a plastic cover.

Four thin paper cover cards were placed, in turn, over the three samples during photometric measurements. The cover cards were white (R = 0.88) or black (R = 0.06) and had either large or small square holes (70 or 14 mm on a side) cut in their centers and through which the border of each sample could be viewed.* The purpose of the cover cards was to determine how stray light from areas outside the measurement region affected the photometric measurements.

The ratio of the luminance of the dark cards (L_b) to that of the light cards (L_w) was defined as the sample contrast. All four laboratories made three measurements in random order of each of the three samples with each of the four cover cards.

Results

The luminance ratio (L_b/L_w) measurements were submitted to an analysis of variance (ANOVA) to determine whether there were significant differences among the laboratories, the samples, and the cover cards, and whether there were significant interactions among these variables; summary data are given in **Table 3**. Each laboratory could accurately repeat its own measurements, but there were differences among laboratories, samples, and cover cards. Further, all possible interactions among these factors were statistically significant ($p < 0.001$). Although not conclusive, it may reasonably be inferred that the statistical results were caused by stray light that affected measurements to different degrees.

Laboratories 2 and 3 produced statistically identical results as well as the lowest luminance ratio values under all conditions. Stray light from brighter adjacent regions can increase the measured luminance of darker samples so that the measured luminance ratios (L_b/L_w) will approach unity. The two laboratories minimized the influence of stray light on the measurements.

Laboratory 1 produced relatively higher contrast values under all conditions, probably because a nonstandard lighting geometry (a box) was used. Nonstandard equipment is expected to produce such discrepancies under controlled conditions.

**Reflectance factors (R) were determined using a cool-white fluorescent light source, a Hagner model S2 photometer with 1 degree measuring field, a barium sulfate plate as a reference and employing a 0 degree incident and 45 degree measurement geometry.*

Table 3—Measured Contrast (L_b/L_w) for Task 1. Each entry represents the average of three measurements. The samples are described in Table 2.

Lab	Covercard		Sample		
	Color	Aperture	A	B	C
1	black	small	0.087	0.424	0.893
		large	0.098	0.418	0.876
	white	large	0.113	0.437	0.876
		small	0.150	0.507	0.880
2	black	small	0.078	0.399	0.855
		large	0.079	0.407	0.864
	white	large	0.084	0.411	0.873
		small	0.088	0.418	0.866
3	black	small	0.075	0.404	0.861
		large	0.072	0.406	0.843
	white	large	0.088	0.401	0.858
		small	0.089	0.424	0.874
4	black	small	0.127	0.466	0.880
		large	0.127	0.465	0.888
	white	large	0.132	0.476	0.892
		small	0.155	0.500	0.895

Table 4—Description of the paint samples.

Sample number	Glidden* code	Nominal color	Approximate Munsell Destination[2],** hue	value	chroma
1	70-9	very white	could not be matched with any chip		
2	70-11	white		"	
3	70-14	white		"	
4	70-16	dull white	10 YR	9/	2
5	79-45	light grey	N	8.5/	
6	79-47	grey	N	7.25/	
7	79-50	grey	N	5.5/	
8	79-52	dark grey	N	3.25/	
9	71-85	light pink	2.5 YR	9/	2
10	71-89	pink	7.5 R	7/	8
11	71-92	red	6.25 R	5/	12
12	73-45	light yellow	7.5 Y	9/	4
13	73-49	yellow	5 Y	8.5/	8
14	73-52	dark yellow	3.75 Y	8/	14
15	75-29	light green	7.5 GY	9/	2
16	75-33	green	7.5 GY	8/	6
17	75-36	dark green	7.5 GY	5/	8
18	77-69	light blue	5 PB	8/	2
19	77-73	blue	5 PB	6/	6
20	77-76	dark blue	5 PB	3/	6
Background		white	N	9.25/	

Glidden Paint Company Inc., 925 Euclid Ave., Cleveland, OH, USA 44115

****These values represent one of the experimenter's matches under cool-white fluorescent illumination and should only be considered as approximately correct under other illuminants.***

The highest luminance ratios were provided by Laboratory 4 for two related reasons. The photometer used was highly susceptible to internal light scatter, and in combination with a translucent hemisphere* the luminance ratios were elevated to significantly higher values. Both sources of measurement error were identified by re-measuring with another photometer and by covering the translucent hemisphere. Under these conditions Laboratory 4 produced luminance ratios almost identical to those from Laboratories 2 and 3, in which stray light was minimized by their procedures.

