IMPROVED SCREEN FOR REAR-PROJECTION VIEWERS

Technical Reports Nos. — 47 and 48

December 5, 1969

Electronics Research

CORNING ELECTRONICS
A DIVISION OF CORNING GLASS WORKS
RALEIGH, NORTH CAROLINA

CORNING GLASS WORKS
ELECTRO-OPTICS DEPARTMENT
RALEIGH, NORTH CAROLINA

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Date - December 5, 1969

Periods Covered - October 10 to November 7, 1969
November 7 to December 5, 1969

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TECHNICAL REPORTS NOS. P-19-47 and 48

1. Introduction

Eight experimental scattering-type screens and one commercial scattering-type screen have been evaluated in terms of observed resolution and judged quality by the Aerospace Group of the Boeing Company. Their final report is included in this report as Appendix CG3.

In the quality tests, each of the 12" x 15" screens was compared side by side with every other screen in a projector using standard imagery. Observations were made by several experienced photointerpreters and a quality scale factor Z was determined for each screen depending on how many times it was chosen as the better screen. For the resolution tests, a standard USAF tribar resolution chart was projected onto the screens and the photointerpreters recorded the highest resolvable spatial frequencies. The correlation of these quality and resolution judgments with measured screen properties such as axial gain, brightness variations, MTF, substrate transmittance, etc., was then investigated. In general, the differences among screens were found to be small both in judged quality and in judged resolution. This was true in spite of the fact that significant differences existed in measured screen properties. These results can be understood when the following factors are taken into account:

1. Projector MTF
2. Projector brightness
3. Ambient light level

In many of the tests these factors had the effect of diminishing observed differences among screens.

2. Projector MTF

The highest resolution reported in CG3 is about 4 li/mm (p. B9) for the unaided eye viewing, from a distance of about 7 inches, a high contrast target projected onto the rear-projection screen under acceptable ambient light conditions.

On the other hand, typical square-wave MTF values obtained by the contact method (P-19-41) for these screens were 0.97 at 5 lines/mm, 0.91 at 10 lines/mm, and 0.75 at 15 lines/mm. If these contact MTF values are even approximately valid for projected resolution targets, then the MTF of the projector must have been the controlling factor in the resolution determinations of CG3.

It is possible to estimate the projector MTF from the limit-of-resolution determinations described in 2.7.3 of CG3, in conjunction with the square-wave response of the eye. With screen removed, the target images in the screen plane were observed by use of a 7X magnifier. The independently-measured contrast C_T and maximum resolvable resolution number RN for each target contrast are reproduced here from p. 15 of CG3. Included also are the corresponding

TABLE I

Limit-of-resolution data on targets of CG3

Contrast (C_T)	Modulation (M_T)	Resolution Number (RN)	Spatial Frequency (F) (mm^{-1})
4.45	0.69	43.5	13
0.86	0.30	42.0	11.2
0.38	0.16	40.0	9
0.073	0.035	22.0	1.12

modulation of the target

$$M_T = \frac{C_T}{2 + C_T} ,$$

and maximum resolvable spatial frequency for that target

$$F = \frac{2^{RN/6}}{11.4} ,$$

calculated from C_T and RN. Square-wave modulation thresholds for the human eye are adapted from the data of DePalma and Lowry[1] and are plotted in Fig. 1. for a viewing distance of 7 inches. The 7X magnifier used at 7 inches effective viewing distance provides a magnification of approximately 6. The effect of the magnifier is to reduce the spatial frequency on the retina by a factor of 6. Thus, for a target having modulation M_T and a maximum resolvable spatial frequency F, the appropriate point of the eye response curve is at $\frac{F}{6}$ in Fig. 1. The corresponding modulation threshold is read from the curve. The product of the target modulation M_T and the projector modulation $M_P(F)$ must be equal to this modulation threshold M_{TH} at frequency F/6. Hence the projector square-wave MTF is

$$M_P(F) = \frac{M_{TH}\ (F/6)}{M_T} \quad . \tag{1}$$

When these calculations are carried out for the four resolution targets listed in Table I, the results are as shown in Table II and in Fig. 1. The intersection of the

TABLE II

Target Modulation	Observed Resolution with 6X Magnification		Modulation Threshold of Eye	Projector Modulation
M_T	F (mm^{-1})	F/6 (mm^{-1})	$M_{TH}\ (\frac{F}{6})$	$M_P(F)$
0.69	13	2.17	.010	0.014
0.30	11.2	1.87	.0075	0.025
0.16	9	1.50	.0045	0.028
0.036	1.12	0.187	.0022	0.063

eye modulation threshold curve and the projector modulation curve falls at 4.6 lines/mm. This implies that even with a perfect rear-projection screen the maximum resolution would be 4.6 lines/mm. This low projector MTF largely explains the 4 lines/mm limit to the observed resolution and also explains the difficulty encountered in distinguishing significant differences in resolution and quality among the screens.

The above calculation is not highly accurate, because of differences in experimental conditions for the eye response measurements of DePalma and Lowry and the projector resolution determinations. The eye modulation threshold depends upon the observer, the nature of the test object, the threshold criterion chosen, the angular field covered by the target, the luminance, and the condition of visual adaptation.1/ The eye response data of Fig. 1. were adapted from an experiment in which the target was square-wave over a broad angular field, the luminance was 20 F.L., and the criterion for threshold was ability to detect modulation.1/ Thus in the CG3 projector resolution measurements the observer was different, the threshold criterion was more stringent, and the angular field was smaller. For these reasons, the projector MTF calculation must be considered as an estimate.

While the above analysis shows that the projector MTF was much lower than expected, it is also not clear from the CG3 measurements that even the best screens did not degrade the resolution. Direct viewing of the projected image with a 7X magnifier gave a limit of resolution of 13 li/mm without a screen. With a screen in place the limit of resolution with the 7X magnifier was about 7 li/mm for the average screen, perhaps 8 li/mm for the best screens (CG3, p. B 16). Thus it remains to be proved that contact square-wave MTF values provide a realistic measure of resolution in the projection situation.

3. Ambient Light

The ambient light level was 3 F.C. (CG3, p. 7) and caused little modulation degradation in the resolution measurements. This was because the average film density was low for the resolution targets and the minimum input illumination to the screens was 10 F.C. (CG3, p. 13). But in quality tests, average film density was about 1.0 and the ambient-to-projector illumination ratio was often greater than unity. The approximate calculations below show a degradation of modulation by this effect of as much as a factor of 5. Trapped projector light was generally negligible compared with ambient.

Reflected ambient light and trapped projector light both have the effect of degrading the observed modulation transfer by a constant factor for all spatial frequencies. The ratio of the modulation, or contrast, γ displayed by the screen to the modulation γ_0 projected onto the screen can be calculated in an approximate fashion by reference to Fig. 2. The displayed modulation is

$$\gamma = \frac{\left(B_D^{max} + B_T + B_R\right) - \left(B_D^{min} + B_T + B_R\right)}{\left(B_D^{max} + B_T + B_R\right) + \left(B_D^{min} + B_T + B_R\right)} \quad , \qquad (2)$$

where B_D^{max} and B_D^{min} are the maximum and minimum brightnesses directly transmitted through a local area of the screen, B_T is the brightness of the trapped projector light contributed by all parts of the screen, and B_R is the reflected ambient brightness. Since the modulation projected onto the screen is

$$\gamma_0 = \frac{B_D^{max} - B_D^{min}}{B_D^{max} + B_D^{min}} \quad , \qquad (3)$$

the transfer of modulation by the screen can be written

$$\frac{\gamma}{\gamma_0} = \frac{1}{1 + \dfrac{2B_T + 2B_R}{B_D^{max} + B_D^{min}}} \quad . \qquad (4)$$

The trapped light in Eq. (4) can be expressed in terms of the measured trapped light ratio

$$\alpha_T = B_T/\overline{B}_D = \frac{B_T}{\frac{N}{2}\left(B_D^{max} + B_D^{min}\right)} \quad , \qquad (5)$$

where

$$N = \frac{\bar{B}_D}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} \tag{6}$$

is the ratio of the average brightness over the whole screen to the local average brightness.

The reflected ambient light B_R in Eq. (4) is expressible in terms of the measurable quantity $R_D T_S$. Since the ambient reflected light suffers one diffuse reflection and two traversals through the substrate, the reflected brightness is proportional to $R_D T_S^2 E_{amb}$. The local transmitted brightness makes a single pass through the substrate and is thus proportional to $T_S \left(E_D^{max} + E_D^{min}\right)$. The quantities E_D^{max} and E_D^{min} are the incident illumination maxima and minima in the local area corresponding to transmitted brightness B_D^{max} and B_D^{min}. The ambient illumination is E_{amb}. The reflected brightness as a fraction of the incident local average brightness is thus approximately

$$\frac{B_R}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} = \frac{R_D T_S^2 E_{amb}}{\frac{1}{2} T_S \left(E_D^{max} + E_D^{min}\right)} = \frac{R_D T_S E_{amb}}{\bar{E}_D / N} \tag{7}$$

where

$$N = \frac{\bar{E}_D}{\frac{1}{2}\left(E_D^{max} + E_D^{min}\right)} = \frac{\bar{B}_D}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} \tag{8}$$

Equation (7) holds if the reflected and transmitted light have approximately the same angular distribution.

Equations (4) - (8) can now be combined to yield

$$\frac{Y}{Y_0} = \frac{1}{1 + N\left(\alpha_T + R_D T_S \frac{E_{amb}}{\bar{E}_D}\right)} \tag{9}$$

Quality test II, in which the open gate screen brightness was limited to 10 F.L. for all screens, was most strongly affected by ambient light. A sample calculation of γ/γ_0 will be made for the LS-60 screen. According to CG3, p. 5, the projector provided a maximum of about 30 F.C. open gate to the screen under standard conditions. In order to reduce the brightness of screen LS-60 to 10 F.L. it was necessary to reduce this open gate illumination to

$$30 \text{ F.C.} \times \frac{10 \text{ F.L.}}{79 \text{ F.L.}} = 3.75 \text{ F.C.} \quad ,$$

since under 30 F.C. illumination this screen produced a brightness of 79 F.L. (LBRT-I = 1.82 from CG3, p. A2). Because the average imagery density was about 1.0, the average illumination projected onto this screen was $\overline{E}_D$ = 3.75 F.C./10. Then $E_{amb}/\overline{E}_D$ = 3 F.C./0.375 F.C. = 8. The assessment of image quality was made with emphasis on dense, shadowed areas of the imagery where the transmission was as low as 2% (CG3, p. 10). Then for an average film transmittance of 10%, the value of N was 5. The product $R_D T_S$ was calculated from the values in Table II of P-19-40 for all screens except LS-60, for which a separate measurement was made. The value for LS-60 was $R_D T_S$ = 4.4%. The value α_T = 0.11% can be found in Table A-1 of CG3. The quantity γ/γ_0 can now be calculated for this screen under the conditions of the test. The results of such calculations for all the screens appear in Table III.

Table III

Parameters describing the effect of reflected ambient light and trapped projector light on the observed MTF.

(Quality Test II)

Screen	α_T (%)	$R_D T_S$ (%)	$E_{amb}/\bar{E}_D$	$\frac{Y}{Y_0}$	Z
AQ-20	0.062	2.1	1.0	0.90	1.01
AQ-17	0.081	3.1	2.8	0.70	0.67
AQ-11	0.133	4.9	3.6	0.53	0
AR-27	0.086	4.4	4.7	0.49	0.24
AQ-18	0.630	6.6	4.4	0.41	-0.08
LS-60	0.110	4.4	8.0	0.36	0.40
AL-5	0.135	9.2	4.0	0.35	-0.67
AR-28	0.240	6.6	10.7	0.22	-0.58
AL-4	0.740	14.0	5.4	0.21	-1.01

The quality factor Z is plotted against γ/γ_0 in Fig. 3, where it can be seen that the correlation is very good. The effectiveness of substrate darkening in suppressing reflected ambient light is well demonstrated. This is in excellent agreement with the correlation of -0.89 reported in CG3, Table C-10, between Z and $R_D T_S^2$. Figure 4 shows this correlation. The displacement of the LS-60 point from the others prompted a remeasurement of $R_D T_S^2$, this time by a direct method. The value of 2% obtained for LS-60 should replace the earlier value of 6.3%. This change causes LS-60 to fall in line with the others.

When γ/γ_0 is calculated for the Quality I and Quality II tests, the results are not so clear cut as in test II because the ambient light was not as large relative to the illumination provided by the projector. These results are plotted in Figs. 5 and 6. In Quality test I, projector luminance was held constant. Figure 5 shows the quality factor increasing as γ/γ_0 increases, at low values of γ/γ_0 in test I. But at high values of γ/γ_0, the reduced screen luminance caused a rapid drop in judged quality. LS-60 performed best here because of its high efficiency and adequate ambient light rejection.

In the Quality III tests, screen luminance was maintained constant, except for screen AQ-20. Figure 6 shows a general dependence on γ/γ_0 except for screen AQ-17 and AQ-20. The reduced luminance of AQ-20 explains its low judged quality, but no good explanation for the performance of AQ-17 is apparent.

As mentioned earlier, ambient light was of much less influence in the resolution determinations. The lowest value of γ/γ_0 calculated by use of Eq. (9) for the constant-luminance case was 0.93. Nevertheless, for the low-contrast targets a significant correlation was noted between RN and $R_D T_S^2$ (CG3, pp C13 and C15).

4. Projector Brightness

The illumination produced on the screen by the projector affected the tests through the ratio $E_{amb}/\bar{E}_D$ as described above. Also, in some cases the screen luminance fell low enough to cause decreased visual acuity, as in Fig. 5. If projector power had been unlimited, it would have been of great interest to see whether the highest resolution could be obtained by highly illuminating the very dark substrate screens.

5. Screen Parameters

The list of screen parameters in Table A-1 of CG3 was purposely made redundant on the chance that some unexpected correlations might be discovered. The following list is probably sufficient for interpreting the results:

$T_{30}T_S$

$R_D T_S^2$ or $R_D T_S$

T_S

V_{30}

α_T

MTF

DRTHI

The correlations found between these parameters and resolution and judged quality are found in CG3, pp. C10 - C-15.

The last three parameters had negligible effect on the outcome, although dry thickness DRTHI correlated extraordinarily well with quality in the Quality II test and with resolution in the resolution tests. This must be considered as fortuitous, arising largely because the inefficient screens AL-4 and AL-5 had very thin layers, and the screen which was given the greatest substrate darkening, AQ-20, had the thickest layer. The low projector MTF precluded any significant dependence on MTF values of the screens at 6 li/mm, which were not very different anyway. The trapped light ratio α_T would be important only if the ambient light were quite low, which was not the case.

The parameter $T_{30}T_S$ is basically a measure of screen efficiency and could equally well be replaced by LBRT, $B(0)T_S$, or $T_{45}T_S$, for which the correlations were very similar. Not unexpectedly, at constant projector illumination $T_{30}T_S$ correlates highly with quality and with resolution for the high-contrast target. The correlation vanishes, however, for low-contrast targets.

A significant correlation exists for $R_D T_S^2$ in Quality test II for the reasons explained earlier. In all the other tests the correlation is weak, although in the constant-screen luminance resolution test with LS-60 excluded, the correlation may reflect a real ambient and trapped light effect.

Large correlations were found for the brightness variation V_{30} in the resolution tests and in Quality Test II. The latter is understandable in view of the strong dependence of V_{30} on B(0). The surprisingly high correlation in the resolution tests is at least partly fortuitous, since the low efficiency screens AL-4 and AL-5, which nearly always gave inferior performance, had very high brightness variation.

6. Variation of Resolution with Viewing Angle

This phenomenon should be investigated further. Since it occurs for all screens, it could be a property of the projector. Also, if the screens were being used to best advantage, i.e., in a high-MTF system, the effect might be smaller or even more pronounced.

7. Effect of Target Contrast

One unexpected result is that the darker screens showed lower resolution than the lighter screens for high contrast targets, but the reverse was true for low contrast targets. Figure 3-10 of CG3 illustrates this point for constant projector output and corresponding results hold for constant screen luminance. The greater separation of screens on the resolution scale for low contrast targets can be explained by reference to the slope of the eye response curve. At very low contrasts a given fractional change in modulation produces a greater fractional change in detectable spatial frequency than at higher contrasts. However this does not explain the observed interchange of rankings of light and dark screens, as occurs most convincingly for screens LS-60 and AQ-20. If this effect persists in a more ideal projector arrangement, incorporation of heavier substrate darkening may be justified.

8. Conclusions

Significant dependences on some screen parameters, notably efficiency $T_{30}T_S$ and diffuse reflectance times substrate transmittance R_DT_S, were established by the tests. The more efficient screens performed best for a fixed projector output.

The projector MTF limited observed resolution to about 4.6 li/mm, whereas the screens should have been capable of displaying considerably higher resolution.

Quality tests were dominated by the projector MTF and by the ambient-to-projector illumination ratio. Calculations based on the known ambient light level revealed a strong R_DT_S dependence, which was one of the principal aims of the investigation. The importance of T_S was underscored by an unexplained superiority of dark screens for the low contrast resolution targets.

No physical justification is apparent for the large negative correlation between brightness variation V_{30} and resolution. While it is partly fortuitous, it may be significant.

Similarly, the reason for the observed increase of resolution with viewing angle is obscure. This effect may or may not be evident under ideal projection conditions.

Ambient light was generally high enough that the trapped light ratio α_T had little effect. Likewise, measured contact MTF values for the screens were not sufficiently different at 5 li/mm to have an observable influence on the results.

