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VARIABLES INFLUENCING THE NIGHTTIME LEGIBILITY OF HIGHWAY SIGNS

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16. Abstract

Four studies were carried out to evaluate the nighttime legibility of signs made with retro-reflective materials.

The first study investigated the effect of sign background luminance, legend luminance contrast, surround luminance, background color, glare illuminance and angle, and subject age on sign legibility.

The results indicate that legend luminance contrast is the most important variable in sign legibility at night, and that there is a relatively narrow range of optimum contrast.

Background luminance is a significant factor as well. In general, as background luminance increases, legibility increases and legend contrast requirements decrease.

Environmental glare has a relatively small effect on sign legibility, noticeable only at very small angles and high intensities. Increases in legend luminance contrast, background and surround luminance all reduce glare effects.

Sign background color and surround luminance both have relatively minor effects on legibility.

In general, the older subjects did much poorer than the younger subjects. However, the difference was minimized by high-luminance backgrounds.

The next two studies were carried out under field conditions. Small signs were used, and subjects rode towards them, pressing a button to indicate the distance at which they became legible. The results indicate that the usually obtained age effect on legibility of signs is eliminated if the age groups are matched in terms of their low-luminance/high-contrast visual acuity. Furthermore, an apparent improvement in legibility with the presence of glare was obtained at a glare angle of 2^{o}; substantial disability glare effect was present for a glare angle of 0.2^{o}.

The fourth study was carried out to evaluate possible glare effects associated with bright highway signs. The results indicate that most retroreflective signs do not pose glare problems. Possible exceptions are signs (e.g., construction warning signs) placed very close to targets of interest, advertising signs, and internally illuminated signs.

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EXECUTIVE SUMMARY

Introduction

This report describes four studies concerned with the nighttime legibility of retroreflective signs.

The first study was a laboratory investigation of the effect of several relevant variables on legibility. These data were used as input to a computer legibility model, also developed as part of this project.

Two studies were carried out to measure the legibility distance of signs under field conditions.

The fourth study measured the disability glare effects associated with signs.

In this summary all four studies will be briefly reviewed. More comprehensive descriptions of the studies are presented in the main portion of the report.

LABORATORY STUDY OF VARIABLES AFFECTING THE NIGHTTIME LEGIBILITY OF HIGHWAY SIGNS

The purpose of this study was to assess the effect of several variables on the nighttime legibility of traffic signs.

METHOD

Variables

Environmental glare-illuminance. Five glare levels as described in the following table:

GLARE LEVEL*		APPROXIMATELY EQUIVALENT TO:
LUX	Ft-c	
0	0	No glare
0.0006	0.00006	Low beams at 1580 m
0.0059	0.00055	Low beams at 500 m
0.059	0.0055	Low beams at 160 m
0.59	0.055	High beams at 350 m

*Measured at the observer's eye.

Environmental glare-angle. Five levels: none (source to the edge of the sign), 0.7°, 3.5°, 7.5°, and 15°.

Sign background color. Seven levels: green, blue, red, and black, all of which used white legends; and white, yellow, and orange, all of which used black legends. These are typical traffic-control sign colors.

Sign background luminance. The sign background is that part of the sign on which the legend is placed. This variable could be changed by as much as 1000:1. The actual luminance values depended on the sign background color. However, the values investigated encompassed the range found in use today, as well as levels substantially higher.

Legend size. Four legend sizes were used on the test equipment. These corresponded to:

3.6 m/cm (30 ft/in) letter height
4.8 m/cm (40 ft/in) letter height
6.0 m/cm (50 ft/in) letter height
7.2 m/cm (60 ft/in) letter height

Sign legend luminance. The luminance of the white legend could be varied from 0.038 to 733.0 cd/m^2.

Surround luminance. Sign surround is the ambient setting against which the sign is seen. The luminance of the surround could be set at any of three levels, 0.03, 3.43, and 17.0 cd/m^2, approximating a dark rural, moderately lighted urban, and brightly lighted urban surround, respectively.

Subjects. Small groups of younger and older persons served as subjects in this study. They had been screened on several vision variables, and the two groups were matched on these variables as closely as possible.

Procedure

A simple optical device was developed which provided close control of the sign variables mentioned. The simulated sign consisted of a square background measuring about 30 cm on a side and a centered single Landolt ring, the gap of which could be oriented in any of four directions. A trial consisted of a one-second exposure to the sign, after which the subject was required to indicate his/her best guess as to the position of the ring gap. Different size rings were used to simulate different viewing distances. The basic data resulting from this procedure were curves describing the percent correct identifications of ring gap orientations as a function of the variables of interest. This, in turn, provided the estimated legibility distance.

RESULTS

Young Subjects

The most important single variable determining sign legibility at night is legend luminance contrast. Figure E1 illustrates this for signs having two background luminance levels, i.e., green signs having white legends. Three points are particularly worth noting:

1) Legibility increases rapidly with luminance and contrast at first, then more slowly. Although it is apparent only for the higher luminance background on these figures, there is a point beyond which further increases in contrast do not improve legibility. For example, with a background luminance of 3.8 cd/m^2, peak legibility is achieved at a contrast of about 50:1, although the improvement beyond 7 to 10:1 is modest.

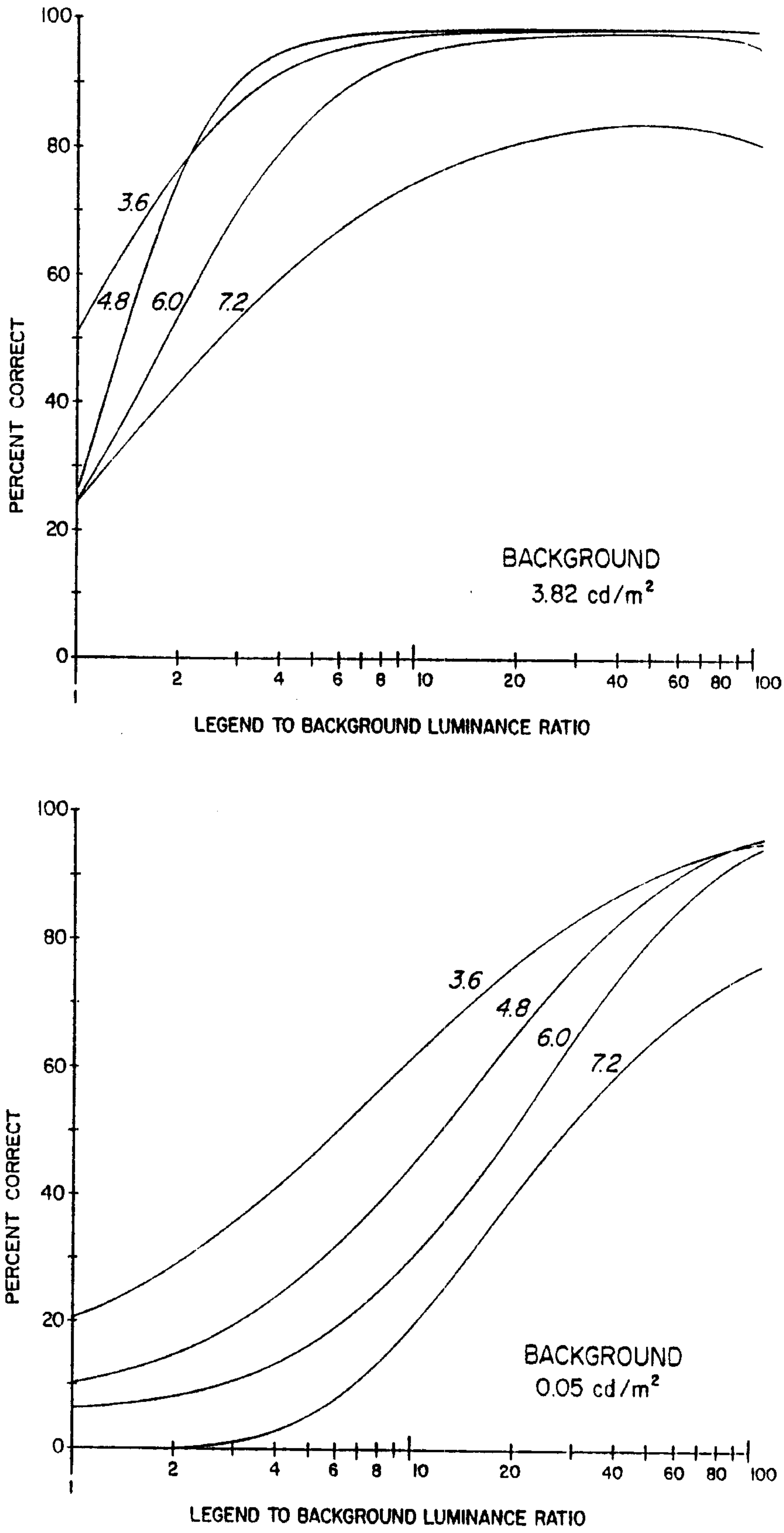


Figure E-1. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance contrast and two levels of background luminance (3.82 and 0.05 cd/m^2). Dark surround (0.034 cd/m^2). Young subjects.

2) Contrast requirements (to achieve a given legibility level) depend on background luminance. The higher the background luminance, the lower the contrast requirements. As a rough rule-of-thumb, the data suggest that changing background luminance by a factor of ten requires the contrast ratio be changed by a factor of two to maintain a given legibility level. However, this does not apply to signs at luminance levels as low as 0.034 cd/m^2, which includes badly deteriorated retroreflective, non-reflective, and black background signs. The legibility of such signing is determined by legend luminance alone. The optimum legend luminance range appears to lie between 10 and 100 cd/m^2 for signs having very low luminance backgrounds.

3) Although not apparent in Figure E-1, increases in contrast beyond the asymptotic range may lead to declining performance, due to irradiation. The effect varies from person to person and more seriously impairs older persons. It is reduced or eliminated by higher surround and background luminance levels.

Environmental glare had relatively little effect on sign legibility, except at the smallest angle and highest glare levels tested. An example of these results is provided in Figure E-2. With no glare or the lower glare levels, 85th percentile legibility of 6m/cm is achieved at a contrast of about 10:1. Introduction of the highest glare level reduces performance to about 70% correct at 10:1, but increasing legend luminance and contrast to about 30:1 restores legibility to the original level.

The effects of environmental glare can be reduced by increases in surround luminance and sign background luminance. The latter point is important, because glare also reduces sign conspicuity, probably to a greater extent than it does legibility.

There are minor effects on legibility associated with background color. An example for white legend combinations is shown in Figure E-3. In general, blue performed best (i.e., required the lowest contrast ratio to achieve a given level of legibility), followed by green and red. As long as reasonable contrast levels are used, the differences between colors are small in terms of legibility distance. The differences probably arise from changes in the spectral sensitivity of the eye associated with changes in adaptive luminance.

Similar data for black legend signs are provided in Figure E-4. Legibility differences between the three background colors are small.

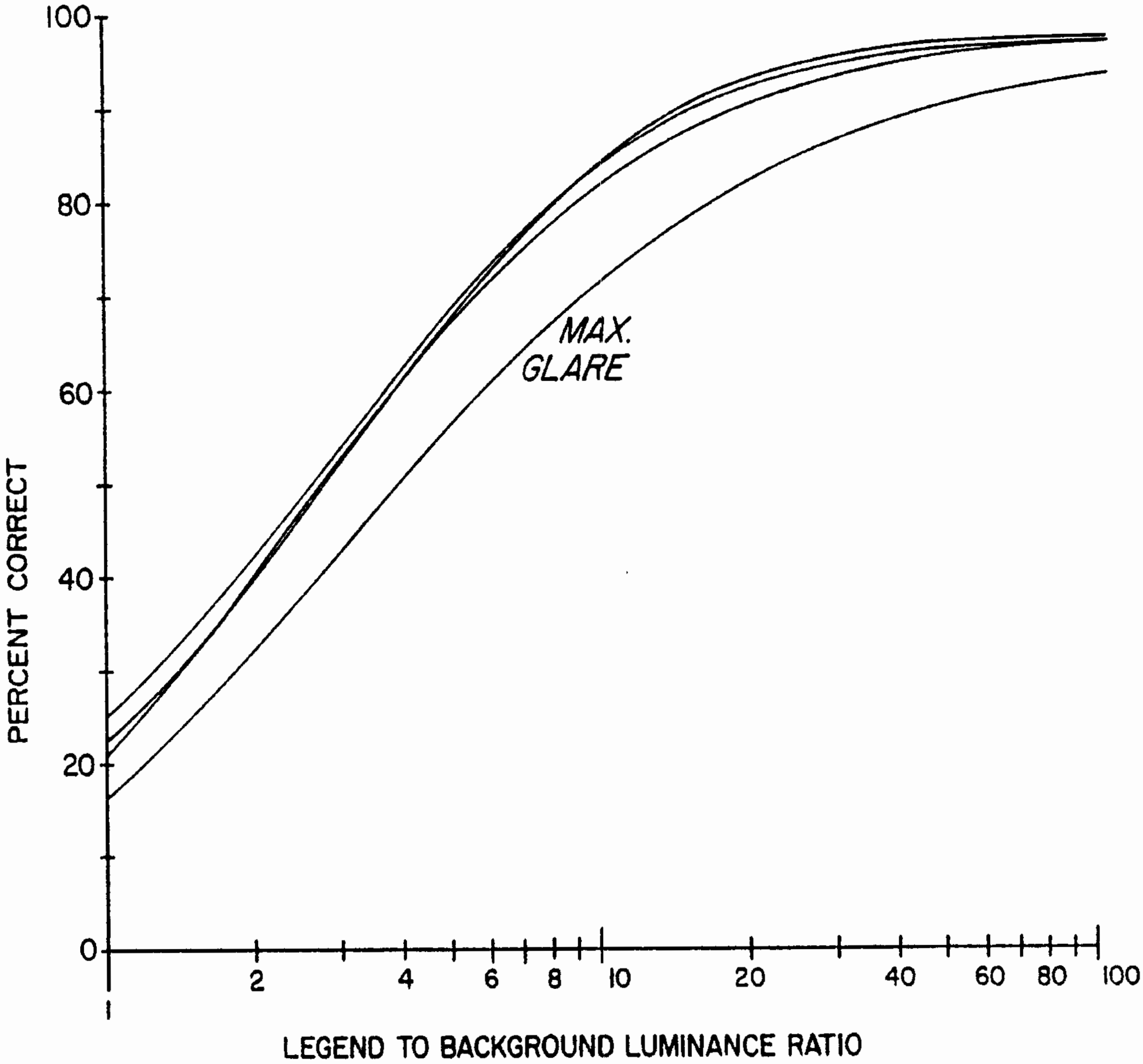


Figure E-2. Percent correct responses as a function of legend luminance contrast and four levels of glare illuminance. Glare angle 0.7^{o}, dark surround (0.034 cd/m^2), 6 m/cm legend, 0.4 cd/m^2 green background. Young subjects.