A Tukey test of multiple comparison was performed on the average luminance ratio measurements for each cover card to identify cards that influenced the measurements differently.[3] The white cover card with the small aperture produced significantly higher ($p < 0.05$) luminance ratios in a manner consistent with increased stray light; the white card with the large aperture elevated the luminance ratios some what less. The two black cards produced significantly lower luminance ratios. The aperture sizes, however, were not important for the luminance ratios obtained with the black cover cards.

The hemisphere was fabricated from translucent white plastic. Light inside the hemisphere caused the exterior surface to act as a very bright luminous field adjacent to the sample areas being measured.

Conclusions

The highest luminance ratios (i.e., the lowest contrasts) were associated with Laboratory 4, using the small aperture white cover card; the lowest ratios were associated with Laboratories 2 and 3 using the black cover cards. The other luminance ratios were rationally ordered between the two extremes according to the stray light hypothesis. Statistically significant interactions between the cover cards and the other experimental variables supported the conclusion that stray light is the main cause of inconsistent results.

Recommendations

1) Standard hemisphere lighting should be used when precise comparisons between contrast measurements are important. Non-standard lighting geometries (as used by Laboratory 1) may produce internally consistent results, but they may be significantly different from those produced when standard, hemisphere lighting is used. The hemisphere cover should be opaque to limit stray light in the photometer. An opaque cover provides the additional benefit of limiting ambient room illumination on the samples.

2) A photometer's susceptibility to stray light should be evaluated and documented in all publications where contrast measurements are important. As in this study, black and white cover cards of the same aperture size could be placed over a reflectance sample under hemisphere conditions. The ratio of the luminance ratios obtained with the black and white cover cards would be determined. Photometers yielding luminance ratios close to unity under these test conditions would be preferred.

3) The amount of stray light contributing to contrast measurements will depend upon the luminances of the areas surrounding the sample and the size of the sample. A standard cover card of low luminance and having small aperture should be used to standardize contrast measurements and reduce stray light.

Task 2

Description

Task 2 was designed to determine whether consistent contrast measurements can be obtained under more realistic conditions than those of Task 1. Colored paint samples applied to a common white paper (**Table 4**) were supplied for photometric measurement to determine the importance of spectral reflectances on contrast measurements. The four laboratories were again instructed to make measurements in a hemisphere or facsimile as well as in a windowless environment avoiding veiling reflections that simulated a realistic office. It is highly unlikely that a practitioner would have a hemisphere for standard photometric measurements. After all, one of the four lighting laboratories didn't have one. Thus, a windowless environment avoiding veiling reflections might be used as a field standard. It was therefore possible to compare measurements from a standard hemisphere or facsimile with those from the proposed field standard and, further, to determine how consistent the measurements in the windowless environment would be.

Measurements were to be taken with the laboratory photometer as well as with a relatively inexpensive luminance photometer supplied with the paint samples (Minolta, Model nt-1 degree with a #135, 400-mm close up lens). In this way it would be possible to compare the results from the best laboratory photometer with those from a common, less expensive, luminance photometer that might be used by a practitioner.

The ratio of the luminance of the paint sample (L_p) to the luminance of the adjacent paper (L_w) was defined as the paint sample contrast. Photometric measurements were made with each paint/paper sample placed on top of a gray, opaque backing plate supplied for the task. Each laboratory was asked to report values of L_p and L_w for each combination of lighting geometry (hemisphere or windowless environment), type of photometer (laboratory or that supplied), and paint/paper sample (20 different colors on common paper backing).

Results

A series of ANOVA's were performed on the luminance ratios, each averaging across a different independent variable to gain residual mean square errors for the denominators of the F ratios. For the ANOVA ignoring the paint/paper samples as a variable there were no significant differences among laboratories, photometers, and lighting geometries, nor were there any significant ($p \geq 0.5$) interactions among variables. This is a relatively uninteresting analysis, however, because the variations in luminance ratios associated with the other variables are small compared to those associated with the different paint/paper samples. In other words, the differences in the luminance ratios associated with all the other variables were not significantly larger than the (deliberately) large differences in luminance ratios associated with the various paint/paper samples that formed the basis for the "residual error" term in this ANOVA. Consequently, these results will not be discussed further.