REFERENCES

1. J. J. DePalma and E. M. Lowry, J. Opt. Soc. Am. 52, 328 (1962).

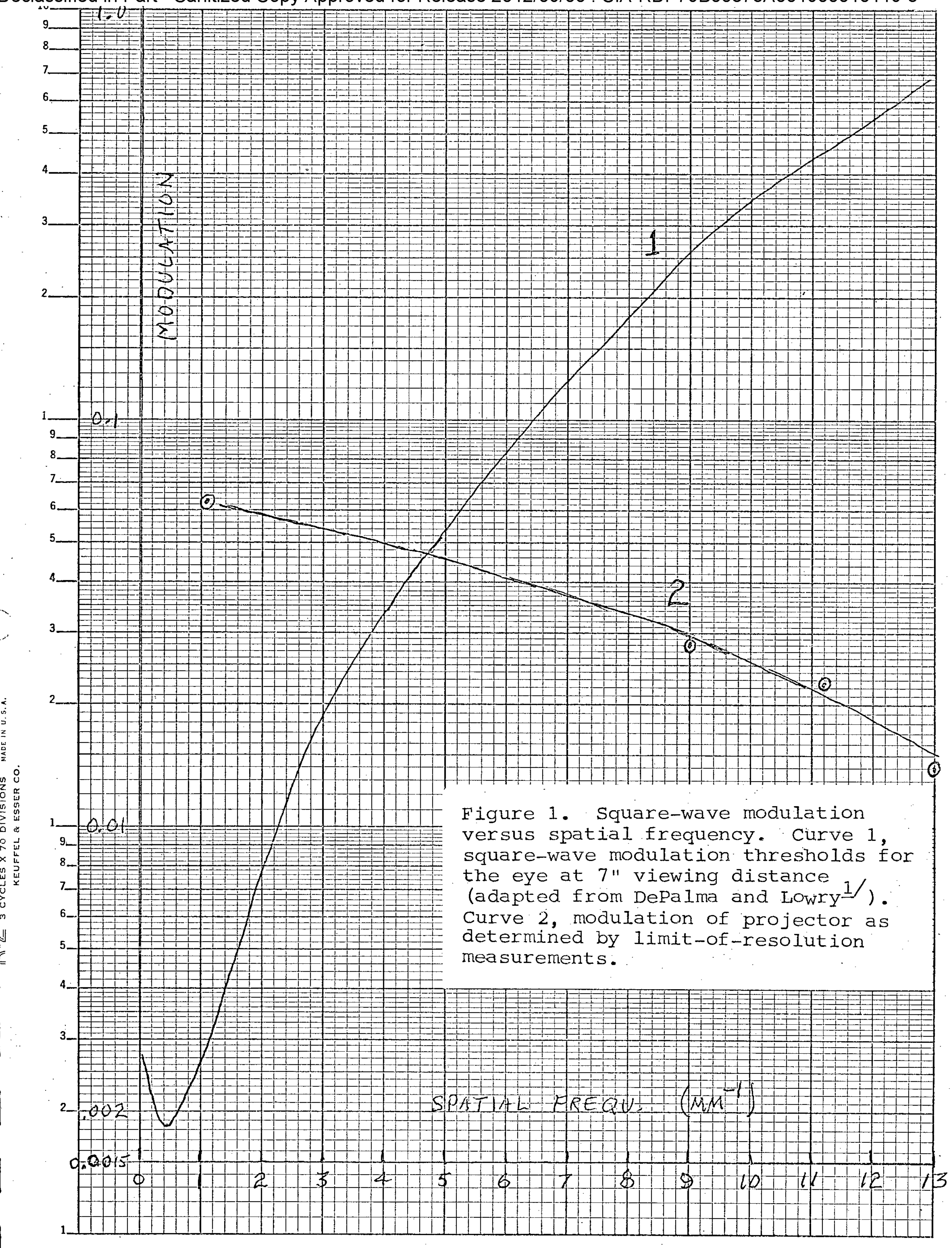

Figure 1. Square-wave modulation versus spatial frequency. Curve 1, square-wave modulation thresholds for the eye at 7" viewing distance (adapted from DePalma and Lowry[1/]). Curve 2, modulation of projector as determined by limit-of-resolution measurements.

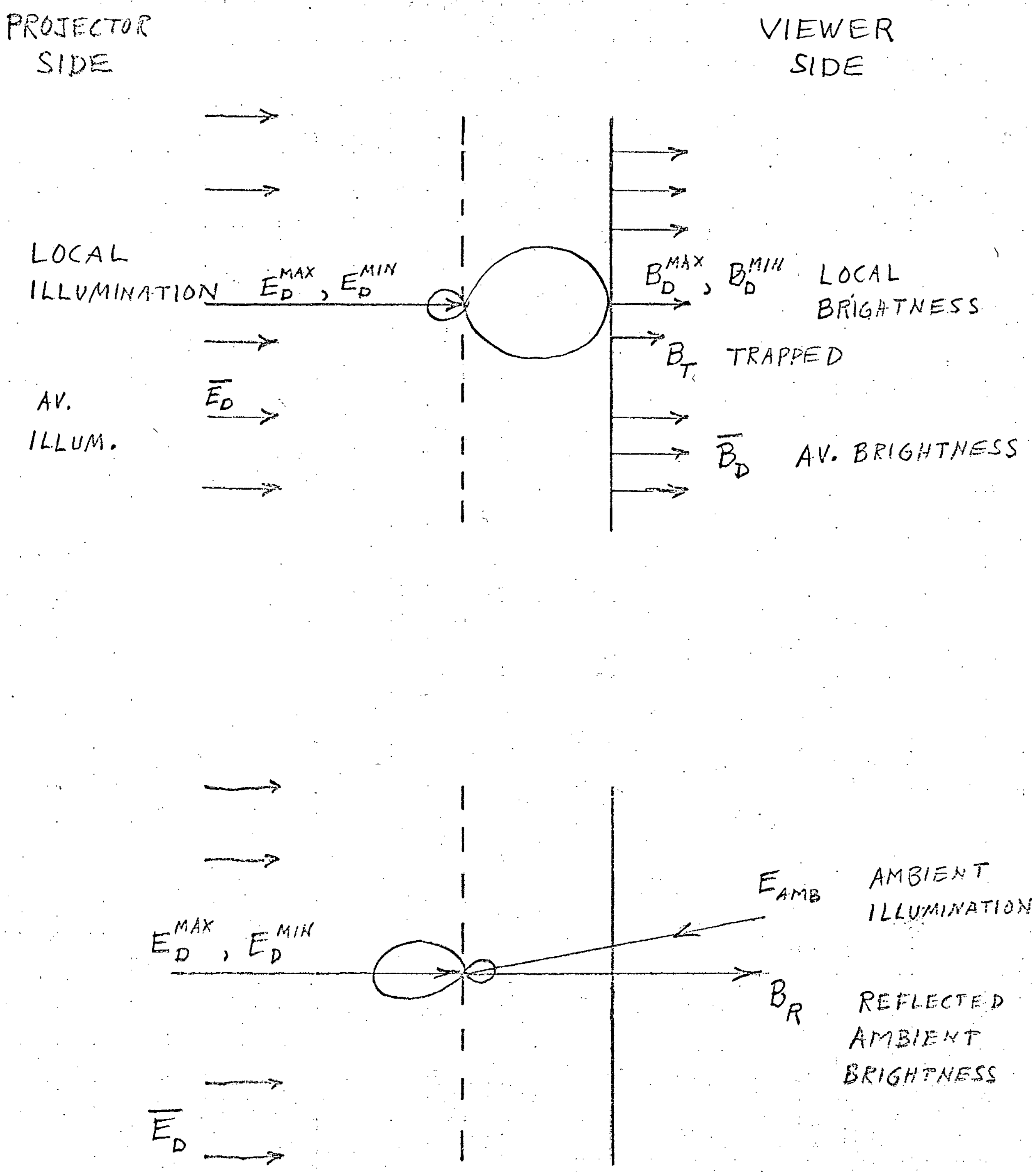

Figure 2. Geometry and nomenclature for describing trapped projector light and reflected ambient light.

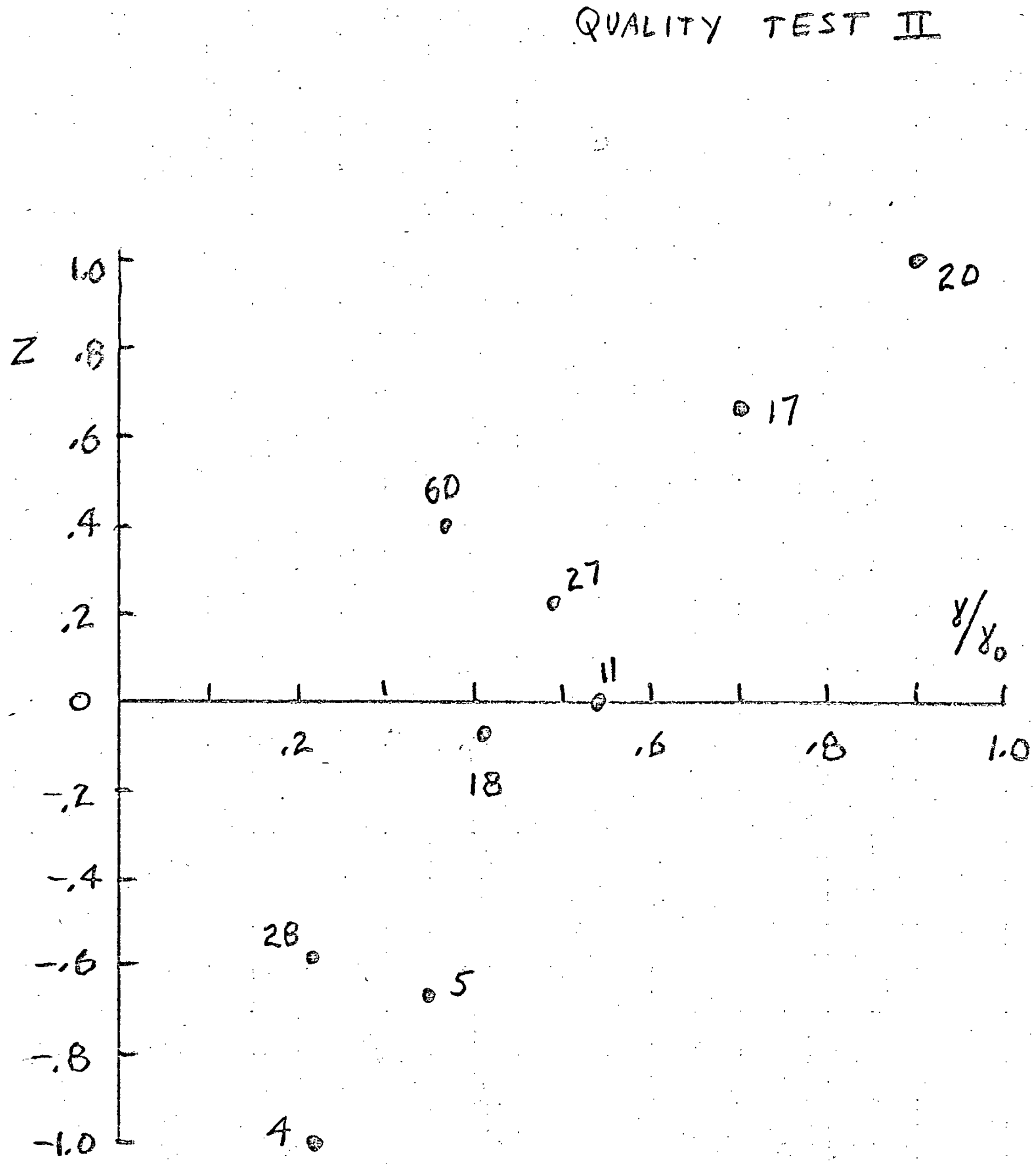

Figure 3. Quality scale factor Z versus modulation transfer factor γ/γ_0 produced by reflected ambient and trapped projector light. Numbers beside points are abbreviated screen numbers. Data for Quality Test II.

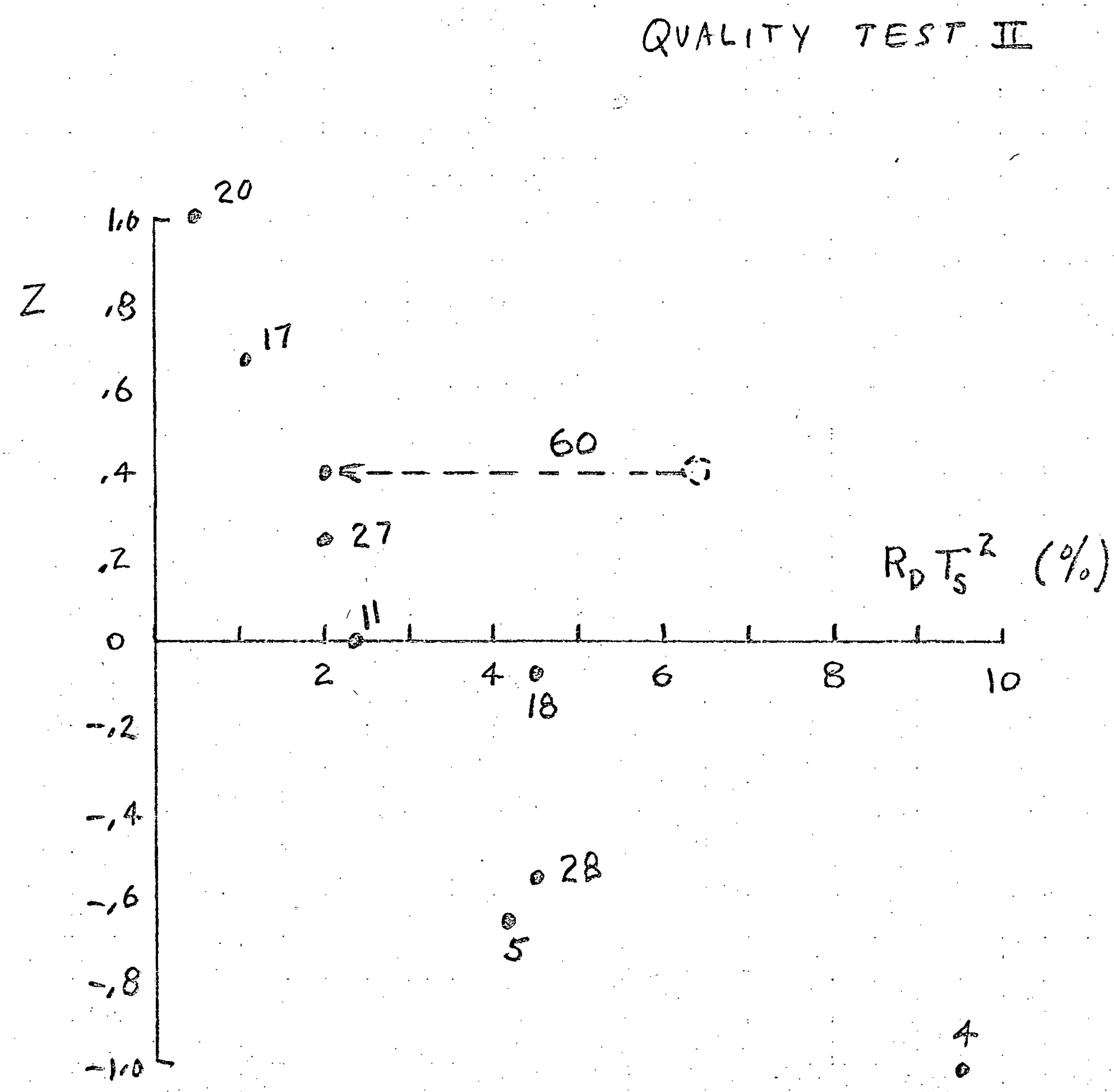

Figure 4. Quality scale factor Z versus $R_D T_S^2$ for Quality Test II. Screen LS-60 has corrected value of $R_D T_S^2$.

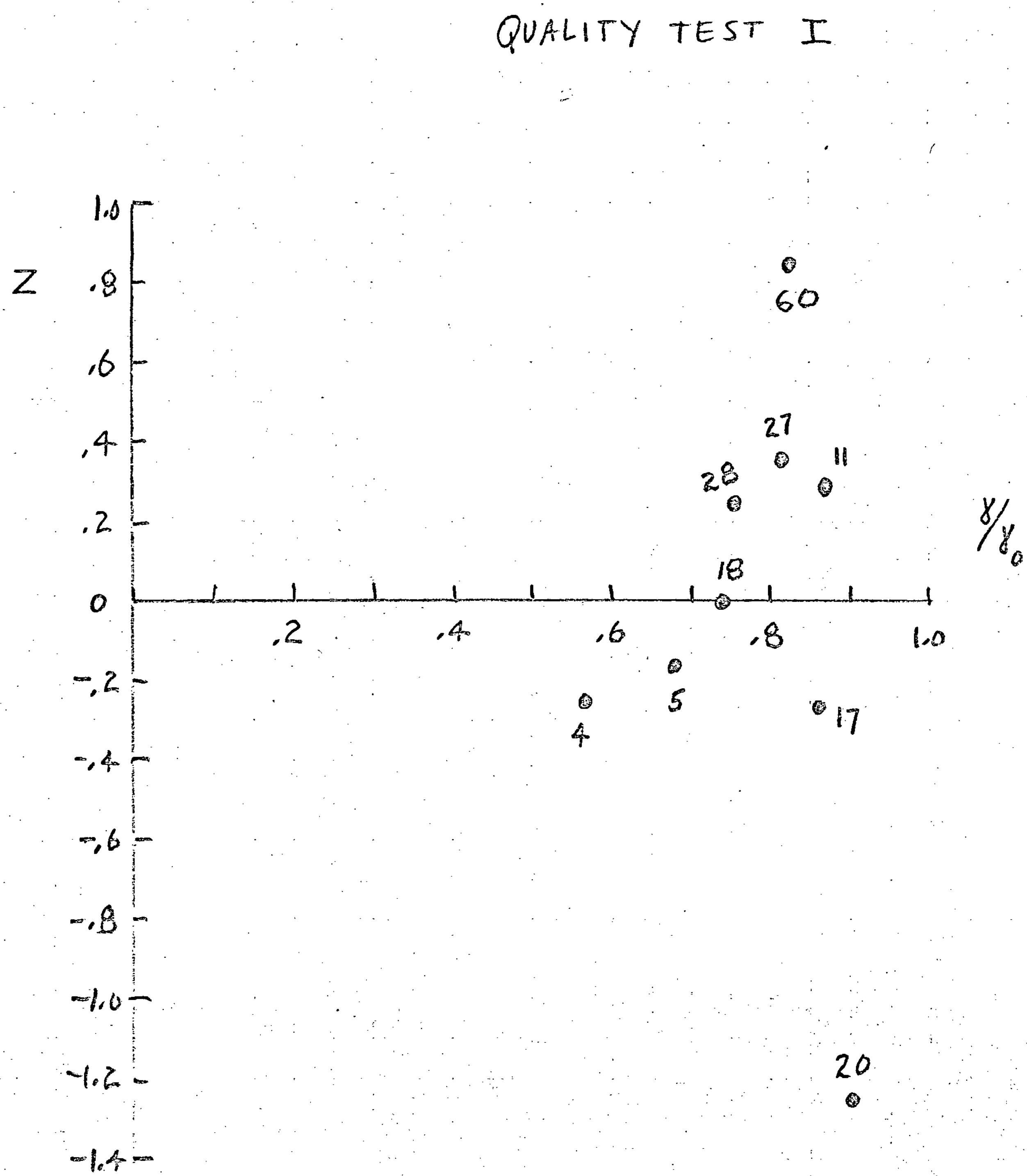

Figure 5. Quality scale factor versus γ/γ_0 for Quality Test I.