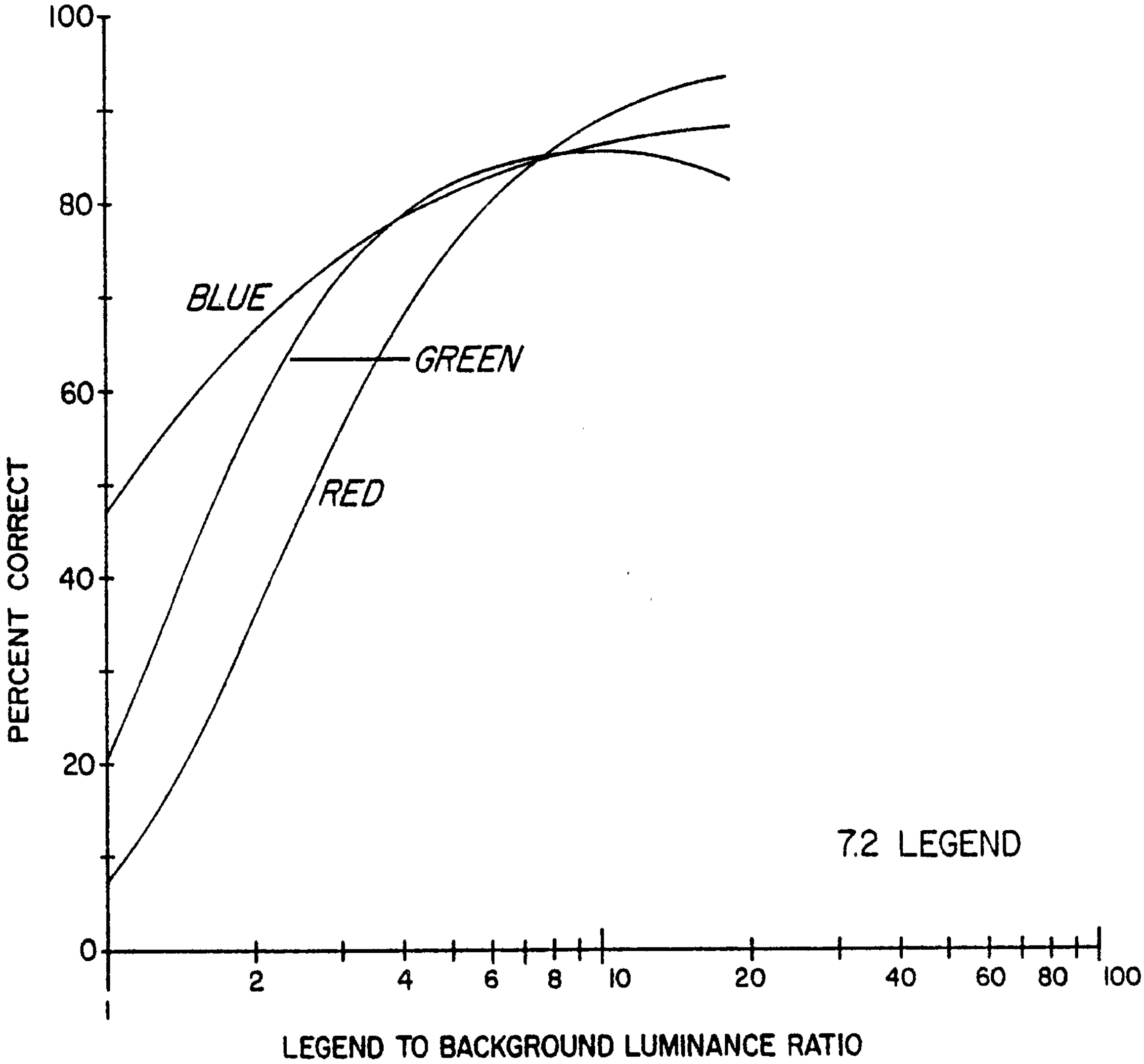


Figure E-3. Percent correct responses as a function of legend luminance contrast for green, red, and blue backgrounds. Dark surround (0.034 cd/m^2), 7.2 m/cm legend, 34.4 cd/m^2 background. Young subjects.

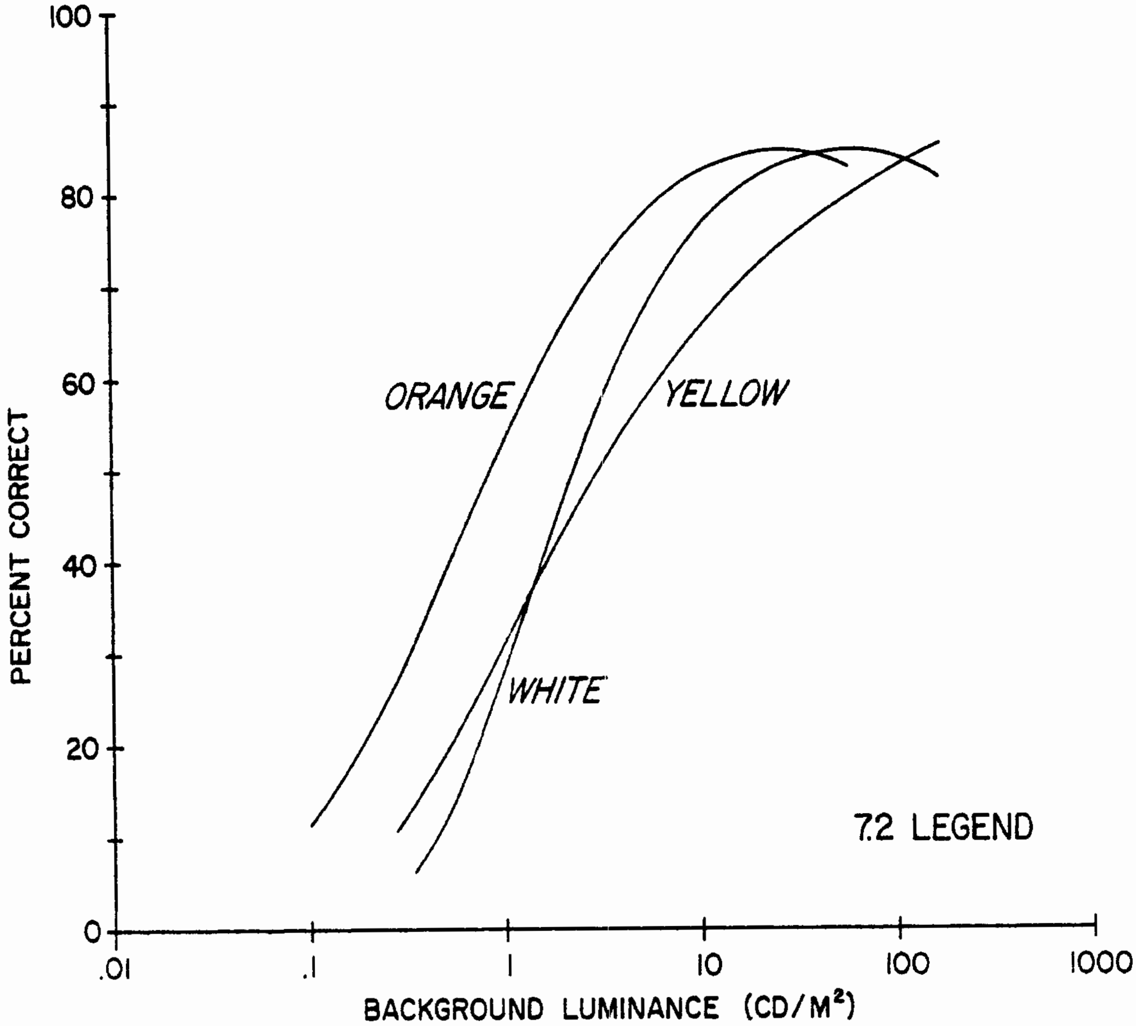


Figure E-4. Percent correct responses as a function of background luminance and color. Dark surround (0.034 cd/m^2). Young subjects.

The legibility of signs using black legends is determined by background luminance. As in the case of black background signs, contrast is not a relevant parameter. The optimum range of background luminance for white, yellow, and orange backgrounds is about 10 to 100 cd/m^2.

Older Subjects

Figure E-5 illustrates typical results comparing younger (average age - 24 years) and older (average age - 68 years) subjects at two background luminance levels. It is clear that the older subjects performed less well, i.e., they required more contrast for a given level of legibility performance and had lower peak legibility. However, it is important to note that increasing sign background luminance substantially improves the performance of the older subjects. This point is well illustrated by Figure E-6.

Each part of Figure E-6 is for a different background luminance level. Plotted on it are the legend luminance contrast levels associated with 85th percentile performance at the indicated legibility distances. At a background luminance of 34.4 cd/m^2, both groups could achieve legibility distances of 7.2 m/cm; the older subjects requiring about twice the legend luminance contrast. At a background luminance of 3.4 cd/m^2 (which is a fairly bright sign in present practice), the older subjects could not achieve a legibility distance of 7.2 m/cm within the contrast range indicated. Note also the substantial age-related change in contrast requirements at this background level.

The trend noted above continues as the backgrounds grow darker. At 0.34 cd/m^2 the older subjects could not reach 6m/cm within the range indicated, although the younger subjects were still capable of 7.2 m/cm. At 0.034 cd/m^2 performance was degraded further.

The difference between young and old observers is especially large when considering signs with very low luminance backgrounds (e.g., black or non-reflective), as illustrated in E-6. The same is true for signs using a black legend (see example in Figure E-7). Where such combinations must be used it would be appropriate to use a maximum legibility criterion of 4.8 m/cm, rather than 6.0 m/cm or better, to allow for the special problems of older drivers.

Legend luminance contrast beyond that associated with maximum legibility was much more likely to degrade the performance of older subjects. Hence, care must be taken that combinations with excessive legend contrast are not used.

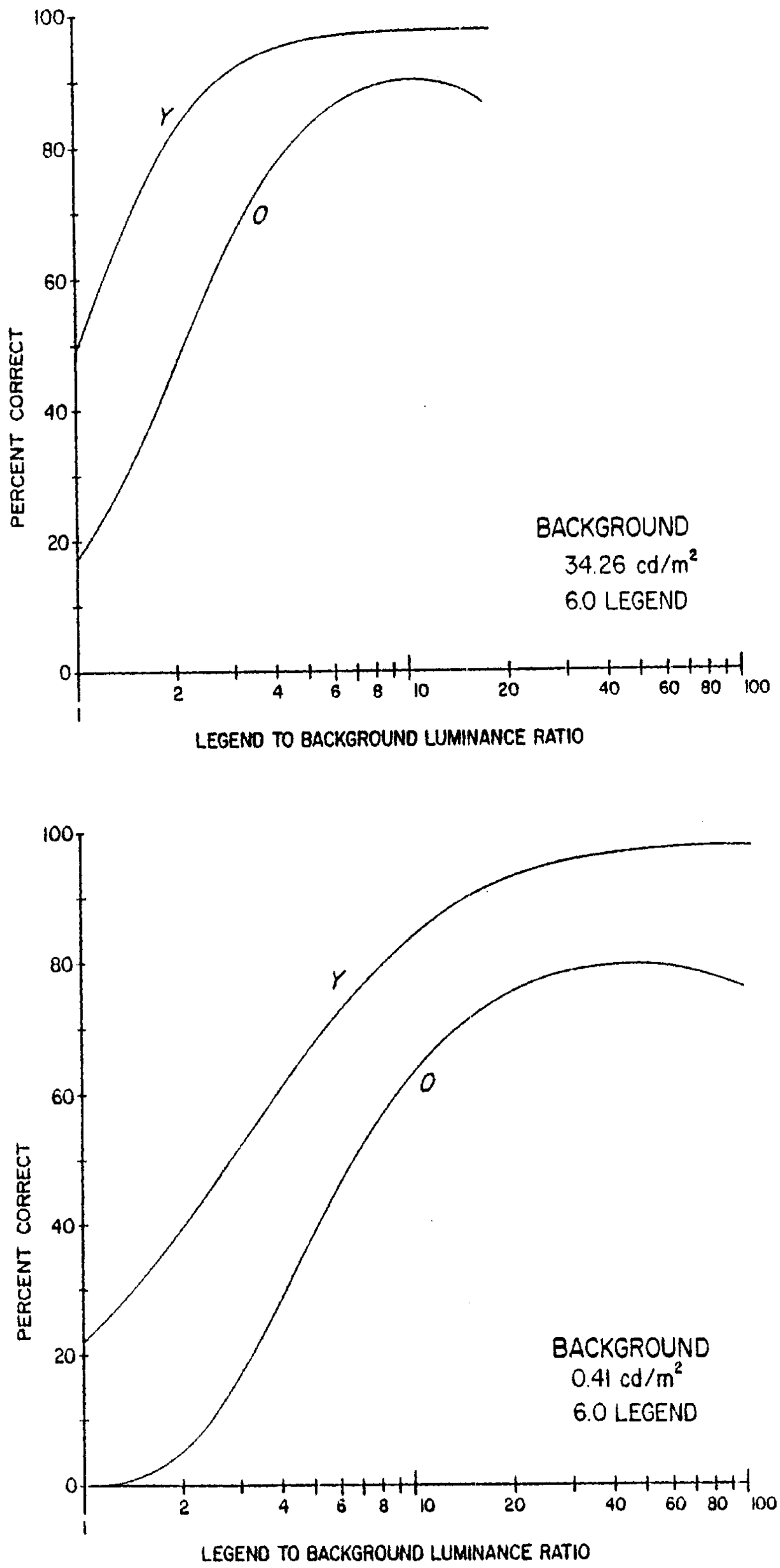
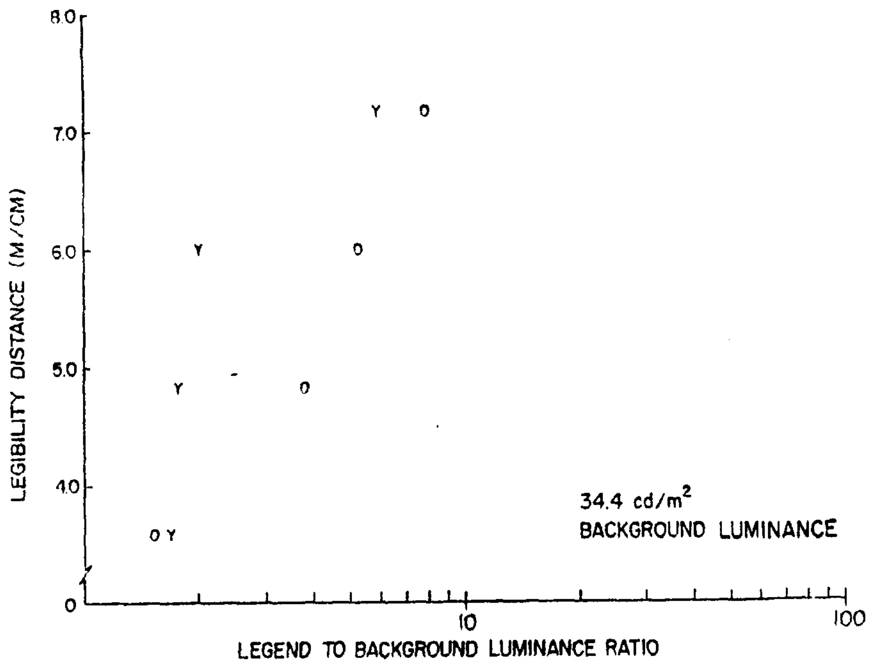


Figure E-5. Percent correct responses as a function of legend luminance contrast and two levels of background luminance (34.25 and 0.41 cd/m^2) for older as compared with younger subjects. Legend size 6.0 m/cm. Green background, dark surround (0.034 cd/m^2).