Photometers were not significantly different in any of the other statistical analyses. This implies that under similar realistic conditions consistent photometric measurements can be obtained with the less expensive photometers. There was, however, a barely significant ($p \leq 0.05$) interaction between the laboratories and photometers in the ANOVA averaging across lighting geometry. This finding was probably due to inaccurate readings or recordings of one or two samples from Laboratory 1, since the values from the two photometers agreed well for most samples for this laboratory and since all other laboratories produced statistically equivalent results with the two photometers.

Laboratories and lighting geometries were significantly different, as was the interaction between the two variables ($p \leq 0.001$) in the ANOVA averaging across photometers. These results were due to unusually low luminance ratios in the windowless environment of Laboratory 3. Each laboratory provided photographs of its experimental arrangements. Examination of the photographs from Laboratory 3 showed that the photometers were placed very close to the sample in the windowless environment, and that the shadow of the photometer was cast over the paint samples during measurements. Thus, a portion of the overhead ceiling luminaires responsible for veiling reflections was masked and gave unusually low luminance ratios in the windowless environment.

Paint/paper samples were highly significant in all three analyses. Further, they interacted with all the other variables except the photometers, as stated previously. **Table 5** summarizes the measurements yielding the significant interaction for lighting geometry, laboratory, and sample. Comparing the results from the different laboratories, there were systematic differences among the paint/paper samples. The range of luminance ratios from the different labora-

Table 5—Luminance ratio L_p/L_w measurements for Task 2. Each cell represents the average of 2 measurements; one for each photometer type.

	Windowless Office				Hemisphere			
Sample	Lab 1	Lab 2	Lab 3	Lab 4	Lab 1	Lab 2	Lab 3	Lab 4
1	1.02	1.05	0.96	1.03	1.04	1.03	1.03	1.03
2	1.00	1.01	0.93	0.99	1.02	1.02	1.02	1.00
3	1.02	1.05	0.96	1.03	1.04	1.05	1.04	1.04
4	0.99	0.99	0.90	0.98	1.00	1.00	1.00	1.00
5	0.96	0.97	0.83	0.95	0.98	0.98	0.96	0.97
6	0.64	0.58	0.49	0.55	0.62	0.61	0.58	0.60
7	0.33	0.23	0.23	0.24	0.27	0.22	0.18	0.25
8	0.99	1.01	0.93	0.98	1.02	1.01	1.01	1.01
9	0.96	0.97	0.88	0.95	0.98	1.03	0.97	0.98
10	0.85	0.87	0.78	0.84	0.88	0.89	0.87	0.86
11	0.94	0.96	0.89	0.95	0.97	0.97	0.97	0.96
12	0.65	0.69	0.65	0.69	0.69	0.69	0.69	0.70
13	0.28	0.30	0.28	0.31	0.31	0.29	0.30	0.32
14	0.81	0.80	0.75	0.80	0.81	0.80	0.80	0.79
15	0.38	0.37	0.35	0.37	0.38	0.36	0.38	0.38
16	0.12	0.11	0.11	0.12	0.13	0.10	0.11	0.13
17	0.81	0.81	0.76	0.81	0.82	0.82	0.81	0.81
18	0.61	0.61	0.58	0.61	0.62	0.61	0.63	0.63
19	0.29	0.29	0.26	0.30	0.31	0.29	0.29	0.31
20	0.12	0.11	0.11	0.12	0.14	0.12	0.11	0.14

tories was only 8 percent for the paint/paper samples (high luminance ratios). Since both photometers gave the same results, these differences must have been due to the interaction between the colored paint samples and the different light sources used in the windowless environments and hemispheres, and not due to potential differences in spectral sensitivity for the two photometers. (Laboratory 1 used incandescent sources of illumination, whereas the other laboratories all used different types of fluorescent lamps.) A more thorough investigation would be required to determine accurately the magnitudes of photometric errors from colored samples under different light sources using different photometers. In principle, it should be possible to calculate expected differences before measurements are taken.