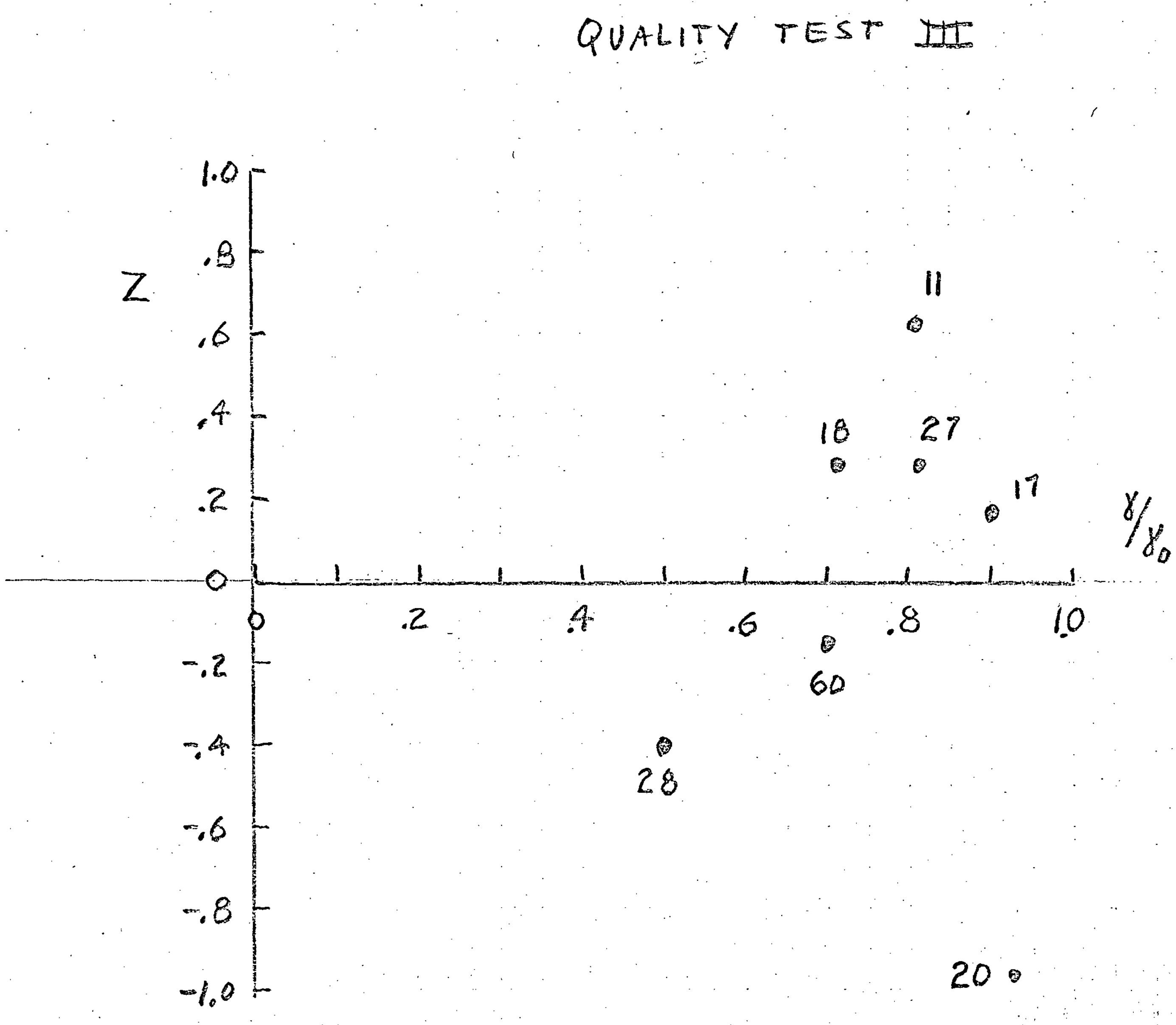

Figure 6. Quality scale factor versus γ/γ_0 for Quality Test III.

FINAL REPORT

REAR PROJECTION SCREEN
EVALUATION STUDY

CG-3

29 AUGUST, 1969

CORNING P. O. 08209

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THE BOEING COMPANY AEROSPACE GROUP SEATTLE, WASHINGTON

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This report is prepared for the Corning Glass Works in fulfillment of Purchase Order No. 08209

CONTENTS

ABSTRACT

Nine rear projection screens, eight experimental and one a standard type, were evaluated. The evaluation was based on two measures, judged screen quality and judged resolution. Screen quality judgments were made by image interpreters while viewing operational imagery on pairs of screens mounted side by side in a Richardson rear screen projector. Resolution measurements were made by skilled observers viewing tribar resolution charts at five contrasts and three viewing angles with the screens mounted in the same viewer.

The differences among screens in both judged quality and judged resolution were small. Quality judgments were strongly affected by screen luminance - observers preferred the brighter screens. When screen brightness was changed, the quality judgments also changed. Screen parameters related to the distribution of luminance such as axial gain and brightness variation were positively related to the judged quality of the screens when large inter-screen brightness differences existed and negatively correlated with judged quality when inter-screen brightness differences were eliminated by matching their on-axis brightness. Screen resolution was considerably lower than the visual capabilities of the observers. Low contrast targets yielded lower resolution than high contrast targets. With low contrast targets, resolution was worse with on-axis viewing. The observers could distinguish higher spatial frequencies with the aid of a 7X tube magnifier. The screen with the best resolution with low resolution targets had the worst resolution with high contrast targets.

1.0 INTRODUCTION

This report describes a study conducted to evaluate eight experimental rear projection screens produced by the Electronic Research Laboratory of the Corning Glass Works. To obtain a comparison with currently available materials, a ninth screen manufactured by the Polacoat Company and in regular use in rear projection viewing devices was included in the study.

Many screen characteristics have been used as a basis for comparison and evaluation, among which are: (1) spatial distribution of luminance; (2) contact resolution; (3) breakup magnification; and (4) microphotometer-measured brightness of a spot. The spatial distribution of luminous energy is more important for group viewing than for use by an individual interpreter. Spreading of the image over a large angle may actually lead to a reduction of the resolution capability of a screen. Contact resolution is commonly reported for screens (Klaiber, 1966, McHail and Soll, 1962), but there is no indication it is related to the resolution of a projected image. Other measures, for example breakup magnification, the maximum magnification which can be used to view an image on the screen before it breaks up, and the fidelity with which the microphotometer-measured brightness characteristics of a small spot of light are maintained by the screen, both appear to be valid indices of screen quality. Unfortunately, they do not agree with each other (McHail and Soll, 1962).

Two measures were selected for use as indices of screen quality in the present study, judged quality and judged resolution. Both involved projected images. To collect the first, a potential rear screen projector user, an image interpreter, judged the quality of the screens as they displayed the same imagery he normally worked with. The second measure, resolution judgements obtained with a range of target contrast levels, was designed to simulate some of the critical information elements of imagery.

Initially two tests were planned, one involving judged quality and the other involving judged resolution, with three subjects to be included in each, as described in the test proposal (DK-423, Firm Proposal - Rear Projection Glass Screen Evaluation Study). These two tests were carried out as planned. During the testing the projector brightness was maintained at the maximum level normally available (referred to hereafter as "normal brightness").

Preliminary analysis of data from the two tests initially planned indicated that judgements were closely related to screen brightness, so the study was expanded to include other brightness conditions. In all, the following four tests were conducted:

- Judged Resolution - After completing the initial test at normal, unadjusted brightness, the test was partially repeated with the brightness of the screens matched by varying projector lamp voltage.
- Screen Quality Test I - Three interpreters judged screen quality with normal, unadjusted screen brightness, as initially planned.
- Screen Quality Test II - A fourth interpreter judged screen quality with screen brightness matched by varying the projector lamp voltage.
- Screen Quality Test III - Three additional interpreters judged screen quality with screen brightness matched by means of neutral density filters.

These tests are summarized in TABLE 1-1.

TABLE 1-1

TESTS CONDUCTED DURING SCREEN STUDY

TEST	SUBJECTS	SCREEN BRIGHTNESS CONTROL METHOD	SCREEN BRIGHTNESS LUMINANCE (FL)[a]	SCREENS
JUDGED RESOLUTION	3	NONE	10-107	9
	2	LAMP VOLTAGE	10	9
QUALITY I	3	NONE	10-107	9
QUALITY II	1	LAMP VOLTAGE	10	9
QUALITY III	3	FILTERS	30	7

[a] Approximate open gate screen luminance in foot lamberts. Appendix A describes the measurement techniques used.

2.0 METHOD

2.1 PROJECTION EQUIPMENT AND SCREENS

Nine rear projection screens were included in the study, consisting of eight experimental and one standard type screen, manufactured as "Polacoat" and used in many rear projection viewers. All nine screens were 12 x 15 inches in size and consisted of a diffusing layer on heavy glass. The diffusing layer on the experimental screens consisted of small particles of glass in a binding medium. The diffusing surface was on the side away from the interpreter. The experimental screens included an antireflection coating on the side toward the interpreter. Physical parameters measured on each screen are listed in TABLES A-1 and A-3 of Appendix A. These tables include screen brightness measurements made during the study.

The screens were viewed in a Richardson Model 705M rear screen projector. For the quality studies, a frame was placed in the 30 by 30 inch viewing area of the projector, which allowed two screens to be mounted side by side, as illustrated in Figure 2-1. For the resolution study a different frame was used to support a single screen in the center of the viewing area. Projector magnification was fixed at 15x. Test subjects had control over the projector focus and were encouraged to adjust it whenever necessary. Using normal line voltage, the projector gave an open gate brightness at the back of the screen of between 29 and 33 foot candles, as measured by a cosine receptor head. Control of the illumination level is discussed in the sections below which describe the individual tests.

Lamps were replaced several times during the testing. When possible, screen brightness was measured for the different lamps. The typical difference between a used bulb at the end of its normal life expectancy, approximately one hour, and a new lamp was 5 per cent in either direction.

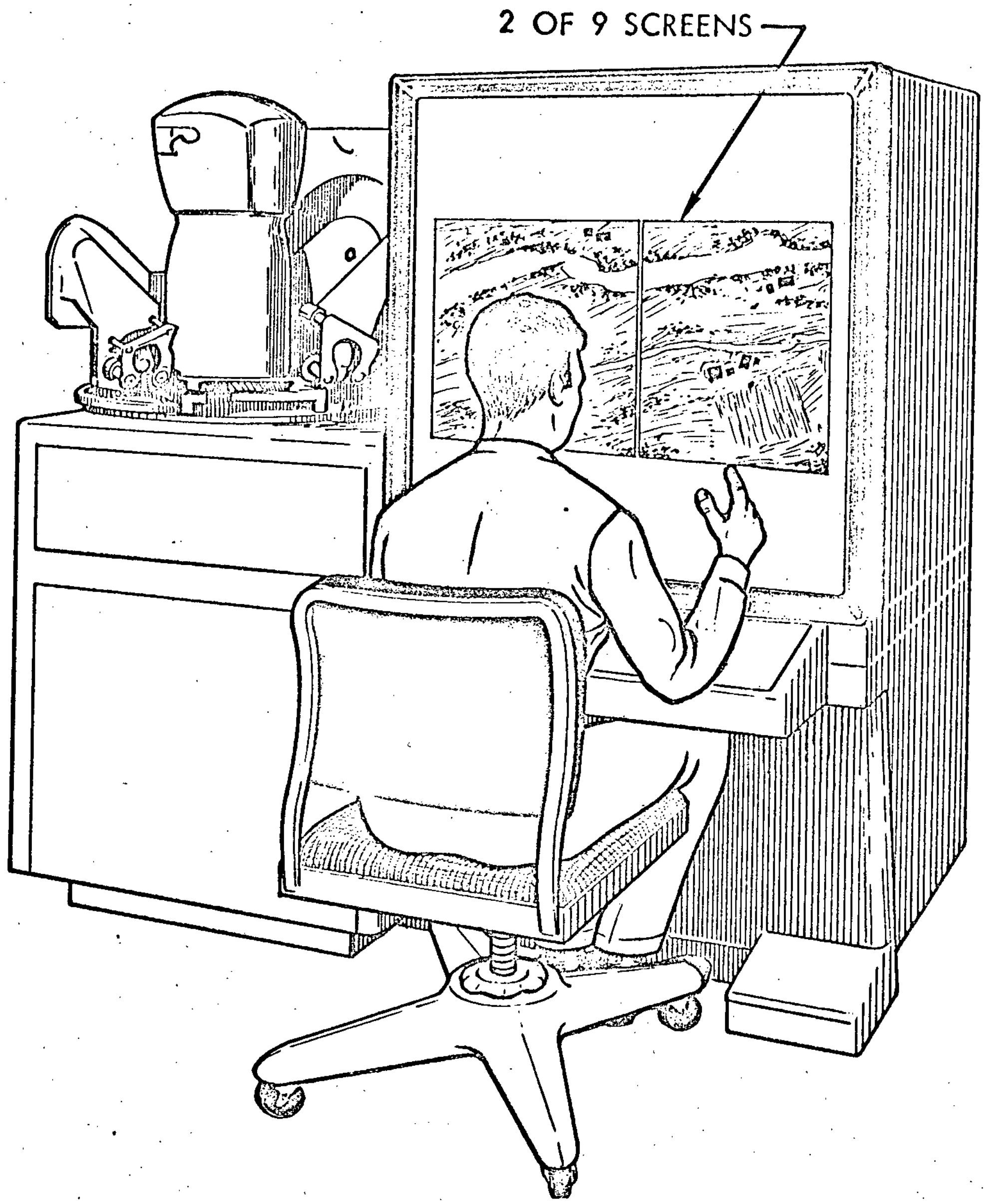

FIGURE 2-1

INTERPRETER VIEWING TWO SCREENS MOUNTED
IN THE REAR SCREEN PROJECTOR

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The left-hand screen was generally 5 to 10 per cent brighter than the right-hand screen because of lamp filament misalignment. The design of the experiments eliminated any effect on the final results due to this difference.

Room illumination was provided by indirect flourescent lighting located so there were no glare sources in the subject's line of sight. Illumination near the screens was approximately three foot candles and the luminance of the area adjacent to the screens was approximately two foot lamberts. This illumination was adequate for reading test materials.

2.2 IMAGERY

Imagery for the resolution test was prepared from a USAF tribar resolution chart by varying exposure time to obtain copies at the five contrast levels listed in TABLE 2-1. The microdensitometer measurements used to calculate contrast were obtained on the smallest bars typically resolved on each target. Brightness of the large square in the highest contrast target was measured on a screen in the projector and yielded a contrast of 6.87 and a modulation of .77. The resolution target background density was constant for all five levels. All five copies showed good definition under magnification at higher spatial frequencies than could be resolved under any viewing condition with the rear screen projector. The highest contrast copy of the target showed a slight tendency for the bars to fill into the spaces.

The spatial frequency of the elements in the tribar resolution chart was specified in terms of a resolution number (RN), which was related to spatial frequency on the screen as follows:

$$\text{Frequency (lines/millimeter)} = \frac{2^{(RN/6)}}{11.4}$$

Frequency values for a range of resolution numbers are listed in TABLE 2-2.

The imagery for the screen quality testing consisted of 18 frames of large scale operational imagery on a 9-inch format. The frames were selected

TABLE 2-1

CONTRAST CHARACTERISTICS OF RESOLUTION TARGETS

?.

C^a	M^b
23.0	.92
4.45	.69
.86	.30
.38	.16
.073	.035

$^aC = \frac{B_1 - B_2}{B_2} = \frac{2M}{1-M}$, where B_1 and B_2 are the luminance of the brighter and darker areas, respectively.

$^bM = \frac{B_1 - B_2}{B_1 + B_2} = \frac{C}{2+C}$

TABLE 2-2

SPATIAL FREQUENCY ON PROJECTION SCREEN

FOR EACH RESOLUTION NUMBER

RESOLUTION NUMBER	SPATIAL FREQUENCY (1/mm)[9]
19	.79
20	.89
21	1.00
22	1.12
23	1.25
24	1.40
25	1.57
26	1.78
27	2.00
28	2.24
29	2.49
30	2.80
31	3.14
32	3.56
33	3.99
34	4.47
35	4.99
36	5.60
37	6.29
38	7.11
39	7.98
40	8.95
41	9.98
42	11.20
43	12.57
44	14.22

so that half had normal contrast and half had a lower than normal contrast, usually because of ground haze. The selections were made by personnel whose normal task was assessment and improvement of image quality. On each frame a heavily developed ground area was marked off for viewing by the interpreter when he was making a quality judgement. Transmission of the imagery in these areas typically varied from 2 to 25 per cent, measured over a spot approximately 1/6 inch wide on the imagery.

2.3 TEST OBSERVERS

A total of ten test observers were used. The three resolution test observers normally worked on quality control of operational imagery and had used tribar resolution targets in the past. The seven screen quality test observers were experienced image interpreters. All ten observers stated they had 20/20 visual acuity (corrected) in clinical tests. Most of the observers wore glasses and one of the resolution observers had useful vision in only one eye.

2.4 QUALITY TEST I

Each interpreter in the first screen quality test judged 144 pairs of screens, 72 with normal and 72 with low contrast imagery. The 72 pairs provided that each of the 36 possible pairings would appear twice, with the screen positions reversed to counterbalance the effect of any tendency to left or right responses. Screen pairs and frames of imagery were presented in a random sequence, with the restriction that the same screen or frame did not appear in two consecutive trials. The three interpreters made a total of 432 judgements.

The interpreters were told to use their own experience and judgement as a basis for picking the best screen in each pair, but it was suggested that they attempt to compare screens in terms of the amount of information that could be extracted from the imagery. Specific features mentioned as possibly providing a basis for choice included small, barely resolvable objects and low contrast edges such as the base of a building in a shadow area. To make a comparison, an interpreter would generally study one or more ground features on one screen and then on the other, adjusting projector focus as he desired. This process might be repeated several times during the 1 3/4 minutes allowed for a trial. A choice was required on each trial, even though an interpreter would sometimes complain that the two screens were identical.

The three interpreters were tested as a group, all three judging one of the screen pairs before the next pair was installed. While one observer was viewing a pair of screens, the other two were seated outside the test room. The necessity for obtaining independent judgements was stressed and they were cautioned not to discuss their choices with each other.

Screen brightness was maintained at the maximum level during this test. On-axis luminance of the screens varied from 10 to 107 foot lamberts, depending on the transmission characteristics of each screen. The measurement technique and luminance data are included in Appendix A.

2.5 QUALITY TEST II

The second quality test was like the first except that a single interpreter served as an observer, and screen luminance was controlled at an on-axis value of 10 foot lamberts. Control was achieved by varying the voltage on the projection lamp, as described in Appendix A. The interpreter viewed only one member of a screen pair at a time. The other screen was covered with a sheet of cardboard hinged so it could be swung aside quickly. When shifting from one screen to the other, both were covered while the lamp voltage was adjusted to the proper level for the screen to be viewed.

2.6 QUALITY TEST III

The third quality test was conducted in much the same manner as the first. Three interpreters were tested, but only one was present at a time. Only seven of the screens were tested; screens AL-4 and AL-5 were excluded because they were generally poor in all the previous testing. Screen brightness was controlled with neutral density filters to maintain a luminance level of approximately 30 foot lamberts for six of the screens. The seventh, screen AQ-20, had a very low transmission and a brightness of approximately 14 foot lamberts. Brightness was matched over a 30 degree area, using the measurement technique and data contained in Appendix A.

2.7 RESOLUTION TEST

2.7.1 Initial Resolution Test

Resolution judgements were obtained for each of the nine screens at the five target contrast levels and three viewing angles, 0, 22, and 45 degrees, for a total 135 judgements per set. Three subjects each completed three such sets of judgements under the maximum brightness level normally available, for a total of 1215 judgements, thus completing the resolution testing as described in the test proposal, DK-423. Additional judgements were made under other brightness and viewing conditions, as described later in this section.

Screen resolution was measured by having the observers estimate the smallest element in the tribar resolution chart they could distinguish. Before testing started, the three subjects discussed and agreed upon a single criterion for their judgements; the element named was to be the smallest in which the space between both the horizontal and vertical bars could be seen. The observers were allowed to change projector focus freely and indicated different settings were sometimes required for the horizontal and vertical portions in a single element.

To enable the observers to maintain the proper viewing angle,sheets of poster board were mounted chin high at angles of 0, 22, and 45 degrees off the screen axis. Two of the subjects kept the proper sheet centered between their eyes; the third aligned his one good eye. The experimenter sat to one side of the projector and positioned the target vertically to the height of the subject's eyes.