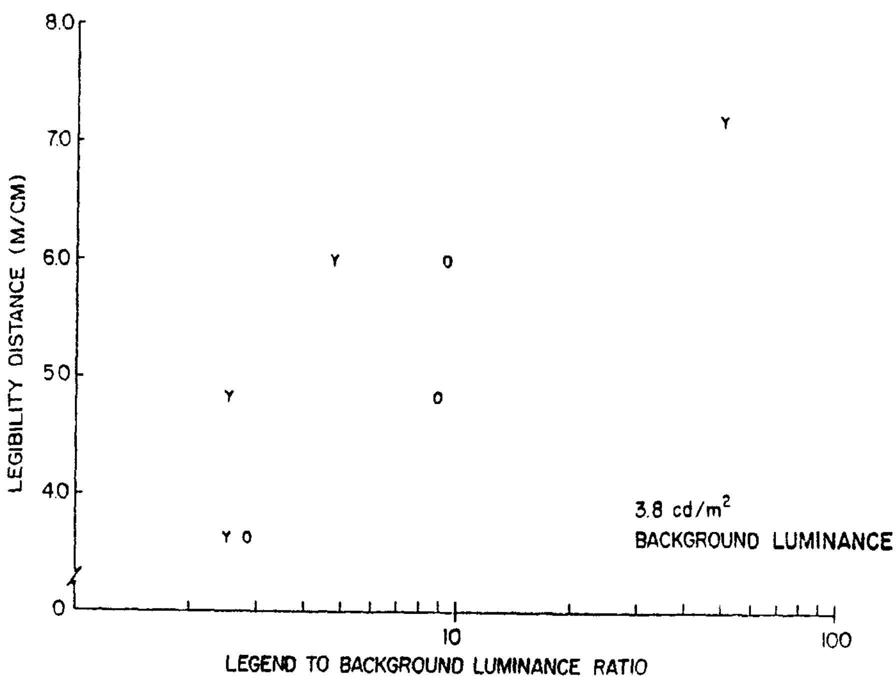
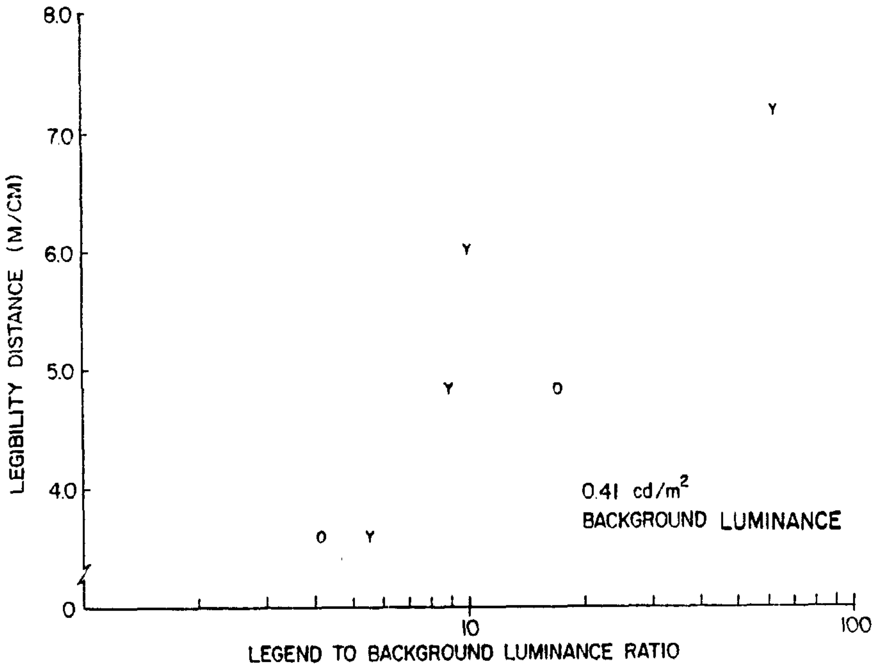
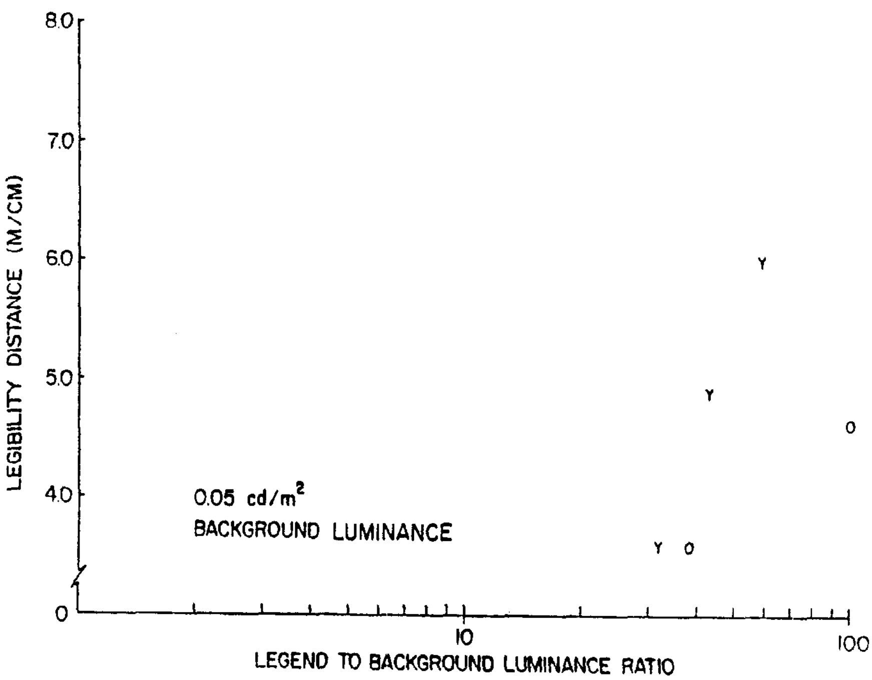


Figure E-6. Legibility as a function of background luminance and legend luminance contrast for younger as compared with older subjects. Green background, dark surround (0.034 cd/m^2).


LEGIBILITY DISTANCE (M/CM)
8.0
7.0
6.0
5.0
4.0
0
0.41 cd/m²
BACKGROUND LUMINANCE
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO


LEGIBILITY DISTANCE (M/CM)
8.0
7.0
6.0
5.0
4.0
0
0.05 cd/m²
BACKGROUND LUMINANCE
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

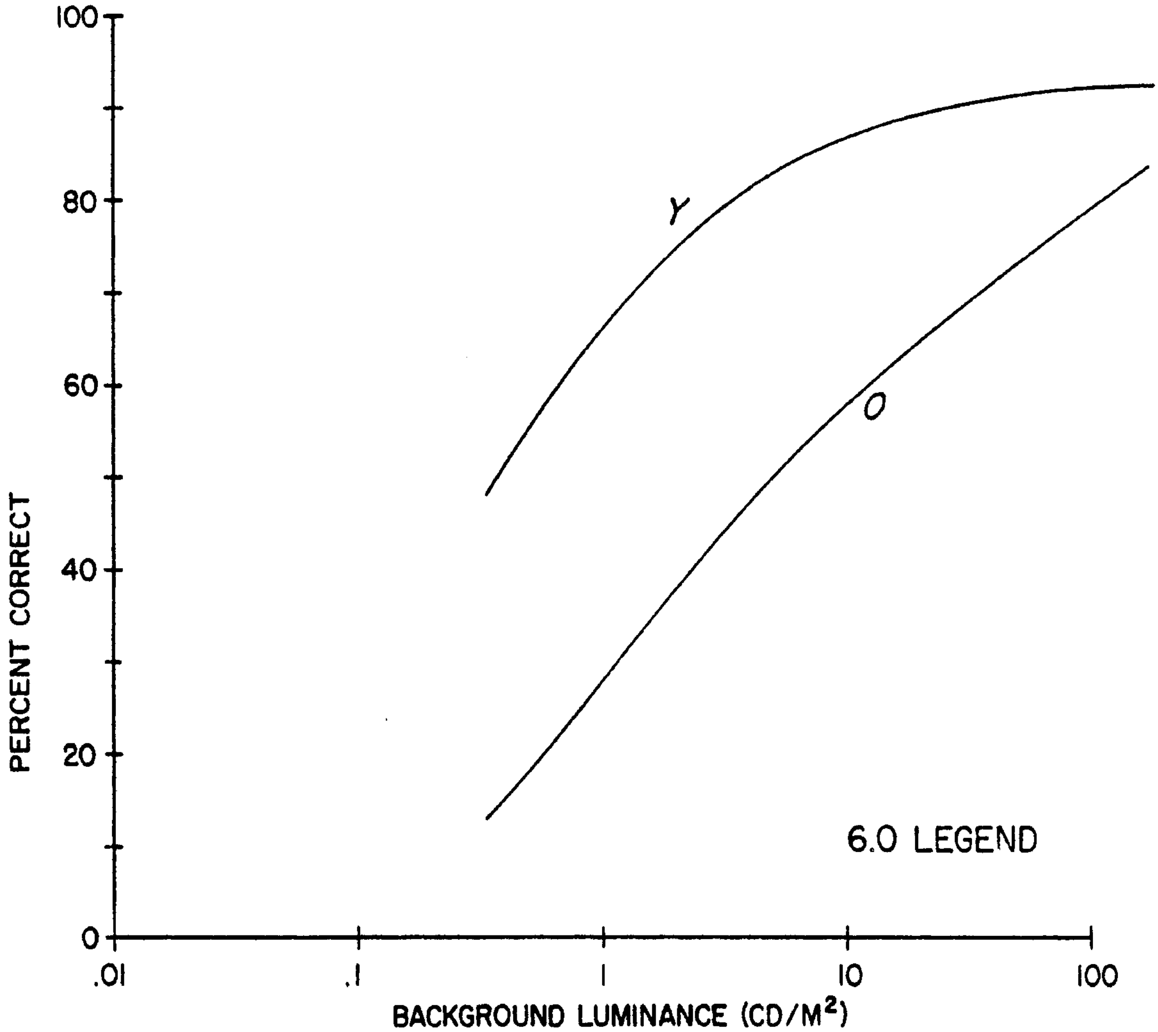


Figure E-7. Percent correct responses as a function of background luminance and legend size for older as compared with younger subjects. White background, dark surround (0.034 cd/m^2).

Figure E-8 compares glare response data for young and older subjects. In each case only the smallest angle and highest level glare resulted in a significant decrement.

Surround luminance had more of an effect in the case of older subjects than younger subjects (Figure E-9). Increasing surround luminance reduced the effect of excessive contrast and improved legibility for the older subjects.

CONCLUSIONS

1. Legend luminance contrast is the most important variable affecting sign legibility under night driving conditions. The optimum level depends on sign background luminance. For typical retroreflective signs, it would be in a range of 30-50:1. For highly reflective signs the contrast can be much less, i.e., 5:1. Contrast in excess of the maximum recommended may affect legibility adversely, especially for older drivers.

2. Background luminance is a significant factor in sign performance. In particular, high levels of background luminance increase conspicuity, reduce the effects of environmental glare, and improve legibility distance for all drivers, but especially older drivers.

3. Environmental glare appears to be a negligible factor in sign legibility unless high intensity sources appear quite close to the sign.

4. Sign background color has a small effect on legibility.

5. Signs having one very low luminance component (either legend or background) seem to pose a special problem to older drivers. Because of this, it would be desirable to assume shorter legibility distances (about 10-20%) for these signs than for signs having both the legend and background reflectorized.

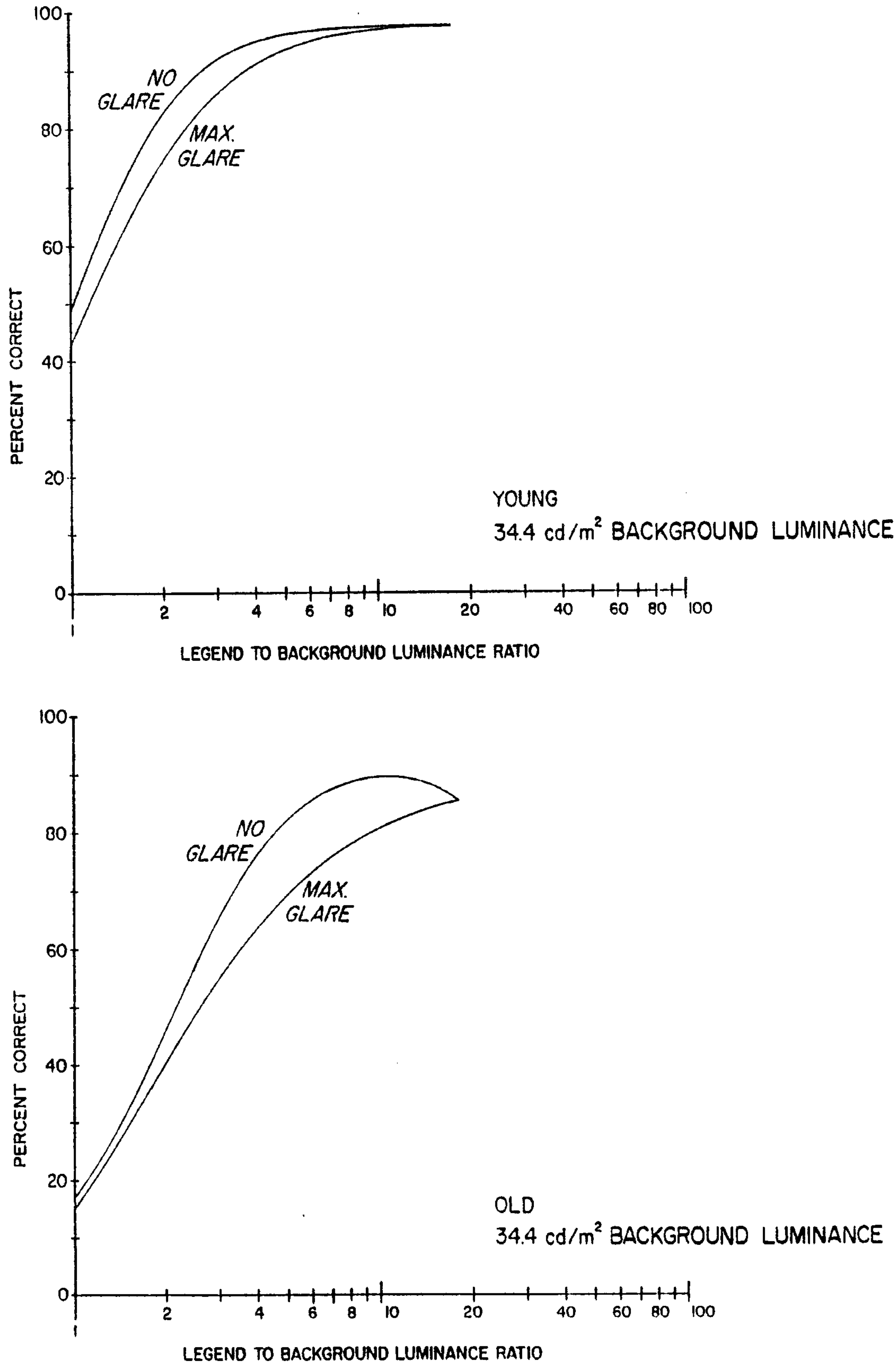
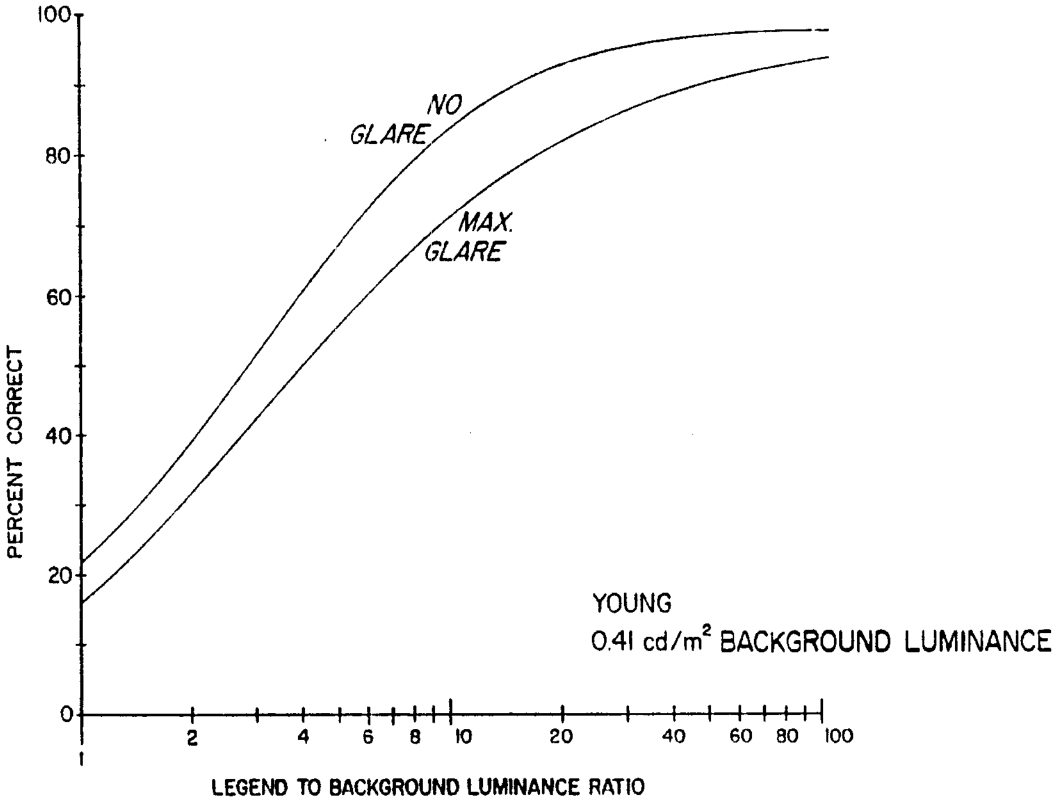
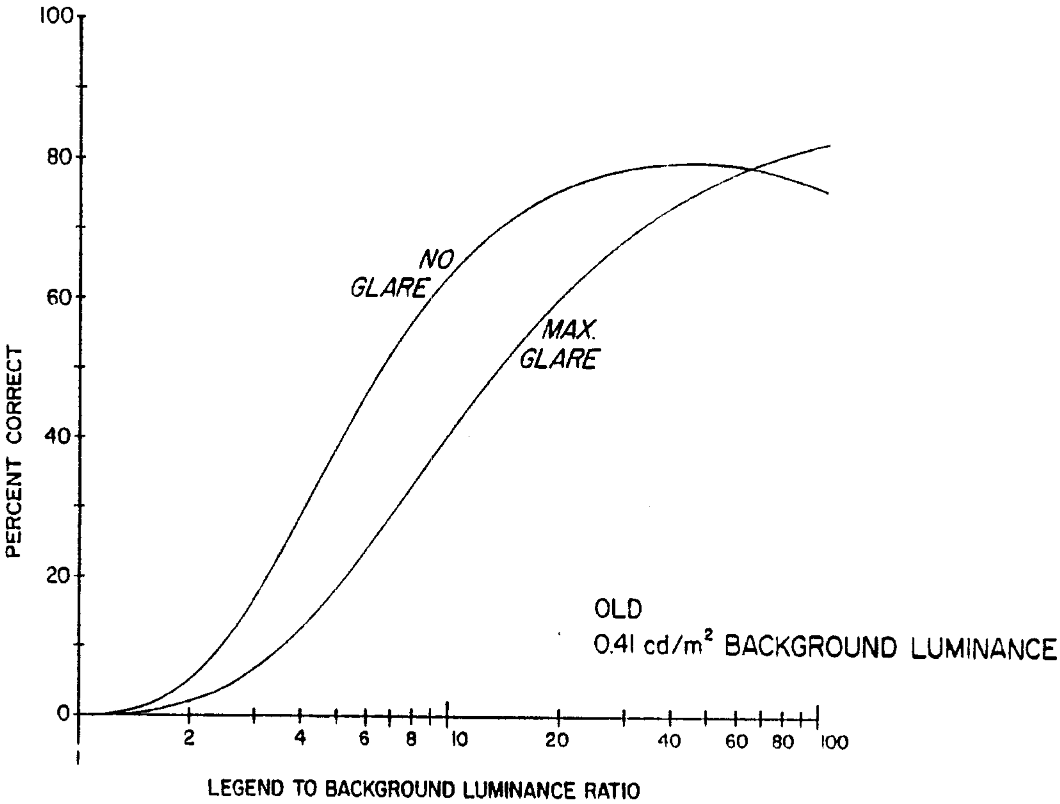


Figure E-8. Percent correct responses as a function of glare, two levels of background luminance (34.4 and 0.41 cd/m^2), and legend luminance contrast for younger as compared with older subjects. Dark surround (0.034 cd/m^2), green backgrounds.