Conclusions

Keeping in mind the conclusions from Task 1, consistent results were obtained from the colored paint/paper samples where common photometers, lighting geometries, and light sources were employed. Except for one case, the differences in luminance ratio were always less than 3 to 4 percent when these criteria were met, even in the windowless environment. In total, this means that with relatively casual instructions and moderate care in procedures (e.g., do not place the photometer too close to the sample) contrasts can be evaluated consistently as long as precautions are taken to limit stray light and to illuminate the sample with a consistent spectral power distribution.

Recommendation

The windowless environment avoiding veiling reflections should be used as a working standard for lighting practitioners as long as the spectral power distribution of the light source is defined, the photometer is placed far enough away from the sample to avoid casting a shadow on it, and, following the conclusions from Task 1, proper evaluation has been made of the influence of stray light on the measurements.

Task 3

It is necessary to know the contrast of the task under actual viewing conditions in order to predict visual performance in field situations. For routine measurements it is also necessary that the technique be simple to use by relatively inexperienced individuals. Contrast measurements of small targets (e.g., pencil strokes on a piece of paper) are very difficult or even impossible to obtain under actual viewing conditions with a conventional luminance photometer. A comparison method was therefore devised to determine whether accurate contrast measurements of printed targets, both large and small, could be obtained under realistic viewing conditions by inexperienced subjects recruited by the four laboratories.

Subjects were required to match the brightnesses of printed material with standard, matte, achromatic cards. Typically, subjects placed a pair of identical cards close together so that the printed area of interest was flanked on two sides by cards of the same luminance. These standard achromatic cards (Munsell matte, neutral cards; 32 steps in value ranging from 1.75 to 9.5) were 38 mm square and thus large enough to permit luminance measurements with a conventional hand-held photometer and close-up lens. All photometric measurements for this task were obtained with the inexpensive photometer supplied for Task 2.

Typically, after several iterative comparisons the subject would choose a pair of standard cards that he or she believed to match, as closely as possible, the brightness of the printed area of interest. Using the hand-held photometer the subject would then make a luminance measurement of one of the matching cards under the same lighting geometry used in making the match. This luminance measurement was followed by another luminance measurement of the actual printed area, if it was sufficiently large. The luminance of small printed areas was never measured directly.

Each of the four laboratories tested ten subjects in the "windowless offices" used for Task 2; all followed the same instructions. The printed materials were presented to subjects in different, unsystematic order. In all, each subject evaluated 16 areas of various colors, specularities, and sizes from five printed materials (**Table 6**). After completing all brightness matches and luminance measurements, taking approximately 45 min, subjects completed a short questionnaire (**Appendix 1**).

Results

Ten of the 16 printed areas were large enough for direct luminance measurements (**Table 6**). Every subject provided two estimates of luminance for each of the ten samples, one from direct measurement of the sample (L_d) and another from measurement of a brightness-matched card (L_c). The ratio of the L_c value to the L_d value was calculated for each subject and then used as the dependent variable in an ANOVA for statistical comparison of the four laboratories, the ten samples, and their interaction. Average values of L_c/L_d are given in **Table 7**. There were highly significant differences among the laboratories ($p \leq 0.001$), but no significant differences among the printed samples ($p \geq 0.4$). The interaction among laboratories and samples was not significant

($p \geq 0.9$).

Figure 1 shows the mean values of L_c/L_d averaged across all subjects. If both luminance estimates were identical, on average, then $L_c/L_d = 1.0$. When the ratio was greater than unity, then the luminances obtained with the matching method were overestimated in relation to the direct method. As the hand-held photometer used in this task provided luminance measurements consistent with those of the different laboratory photometers used in Task 2, it can be more strongly argued that when the ratios were greater than unity the luminances of sample material were overestimated in the matching method.

The average L_c/L_d ratios for the achromatic samples were, within a few percent, equal to unity. A Tukey test of multiple-paired comparisons showed that there were no statistically significant differences among the luminances of the achromatic samples, and a linear regression revealed a correlation (r^2) of 0.99 for the paired L_c and L_d values (**Figure 2**). These results strongly imply that inexperienced subjects can make consistent luminance measurements with a hand-held photometer, and that they can also make accurate luminance measurements of achromatic material using the brightness matching method with achromatic standard cards.