Initially a fixed viewing distance of ten inches was planned. During the practice session, the subjects indicated they could resolve smaller targets by moving closer so they were allowed to view the screens at the nearest comfortable position. This was typically five to seven inches from the diffusing surface of the screen.

During testing, a single screen was mounted and judgements were obtained at each of the 15 target contrast-viewing angle conditions. These conditions were presented in random order, with no angle and no contrast repeated on consecutive trials. Then another screen was mounted and the 15 viewing conditions were repeated following a new random sequence. A single one-hour test session was usually sufficient to obtain the 15 judgements on each of the nine screens. Each subject received three test sessions in this manner.

2.7.2 Additional Resolution Testing

Two facts emerged which led to an extension of the resolution testing. The first screen quality test had identified screen brightness as an important factor in judged quality, and the resolution test subjects had indicated they felt that even at the closer viewing distance, their responses were still partially limited by visual acuity.

Additional resolution judgements were obtained under the same controlled brightness conditions used in the second screen quality test; i.e., the lamp voltage was adjusted to obtain an on-axis luminance of 10 foot lamberts for each screen. Following this, resolution judgements were obtained under both luminance conditions with a 7X Bausch and Lomb tube magnifier used as a viewing aid. The amount of data obtained under these conditions is listed in TABLE 2-3.

2.7.3 Projector Resolution Testing

The quality of the projector optical system was measured by viewing the arial image with a tube magnifier in the plane of the screen. The resolution values obtained with each target contrast were

TABLE 2-3

SCREEN RESOLUTION DATA

	PRIMARY TEST	ADDITIONAL TESTING		
SCREEN LUMINANCE	NORMAL	NORMAL	CONTROLLED TO 10 FL	
VIEWING MAGNIFICATION	1X	7X	1X	7X
TEST OBSERVERS[a]	1,2,3	2	2,3	2
SETS OF DATA FOR EACH SUBJECT	3	1	1	1

[a] The subject with useful vision in only one eye was number 2.

as follows:

CONTRAST	RESOLUTION NUMBER
23.0	41.5
4.45	43.5
.86	42.0
.38	40.0
.073	22.0

3.0 RESULTS

3.1 SCREEN QUALITY JUDGEMENTS

The quality data were analyzed by calculating the proportion of time each screen was chosen as best. These proportions were converted to normal deviate Z scores corresponding to the proportions of a dichotomous unit normal distribution. The effect of this was to increase the weight given to extremely high or low proportions.

The quality scale values obtained in each of the three tests are plotted in Figure 3-1 and listed in TABLE 3-1. Connecting lines were used in the figure to show the scale values a screen received on each test. Some of the screens, for example AQ-20, varied spectacularly between studies. Others, such as AL-4 and AL-5, were consistently poor and some, such as AQ-11 and AR-27, were consistently among the best liked screens. The range of screen scale values was smallest in Test III.

Quality scale values were calculated separately for each imagery contrast level. These values are plotted in Figure 3-2 for each quality test. The magnitude of the differences between imagery contrast levels was generally small relative to the differences between screens.

To assess the effect of imagery density on screen quality judgements, the 18 frames were divided into halves on the basis of density and the data obtained in Test III were reananlyzed. The resulting scale values can be found in TABLE 3-2 and Figure 3-3. Differences as a function of imagery density were very small in comparison with the differences between screens.

3.2 SCREEN RESOLUTION

The resolution data obtained during the testing were described in TABLE 2-3. The principle data were three replications by three

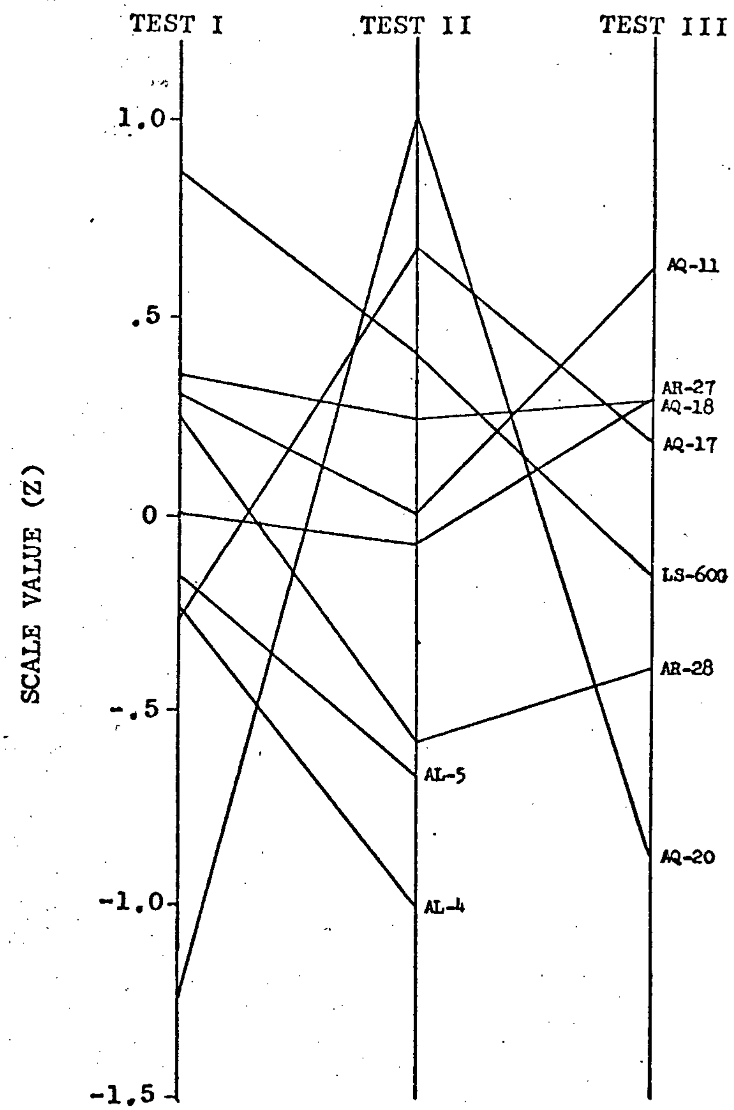

FIGURE 3-1 SCREEN QUALITY SCALE VALUES IN EACH TEST

TABLE 3-1

SCREEN QUALITY SCALE VALUES

IMAGERY CONTRAST	TEST I			TEST II			TEST III		
	COMBINED	NORMAL	LOW	COMBINED	NORMAL	LOW	COMBINED	NORMAL	LOW
SCREEN									
AL-4	-.24 .40	-.27	-.21	-1.01 .16	-.67	-1.54			
AL-5	-.16 .44	-.16	-.16	-.67 .25	-.88	-.49			
AQ-11	.30 .62	.16	.44	0 .50	0	0	.61 .73	.46	.79
AQ-17	-.27 .39	-.35	-.21	.67 .75	.49	.89	.18 .57	.22	.14
AQ-18	0 .50	0	0	-.08 .47	-.16	0	.29 .61	.30	.29
AQ-20	-1.25 .11	-1.30	-1.19	1.01 .84	.68	1.54	-.88 .19	-.97	-.83
AR-27	.35 .64	.38	.32	.24 .60	.49	0	.29 .61	.27	.29
AR-28	.24 .60	.33	.16	-.58 .28	-.49	-.67	-.40 .34	-.21	-.61
LS-60G	.86 .80	1.03	.73	.40 .66	.49	.32	-.15 .44	-.15	-.14

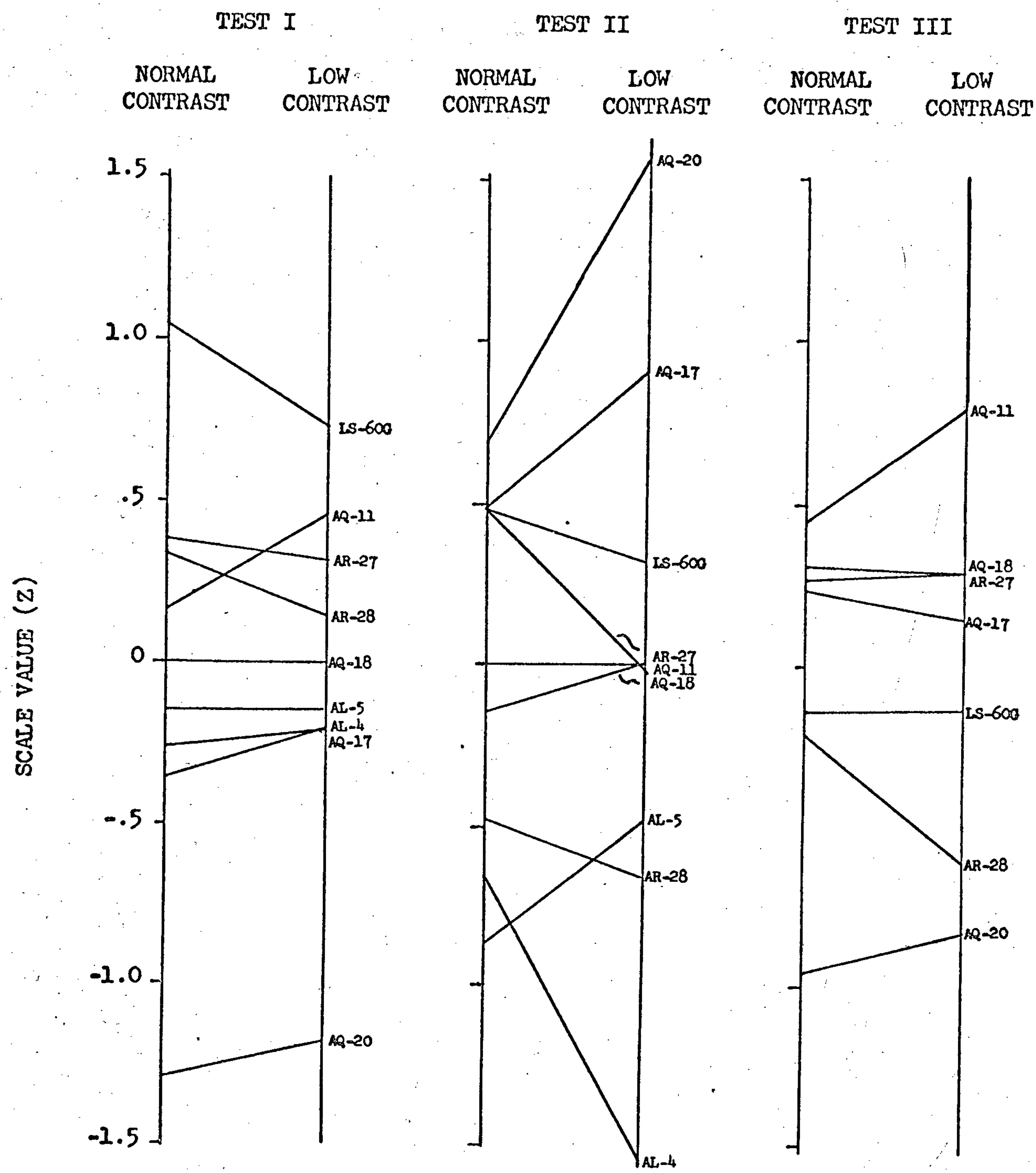

FIGURE 3-2. EFFECT OF IMAGERY CONTRAST ON SCREEN QUALITY SCALE VALUES IN EACH TEST

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TABLE 3-2

QUALITY SCALE VALUES FOR EACH SCREEN
AS A FUNCTION OF IMAGERY DENSITY

SCREEN	IMAGERY DENSITY	
	LOW	HIGH
AQ-11	.44	.74
AQ-17	.23	.13
AQ-18	.44	.20
AQ-20	-.74	-1.04
AR-27	.25	.33
AR-28	-.36	-.44
LS-60G	-.10	.20

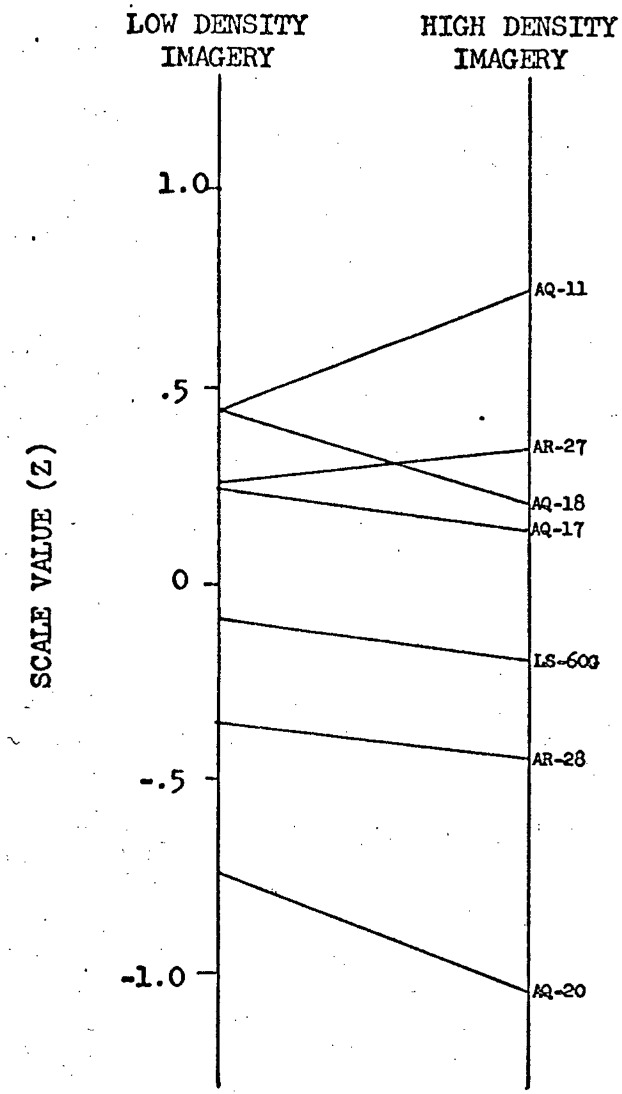

FIGURE 3-3. EFFECT OF IMAGERY DENSITY ON SCREEN QUALITY SCALE VALUES IN TEST III

observers with normal screen luminance and no magnification aids. However, in order to assess the affect of screen luminance, analyses were also performed on the remainder of the data. Four analyses of variance, each involving a full factorial design, were performed to identify which variables were associated with differences in resolution. The basic data set of 135 resolution judgements on nine screens at five target contrast levels and three viewing angles was included in each analysis. The additional factors were as follows:

1. Three observers, three replications, normal screen luminance and no magnification (this was the primary analysis);
2. Observers 2 and 3, one replication, normal and controlled screen luminance, no magnification;
3. Observers 2 and 3, one replication, controlled screen luminance, no magnification; and
4. Observer 2, one replication, normal and controlled screen luminance, 1X and 7X magnification.

The most important results from these analyses are reported in this section. Summary tables for each analysis and the associated data are located in Appendix B. The summary tables include a statement of the statistical significance of the differences in resolution associated with each of the test variables. These will be indicated in the text below as the probability (P) that the differences discussed were due to chance.

At normal luminance levels, the screens differed in resolution ($P < .01$). As Figure 3-4 illustrates, the differences fell generally into two groups. A Duncan's multiple range test indicated that the two groups differed from each other, but within a group only screens LS-60G and AQ-11 differed ($P < .05$).

The test of the effects of screen luminance on the resolution of each screen was very insensitive because of the small quantity of data available. Luminance effects were tested in the second and third

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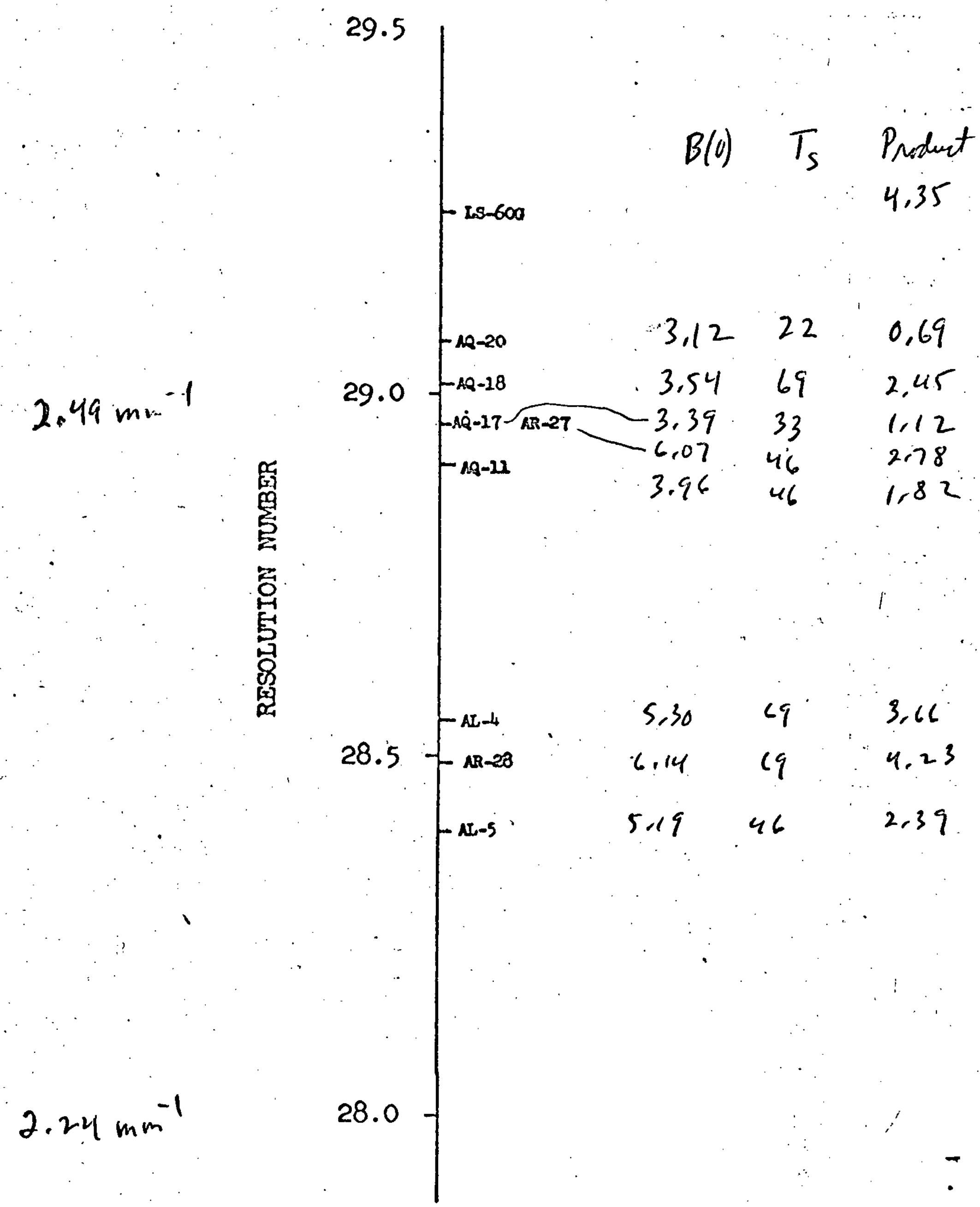

FIGURE 3-4. RESOLUTION FOR EACH SCREEN UNDER NORMAL LUMINANCE FOR THREE OBSERVERS

analyses of variance. In the second, luminance had no overall effect and screens differed from each other ($P<.05$) but not as a function of luminance condition. In the third analysis, which included only the controlled-luminance half of the data from the second analysis, screens did not differ significantly in resolution. The resolution values in question are plotted in Figure 3-5.