100
80
60
40
20
0
PERCENT CORRECT
NO GLARE
MAX. GLARE
YOUNG
0.41 cd/m² BACKGROUND LUMINANCE
1
2
4
6
8
10
20
40
60
80
100
LEGEND TO BACKGROUND LUMINANCE RATIO


100
80
60
40
20
0
PERCENT CORRECT
NO GLARE
MAX. GLARE
OLD
0.41 cd/m² BACKGROUND LUMINANCE
1
2
4
6
8
10
20
40
60
80
100
LEGEND TO BACKGROUND LUMINANCE RATIO

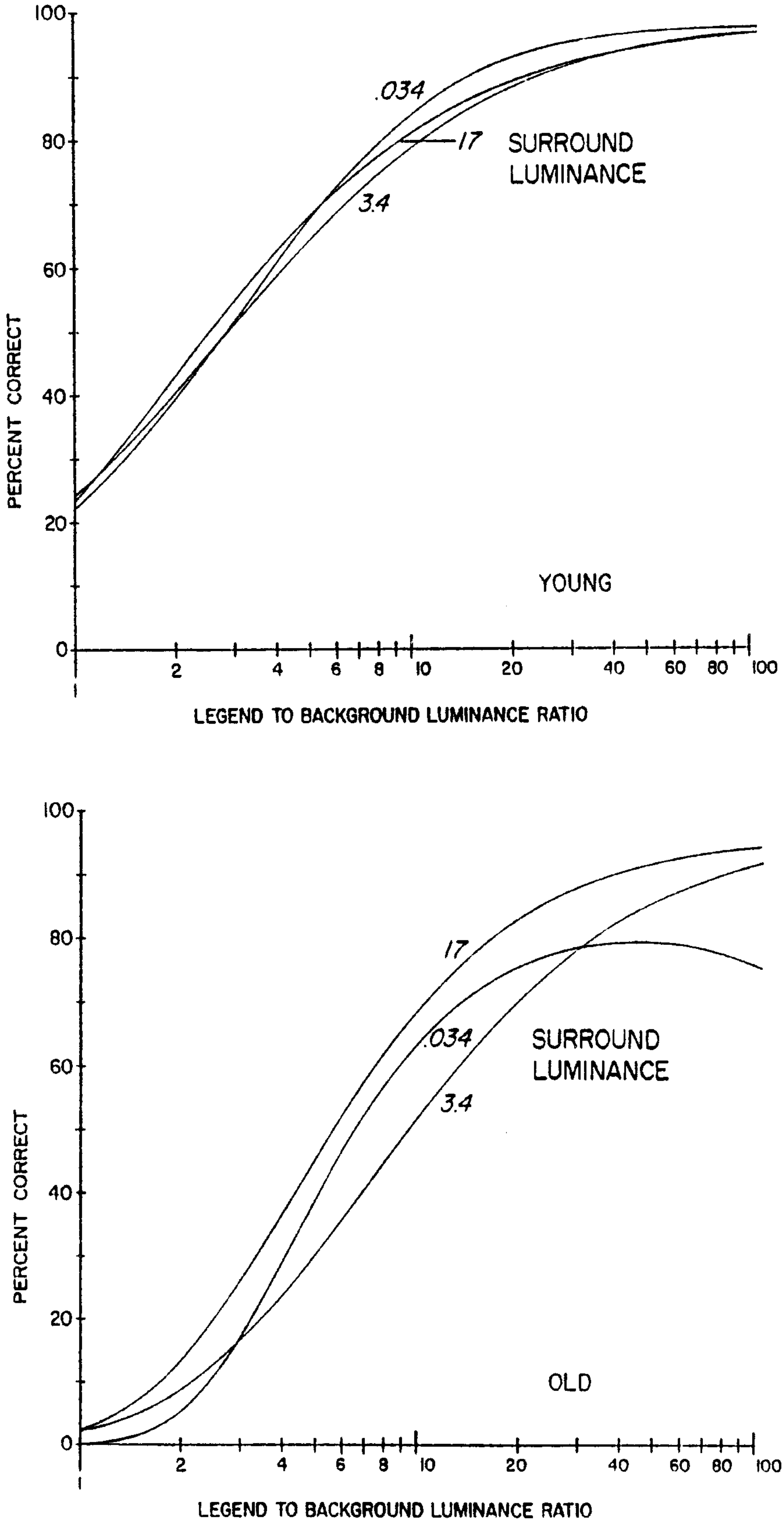


Figure E-9. Percent correct responses as a function of surround luminance and legend luminance contrast for younger as compared with older subjects. Green backgrounds (0.41 cd/m^2), 6.0 m/cm legend.

FIELD EXPERIMENTS

Two field studies were carried out to measure sign legibility under actual driving conditions.

EXPERIMENT 1

METHOD

Variables

Sign luminance and contrast characteristics. Five legend and background combinations were tested. The specific luminance (in $cd/lx/m^2$ at 0.2° and -4°) and contrast ratios were as follows:

Legend	Background	Contrast Ratio
115	36	3:1
325	36	9:1
1200	36	33:1
1200	15	80:1
115	0.06	1916:1

Environmental glare. One glare angle (2.0°) and two glare illuminance levels (0.017 and 0.17 lux measured at the subject's eyes) were used.

Subjects

Twelve subjects participated in the study. Half were between 20 and 30 years of age (mean = 26 years), half were between 59 and 75 years of age (mean = 68 years). These persons were prescreened and the groups matched on several visual variables. In particular, they were matched in terms of high luminance acuity under both high and low contrast conditions, and low luminance-high contrast acuity as well.

Procedure

The study was carried out on an unused roadway in a dark environment. The test signs and glare sources were set up at the edge of the road. Three subjects (one driver and two passengers) were run at a time. The test vehicle was driven along the right lane of the facility and the subjects indicated on each run when they could detect the orientation of the test letter.

RESULTS

The results of the study indicated that legibility distances in the presence of glare were significantly longer than they were in the absence of glare.

One of the most interesting findings was that the two subject age groups provided legibility distances that were not statistically different. This suggests that the usual finding of an age-related visual decrement is a result of visual rather than information-processing changes.

The longest legibility distances were provided by the letter/background combinations yielding contrast ratios of 33:1 and 9:1. Further increase in the contrast ratio (to 80:1) or a decrease (to 3:1) was accompanied by a performance decrement. However, the contrast levels were partially confounded with background luminance levels, and therefore this effect cannot be conclusively attributed to contrast alone.

EXPERIMENT 2

METHOD

Variables

The second study was carried out to examine glare effects of smaller glare angles than the one tested in the first study. Only one sign was used (legend 325 and background 36 $cd/lx/m^2$ at 0.2° and -4°) and one glare illumination level (0.0098 lux). Three glare angles were used (0.2°, 0.6°, and 1.5°).

Procedure

The test was carried out in a manner similar to the first test. A different facility was used and the subject vehicle was driven at a lower speed. Three subjects (19-27 years of age) participated.

RESULTS

The results of this study indicated a significant legibility-distance decrement for the smallest glare angle only. The legibility distance for the other two glare angles did not differ significantly from those for the no-glare condition.

DISCUSSION

There are several practical ramifications of the present findings. First, nighttime legibility performance of older drivers can be comparable to that of the younger drivers if the two age groups are matched on their low-luminance (nighttime) visual acuity. This conclusion has obvious implications for driver licensing (currently relying primarily on high-luminance visual-acuity screening). Furthermore, when correcting older driver vision, ophthalmologists and optometrists should pay attention to visual acuity under both high-luminance and low-luminance conditions. This procedure might lead to two different corrections: one optimal for the daytime and one for the nighttime.

Second, the optimal legibility performance is likely to be achieved by contrast ratios (between legend and background) in the intermediate range. (The exact optimum will depend on other parameters, including the background luminance.)

Third, legibility performance appears to be a robust process, unaffected by glare unless the glare angle is extremely small or glare level very high. (The robustness of the legibility performance should be contrasted with the susceptibility to glare of detection performance [e.g., Schober, 1967]). Furthermore, glare sources positioned outside of the fovea (at 2° under the conditions of Experiment 1) might even lead to improved legibility of the legend. Confirmation of the present findings as well as delineation of the conditions leading to improvement of performance with glare present is required to establish glare-enhancement as a reliable phenomenon.

THE SIGN AS A GLARE SOURCE

This was a laboratory study that measured disability glare from bright signs in the field of view.

METHOD

Variables

Glare illuminance. Five levels of glare were used, i.e., none, 0.904, 0.101, 0.0104 and 0.0012 lux, measured at the subject's eye.

Glare angle. Five glare angles were tested. These were (measured from the edge of the simulated sign to the center of the target disc): 0.25°, 0.75°, 1.5°, 3.0°, 5.0°.

Subjects. Five young subjects (mean age = 26 years) participated in the study. The subjects had been screened for several visual characteristics and were selected to be representative (of young persons) and relatively homogeneous on low-luminance measures.

Procedure

Subjects were run individually. For a given series of trials they were exposed to a particular combination of the independent variables and a measure obtained of the target disc luminance required to achieve threshold performance. The target disc was exposed for one second at a time. This process was repeated for each combination of variables.

RESULTS

The results of the study suggest that retroreflective signs as presently used generally do not pose a significant glare problem. For most applications, sign luminance levels can be significantly greater than they commonly are at present. However, very bright signs placed close to a low-contrast object (e.g., construction area signs) may provide significant disability glare; hence care should be taken to position them to ensure that traffic is moved clear of possible conflicts. Some types of signs (e.g., internally illuminated, advertising signs) may provide substantial disability glare if placed relatively near a roadway. It may be desirable to control the use of such signs.

1.0 LABORATORY STUDY OF VARIABLES AFFECTING THE NIGHTTIME LEGIBILITY OF HIGHWAY SIGNS

1.1 Method

In this phase of the project laboratory data were collected to assess the effect of several variables on the legibility of signs under night viewing conditions.

1.1.1 Variables. The following variables were investigated:

1.1.1.1 Glare Illuminance. The glare source was circular and subtended an angle of about 0.2° at the observer's eye. Glare was measured in the plane of the subject's eyes, using a Pritchard photometer.

Five levels of glare were utilized, as described in the table below:

Glare Illuminance		Approximately Equivalent to:
Lux	Ft-c	
0	0	
0.0006	0.00006	Low beams at 1580 m
0.0059	0.00055	Low beams at 500 m
0.059	0.0055	Low beams at 160 m
0.59	0.055	High beams at 360 m

Some data were taken at a still higher level (5.9 lux, 0.55 ft-c), approximately equal to high beams at 110 meters. The results did not differ from the 0.59 lux level and a long dark-adaptation time (one minute) was required between trials. As a result this level was little used and is not reported separately. "Max glare" in the Results section refers to the 0.59 lux level.

1.1.1.2 Glare Angle. Five levels of glare angle were utilized. These were:

1. None (source to the edge of the sign)
2. 0.7°
3. 3.5°
4. 7.5°
5. 15.0°

The angles were measured from the center of the legend on the sign to the edge of the glare source.

1.1.1.3 Sign background color. Seven colors were used. These were:

1. Green
2. Blue
3. Red
4. Black
5. White
6. Yellow
7. Orange

The colors conformed to Federal Specification LS 300 C and were provided by retroreflective-sign materials. White legends were used with the first four backgrounds, black with the last three.

1.1.1.4 Sign background luminance. The background luminance values used for the various colors are listed in Table 1-1. Different test procedures were used, depending on the background color. For example, when using green, blue, or red, background luminance was set at one of the values shown for those colors and legend luminance was varied to determine the response function. Black backgrounds were handled the same way, except there was only one luminance value (0 cd/m^2) for the background. In the case of white, yellow and orange backgrounds, legend luminance was constant (0 cd/m^2) and background luminance was varied through the range shown to determine the response function.

1.1.1.5 Sign legend luminance. The luminance of the white legend could be varied from 0.038 cd/m^2 (0.011 ft-L) to 733.0 cd/m^2 (214.0 ft-L) in 23 steps as shown in Table 1-2.

1.1.1.6 Surround luminance. The luminance of the wall behind the sign display was varied in three steps: 0.03, 3.43, and 17 cd/m^2 (0.01, 1.0, and 5.0 ft-L).

1.1.1.7 Subject characteristics. A careful visual screening was carried out in an effort to select homogeneous subject groups for this study. The procedures are explained in Appendix A, which also contains a table listing the visual characteristics of the subjects who participated in this study.

1.1.2 Equipment. A schematic of the laboratory apparatus is provided in Figure 1-1. With some modifications, it is the same as that used by Olson and Bernstein (1977).

TABLE 1-1

LUMINANCE VALUES (cd/m^2) FOR VARIOUS BACKGROUNDS USED IN STUDY

FILTER NUMBER	FILTER PERCENT TRANSMISSIVITY	COLOR					
		GREEN	BLUE	RED	WHITE	YELLOW	ORANGE
None	100.0	34.3	34.3	34.3	205.6	156.6	57.2
1	77.0				158.6	119.2	43.9
2	53.0				109.6	83.3	30.1
3	26.0				57.2	40.1	14.6
4	12.0	3.82			25.8	19.0	6.6
5	8.0				17.0	12.6	4.5
6	6.0				12.5	9.5	3.3
7	3.0				6.3	4.8	1.68
8	1.25	0.41	0.39	0.45	2.71	2.04	0.75
9	0.95				1.95	1.47	0.55
10	0.62				1.26	0.96	0.36
11	0.75				0.72	0.54	0.20
12	0.17	0.05			0.36	0.27	0.096

The "sign" display was provided by the box diagrammed in the upper left corner of the figure. By means of two projectors it allows nearly independent control of background and legend luminance. The key components of the sign box are (as identified in Figure 1-1):

A. a piece of plate glass, which acts as a partially reflecting mirror,

B. a slide mounting, into which aluminum panels with retroreflective materials can be placed, and

C. a clear acrylic sheet in a rotatable mounting. The legend was attached to this sheet.

Background luminance was provided by projector L_1. (All light sources were ordinary 35 mm slide projectors. An aluminum mask with a small hole drilled through was inserted just behind the slide position to restrict the beam to the desired size.) The beam from L_1 was reflected by the mirror at D and into the side of the sign box. It passed through A, was retroreflected at B, and returned toward L_1. About 8% of this illuminance was reflected by A through C, toward the subject at E, 15.24 meters (50 feet) away. With just L_1 operating, the subject saw a uniformly illuminated surface, the color of which was determined by the material used at B,

TABLE 1-2

LUMINANCE VALUES (cd/m^2) OBTAINABLE WITH WHITE LEGENDS

FILTER NUMBER	FILTER PERCENT TRANSMISSION	LEGEND LUMINANCE
None	100.0	723.0
1	76.6	562.0
2	45.3	332.0
3	33.3	244.0
4	25.8	189.0
5	19.2	140.0
6	8.55	61.7
7	4.77	34.9
8	3.45	25.3
9	2.79	20.5
10	1.74	12.8
11	.808	5.93
12	.477	3.49
13	.354	2.59
14	.281	2.06
15	.195	1.43
16	.104	0.76
17	.047	0.34
18	.043	0.312
19	.028	0.206
20	.0220	0.161
21	.0112	0.082
22	.0051	0.038

and the luminance of which was varied by neutral density filters in the slide tray of L_1.