The luminances, however, of the three blue samples were generally overestimated with the matching technique. The Tukey test showed that luminances of the blue samples were statistically higher than those of the achromatic samples. A linear regression of L_c vs L_d values for the blue samples also showed systematically higher luminances for L_c than for L_d, as well as a lower correlation between the two luminance measurements ($r^2 = 0.73$). Since subjects made accurate luminance measurements of the achromatic samples with a hand-held photometer, it is logical to conclude that the brightness matching of

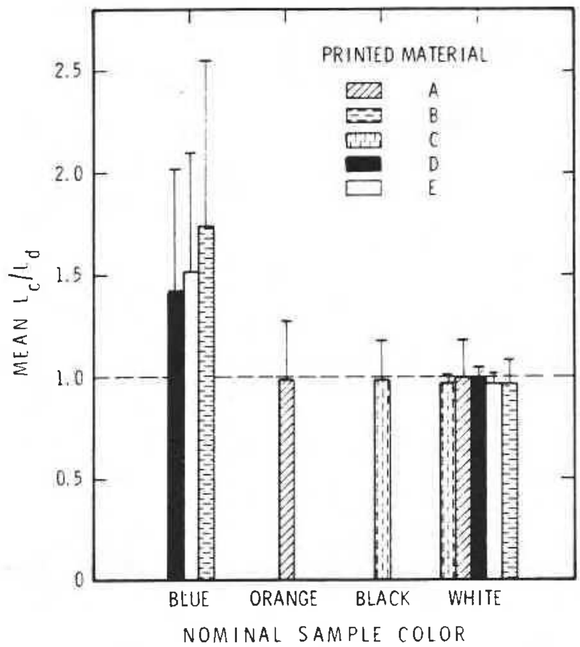

Figure 1—Average L_c/L_d ratios for printed materials of Task 3. Ratios greater than unity (dashed line) represent an overestimation of luminance by the brightness matching technique, relative to the photometric method. The bars represent mean L_c/L_d ratios for the measurement areas of each printed material. Vertical lines extending from the top of the bars represent standard deviations about the means.

Table 6—Description of samples for Task 3. Asterisk (*) identifies areas too small for conventional photometry

Printed material	Nominal specularity	Area	Nominal color	Approximate # Munsell notation
A Cover of Lighting Research & Technology Journal, 17 (3), 1985	matte	1	orange	2.5 YR 7/10
		2	white	N 9.25/
		3*	black	N 3.25/
		4*	black	N 3.25/
B Cover of Building Research Note no.221, NRC Publication, 1985	matte	5	blue	2.5 PB 5/10
		6	white	N 9.25/
C Stationery of the IES of North America; envelope	matte	7	black	N 3.5/
		8	white	N 9.25/
		9*	yellow	7.5 Y 8.5/12
		10*	black	N 3.5/
D Stationery of the Electricity Council Research Centre, letterhead	matte	11	blue	5 B 5/8
		12	white	N 9.25/
		13*	blue	5 B 5/8
E Cover of LD + A Journal 13(3), 1983	glossy	14	white	N 9.25/
		15	blue	5 B 3/4
		16*	orange	2.5 YR 6/10

 # These values represent one of the experimenters matches under cool-white fluorescent illumination and should only be considered as approximately correct under other illuminants.

Table 7—Average measured contrast for Task 3 at each luminance border, identified by the dark and light areas on each side of the border. The areas are described more fully in Table 6