Resolution was affected by viewing angle ($P<.01$) and target contrast ($P<.01$). The effect of viewing angle was related to target contrast ($P<.01$). As may be seen in Figure 3-6, resolution was worse at low contrast levels and, for low contrast targets, at small viewing angles. The effect of viewing angle also appeared to differ between observers, although no statistical test was made. As Figure 3-7 illustrates, the greatest degradation in resolution at a 0 degree viewing angle occurred with Observer 2, who had only one good eye and could come closer to achieving a viewing angle of exactly 0 degrees.

The resolution values obtained were considerably lower than the capabilities of the human eye. In Figure 3-8, resolution at each contrast level can be compared with typical visual acuity and with judged resolution values obtained by direct viewing of the resolution targets used in the present study.

Viewing angle had an effect on the relative resolution values for the screens ($P<.05$). As Figure 3-9 illustrates, the resolution values for the screens extended over a greater range at a viewing angle of 0 degrees. The screens shifted their relative position on the resolution scale; for example AQ-20 was the best screen at 0 degrees but sixth at 45 degrees.

Target contrast also had an effect on the relative resolution scale values for the screens ($P<.01$). Figure 3-10 shows resolution for the screens which had the highest and lowest resolution values with target contrasts of .073 and 23. Screen AQ-20 is noteworthy in that it is the best of the nine screens with a target contrast of .073 and the worst with a contrast of 23.

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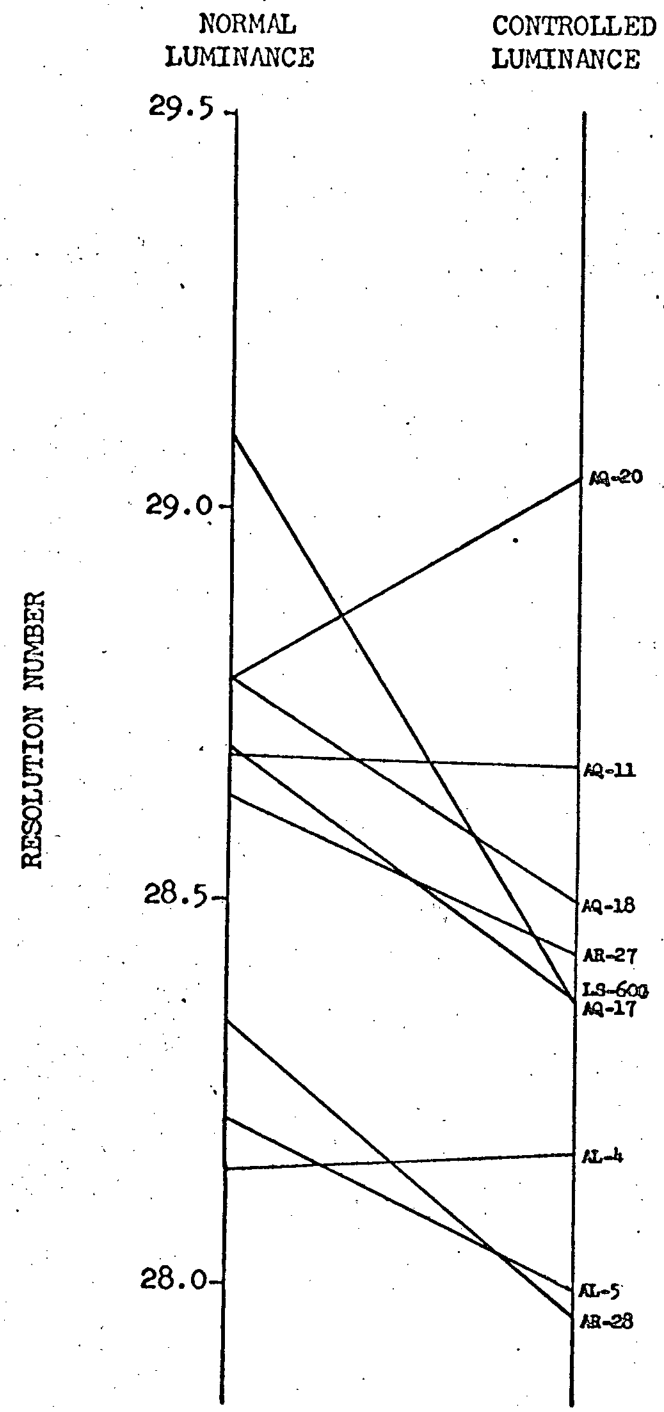