The legend consisted of a single Landolt ring, centered on C. The mounting permitted it to be turned by an electric motor so that the ring gap could appear at the 3, 6, 9, or 12 o'clock positions.

The legend was illuminated by projector L_2. The beam from this unit was directed toward a mirror mounted just below the subject's eyes, and reflected toward C. The arrangement incorporating the mirror just below the subject's eyes was necessary to keep the observation angle small (about 0.3° in this case).

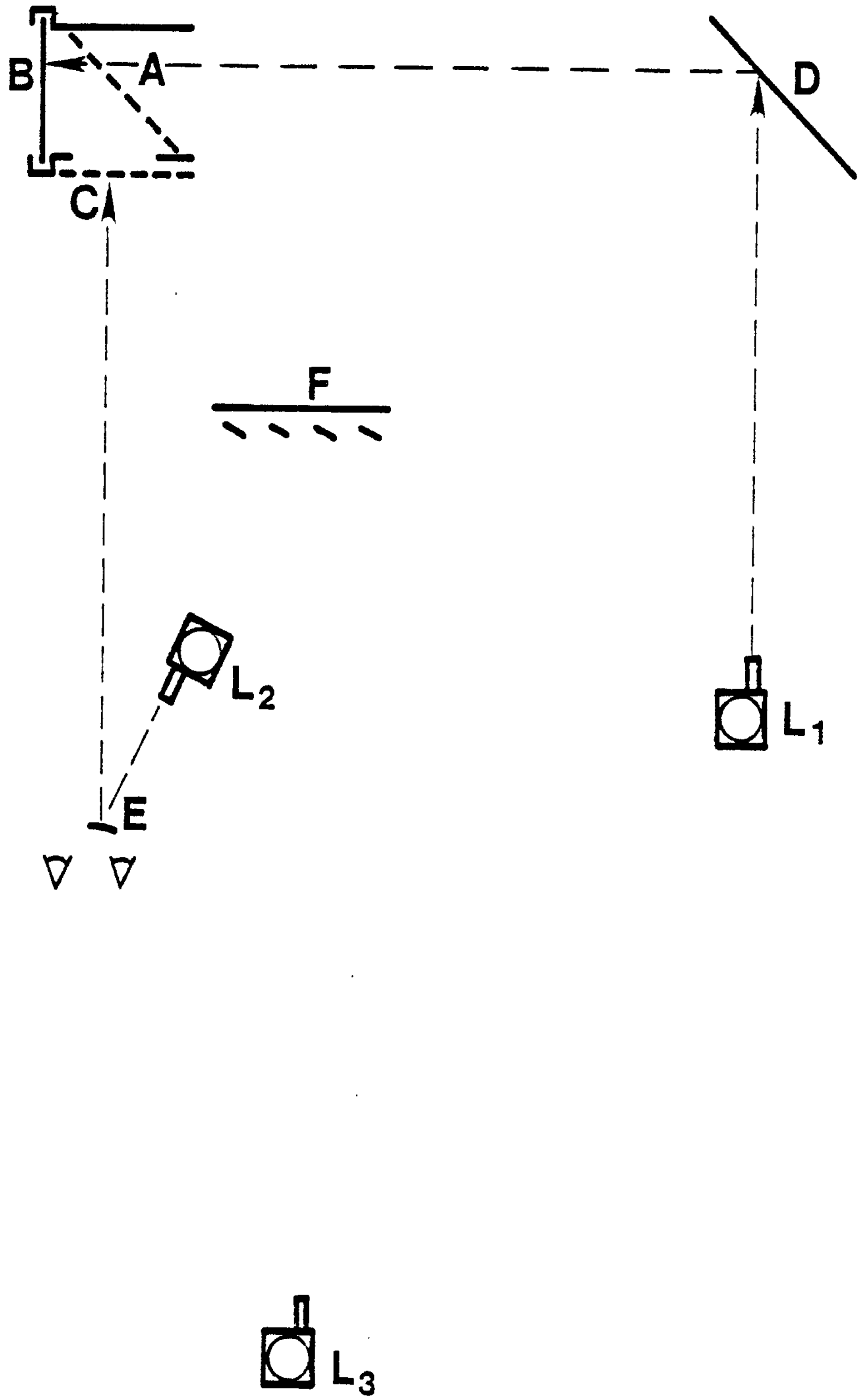


Figure 1-1. Schematic of equipment for laboratory study.

The white legend was made of white enclosed-lens retroreflective sheeting. Four legends were used, their sizes corresponding to viewing distances of 7.2, 6.0, 4.8, and 3.6 m/cm (60, 50, 40, and 30 ft/in letter height). Legend luminance was varied by use of neutral density filters in the slide trays of L_2.

It should be noted that illuminance from L_2 interacted to some degree with that from L_1. That is, about 8% of the legend illuminance which passed through C was reflected by A toward B. Then, 8% of that retroreflected at B was reflected again at A and seen by the subject as added to the background luminance. Disregarding losses at B and C, this means that about 0.6% of the legend illuminance was added to the background. This effect was of practical consequence only for low background-high legend luminance conditions. However, measurements were made of actual background luminance at all levels of legend luminance, and these values used in the data analysis. See Appendix B for details.

Glare was provided by a third projector (L_3 in Figure 1-1), situated about 5 meters behind the subject. The beam from this unit was reflected from one of four mirrors attached to a panel (F in the Figure) located 3.4 meters forward of the subject. Normally, three of the mirrors were covered. The glare angle was determined by the mirror in use.

Not shown in the schematic is a compensatory tracking task, the display of which was located just below the sign box. The tracking task was in the form of a horizontal bar, the length of which was altered randomly at a rate averaging about 0.1 Hz. Using a finger-actuated joy-stick control, the subject was instructed to maintain the bar about half way across the screen.

The tracking task served two functions: First, it gave the subject something to do between trials, helping to reduce boredom. Second, and more important, it ensured that the subject's eyes were in a constant position relative to the sign box and accommodated to the proper distance. Performance on the task was not scored.

Figure 1-2 is a photograph of the laboratory, taken from just behind the subject's position. The subject's head was restrained both vertically and horizontally to ensure that his/her eyes remained at the desired position at all times. The sign box and tracking task are located at the far end of the lab. The black panel extending off to the right side of the picture is the mount for the glare mirrors. Just off the left shoulder of the subject, the legend projector (L_2) can be seen.

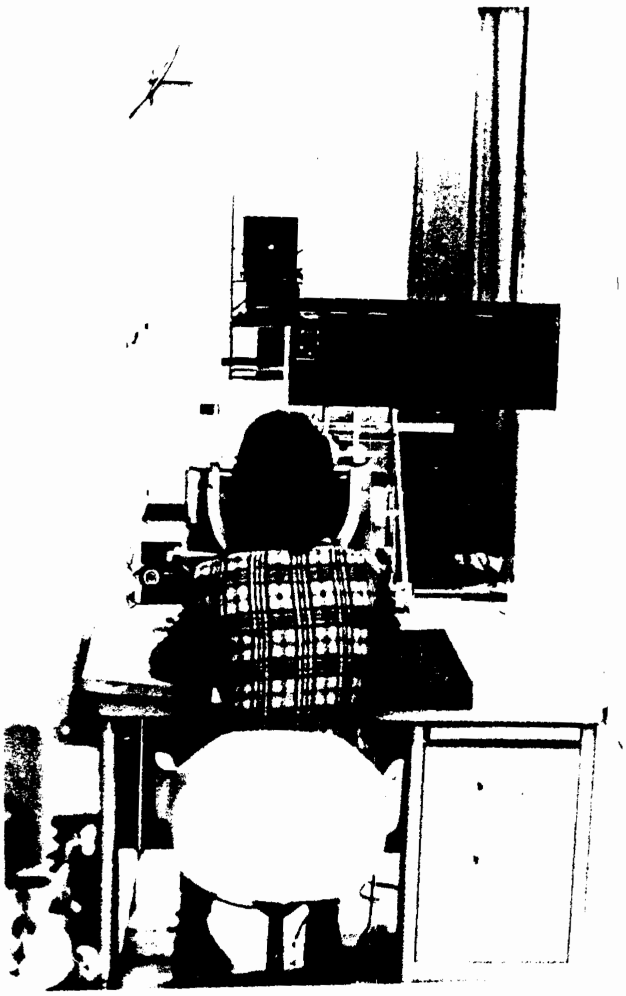


Figure 1-2. Photograph of laboratory arrangement, taken from just behind the subject's position.

Figure 1-3 is a view of the subject's station from the front. The subject's face is nearly hidden behind the mirror (E, in Figure 1-1) used to reflect the legend projector's beam. The legend projector (L_2) can be seen reflected in the lower portion of the mirror. The subject's left hand rests on the joy stick used to control the tracking task. His right hand rests on a response box. The box contained four buttons corresponding to the possible positions of the gap in the Landolt-ring legend. The subject responded to each stimulus presentation by pressing the button corresponding to his/her best guess of the gap position.

Figure 1-4 is a photograph of the sign box and tracking task device.

Figure 1-5 is another view of the same equipment seen from the side. Also shown is the mirror (D, in Figure 1-1) used to reflect the beam from the background projector, and the floodlamps behind the sign box used to increase the surround luminance.

A photograph of the experimenter's station is provided in Figure 1-6. It included a variac control for the legend and background projectors (item a in the photograph), a control console containing buttons for setting the position of the Landolt-ring gap, and lights to indicate the subject's response (item b), and controls for changing the neutral density filter slides in each projector (item c).

1.1.3 <u>Experimental Design</u>. The large number of independent variables and the levels of each made a conventional orthogonal design impractical. Rather, a partially replicated design was used, in which complete data were taken on one set of variables to form a frame of reference, and partial data were taken on other combinations of interest.

The basic data consisted of the white on green combination, all levels of legend size and background luminance at the lowest level of surround luminance.

Other data on surround luminance were taken on green backgrounds at 34 and 0.41 cd/m^2, 6.0 m/cm legend, and glare at the maximum intensity and minimum angle.

Glare data were taken on green backgrounds at 34 and 0.41 cd/m^2.

Data on red and blue backgrounds were taken at the two luminance values shown in Table 1-1.

Finally, data on black, white, yellow and orange backgrounds were taken with all legend sizes.

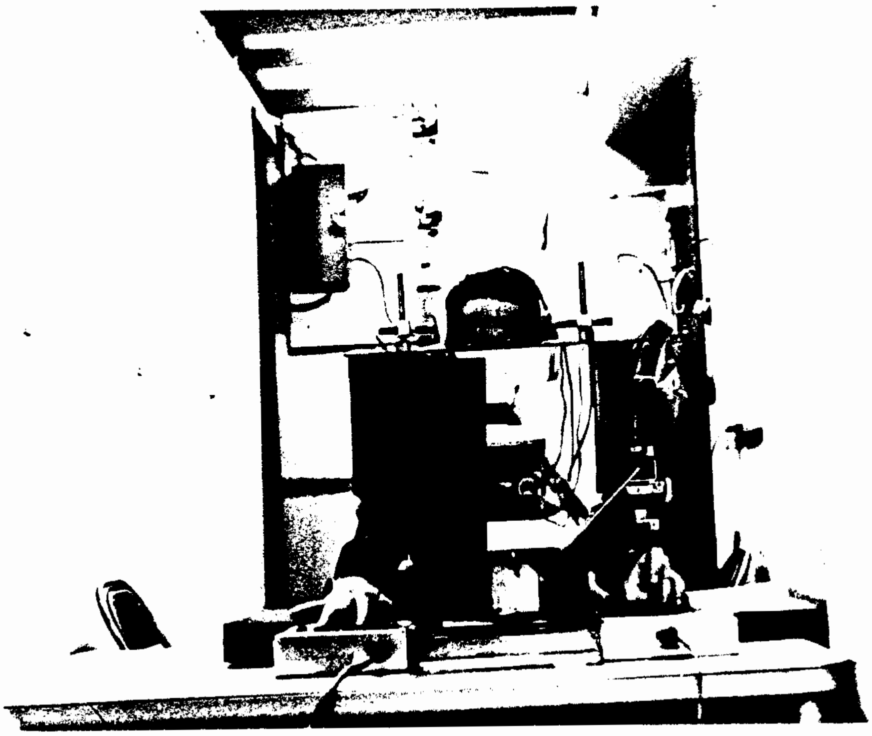


Figure 1-3. Photograph of subject's station as seen from the front.

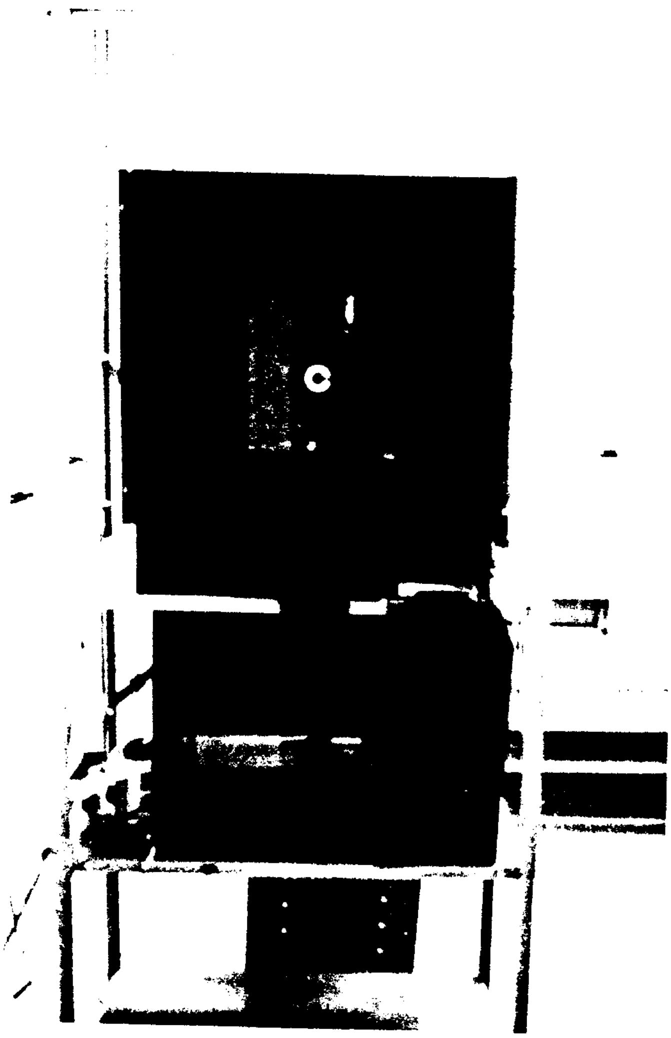


Figure 1-4. Close-up photograph of sign box and tracking task display.

Figure 1-5. Photograph of sign box from the side.

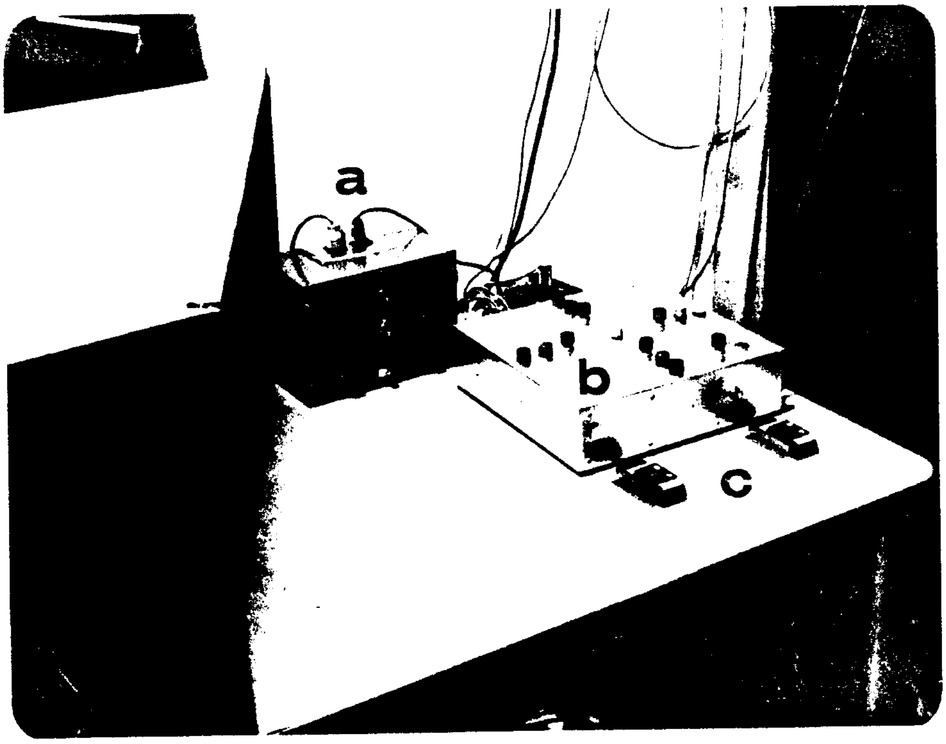


Figure 1-6. Photograph of experimenter's station. Labels identify:

Variac controls to projector lamps (a)
Control console (b)
Projector advance controls (c)

1.1.4 Procedure. A complete replication of the variables listed in the preceding section required about twelve half-day sessions. On the first occasion the subject reported for data collection, he/she was seated at the station, the instructions were read, and questions answered. The head support was adjusted, as was seat height, etc., until the subject was comfortable. The laboratory lights were then switched off so that dark adaptation could begin. In the first session, practice trials were given during the dark adaptation period (about ten minutes), to ensure that the instructions had been completely understood.