Border	Areas		Card matching method					Photometry method				
No.	No.	Color	Lab 1	Lab 2	Lab 3	Lab 4	Mean	Lab 1	Lab 2	Lab 3	Lab 4	Mean
1	4/2	black/white	0.07	0.06	0.08	0.16	0.09					
2	2/1	orange/white	.61	.62	.55	.67	.61	0.67	0.59	0.56	0.56	0.60
3	3/1	black/orange	.20	.17	.16	.34	.22					
4	5/6	blue/white	.45	.36	.35	.40	.39	.23	.19	.21	.22	.21
5	7/8	black/white	.13	.10	.10	.12	.11	.13	.09	.09	.12	.11
6	10/8	black/white	.08	.08	.08	.10	.01					
7	7/9	black/yellow	.20	.13	.15	.17	16					
8	11/12	blue/white	.48	.37	.33	.40	.40	.30	.26	.28	.29	.28
9	13/12	blue/white	.51	.28	.37	.39	31					
10	15/14	blue/white	.11	.10	.16	.16	.13	.07	.06	.12	.10	.09
11	15/16	blue/orange	.39	.28	.50	.33	.38					

chromatic samples with achromatic standard cards produced these difficulties. It should be noted, however, that the average L_c/L_d ratio was close to unity for the orange sample, although the measurements were more variable (**Figures 1** and **2**). Too few materials were tested for any general conclusions to be reached about brightness matching of chromatic samples and achromatic cards, but earlier published results are consistent with those reported here.[4–7] In particular, the earlier studies show that brightness/luminance ratios for blues are typically greater than unity. Oranges, on the other hand, are usually closer to unity.

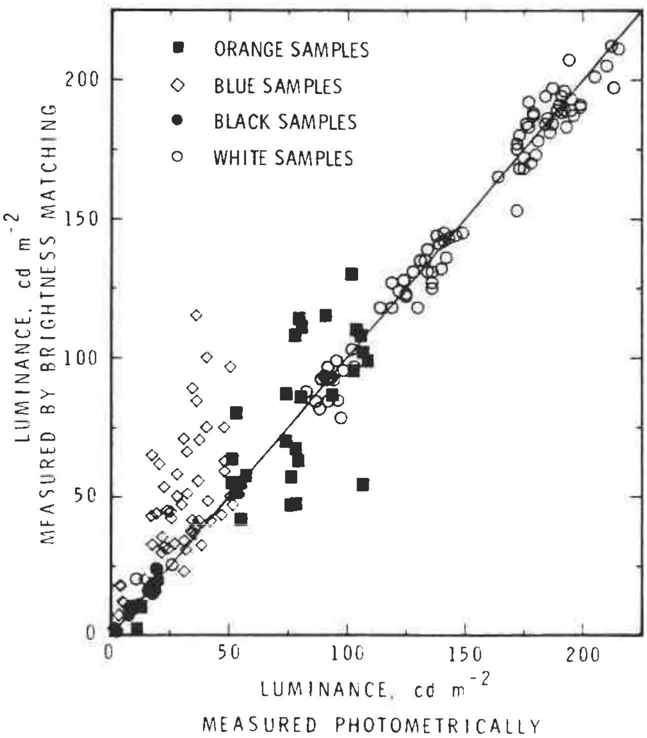

Figure 2—Comparison of the photometric and brightness matching methods for determining the luminances of samples described in Table 6. Points lying on the diagonal line represent perfect agreement between the two methods.

From the 16 different printed areas, the contrasts of the 11 luminous borders could be evaluated with the comparison method. Border contrast for the comparison method was defined as the luminance of the darker area (L_{cm}) to that of the lighter area (L_{cn}). An ANOVA was performed on these ratios and, as expected, the borders were significantly different ($p \leq 0.001$). The four laboratories were also significantly different ($p \leq 0.004$), but the interaction between laboratories and borders was not. A similar ANOVA using the border contrasts obtained with the direct measurement method was also performed, however, only five of the 11 borders could be measured and, therefore, analyzed. For this analysis border contrast was defined as the luminance of darker area (L_{dm}) to that of the lighter area (L_{dn}). Again, the borders and the laboratories were significantly different, but in this analysis, the interaction between border and laboratory was also significant ($p \leq 0.001$). The four laboratories must have been significantly different due to the different spectral power distributions of the light sources used in each windowless environment and not to differences in their ability to produce accurate luminance measurements, since the laboratories were not significantly different in the earlier statistical analysis using L_c/L_d as the dependent variable. A significant interaction between border and sample would also be expected when the spectral power distributions were dissimilar, as was the case for the direct measurement method, since the contrast of the colored samples should be differentially affected by different light sources. The interaction may not have been signifi cant in the ANOVA using the comparison method data due to the greater variability in making luminance matches to the colored samples as discussed previously. Average border contrast values using the two methods are given in **Table 7**.