FIGURE 3-5. RESOLUTION FOR EACH SCREEN UNDER EACH LUMINANCE CONDITION FOR OBSERVERS 2 AND 3

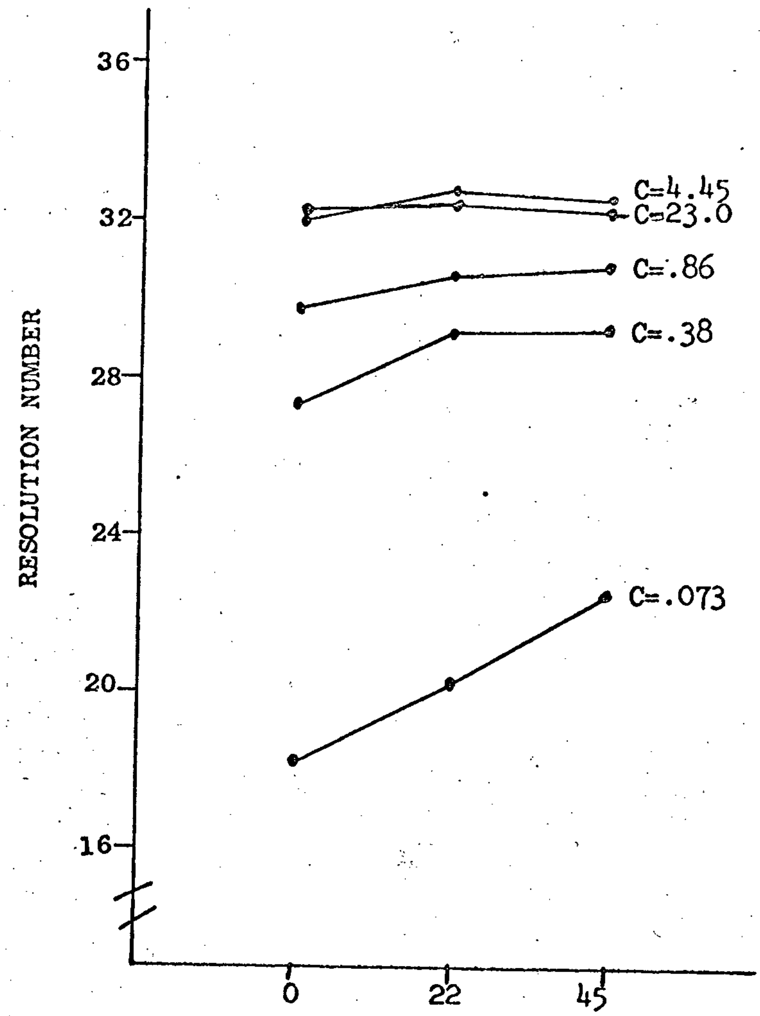

FIGURE 3-6. EFFECT OF VIEWING ANGLE AND CONTRAST ON RESOLUTION WITH NORMAL SCREEN LUMINANCE FOR THREE OBSERVERS

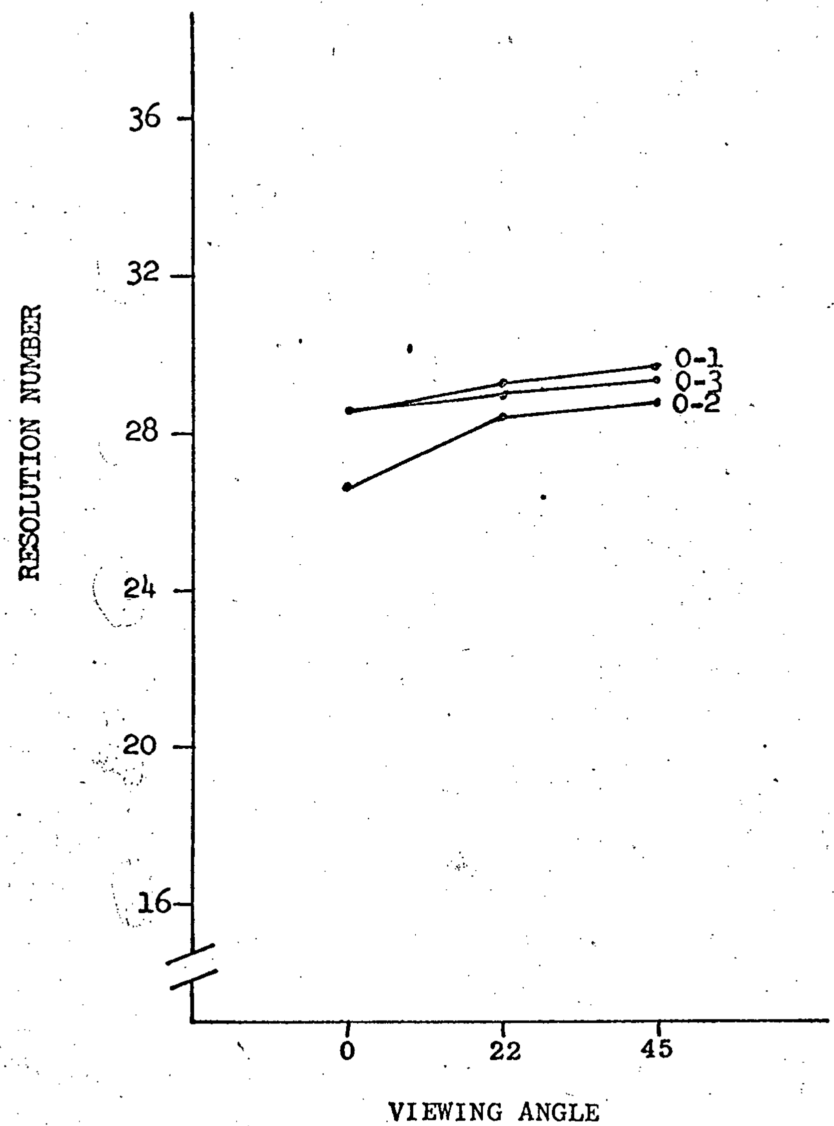

FIGURE 3-7. RESOLUTION FOR EACH OBSERVER AT EACH VIEWING ANGLE WITH NORMAL LUMINANCE

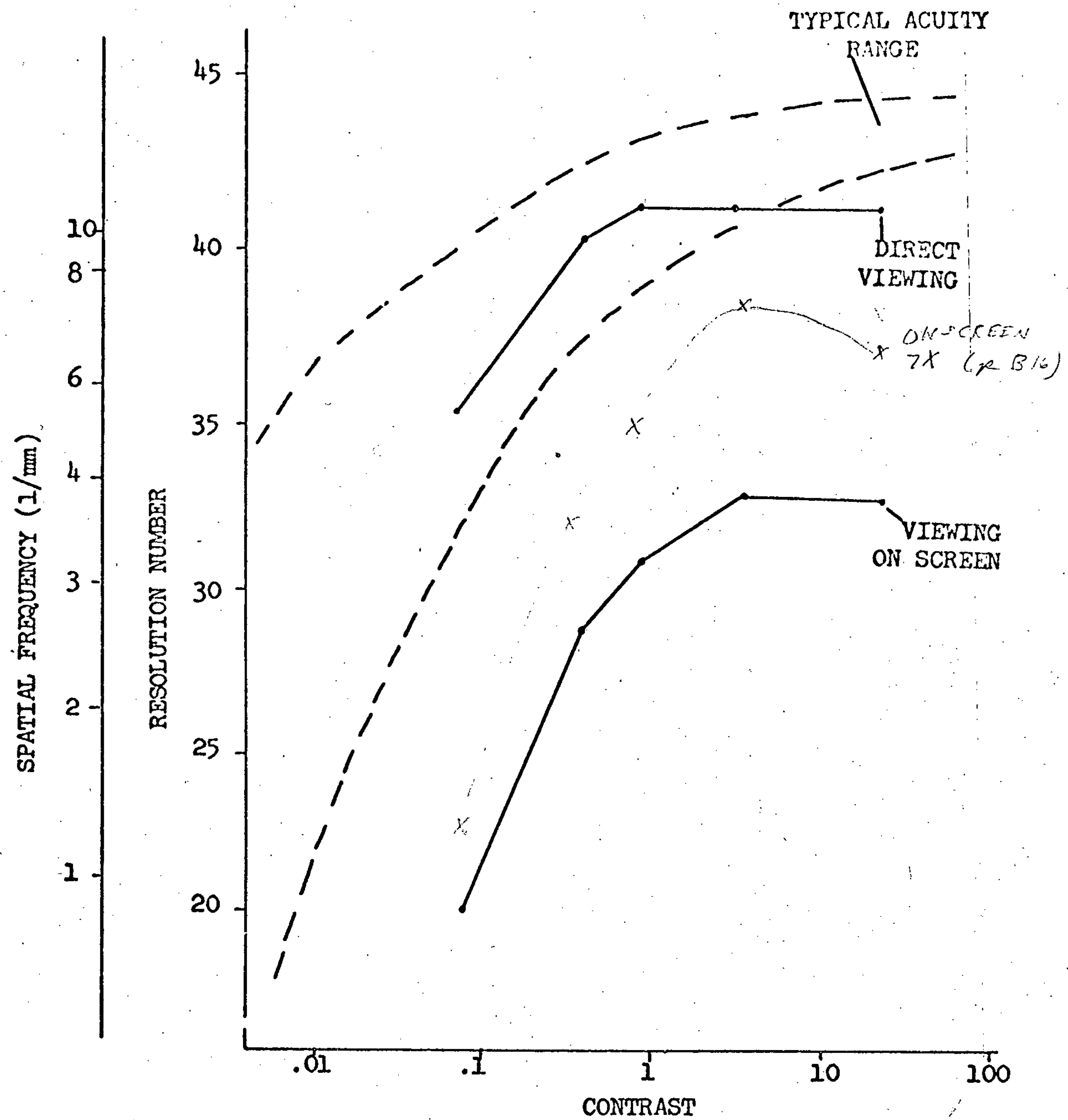

FIGURE 3-8. SCREEN RESOLUTION AS A FUNCTION OF CONTRAST LEVEL COMPARED TO VISUAL ACUITY DATA

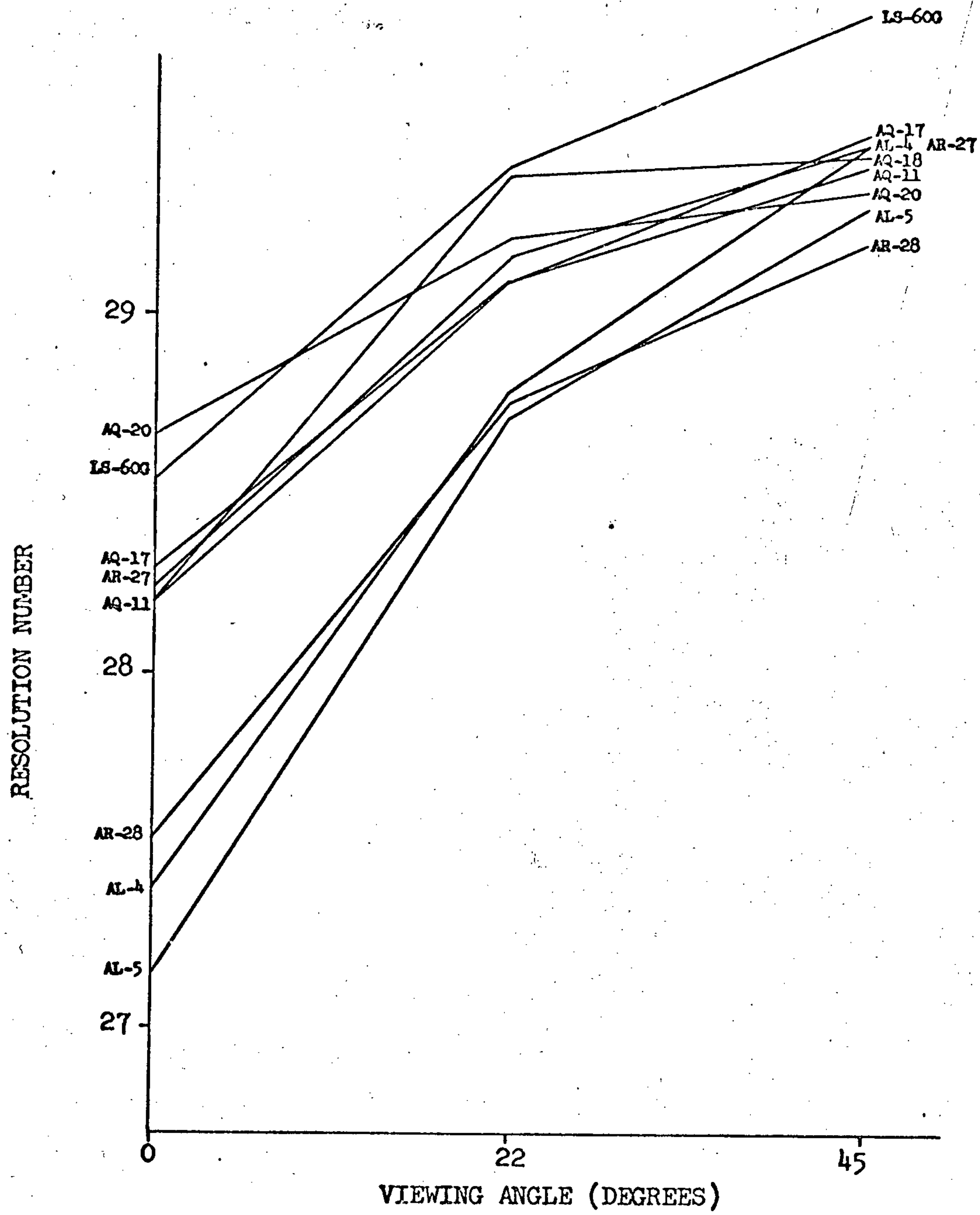

FIGURE 3-9. RESOLUTION AS A FUNCTION OF VIEWING ANGLE FOR EACH SCREEN

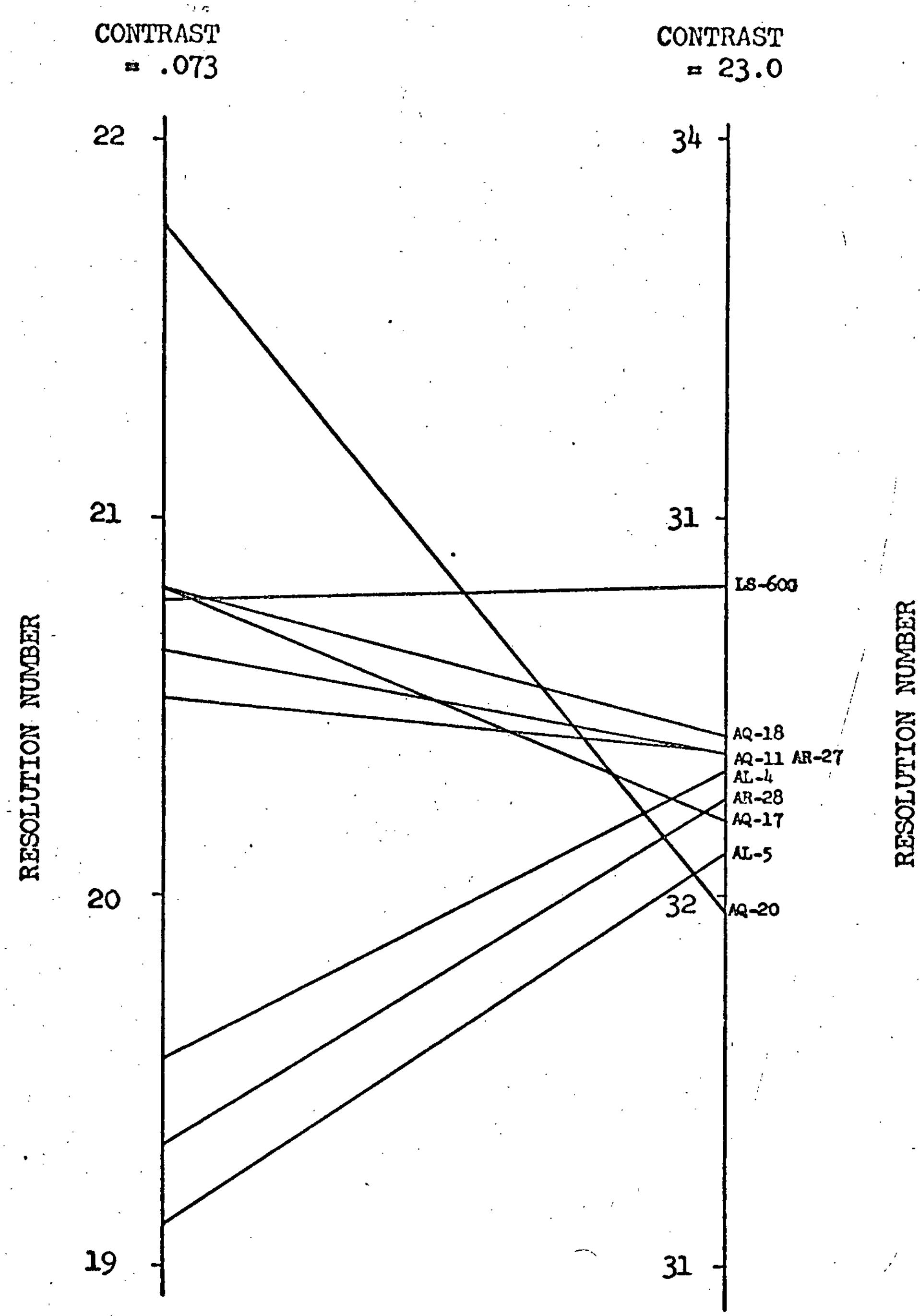

FIGURE 3-10. RESOLUTION FOR EACH SCREEN AT MINIMUM AND MAXIMUM CONTRAST UNDER NORMAL LUMINANCE

The 7X tube magnifier enabled Observer 2 to distinguish smaller targets ($P<.01$), increasing resolutions from 27.9 to 32.4. Improvements occurred for each viewing angle, target contrast level and screen, although the amount of the improvement was not constant ($P<.01$ for each of the three factors). In the case of screens, some showed more improvement than others. As Figure 3-11 illustrates, the screens were very similar at 1X but fell into two distinctly different groups at 7X.

3.3 RELATIONSHIPS BETWEEN VARIABLES

Relationships between the many variables obtained for each screen were measured by calculating correlation coefficients for the following:

- Between screen parameters,
- Between quality scale values,
- Between resolution values,
- Between quality and screen parameters,
- Between resolution and screen parameters,
- Between quality and resolution values

Only the most important correlations will be discussed in the text. They are all listed in the tables in Appendix C. Included with each table is an indication of which correlations were significantly different from zero. The correlations involving quality judgements were essentially the same whether based on judgements obtained with one or both imagery contrast levels so only the correlations for both contrast levels were reported. One of the parameters, log brightness (LBRT), varied between tests. For Test II the screen luminance was adjusted to keep LBRT constant between screens so the values measured in Test I were used in the computation of correlations. In Test III, a different method of calculating LBRT was used. It is described in Appendix A.

3.3.1 Screen Parameters

The intercorrelations between screen parameters indicated the existence of a set of parameters highly related to each other which generally involved the level and distribution of screen luminance. These included B(O), V_{45}, V_{30}, T_S, B(O)T_S, $T_{45}T_S$, $T_{30}T_S$, and LBRT. MTF was positively related to this set, while measures of substrate transmission, T_{90}, T_{45}, and T_{30} generally were not correlated with it.

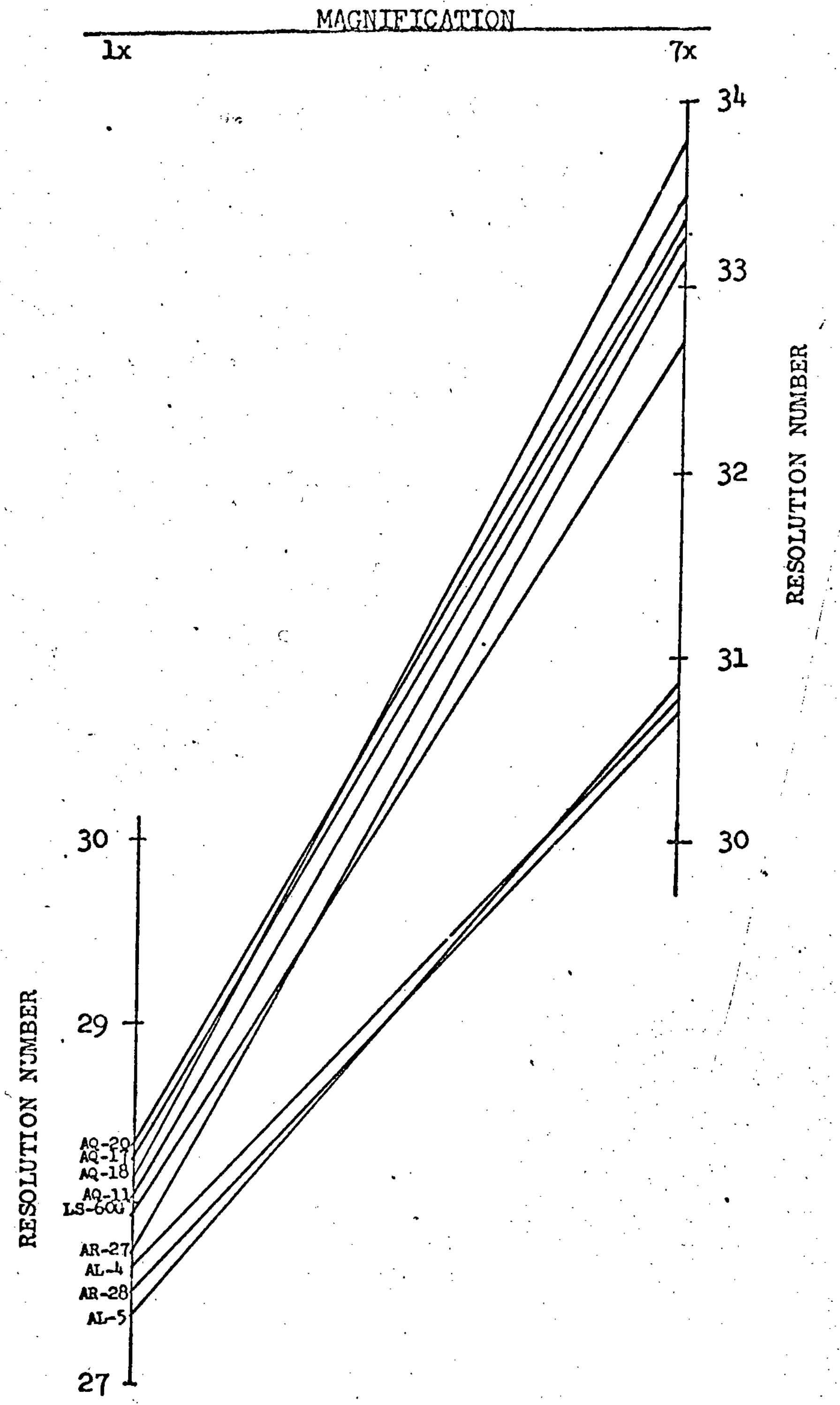

FIGURE 3-11. EFFECT OF MAGNIFICATION ON RESOLUTION FOR EACH SCREEN FOR OBSERVER 2, AVERAGED OVER BOTH LUMINANCE CONDITIONS

3.3.2 Quality Judgements

The intercorrelations between the scale values in the three quality tests were calculated for all the screens tested and again with screens AQ-20 or LS-60G exlcuded. The only statistically significant correlation was a value of 0.75 for Tests I and III with screen LS-60G excluded from the analysis.

3.3.3 Resolution

Generally positive correlations occurred for resolution at different viewing angles and for average resolution under both screen luminance conditions. Between resolution scores at the extremes of target contrast there was essentially zero correlation when the screen luminance was normal; with controlled luminance these correlations were positive.

3.3.4 Quality/Screen Parameters

The set of screen luminance related parameters listed in Section 3.3.1 was generally positively correlated with quality under normal screen luminance in Test I and negatively correlated under controlled screen luminance in Tests II and III. The negative correlations were obtained in Test III only if screen AQ-20 was excluded from the analysis; when it was included the correlations generally went to zero.

3.3.5 Resolution/Screen Parameters

The set of screen luminance parameters (listed in Section 3.3.1) and MTF, were generally negatively related to resolution scores under both screen luminance conditions. This relationship varied with target contrast when normal screen luminance was used. With the low contrast targets the correlation was negative, but with high contrast it became positive. The shift in the correlation was a result of the shift in relative resolution scores for each screen illustrated in Figure 3-10.

3.3.6 Resolution/Quality

Under normal luminance conditions, the correlation of resolution with quality judgements showed the same reversal of sign as did the correlation of resolution with screen parameter. With high contrast resolution targets the correlations were positive; with low contrast they were

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negative. The correlations between average resolution and quality were essentially zero. For controlled screen luminance, the correlations of resolution and quality were positive for all contrast and viewing angles.

3.4 REGRESSION EQUATIONS

Regression equations defining screen quality and resolution scores as a function of screen parameters are listed in Appendix D. In general, different parameters were found to predict screen quality or resolution for each different viewing condition or combination of screens included in the analysis.

4.0 DISCUSSION

No single screen was consistently judged best by the observers under all test conditions. As screen luminance levels changed between tests, the quality judgements changed. Some screens tended, however, to fall consistently at the upper or lower end of the quality continuum. Screens AQ-11 and AR-27 were consistently at the good end and AL-4 and AL-5 were consistently at the poor end. Some screens, particularly AQ-20 and LS-60G, varied in relative judged quality between the tests. (Refer to Figures 3-1 and 3-4)

Changes in screen luminance might have had much less effect if the overall levels had not been so low. ,In Test III, where the screens were matched in brightness at the maximum output level of the projector an open gate level of only approximately 30 foot lamberts was achieved.

The largest variations in relative screen quality occurred in Test II. The results in this test must be interpreted cautiously, since the luminance control technique introduced color differences between the screens which may have affected judgements. Also, the use of on-axis brightness measurement to match screens resulted in higher off-axis brightness for the low gain screens than for the high gain screens.

The differences in resolution between the screens were small, approximately one resolution number. The best screens in the quality test were also among the best in the resolution test. The inverse was only partially true. For example, screen AQ-20 had good resolution but was judged poor in Quality Tests I and III, and screen LS-60G had the best resolution and varied widely in judged quality over the three tests. (Refer to Figures 3-1 and 3-4)

Resolution was much lower than the capabilities of the human visual system (Figure 3-8). The highest frequencies resolved were between 3 and 4 lines per millimeter for high contrast targets and less than

See page B17
RN 35,58 → 5,3 li/mm
But this is ave of 1X and 7X

one line per millimeter for the lowest contrast target. This was initially considered to be the limiting resolution for the screens, but use of a 7X tube magnifier as a viewing aid allowed significantly higher frequencies of up to six lines per millimeter to be resolved.

With low contrast targets, resolution was better off-axis. This appeared to result from a bright spot in the screen which tended to wash out a low contrast image. The decrement on-axis was greatest for the one observer who could most nearly achieve an exact on-axis viewing position because he had only one good eye, implying that the decrement exactly on-axis is probably larger than in the averages reported in this study. The resolution targets had a constant, high background brightness. Data on targets with darker backgrounds would be helpful in understanding the on-axis resolution degration which was observed.

The relative resolution of screens varied as a function of target contrast and viewing angle. Screen AQ-20 in particular showed large shifts. It was the best screen at a 0 degree viewing angle, but was sixth at 45 degrees. It was the best screen with low contrast targets and the worst with high contrast targets. A possible interpretation is that this screen has a generally poor resolution capability, but its low transmission and low brightness gain result in less washout of low contrast targets viewed on-axis. Whatever, the explanation it is obvious that a best screen cannot be chosen on the basis of resolution data without considering viewing angle and target contrast.

The wide changes in judged quality and resolution for a given screen under the several test conditions effectively eliminated any consistent correlations with the physical parameters used to describe the screens. However, these correlations do help identify some of the factors which influenced observers' judgements. With normal screen luminance the brighter high gain, high transmission screens were preferred. Brightness in the second and third studies was matched over a relatively small angle making those screens with the widest distribution of luminance (low gain) appear brightest and possibly causing the generally negative correlations between quality and parameters measuring screen brightness distribution.

The conclusion that brightness is the primary determinant of screen quality, although implied by these results, does not appear to be warranted. The nine screens tested were very similar in most obvious qualities except brightness. Interpreters frequently complained that they were looking at identical screens and sometimes stated they had to use some aspect of brightness to make their decision. Screens AL-4 and AL-5, which were generally judged poor, were intermediate on the brightness parameters and differed from the other screens in that they had a thinner diffusing layer (DRTHI) and higher scattering layer reflectance (R_D).

The regression equations predicting screen performance (quality or resolution) from screen parameters contained different parameters for each test condition. This was caused by the same factors which produced the shifts in the correlations. First, the best screens differed as a function of test condition, and second, the high intercorrelations between screen parameters made them easy to interchange.

The size of the screens studied must be considered when using the results to choose a screen for use with an imagery scan task. With a larger display area, brightness at the screen edges would be more difficult to maintain and a lower gain screen would become more desirable.

5.0 CONCLUSIONS

The following conclusions are suggested by the data:

1. The differences among the screens in both judged quality and judged resolution are small.
2. Quality judgements were strongly affected by screen luminance - observers preferred the brighter screens and, when brightness was matched over a central angle, preferred the screens with higher brightness toward the edges. Parameters relating to brightness distribution (B(O), V_{45}, etc.) and overall brightness (LBRT) appear, therefore, to be related to the judged screen quality.
3. Some of the screens were generally better on both quality and resolution under all test conditions and others were consistently poor.
4. Whereas there was some general agreement between the resolution and judged quality test results, they did not provide the same information with enough consistency to indicate that the simpler resolution test could be used alone as an indication of screen quality.
5. In future screen development, consideration must be given to the availability and cost of high output light sources.
6. The screen which provides the best resolution at one target contrast may not be best at some other contrast. The cause for this was not directly apparent from the data.

6.0: REFERENCES

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Klaiber, R. J., Physical and Optical Properties of Projection Screens. NAUTRADEVCEN IH-63, 1966.

APPENDIX A

PROJECTION SCREEN PHYSICAL PARAMETERS

Physical parameters measured on each screen are listed in TABLES A-1 and A-3. Descriptions of the screen parameters are in TABLE A-2. The values in TABLE A-1, including those for the Polacoat screen (LS-60G), were made by the manufacturer of the experimental screens. The screen brightness measurements in TABLE A-3 were made while the screens were mounted in the rear projection viewer. The measuring instrument was a Gamma Scientific Model 700 Photometer with a Model 700-2 Photometric Telescope with a 1 degree, 0.06 inch aperture.

The luminance values in TABLE A-2 were measured with normal line voltage on the projector lamp. For Quality Test II, the lamp voltage was adjusted to obtain a 10 foot lambert (FL) luminance at 0 degrees. Neutral density filters were used to match brightness in Quality Test III. To select the filters, luminance levels measured at 0, 5, 10, and 15 degrees were averaged, with off-axis values entered twice. Filters were selected to achieve the best match between averages. The filters available differed by 0.1 density steps. A minimum density filter was used with screen AQ-20 and it was not included in the matching process. Light output was increased by cleaning the projector optics and increasing the voltage on the lamp. The resulting average filtered luminance levels are listed as LBRT-III in TABLE A-1.

TABLE A-1

PARAMETER VALUES OF SCREENS STUDIED

PARAMETER	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
B(O)	5.30	5.19	3.96	3.39	3.54	3.12	6.07	6.14	4.35
V_{45}	72	72	56	50	51	46	70	72	73
V_{30}	62	62	38	36	34	29	53	54	51
T_{90}	56	54	68	64	66	62	74	73	
T_{45}	39	38	49	45	47	45	59	57	
T_{30}	26	26	32	29	30	28	41	41	
R_D	20	20	10.7	9.5	9.5	9.5	9.5	9.5	
T_S	69	46	46	33	69	22	46	69	
$B(O)T_S$	3.66	2.39	1.82	1.12	2.45	0.69	2.78	4.23	4.35
$T_{45}T_S$	27	17	23	15	32	10	27	39	43
$T_{30}T_S$	18	12	15	10	21	6	19	28	30
R_DT_S ($R_DT_S^2$)	9.5	4.2	2.3	1.03	4.5	0.46	2.0	4.5	6.3
αT	.740	.135	.133	.081	.630	.062	.086	.240	.11
LBRT-I	1.68	1.59	1.50	1.43	1.62	1.00	1.63	2.03	1.82
LBRT-III			1.51	1.50	1.51	1.13	1.48	1.53	1.46
*MTF	.918	.878	.892	.874	.854	.805	.906	.925	.959
DRTHI	32	22	74	80	82	89	78	72	76
*Correct MTF values.	0.975	0.985	0.974	0.976	0.970	0.961	0.985	0.971	0.959

TABLE A-2

SCREEN PARAMETER DESCRIPTIONS

PARAMETER	DESCRIPTIONS
B(O)	Scattering layer axial gain
V_{45}	Scattering layer brightness variation within 45° (%)
V_{30}	Scattering layer brightness variation within 30° (%)
T_{90}	Scattering layer transmission within 90° (%)
T_{45}	Scattering layer transmission within 45° (%)
T_{30}	Scattering layer transmission within 30° (%)
R_D	Scattering layer diffuse reflectance (%)
T_S	Substrate transmittance (%)
$B(O)T_S$	Product of B(O) and T_S
$T_{45}T_S$	Screen transmission within 45° (%)
$T_{30}T_S$	Screen transmission within 30° (%)
R_DT_S	Product of R_D and T_S (%)
αT	Trapped light ratio (%)
LBRT-I	Log brightness on axis with 1° cone, Quality Study I
LBRT-III	Log average brightness after filtering, Quality Study III
MTF	Modulation transfer function at 5 l/mm with square-wave target in contact with diffusing surface
DRTHI	Dry thickness (microns)

TABLE A-3

SCREEN LUMINANCE[a]

B(0) Ts → 3,66 2,39 1,82 1,12 2,45 ,69 2,78 4,23 4,35

ANGLE FROM AXIS	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
0°	54 1	40 1	36 1	28 1	44 1	10 1	47 1	107 1	79 1
5°	52 .965	39 .975	35 .972	28 1	44 1	10 1	44 .935	103 .763	78 .987
10°	42 .778	32 .800	32 .889	25 .892	41 .931	10 1	39 .830	82 .765	72 .911
15°	34 .630	25 .625	28 .777	21 .750	36 .818	9 .9	33 .702	63 .589	62 .785
22°	20 .371	16 .400	20 .556	13 .464	25 .518	8 .8	24 .510	38 .355	43 .545
45°	11 .204	7 .175	11 .305	7 .250	15 .341	6 .6	11 .234	14 .131	17 .215

a Values in FL as measured with a 1° acceptance angle sensor.