The data collection procedure depended on the background color being tested. If the color was green, blue, or red, the experimenter first established a background luminance level. The legend projector was then set so that on first exposure the legend and background luminances were the same. Data trials then commenced.

Each trial consisted of a one-second exposure of the particular combination of legend, background, and glare of interest. A one-second exposure was selected to approximate the interval that a driver on a freeway could afford to spend away from his/her primary task while reading a sign. The time of exposure was controlled by solenoid-operated shutters on each projector. A tone warning was sounded two seconds before the shutters were actuated.

Typically, on the first trial, the subject could not discriminate the orientation of the ring gap. For the next trial then, the experimenter increased the legend luminance by one filter step and tried again (with a randomly selected ring-gap orientation). This process was repeated until the subject responded correctly. At that point the experimenter initiated a descending series until the subject could no longer identify the gap position. Using this routine, a total of ten trials were collected on each contrast level through the transition zone.

Having completed the measurements in the low-contrast area, the experimenter then changed to the maximum legend luminance available and repeated the process at high contrast. Typically, there were no problems with high contrast when high background luminance levels were used. At low background luminance levels, the effects of high contrast were quite variable, some persons being much more affected than others.

If the background color was black, the same general procedure was used, except that background luminance was fixed at one level (the background projector was off) and it was not possible to start with a luminance match between the legend and background.

For white, yellow and orange backgrounds the legend projector was turned off, and subject performance was measured while varying background luminance in much the same way as described for white-legend combinations earlier.

1.1.5 Data reduction.

1.1.5.1 Raw data. During the data collection procedure, subject performance was hand-scored on record sheets. Each experimental condition was represented by an N x 10 matrix, where the N rows corresponded to the filters utilized to vary the independent luminance level, and the ten columns corresponded to the maximum number of trial replications. A binary entry ("X" for correct, "0" for incorrect) was made for every trial in the appropriate location.

The record matrices were subsequently summarized by tallying the total number of trials presented at each luminance level and the number of correct responses made. Each number pair was then keypunched on a computer card along with information identifying the subject, experimental condition, and luminance level. The final set of punched cards was entered into a computer which stored the data in a file for later analysis.

1.1.5.2 Preliminary review. The individual subjects' results were examined in order to determine the best analytical procedure for summarizing the data. A computer program was used to convert the response data to percentage scores corrected for the chance guessing factor. (The probability of a correct response based on chance alone was 0.25.) Results were scatterplotted as a function of the logarithm of the luminance values used. Thus, a set of 700 scatterplots (10 subjects x 70 conditions) was generated. These were reviewed to obtain estimates about (1) the shapes of the response functions, (2) the variability between subjects within the age groups, and, (3) the variability between the age groups.

This preliminary examination revealed that, in general, the data are similar in response level and pattern to those of the Olson and Bernstein (1977) study. In particular, it was evident that response patterns are frequently characterized by three distinct regions: at low luminance values responses increase with increasing luminance; at intermediate luminance levels responses maximize--often, but not always, at 100%; at very high luminance levels a response decrement occurs. The performance-improvement region tended to be S-shaped, as is typical of psychometric functions. To a lesser extent, this was also seen in high luminance, performance-decline regions.

Subjects within age groups tended to perform similarly. Nonetheless, despite being closely matched in age and visual acuity, individuals displayed considerable differences in levels and patterns of responses. For instance, extreme luminance levels resulted in performance decrements in some subjects, but not in others. Response patterns were observed to be similar for the two age groups. However, there was a marked difference in level of correct responses--the younger subjects being superior.

1.1.5.3 Computer analysis. The appropriate technique for analyzing psychophysical response data of this nature is an iterated weighted regression (Finney, 1971). The psychometric S-shaped pattern is "straightened out" by converting response percentages to normal equivalent deviates. Because subject response percentages near 0 or 100% carry little information, as do percentages generated by a small number of trials, these values must be weighted accordingly. Each regression produces a set of predicted response levels which are in turn used to reassign the weighting factors and initiate another regression cycle. Computation continues until the regressions stabilize or a satisfactory error tolerance is reached.

In applying this technique to the data, two additional factors were taken into consideration. First, the difference in capability between young and old subjects indicated that the groups should be analyzed separately. Second, the raw data of each group could not be directly compiled for single analyses. Because subjects were shown increasing luminance levels until perfect performance was achieved, if at all, more trials were required in cases of poor performance. A simple combination of subjects' data would therefore introduce heterogeneity biased toward the poorer performers. It was concluded that the analyses should first be conducted for individual subjects; the resulting predictions could then be averaged with equal weight and used for the group's analyses.

A computer program was developed to find one, two, or three best-fitting lines (with determined intersections) for each subject and condition in the manner described above, with log luminance as the independent variable. The number of lines fitted was determined by the number of characteristic response regions present, and the weighting coefficients were corrected for the chance guessing factor using Abbott's formula (Finney, 1971). Predicted values were generated and transformed back to percentages and averaged.

The averaged data for each condition and group were analyzed with a second program developed to find the best-fitting cubic polynomial in a similar manner. The choice of third order polynomials was made to smooth out transitions between the performance regions and handle non-linear trends introduced by averaging over subjects. Thus, each condition could then be described by a set of four coefficients for each group.

1.2 Results

1.2.1 Young subjects.

1.2.1.1 Luminance and contrast characteristics. Figures 1-7 through 1-10 summarize the data for these parameters. Each figure shows the best fit lines describing the percent correct responses for each letter size as a function of luminance contrast. (Contrast in these figures is defined as the ratio of legend to background luminance, L/B.) These figures are for the dark surround, no-glare conditions.

These figures describe the most important relations of this study. They are also representative of the format of those which follow, and are thus worth studying carefully.

For all legend sizes and levels of background luminance, performance was poor in the absence of luminance contrast, although some information was being transmitted, presumably on a basis of color contrast. Initial increases in legend luminance contrast result in improvements in legibility, with the slope and point of asymptote depending on the background luminance. For example, an 85th percentile legibility distance of 6 m/cm was achieved under the following conditions:

Background Luminance (cd/m^2)	Contrast	
34.3	2:1	(Figure 1-7)
3.82	5:1	(Figure 1-8)
0.41	10:1	(Figure 1-9)
0.05	60:1	(Figure 1-10)

Further improvements in legibility distance can be achieved by increases in legend luminance contrast. Using data from the same figures, an 85th percentile legibility distance of 7.2 m/cm (a 20% increase) was achieved under the following conditions:

Background Luminance (cd/m^2)	Contrast
34.3	6:1
3.82	35:1
0.41	60:1
0.05	--

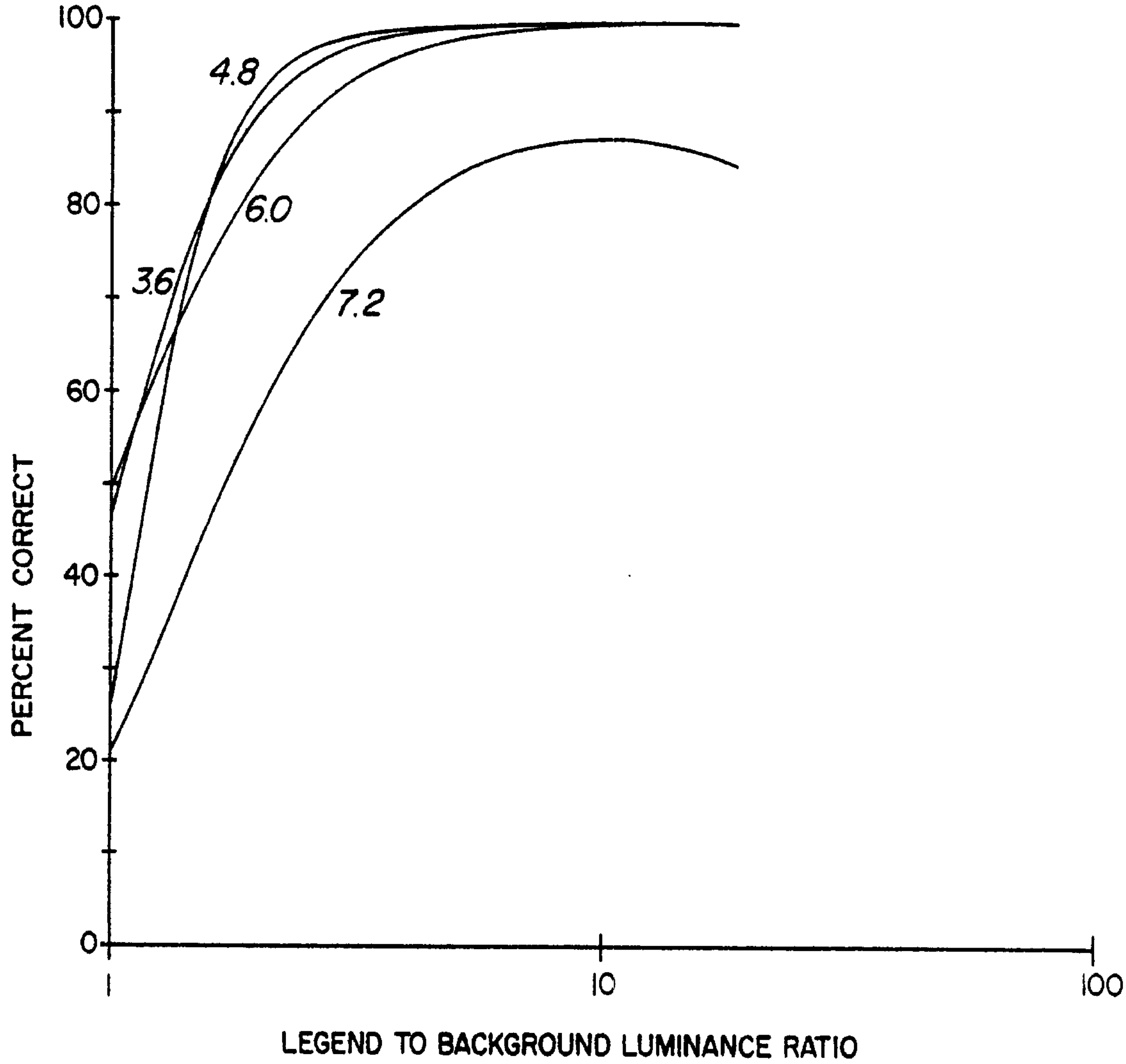


Figure 1-7. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance contrast.
Background luminance: 34.3 cd/m^2. Dark surround (0.03 cd/m^2).
Young subjects.

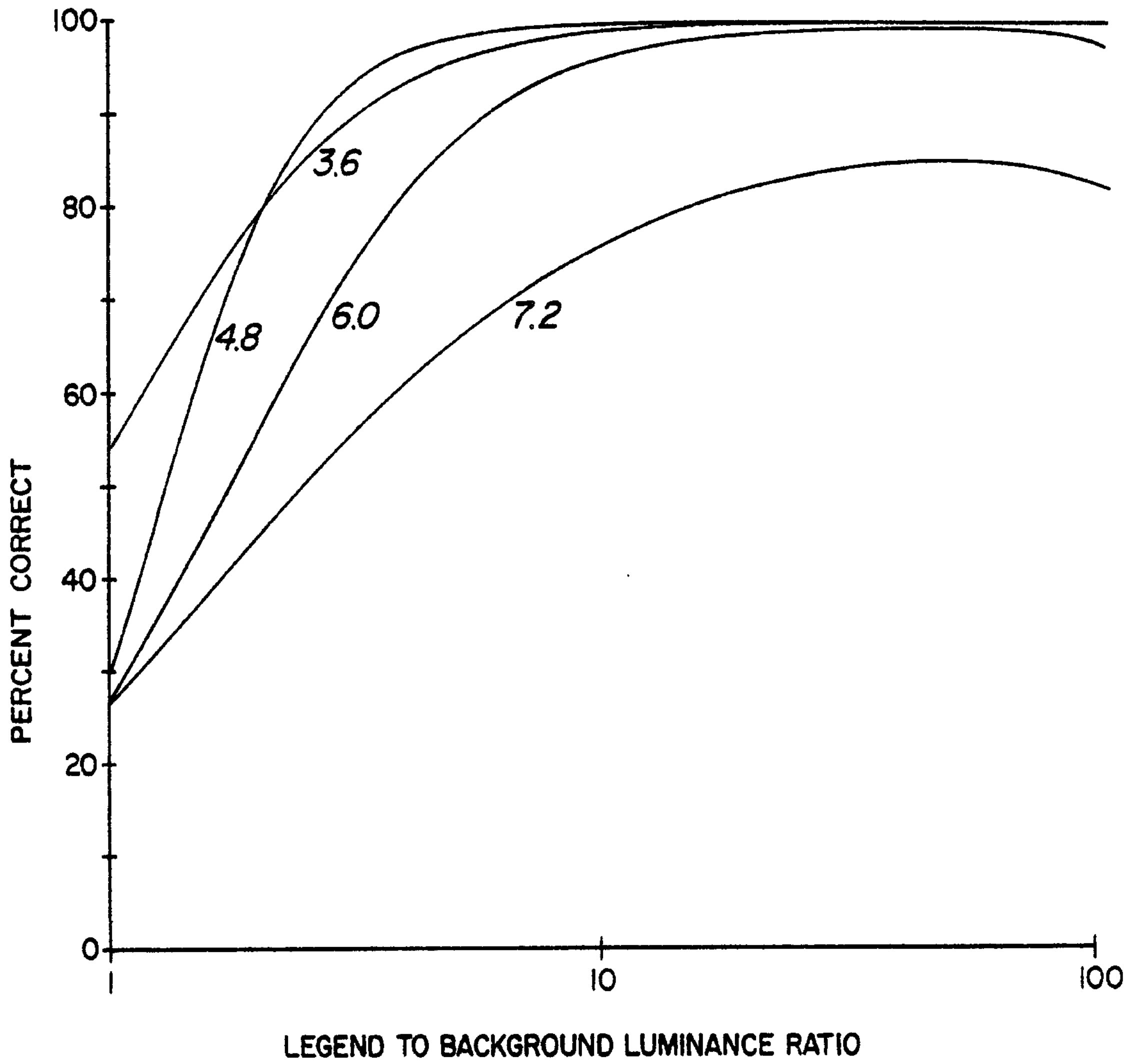


Figure 1-8. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance contrast.
Background luminance: 3.82 cd/m^2. Dark surround (0.034 cd/m^2).
Young subjects.