An ANOVA was also performed on those data where contrast measurements could be obtained using both the comparison and the direct measurement methods. As expected from the two previous analyses, the different borders were significantly different ($p \leq 0.001$) as were the two laboratories ($p \leq 0.02$). As also might be inferred from the previous discussion, the two methods were also significantly different ($p \leq 0.001$) because of the overestimation of the luminances of the blue samples using the comparison method. This interpretation was reinforced by the significant ($p \leq 0.001$) interaction between the border type and the method used to make the measurement, indicating that the two methods agreed well for achromatic or orange samples but differed for the blue samples. (See **Table 7**.)

Regarding the questionnaire, nearly all subjects found the photometer easy to use but most found the matching method difficult to use for chromatic materials. Matching achromatic samples to the achromatic standard cards was easy for most subjects. Interestingly enough, a few subjects who were experienced in making photometric measurements had significantly lower L_c/L_d ratios ($p < 0.039$), indicating that trained subjects may make more accurate assessments of luminances of the blue materials.

Conclusions

The luminances of samples large enough for direct measurement with a luminance photometer can be evaluated accurately by most inexperienced individuals. Accurate matching of achromatic standard cards to achromatic printed samples also seems to be a simple task for inexperienced people. Brightness matching of chromatic samples with achromatic cards was less successful; not only was there greater variability in the matches, but the luminances of the blue samples were generally overestimated. Subjects also reported that brightness matching of chromatic samples with achromatic standard cards was difficult.

Recommendations

1) When possible, direct measurement of contrast with a luminance photometer should be made of printed materials. As this will be impossible for most reading tasks, another technique must be found for evaluating the luminance of small printed targets.

2) For achromatic materials, the matching technique provides results consistent with those for direct measurement. It is reasonable to conclude that, in general, matching achromatic cards with achromatic printed materials will give satisfactory results. The utility of the matching technique for measuring luminance is clearly questionable, however, when achromatic standard cards are used to evaluate chromatic printed samples.

3) Further work will have to be undertaken before the contrast of small, chromatic printed samples can be measured routinely with confidence. It may be possible to obtain satisfactory results with the matching technique if subjects can be trained to make accurate matches between achromatic standard cards and chromatic printed samples. Although less practical, it may be necessary to use a complete array of color standards.

General Discussion

Contrast measurements are rarely, if ever, made by lighting practitioners, although estimates of contrast are specifically required by some lighting sanctioning bodies.[8] In fact, it is impossible to make contrast measurements of small materials (printed letters or numbers) under normal viewing conditions with conventional photometric equipment. Further, the procedures for making contrast measurements and the accuracy of these measurements have not previously been investigated.

In this report some of the key issues of contrast measurement of realistic printed materials were discussed. Stray light is a significant problem in making accurate determinations of contrast. Standard procedures should be devised for evaluating the performance of luminance photometers and for making contrast measurements of printed materials. Without such standards the accuracy of the reported values can only be uncertain.

A windowless environment without veiling reflections seems to be a practical lighting standard for making contrast measurements in the field, as long as a standard light source is used and precautions are taken to minimize stray light and shadowing.

The matching technique described here for contrast measurements of small printed materials works well for estimating luminance if achromatic standards are used to match the brightness of achromatic samples. Brightness matching of achromatic standards with some chromatic samples is, however, inaccurate method of evaluating luminance, at least for inexperienced individuals. More work is required before this matching technique can be used routinely with confidence.

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Appendix 1

Subject Questionnaire for Task 3

Date ______________________________

Name ______________________________

Age ______________________________

Sex ______________________________

Time to make measurements ______________

1. How familiar are you with making photometric measurements?
very familiar — / — / — / — / — / — / — not at all familiar

2. How familiar are you with making measurements for other scientific purposes?
very familiar — / — / — / — / — / — / — not at all familiar

3. How easy did you find the brightness matching with the reflectance papers?
very easy — / — / — / — / — / — / — very difficult

4. How easy did you find the brightness measurements with the spot photometer?
very easy — / — / — / — / — / — / — very difficult