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APPENDIX B

SCREEN RESOLUTION DATA

This section contains summary tables for the four analyses of variance calculated on the resolution data, followed by the averages over the primary factors in each analysis. The design for each of the analyses was a full factorial. Each included the three basic factors - nine screens, three viewing angles and five contrast levels, and the additional factors listed below.

ANALYSIS	OBSERVERS	SCREEN LUMINANCE	REPLICATIONS	MAGNIFICATION
I	1, 2, 3	Normal	3	1X
II	2, 3	Normal, Controlled	1	1X
III	2, 3	Controlled	1	1X
IV	2	Normal, Controlled	1	1X, 7X

TABLE B-1

SUMMARY OF ANALYSIS OF VARIANCE I

SOURCE	df	MS	F	P
Angle (A)	2	215.555	7.75	.05
Contrast (C)	4	6057.953	452.60	.01
Screen (S)	8	11.715	7.74	.01
Observer (O)	2	187.750	289.80	.01
AC	8	60.865	23.96	.01
AS	16	2.671	6.86	.01
CS	32	3.710	4.41	.01
AO	4	27.827	42.95	.01
CO	8	13.385	20.66	.01
SO	16	1.514	2.34	.01
ACS	64	.665	1.00	NS
ACO	16	2.540	3.92	.01
ASO	32	.389	.60	NS
CSO	64	.842	1.30	NS
ACSO	128	.665	1.03	NS
WITHIN	810	.648		

TABLE B-2

RESOLUTION AT EACH TARGET CONTRAST AND VIEWING ANGLE
WITH NORMAL SCREEN LUMINANCE FOR THREE OBSERVERS

	CONTRAST					MEAN
	.23	4.45	.86	.38	.073	
ANGLE						
0°	32.22	32.17	29.98	27.38	18.37	28.02
22°	32.56	32.74	30.75	29.02	20.23	29.06
45°	32.16	32.43	30.83	29.23	22.51	29.43
MEAN	32.31	32.45	30.52	28.55	20.37	28.84

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TABLE B-3

RESOLUTION FOR EACH SCREEN AT EACH VIEWING ANGLE AND TARGET CONTRAST WITH NORMAL SCREEN LUMINANCE FOR THREE OBSERVERS

	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
ANGLE									
0°	27.40	27.16	28.20	28.29	28.20	28.67	28.24	27.53	28.53
22°	28.78	28.71	29.09	29.09	29.38	29.20	29.16	28.76	29.40
45°	29.47	29.29	29.40	29.49	29.44	29.33	29.47	29.18	29.82
CONTRAST									
23	32.33	32.11	32.37	32.19	32.41	31.96	32.37	32.26	32.81
4.45	32.07	32.37	32.44	32.37	32.63	32.30	32.56	32.33	32.96
.86	30.48	30.30	30.48	30.70	30.52	30.52	30.78	30.18	30.70
.38	28.30	28.04	28.55	28.70	28.67	28.78	28.56	28.33	29.00
.073	19.56	19.11	20.63	20.61	20.81	21.78	20.52	19.33	20.78
MEAN	28.55	28.39	28.90	28.96	29.01	29.07	28.96	28.49	29.25

TABLE B-4

SUMMARY OF ANALYSIS OF VARIANCE II

SOURCE	df	MS	F	P
Luminance (L)	1	6.437	21.860	NS
Angle (A)	2	102.919	3.764	NS
Contrast (C)	4	2565.548	159.935	.01
Screen (S)	8	4.634	4.207	.05
Observer (O)	1	160.718		
LA	2	1.858	7.237	NS
LC	4	4.618	29.260	.01
AC	8	31.219	20.696	.01
LS	8	.973	2.100	.25
AS	16	.915	4.482	.01
CS	32	.871	2.376	.01
LO	1	.294		
AO	2	27.041		
CO	4	16.041		
SO	8	1.101		
LAC	8	.144	.905	NS
LAS	16	.560	2.718	.05
LCS	32	.503	1.351	NS
ACS	64	.525	1.230	.25

TABLE B-5

RESOLUTION AT EACH VIEWING ANGLE AND SCREEN LUMINANCE FOR OBSERVERS 2 AND 3

	ANGLE		
	0°	22°	45°
LUMINANCE			
NORMAL	27.65	28.87	29.26
CONTROLLED	27.60	28.70	28.82

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TABLE B-6

RESOLUTION AT EACH TARGET CONTRAST, SCREEN LUMINANCE, AND VIEWING ANGLE FOR OBSERVERS 2 AND 3

	CONTRAST					MEAN
	23	4.45	.86	.38	.073	
LUMINANCE						
NORMAL	32.14	32.25	30.32	28.24	20.02	28.59
CONTROLLED	31.87	31.72	29.76	28.04	20.48	28.37
ANGLE						
0^{o}	31.92	31.71	29.47	26.90	18.12	27.62
22^{o}	32.32	32.36	30.37	28.70	20.17	28.78
45^{o}	31.77	31.89	30.27	28.81	22.46	29.04
MEAN	32.00	31.99	30.04	28.14	20.25	28.48

TABLE B-7

RESOLUTION FOR EACH SCREEN AT EACH SCREEN LUMINANCE, VIEWING ANGLE, AND TARGET CONTRAST FOR OBSERVERS 2 AND 3

	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
LUMINANCE									
NORMAL	28.15	28.21	28.68	28.69	28.78	28.78	28.63	28.34	29.09
CONTROLLED	28.17	28.00	28.63	28.37	28.50	28.93	28.43	27.97	28.37
ANGLE									
0°	27.19	26.85	27.86	27.78	27.72	28.25	27.65	27.26	28.03
22°	28.33	28.47	29.04	28.59	28.91	29.20	28.92	28.54	29.05
45°	28.95	28.99	29.06	29.21	29.28	29.11	29.02	28.64	29.10
CONTRAST									
23	31.79	31.73	32.02	32.10	32.07	32.10	32.07	31.82	32.35
4.45	31.68	31.82	32.09	31.95	32.18	32.21	31.95	31.62	32.39
.86	29.97	29.93	30.01	30.17	30.12	30.07	30.12	29.57	30.37
.38	27.85	27.87	28.35	28.07	28.15	28.57	28.07	28.03	28.28
.073	19.49	19.16	20.82	20.34	20.67	21.34	20.45	19.72	20.24
MEAN	28.16	28.10	28.66	28.53	28.64	28.86	28.53	28.15	28.73

TABLE B-8

RESOLUTION FOR EACH SCREEN AT EACH VIEWING ANGLE AND TARGET CONTRAST UNDER EACH SCREEN LUMINANCE CONDITION FOR OBSERVERS 2 AND 3

		SCREEN								
		AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
NORMAL LUMINANCE	VIEWING ANGLE									
	0°	26.88	26.80	27.93	27.86	27.84	28.21	27.70	27.33	28.27
	22°	28.46	28.64	28.88	28.88	29.23	29.00	28.95	28.59	29.20
	45°	29.11	29.18	29.23	29.33	29.26	29.13	29.24	29.09	29.80
	CONTRAST									
	23	31.92	31.80	32.20	32.03	32.30	32.03	32.13	32.13	32.70
	4.45	31.70	32.13	32.35	32.23	32.53	32.08	32.23	32.23	32.78
	.86	30.12	30.20	30.18	30.52	30.23	30.30	30.58	30.13	30.58
	.38	27.87	27.92	28.37	28.32	28.30	28.47	28.13	28.23	28.57
	.073	19.15	18.98	20.30	20.35	20.52	21.02	20.07	18.95	20.82
CONTROLLED LUMINANCE	VIEWING ANGLE									
	0°	27.50	26.90	27.80	27.70	27.60	28.30	27.60	27.20	27.80
	22°	28.20	28.30	29.20	28.30	28.60	29.40	28.90	28.50	28.90
	45°	28.80	28.80	28.90	29.10	29.30	29.10	28.80	28.20	28.40
	CONTRAST									
	23	31.67	31.67	31.83	32.17	31.83	32.17	32.00	31.50	32.00
	4.45	31.67	31.50	31.83	31.67	31.83	32.33	31.67	31.00	32.00
	.86	29.83	29.67	29.83	29.83	30.00	29.83	29.67	29.00	30.17
	.38	27.83	27.83	28.33	27.83	28.00	28.67	28.00	27.83	28.00
	.073	19.83	19.33	21.33	20.33	20.83	21.67	20.83	20.50	19.67

TABLE B-9

SUMMARY OF ANALYSIS OF VARIANCE III

SOURCE	df	MS	F	P
Angle (A)	2	40.781	3.20	NS
Contrast (C)	4	1184.753	141.33	.01
Screen (S)	8	2.806	2.39	NS
Observer (O)	1	73.633		
AC	8	15.224	26.34	.01
AS	16	.869	3.18	.05
CS	32	.757	1.55	.25
AO	2	12.745		
CO	4	8.383		
SO	8	1.175		
ACS	64	.604	1.12	NS
ACO	8	.578		
ASO	16	.274		
CSO	32	.487		
ACSO	64	.540		

TABLE B-10

RESOLUTION AT EACH TARGET CONTRAST AND VIEWING ANGLE WITH CONTROLLED SCREEN LUMINANCE FOR OBSERVERS 2 AND 3

	CONTRAST					MEAN
	23	4.45	.86	.38	.073	
ANGLE						
0°	31.83	31.50	29.22	27.00	18.44	27.60
22°	32.22	32.17	30.17	28.56	20.39	28.70
45°	31.56	31.50	29.89	28.56	22.61	28.82
MEAN	31.87	31.72	29.76	28.04	20.48	28.37

CG-3

TABLE B-11

RESOLUTION FOR EACH SCREEN AT EACH VIEWING ANGLE AND TARGET CONTRAST
WITH CONTROLLED SCREEN LUMINANCE FOR OBSERVERS 2 AND 3

	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
ANGLE									
0°	27.50	26.90	27.80	27.70	27.60	28.30	27.60	27.20	27.80
22°	28.20	28.30	29.20	28.30	28.60	29.40	28.90	28.50	28.90
45°	28.80	28.80	28.90	29.10	29.30	29.10	28.80	28.20	28.40
CONTRAST									
23	31.67	31.67	31.83	32.17	31.83	32.17	32.00	31.50	32.00
4.45	31.67	31.50	31.83	31.67	31.83	32.33	31.67	31.00	32.00
.86	29.83	29.67	29.83	29.83	30.00	29.83	29.67	29.00	30.17
.38	27.83	27.83	28.33	27.83	28.00	28.66	28.00	27.83	28.00
.073	19.83	19.33	21.33	20.33	20.83	21.66	20.83	20.50	19.67
MEAN	28.17	28.00	28.63	28.37	28.50	28.93	28.43	27.97	28.37

CG-3

TABLE B-12

SUMMARY OF ANALYSIS OF VARIANCE IV

SOURCE	df	MS	F[a]	P
Luminance (L)	1	15.335	16.37	.01
Magnification (M)	1	2806.224	2994.66	.01
Angle (A)	2	221.317	236.16	.01
Contrast (C)	4	3547.639	3786.13	.01
Screen (S)	8	36.996	39.48	.01
LM	1	23.646	25.23	.01
LA	2	15.568	16.51	.01
MA	2	4.757	5.08	.01
LC	4	9.054	9.66	.01
MC	4	25.812	27.55	.01
AC	8	41.524	44.31	.01
LS	8	1.631	1.74	NS
MS	8	15.344	16.37	.01
AS	16	4.952	5.28	.01
CS	32	2.370	2.53	.01

[a] Error mean square was average of the six third and fourth order interactions.

TABLE B-13

RESOLUTION AT EACH VIEWING ANGLE, SCREEN LUMINANCE, AND MAGNIFICATION FOR OBSERVER 2

	ANGLE			MEAN
	0	22	45	
LUMINANCE				
NORMAL	28.51	30.34	31.16	30.00
CONTROLLED	29.31	30.88	30.83	30.34
MAGNIFICATION				
1X	26.44	28.41	28.82	27.89
7X	31.38	32.81	33.17	32.45
MEAN	28.91	30.61	30.99	30.17

TABLE B-14

RESOLUTION AT EACH MAGNIFICATION AND SCREEN LUMINANCE FOR OBSERVER 2

	MAGNIFICATION	
	1X	7X
LUMINANCE		
NORMAL	27.93	32.07
CONTROLLED	27.85	32.83

TABLE B-15

RESOLUTION AT EACH TARGET CONTRAST, SCREEN LUMINANCE, MAGNIFICATION AND VIEWING ANGLE FOR OBSERVER 2

	CONTRAST				
	23	4.45	.86	.38	.073
LUMINANCE					
NORMAL	34.11	34.70	31.92	29.35	19.92
CONTROLLED	33.92	34.68	32.00	29.92	21.17
MAGNIFICATION					
1X	31.85	31.74	29.52	27.41	18.94
7X	36.18	37.65	34.41	31.87	22.15
ANGLE					
0°	33.72	34.28	30.92	27.75	17.89
22°	34.50	35.14	32.47	30.30	20.64
45°	33.83	34.67	32.50	30.86	23.11
MEAN	34.02	34.69	31.96	29.64	20.55

TABLE B-16

RESOLUTION FOR EACH SCREEN AT EACH SCREEN LUMINANCE, MAGNIFICATION, VIEWING ANGLE, AND TARGET CONTRAST FOR OBSERVER 2

	SCREEN								
	AL-4	AL-5	AQ-11	AQ-17	AQ-18	AQ-20	AR-27	AR-28	LS-60G
LUMINANCE									
NORMAL	29.03	29.10	30.60	30.57	30.87	30.47	30.10	28.90	30.40
CONTROLLED	29.40	29.17	30.73	31.03	31.00	31.37	30.77	29.37	30.23
MAGNIFICATION									
1X	27.67	27.40	28.07	28.27	28.10	28.33	27.73	27.53	27.93
7X	30.77	30.87	33.27	33.33	33.77	33.50	33.13	30.73	32.70
ANGLE									
0°	27.15	27.30	29.65	29.80	29.80	30.05	29.45	27.65	29.35
22°	29.40	29.55	31.40	31.20	31.20	31.50	30.80	29.70	30.75
45°	31.10	30.55	30.95	31.40	31.80	31.20	31.05	30.05	30.85
CONTRAST									
23	33.50	33.25	33.83	34.58	34.58	34.42	34.17	33.50	34.33
4.45	33.67	33.75	35.25	35.58	35.17	35.25	35.17	33.25	35.17
.86	31.25	31.50	32.25	32.33	32.42	32.42	32.25	31.08	32.17
.38	28.75	28.83	30.17	30.25	30.67	30.33	29.83	28.33	29.58
.073	18.92	18.33	21.83	21.25	21.83	22.17	20.75	19.50	20.33
MEAN	29.22	29.13	30.67	30.80	30.93	30.92	30.43	29.13	30.32

APPENDIX C

CORRELATION BETWEEN VARIABLES

The tables in this appendix list the correlations between variables in the study. Each table includes a statement of the magnitude of the correlation required to be statistically certain it is different from zero at the .05 level ($r_{.05}$). The values used for Quality Test III computations were Z scores for each subject on each screen, rather than just for each screen as with Tests I and II. The tables contain the following types of correlations:

TABLES	VARIABLES
1, 2	Screen Parameters
3	Quality
4 - 8	Resolution
9, 10	Quality/Screen Parameters
11 - 14	Resolution/Screen Parameters
15	Quality/Resolution

TABLE C-1

INTERCORRELATIONS BETWEEN SCREEN PARAMETERS
- Screen LS-60G Included

SCREEN PARAMETER	V_{45}	V_{30}	$B(O)T_S$	$T_{45}T_S$	$T_{30}T_S$	R_DT_S	α T	LBRT	MTF	DRTHI
B(O)	.87	.84	.69	.45	.50	.40	.09	.70	.62	.45
V_{45}	1.00	.95	.85	.58	.63	.65	.10	.76	.82	-.60
V_{30}		1.00	.71	.37	.41	.68	.22	.65	.67	-.79
$B(O)T_S$			1.00	.90	.92	.77	.34	.91	.87	-.29
$T_{45}T_S$				1.00	.99	.58	.28	.86	.79	.08
$T_{30}T_S$					1.00	.56	.24	.88	.81	.06
R_DT_S						1.00	.73	.61	.62	-.60
α T							1.00	.28	.08	-.34
LBRT								1.00	.85	-.26
MTF									1.00	-.25
DRTHI										1.00

NOTE: df = 7, $r_{.05}$ = .58

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TABLE C-2

INTERCORRELATIONS BETWEEN SCREEN PARAMETERS

Screen LS-60G Excluded

SCREEN PARAMETER	V_{45}	V_{30}	T_{90}	T_{45}	T_{30}	R_D	T_S	$B(O)T_S$	$T_{45}T_S$	$T_{30}T_S$	R_DT_S	α_T	LBRT	MTF	DRTHI
B(O)	0.95	0.87	0.25	0.40	0.59	0.32	0.52	0.84	0.60	0.66	0.45	0.08	0.76	0.81	-0.45
V_{45}	1.00	0.97	-0.03	0.12	0.33	0.58	0.55	0.83	0.50	0.56	0.61	0.19	0.74	0.81	-0.70
V_{30}		1.00	-0.25	-0.10	0.12	0.74	0.50	0.75	0.36	0.41	0.67	0.24	0.65	0.74	-0.83
T_{90}			1.00	0.98	0.92	-0.82	0.11	0.19	0.52	0.54	-0.40	-0.29	0.32	0.26	0.72
T_{45}				1.00	0.97	-0.73	0.12	0.28	0.54	0.56	-0.36	-0.32	0.37	0.32	0.62
T_{30}					1.00	-0.57	0.22	0.45	0.62	0.66	-0.22	-0.29	0.53	0.48	0.44
R_D						1.00	0.26	0.32	-0.12	-0.11	0.70	0.39	0.16	0.28	-0.98
T_S							1.00	0.88	0.90	0.87	0.81	0.78	0.84	0.65	-0.33
$B(O)T_S$								1.00	0.87	0.89	0.75	0.52	0.92	0.82	-0.42
$T_{45}T_S$									1.00	0.99	0.51	0.50	0.89	0.68	0.00
$T_{30}T_S$										1.00	0.49	0.44	0.91	0.71	-0.02
R_DT_S											1.00	0.86	0.57	0.56	-0.69
α_T												1.00	0.36	0.24	-0.33
LBRT													1.00	0.87	-0.32
MTF														1.00	-0.41
DRTHI															1.00

NOTE: $df = 6$, $r_{.05} = .62$

TABLE C-3

INTERCORRELATIONS BETWEEN QUALITY JUDGEMENTS

TESTS	SCREENS EXCLUDED		
	NONE	AQ-20	LS-60G
I - II	-.26	.38	-.48
I - III	.55	-.28	.75[a]
II - III	-.34	.32	-.32

[a] Statistically different from 0 (PL.05).