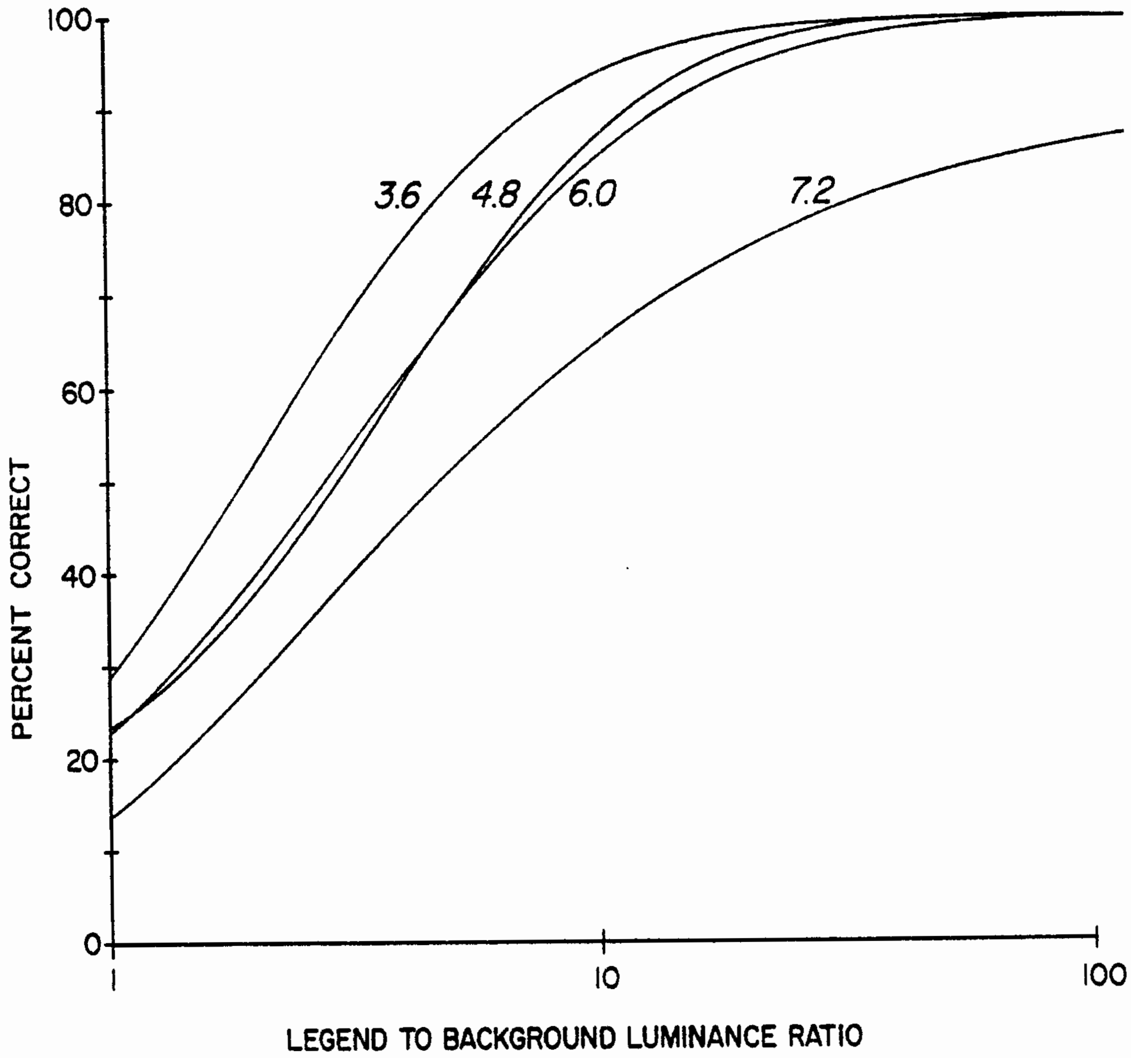


Figure 1-9. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance contrast.
Background luminance: 0.41 cd/m^2. Dark surround (0.034 cd/m^2).
Young subjects.

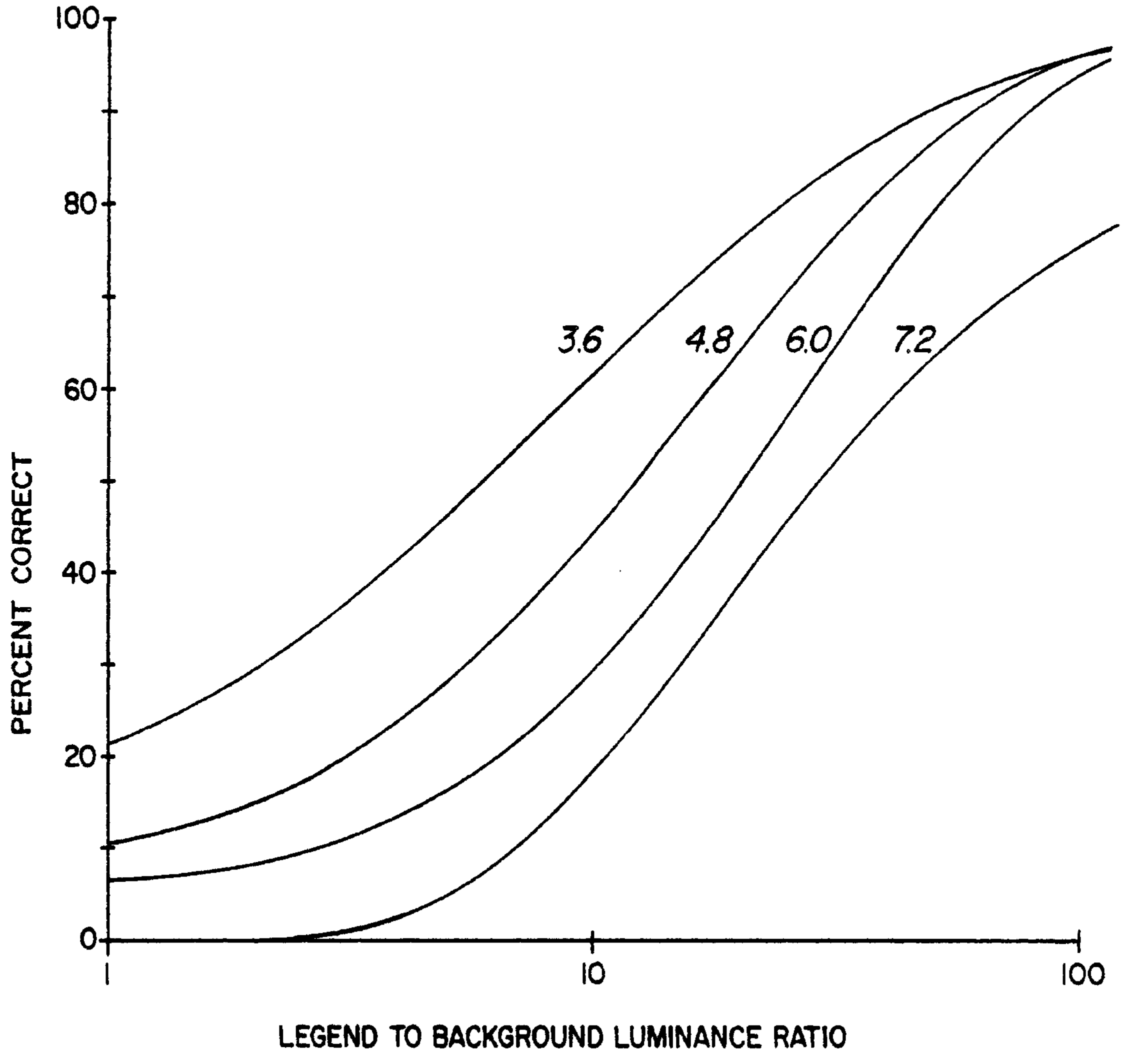


Figure 1-10. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance contrast.
Background luminance: 0.05 cd/m^2. Dark surround (0.034 cd/m^2).
Young subjects.

A legibility of 7.2 m/cm could not be achieved with the 0.05 cd/m^2 background at any level of contrast, although it reached about 80% correct identification at a contrast of about 1000:1. (See note on contrast approximations in Appendix B.)

Increases in legend luminance contrast beyond the level associated with asymptotic performance may lead to legibility losses. This effect varied greatly from subject to subject. It was most pronounced in the case of the older subjects, but was observed in some of the younger subjects as well. This is an argument for setting legend luminance contrast levels at the lowest point in the asymptotic range. However, that range must be based on the poorer performers in the driving population (e.g., the elderly, see Section 1.2.2).

For signs having a "reasonable" background luminance level, a recommendation such as the above is no problem. While "reasonable" cannot be defined with precision, the results of this and the previous study (Olson and Bernstein, 1977) suggest that it would not be much below 0.4 cd/m^2 for a dark environment. When background luminance drops as low as 0.05 cd/m^2 the eye seems to respond solely or largely to legend luminance. In this sense, the 0.05 cd/m^2 background luminance is similar to the black background, a subject which will be covered later. Clearly, if the eye is responding only to legend luminance, contrast is not a relevant parameter. Further, since the actual legend luminance will vary greatly with factors such as viewing distance, headlamp beam, sign location, etc., it is difficult to specify an optimum in terms of materials.

The maximum legibility that can be achieved by a sign is determined in part, by background luminance. In general, the higher the background luminance, the greater the legibility. The difference is most noticeable at the lower luminance levels. In particular, the maximum legibility that can be achieved with a non-reflective background appears to be 10-20% less than can be achieved with a background having significant luminance (i.e., about 0.4 cd/m^2 or more). This "maximum" legibility for non-reflective signs assumes a legend luminance in the range of 10-100 cd/m^2.

As background luminance increases above 0.4 cd/m^2, potential legibility increases as well, although at a slower rate. The difference between the 0.4 and 34 cd/m^2 background levels in this test was about 10% in terms of maximum potential legibility. However, these comments pertain to younger subjects. As will be noted shortly, the differences are much more pronounced in the case of older subjects.

Another means of looking at these data is provided by Figure 1-11. This figure shows for each legend size, the relationship between background luminance and legend contrast requirements. There is a monotonic relationship among the backgrounds, with darker backgrounds requiring more legend luminance contrast. However, the 0.05 cd/m^2 level is noticeably different from the other three.

1.2.1.2 Glare. Four independent variables were considered under this heading: glare illuminance, glare angle, sign background luminance, and surround luminance.

Figures 1-12 and 1-13 summarize the data for intensity and angle respectively. Clearly, only the highest intensity and smallest angle had effects of consequence. In each case, the effects of glare can be compensated for by increases in legend luminance contrast. For example, if a contrast of 10:1 will yield a legibility distance of 6 m/cm under no-or-low-glare conditions, these data suggest that an increase to 20-30:1 is required to maintain 6 m/cm under high glare, small glare angle conditions.

The effects of glare can also be reduced by increases in sign background luminance, as shown by Figure 1-14. This figure is for the same combination of variables as Figure 1-12, except the background luminance is 34 cd/m^2 rather than 0.41. Clearly the glare effect evident at the lower background luminance level (Figure 1-12) is reduced to negligible levels by the higher background luminance (Figure 1-14).

Adverse glare effects are also reduced or eliminated by surrounds characteristic of urban environments or illuminated freeways (Figure 1-15).

1.2.1.3 Surround luminance. Two independent variables were considered under this heading: surround luminance, and sign background luminance.

The results are summarized in Figures 1-16 and 1-17. Clearly, differences associated with surround luminance are negligible.

In a previous study (Olson and Bernstein, 1977) increasing surround luminance was found to improve legibility distance somewhat (5-10%) and reduce the effects of excessive contrast.

Given the relatively minor nature of the effect expected, it probably would have been desirable to use the 7.2 m/cm legend in the test series to improve sensitivity. The 6.0 m/cm legend was selected in deference to the older subjects, who did very poorly with the smaller legend. As will be noted later, the older subjects show significant changes in legibility with changes in surround luminance.

1.2.1.4 Backgrounds using white legends. Figures 1-18 and 1-19 summarize results obtained with the green, blue, and red backgrounds. At high background luminance levels (Figure 1-18) there are no apparent differences associated with the colors. However, at the lower background luminance level (Figure 1-19) there is evidence of differences, with the blue background being best, followed by green and red.

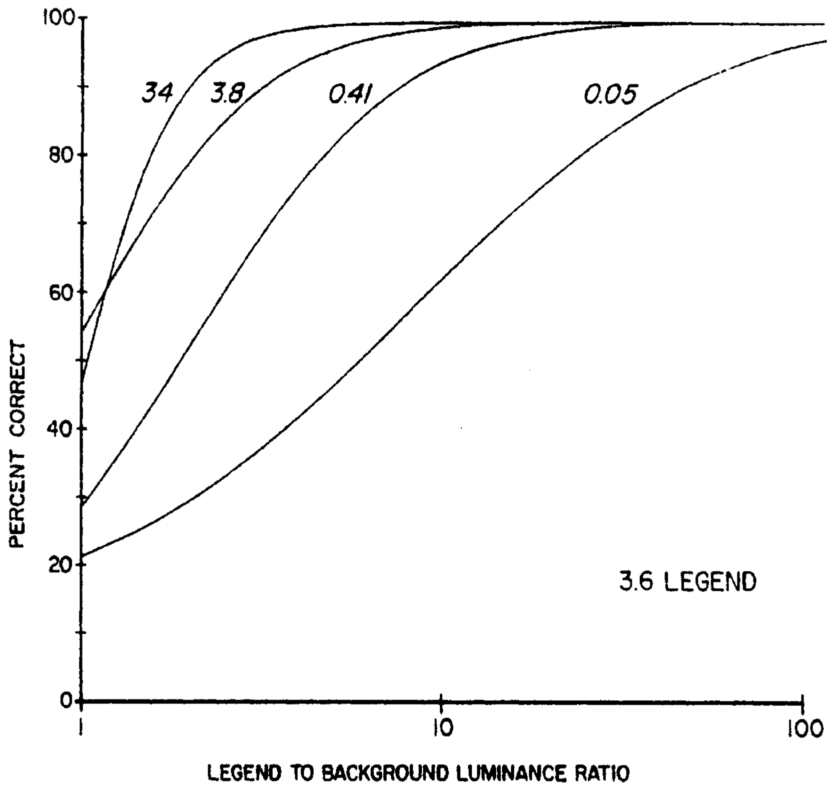
Since luminance readings are made with an instrument which is corrected to the photopic response characteristic of the eye, this result is not unexpected. In all likelihood it is attributable to the change in spectral sensitivity which occurs as the eye dark adapts (Purkinje shift). In any event, the differences are small and of little consequence in terms of legibility distance.

Figure 1-20 summarizes the data obtained for black backgrounds. The general configuration of the figures is the same as that noted earlier for green backgrounds. However, note the decline in legibility for the two smaller legends (6.0 and 7.2 m/cm) when legend luminance exceeded 100 cd/m^2.

It was expected that the results for black backgrounds would correspond closely to those obtained on the lowest luminance (0.05 cd/m^2) green background. Figure 1-21 provides a comparison between the black and lowest luminance green backgrounds for each of the four legend sizes. With the exception of the 3.6 m/cm legend, the fits are relatively close. The discrepancy at the low legend luminance level on the 3.6 m/cm curve is likely attributable to the loss of luminance contrast against the green background. With the black background, at the same level, some luminance contrast would still be present.

1.2.1.5 Backgrounds using black legends. Figures 1-22, 1-23, and 1-24 summarize the results for white, yellow, and orange backgrounds respectively. As in the case of white legend combinations, low luminance (contrast) levels yield poor legibility. Initial increases in luminance result in rapid improvements in legibility, followed by a rather abrupt leveling. Further increases in luminance, beyond the asymptote, may reduce legibility, at least for some persons.

Another way of looking at these data is provided in Figure 1-25, which compares the three backgrounds at each legend size.