TABLE C-4

CORRELATIONS BETWEEN RESOLUTION JUDGEMENTS
OBTAINED UNDER EACH SCREEN LUMINANCE CONDITION

I - Screen LS-60G Included

	NORMAL LUMINANCE		CONTROLLED LUMINANCE
	SUBJECTS 1-3	SUBJECTS 2,3	SUBJECTS 2,3
NORMAL LUMINANCE, SUBJECTS 1-3	1.00	.96	.66
NORMAL LUMINANCE, SUBJECTS 2,3		1.00	.54
CONTROLLED LUMINANCE, SUBJECTS 2,3			1.00

NOTE: df = 7, $r_{.05}$ = .58

II - Screen LS-60G Excluded

	NORMAL LUMINANCE		CONTROLLED LUMINANCE
	SUBJECTS 1-3	SUBJECTS 2,3	SUBJECTS 2,3
NORMAL LUMINANCE, SUBJECTS 1-3	1.00	.97	.87
NORMAL LUMINANCE, SUBJECTS 2,3		1.00	.89
CONTROLLED LUMINANCE, SUBJECTS 2,3			1.00

NOTE: df = 6, $r_{.05}$ = .62

TABLE C-5

INTERCORRELATIONS BETWEEN RESOLUTION SCORES
AT EACH VIEWING ANGLE - Screen LS-60G Included

NORMAL LUMINANCE			
VIEWING ANGLE	0^{o}	22^{o}	45^{o}
0^{o}	1.00	.90	.54
22^{o}		1.00	.68
45^{o}			1.00

CONTROLLED LUMINANCE			
VIEWING ANGLE	0^{o}	22^{o}	45^{o}
0^{o}	1.00	.75	.39
22^{o}		1.00	.11
45^{o}			1.00

NOTE; $df = 7$, $r_{.05} = .58$

TABLE C-6

INTERCORRELATIONS BETWEEN RESOLUTION SCORES
AT EACH VIEWING ANGLE - Screen LS-60G Excluded

NORMAL LUMINANCE			
VIEWING ANGLE	0^o	22^o	45^o
0^o	1.00	.89	.27
22^o		1.00	.40
45^o			1.00

CONTROLLED LUMINANCE			
VIEWING ANGLE	0^o	22^o	45^o
0^o	1.00	.74	.54
22^o		1.00	.22
45^o			1.00

NOTE: df = 6, $r_{.05}$ = .62

TABLE C-7

INTERCORRELATIONS BETWEEN RESOLUTION SCORES
AT EACH TARGET CONTRAST LEVEL - Screen LS-60G Included

NORMAL LUMINANCE					
CONTRAST	23.0	4.45	.86	.38	.073
23.0	1.00	.77	.39	.47	.02
4.45		1.00	.46	.64	.35
.86			1.00	.71	.65
.38				1.00	.85
.073					1.00

CONTROLLED LUMINANCE					
CONTRAST	23.0	4.45	.86	.38	.073
23.0	1.00	.75	.60	.50	.38
4.45		1.00	.81	.75	.40
.86			1.00	.26	-.04
.38				1.00	.79
.073					1.00

NOTE: $df = 7$, $r_{.05} = .58$

TABLE C-8

INTERCORRELATIONS BETWEEN RESOLUTION SCORES AT EACH TARGET CONTRAST LEVEL - Screen LS-60G Excluded

NORMAL LUMINANCE					
CONTRAST	23.0	4.45	.86	.38	.073
23.0	1.00	.39	.17	-.02	-.22
4.45		1.00	.29	.35	.33
.86			1.00	.66	.63
.38				1.00	.94
.073					1.00

CONTROLLED LUMINANCE					
CONTRAST	23.0	4.45	.86	.38	.073
23.0	1.00	.74	.58	.52	.52
4.45		1.00	.79	.80	.58
.86			1.00	.32	.17
.38				1.00	.84
.073					1.00

NOTE: df = 6, $r_{.05}$ = .62

TABLE C-9

CORRELATION OF SCREEN PARAMETERS WITH QUALITY JUDGEMENTS
- Screen LS-60G Included

SCREEN PARAMETER	TEST I	TEST II	TEST III, AQ-20 IN	TEST III, AQ-20 OUT
B(O)	.44	-.65	.04	-.44
V_{45}	.60	-.64	.05	-.56
V_{30}	.39	-.76	.08	-.58
$B(O)T_S$	.71	-.58	.02	-.62
$T_{45}T_S$	.81	-.32	.13	-.51
$T_{30}T_S$	.81	-.33	.10	-.56
$R_D T_S^{\lambda}$	.36	-.73	.09	-.41
α_T	-.03	-.62	.21	.18
LBRT	.80	-.62	.46	-.33
MTF	.86	-.42	.27	-.56
DRTHI	0.	.79	-.41	.45

NOTE: In first 2 columns, df = 7, $r_{.05}$ = .58;
in the third, df = 19, $r_{.05}$ = .37;
in the fourth, df = 16, $r_{.05}$ = .40.

[a] LBRT-I for Tests I and II, LBRT-III for Test III.

TABLE C-10

CORRELATION OF SCREEN PARAMETERS WITH QUALITY JUDGEMENTS
- Screen LS-60G Excluded

SCREEN PARAMETER	TEST I	TEST II	TEST III, AQ-20 IN	TEST III, AQ-20 OUT
B(O)	.59	-.65	.04	-.52
V_{45}	.53	-.81	.10	-.53
V_{30}	.39	-.83	.12	-.57
T_{90}	.52	.29	.24	-.38
T_{45}	.51	.22	.08	-.40
T_{30}	.60	.03	.06	-.50
R_D	-.06	-.71	.48	.44
T_S	.59	-.82	.28	-.31
$B(O)T_S$	.60	-.84	.07	-.62
$T_{45}T_S$	.71	-.60	.21	-.46
$T_{30}T_S$	.72	-.60	.18	-.53
$R_D T_S^2$	.23	-.89	.20	-.32
T	.10	-.60	.21	.12
LBRT	.79	-.76	.70	-.49
MTF	.80	-.71	.42	-.59
DRTHI	-.10	.79	-.45	.47

NOTE: In first 2 columns, df = 6, $r_{.05}$ = .62;
in the third, df = 16, $r_{.05}$ = .40;
in the fourth, df = 13, $r_{.05}$ = .44.

[a] LBRT-I for Tests I and II, LBRT-III for Test III.

TABLE C-11

CORRELATIONS BETWEEN SCREEN PARAMETERS AND RESOLUTION SCORES
WITH NORMAL SCREEN LUMINANCE - Screen LS-60G Included

SCREEN PARAMETER	VIEWING ANGLE			CONTRAST					MEAN
	0^{o}	22^{o}	45^{o}	23.0	4.45	.86	.38	.073	
B(O)	-.64	-.61	-.30	.12	-.19	-.32	-.59	-.76	-.61
V_{45}	-.61	-.48	.07	.42	.07	-.22	-.43	-.75	-.48
V_{30}	-.77	-.66	-.05	.21	-.18	-.30	-.63	-.85	-.66
$B(O)T_S$	-.39	-.20	.20	.67	.27	-.22	-.13	-.58	-.24
$T_{45}T_S$	-.07	.16	.30	.81	.55	-.07	.18	-.29	.08
$T_{30}T_S$	-.10	.12	.28	.79	.53	-.08	.14	-.33	.05
R_DT_S	-.53	-.29	.24	.49	-.04	-.25	-.26	-.57	-.34
αT	-.39	-.14	-.04	.14	-.27	-.24	-.25	-.31	-.28
LBRT	-.49	-.28	.00	.58	.24	-.30	-.26	-.69	-.36
MTF	-.28	-.15	.36	.76	.34	.04	-.03	-.50	-.12
DRTHI	.87	.75	.20	.13	.43	.45	.79	.80	.78

NOTE: df = 7, $r_{.05} = .58$

C12

TABLE C-12

CORRELATIONS BETWEEN SCREEN PARAMETERS AND RESOLUTION SCORES
WITH CONTROLLED SCREEN LUMINANCE - Screen LS-60G Included

SCREEN PARAMETER	VIEWING ANGLE			CONTRAST					MEAN
	0^{o}	22^{o}	45^{o}	23.0	4.45	.86	.38	.073	
B(O)	-.67	-.36	-.70	-.65	-.73	-.64	-.55	-.40	-.71
V_{45}	-.65	-.40	-.79	-.60	-.55	-.31	-.61	-.71	-.76
V_{30}	-.75	-.57	-.63	-.65	-.58	-.33	-.67	-.78	-.82
$B(O)T_S$	-.47	-.34	-.80	-.62	-.50	-.24	-.57	-.56	-.66
$T_{45}T_S$	-.25	-.13	-.66	-.43	-.36	-.10	-.42	-.31	-.41
$T_{30}T_S$	-.29	-.15	-.71	-.45	-.41	-.16	-.45	-.34	-.46
$R_D T_S$	-.40	-.53	-.39	-.60	-.25	.09	-.53	-.65	-.56
α T	-.20	-.48	.19	-.48	-.13	.11	-.34	-.19	-.24
LBRT	-.66	-.50	-.74	-.70	-.75	-.40	-.75	-.55	-.79
MTF	-.39	-.32	-.78	-.40	-.46	-.11	-.61	-.59	-.61
DRTHI	.72	.64	.19	.60	.37	.12	.51	.73	.67

NOTE: df = 7, $r_{.05}$ = .58

TABLE C-13

CORRELATIONS BETWEEN SCREEN PARAMETERS AND RESOLUTION SCORES WITH NORMAL SCREEN LUMINANCE - Screen LS-60G Excluded

SCREEN PARAMETER	VIEWING ANGLE			CONTRAST					MEAN
	0°	22°	45°	23.0	4.45	.86	.38	.073	
B(O)	-.66	-.66	-.38	.30	-.21	-.32	-.69	-.76	-.68
V_{45}	-.84	-.80	-.28	.26	-.34	-.41	-.85	-.89	-.83
V_{30}	-.89	-.84	-.13	.17	-.45	-.38	-.89	-.90	-.87
T_{90}	.42	.37	-.40	.42	.53	.20	.40	.22	.36
T_{45}	.32	.25	-.44	.36	.45	.15	.28	.12	.25
T_{30}	.10	.03	-.52	.36	.34	.02	.06	-.10	.03
R_D	-.79	-.70	.21	-.09	-.58	-.35	-.79	-.66	-.72
T_S	-.59	-.30	-.29	.69	-.01	-.46	-.44	-.64	-.50
$B(O)T_S$	-.72	-.58	-.46	.51	-.22	-.51	-.62	-.80	-.69
$T_{45}T_S$	-.37	-.17	-.50	.71	.18	-.38	-.26	-.50	-.34
$T_{30}T_S$	-.41	-.23	-.54	.67	.16	-.40	-.31	-.55	-.39
R_DT_S	-.73	-.54	-.01	.41	-.49	-.42	-.59	-.68	-.64
α T	-.35	-.05	.17	.51	-.19	-.19	-.16	-.29	-.21
LBRT	-.68	-.52	-.48	.60	.01	-.46	-.58	-.80	-.65
MTF	-.64	-.60	-.26	.62	-.22	-.23	-.57	-.76	-.62
DRTHI	.89	.79	-.09	.03	.52	.43	.89	.80	.83

NOTE

TABLE C-14

CORRELATIONS BETWEEN SCREEN PARAMETERS AND RESOLUTION SCORES
WITH CONTROLLED SCREEN LUMINANCE - Screen LS-60G Excluded

SCREEN PARAMETER	VIEWING ANGLE			CONTRAST					MEAN
	0°	22°	45°	23.0	4.45	.86	.38	.073	
B(O)	-.67	-.36	-.82	-.66	-.74	-.69	-.56	-.47	-.72
V_{45}	-.78	-.50	-.76	-.74	-.72	-.58	-.63	-.66	-.82
V_{30}	-.80	-.61	-.65	-.70	-.65	-.44	-.67	-.79	-.84
T_{90}	.18	.39	-.30	.07	-.25	-.42	.08	.56	.15
T_{45}	.09	.36	-.42	.01	-.32	-.52	.04	.48	.06
T_{30}	-.11	.20	-.59	-.17	-.50	-.66	-.12	.29	-.15
R_D	-.55	-.56	-.14	-.48	-.16	.09	-.40	-.79	-.54
T_S	-.56	-.53	-.39	-.81	-.61	-.30	-.60	-.38	-.61
$B(O)T_S$	-.66	-.51	-.74	-.86	-.78	-.62	-.64	-.46	-.76
$T_{45}T_S$	-.45	-.29	-.54	-.71	-.68	-.52	-.49	-.11	-.50
$T_{30}T_S$	-.50	-.31	-.61	-.73	-.74	-.60	-.52	-.15	-.56
R_DT_S	-.49	-.63	-.29	-.72	-.38	-.08	-.54	-.60	-.60
α T	-.17	-.46	.11	-.46	-.08	.23	-.35	-.29	-.25
LBRT	-.77	-.59	-.70	-.82	-.92	-.65	-.77	-.49	-.83
MTF	-.63	-.52	-.72	-.66	-.81	-.53	-.71	-.48	-.74
DRTHI	.71	.63	.28	.59	.35	.06	.52	.86	.68

NOTE: df = 6 r [illegible]

TABLE C-15

CORRELATIONS BETWEEN RESOLUTION SCORES AND QUALITY JUDGEMENTS

SCREEN LS-60G	EXCLUDED				INCLUDED			
RESOLUTION LUMINANCE CONDITION	Normal		Controlled		Normal		Controlled	
QUALITY TEST	I[a]	III[b]	II[a]	III[b]	I[c]	III[d]	II[c]	III[d]
VIEWING ANGLE								
0°	-.16		.78		-.07		.79	
22°	-.18		.64		.16		.65	
45°	-.30		.53		.38		.36	
RESOLUTION TARGET CONTRAST								
23.0	.82		.92		.86		.93	
4.45	.41		.65		.65		.67	
.86	-.06		.34		.16		.40	
.38	-.34		.65		.11		.62	
.073	-.51		.71		-.31		.53	
MEAN RESOLUTION	-.28	.79	.80	.89	.08	.36	.78	.80

NOTE: For columns 1&3, df = 6, $r_{.05}$ = .62
For columns 2&4, df = 16, $r_{.05}$ = .40
For columns 5&7, df = 7, $r_{.05}$ = .58
For columns 6&8, df = 13, $r_{.05}$ = .44

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APPENDIX D

REGRESSION EQUATIONS

The regression equations calculated for quality and resolution scores are listed in TABLES D-1 and D-2. The screen parameters were not the same for all calculations. The log brightness (LBRT) was LBRT-I from TABLE A-1, except for Quality Test III, where it LBRT-III. Parameter R_D was excluded from all calculations and T_S, T_{90}, T_{45}, and T_{30} were excluded whenever screen LS-60G was included.

TABLE D-1

REGRESSION EQUATIONS FOR SCREEN QUALITY

TEST	SCREENS EXCLUDED FROM ANALYSIS	EQUATION
I	NONE	$Z = -10.13 + 10.94\ MTF + .036\ V_{30} - .58\ LBRT - .059\ R_D T_S - .011\ DRTHI + .14\ T_{45} T_S - 1.21\ B(O)T_S$
	LS-60G	$Z = -11.25 + 10.17\ MTF + .055\ V_{30} - .23\ LBRT - .41\ B(O)T_S + .14\ T_{45} T_S$
II	NONE	$Z = -5.69 + .04\ DRTHI - .06\ T_{45} T_S + 1.31\ \alpha T - .16\ R_D T_S - .79\ B(O) + .13\ V_{45}$
	LS-60G	$Z = 4.27 + .022\ R_D T_S - .11\ V_{45} - .023\ T_S + .76\ B(O)$
III	NONE	$Z = -3.02 + .77\ LBRT - 4.12\ B(O)T_S - .046\ DRTHI + .50\ T_{30} + .11\ V_{45}$
	AQ-20	$Z = -5.65 - 3.40\ B(O)T_S + .29\ T_{45} T_S + .12\ V_{45} - .63\ LBRT$
	LS-60G	$Z = -14.08 + 7.01\ LBRT - .50\ B(O)T_S + .24\ T_{45} - .13\ V_{30}$
	AQ-20 & LS-60G	$Z = -6.57 - 3.43\ B(O)T_S + .29\ T_{45} T_S + .12\ V_{45}$

D2

CG-3

D3

TABLE D-2

REGRESSION EQUATIONS FOR SCREEN RESOLUTION AT NORMAL LUMINANCE

RESOLUTION TEST CONDITION	EQUATION
VIEWING ANGLE	
0^{o}	$RN = 24.07 + .022\ V_{30} + .024\ \text{DRTHI} - 1.49\ \text{LBRT} + 3.88\ \text{MTF} + .018\ T_S - .30\ B(O)T_S$
22^{o}	$RN = 29.36 - .0062\ V_{30} - .0097\ \text{DRTHI} + 1.80\ \alpha T - .18\ R_D T_S - .38\ \text{LBRT} + .028\ T_{45}$
45^{o}	$RN = 27.44 + 1.13\ \text{LBRT} + .75\ \alpha T + .014\ T_S + .049\ T_{45} - .12\ T_{30} T_S - 1.31\ \text{MTF}$
CONTRAST	
23.0	$RN = 28.59 + .16\ T_{45} T_S - .22\ T_{30} T_S + 3.38\ \text{MTF} - .10\ R_D T_S + .012\ V_{30} + .58\ \alpha T$
4.45	$RN = 32.47 + .00036\ \text{DRTHI} - .96\ \text{LBRT} - .86\ B(O)T_S + .15\ T_{30} T_S + .033\ V_{30}$
.86	$RN = 25.78 - .64\ B(O)T_S + 2.27\ \text{MTF} + .018\ \text{DRTHI} + .88\ \alpha T + .052\ V_{30} + .016\ T_{45} T_S$
.38	$RN = 26.68 + .024\ V_{30} + .020\ \text{DRTHI} - .11\ T_{30} + .063\ T_{45}$
.073	$RN = 21.57 + .0060\ V_{30} - .2.18\ \text{LBRT} + .025\ \text{DRTHI} + .59\ \alpha T$
AVERAGE	$RN = 26.10 - .012\ V_{30} + .014\ \text{DRTHI} + .13\ \text{LBRT} + 1.00\ \alpha T - .47\ B(O)T_S + .048\ V_{45}$

CG-3