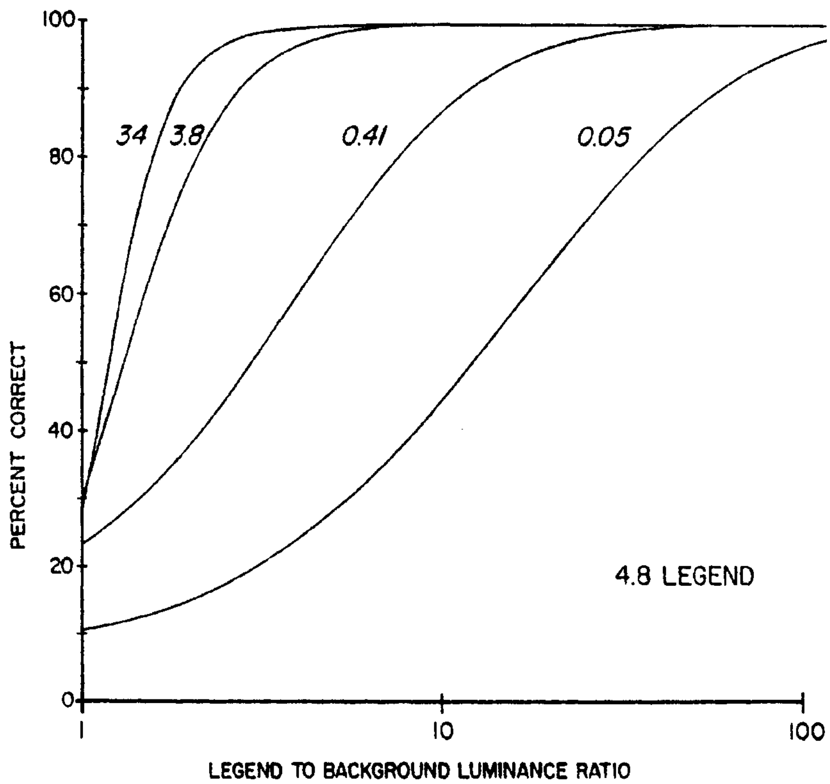
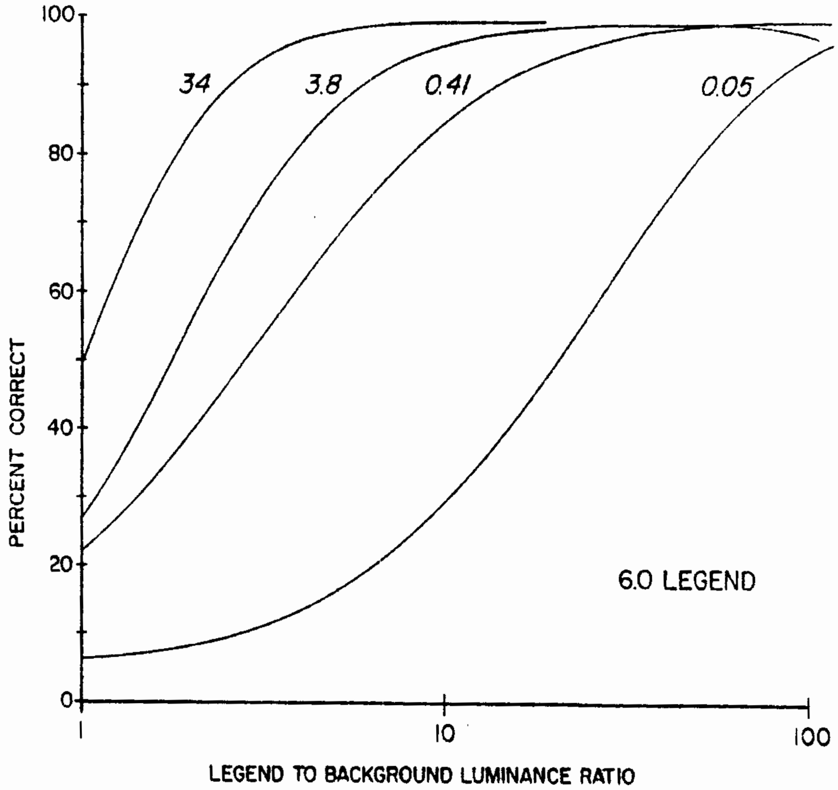
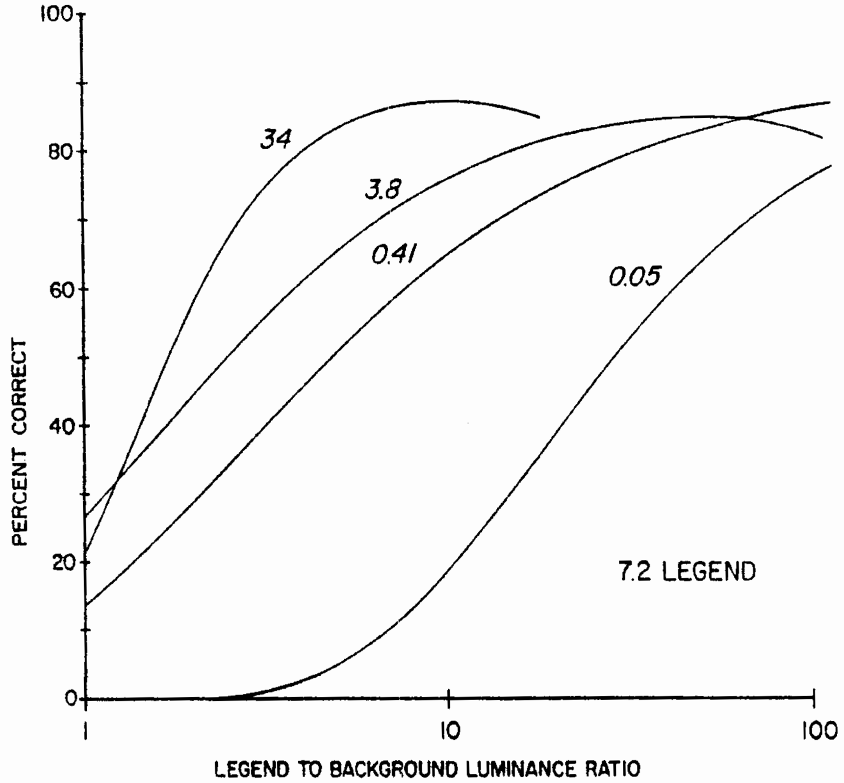


Figure 1-11. Percent correct responses to four background luminance levels (shown in cd/m^2) for each legend size, as a function of legend luminance contrast. Dark surround (0.034 cd/m^2). Young subjects.


100
80
60
40
20
0
PERCENT CORRECT
34
3.8
0.41
0.05
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO


100
80
60
40
20
0
PERCENT CORRECT
34
3.8
0.41
0.05
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

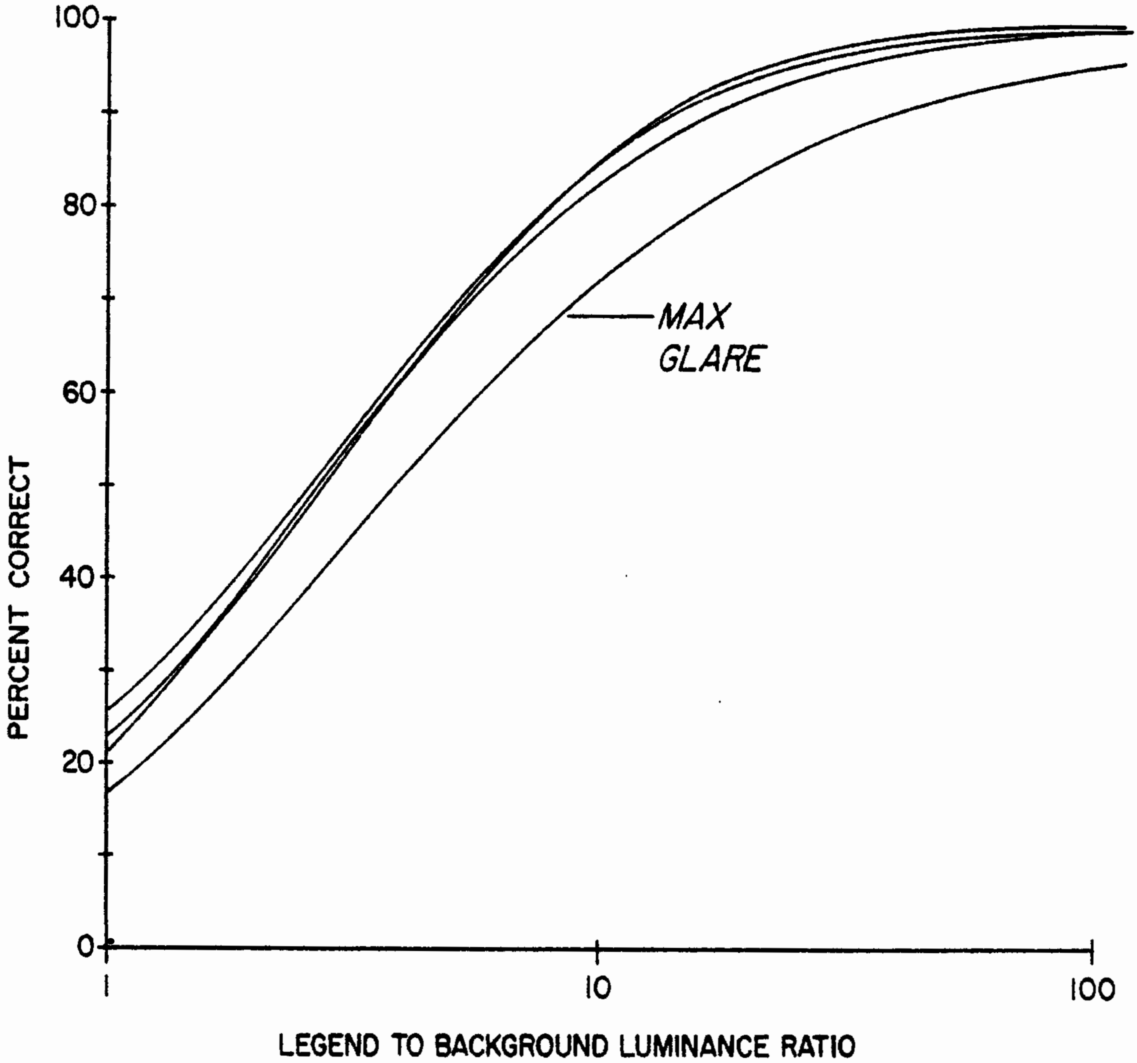


Figure 1-12. Percent correct responses as a function of legend luminance contrast and four levels of glare illuminance. Glare angle 0.7^{o}, dark surround (0.034 cd/m^2), 6 m/cm legend, 0.4 cd/m^2 green background. Young subjects.

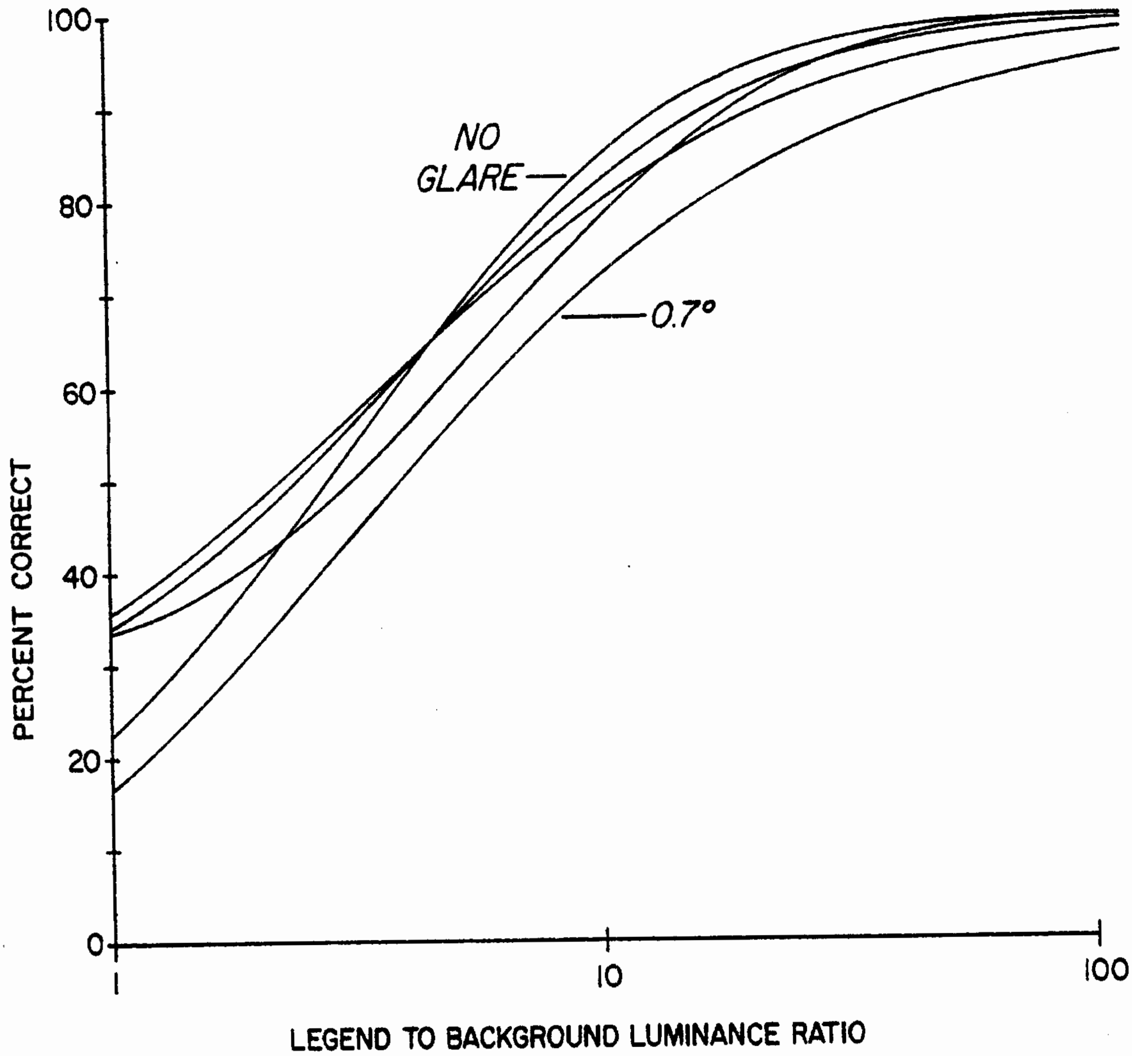


Figure 1-13. Percent correct responses as a function of legend luminance contrast and four glare angles. Glare illuminance 0.38 lux, dark surround (0.034 cd/m^2), 6 m/cm legend, 0.4 cd/m^2 green background. Young subjects.

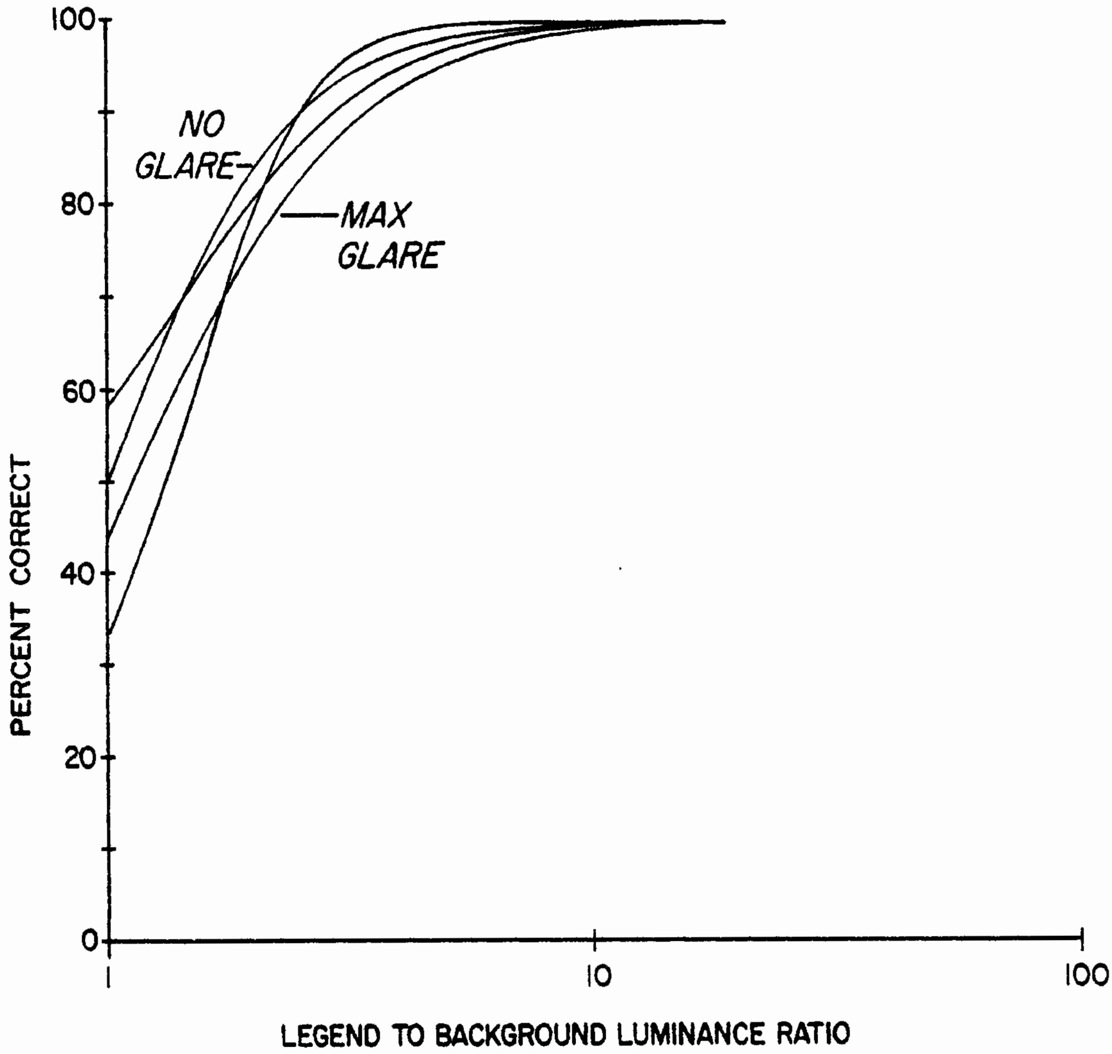


Figure 1-14. Percent correct responses as a function of legend luminance contrast and four levels of glare illuminance. Glare angle 0.7^{o}, dark surround (0.034 cd/m^2), 6 m/cm legend, 34.3 cd/m^2 green background. Young subjects.

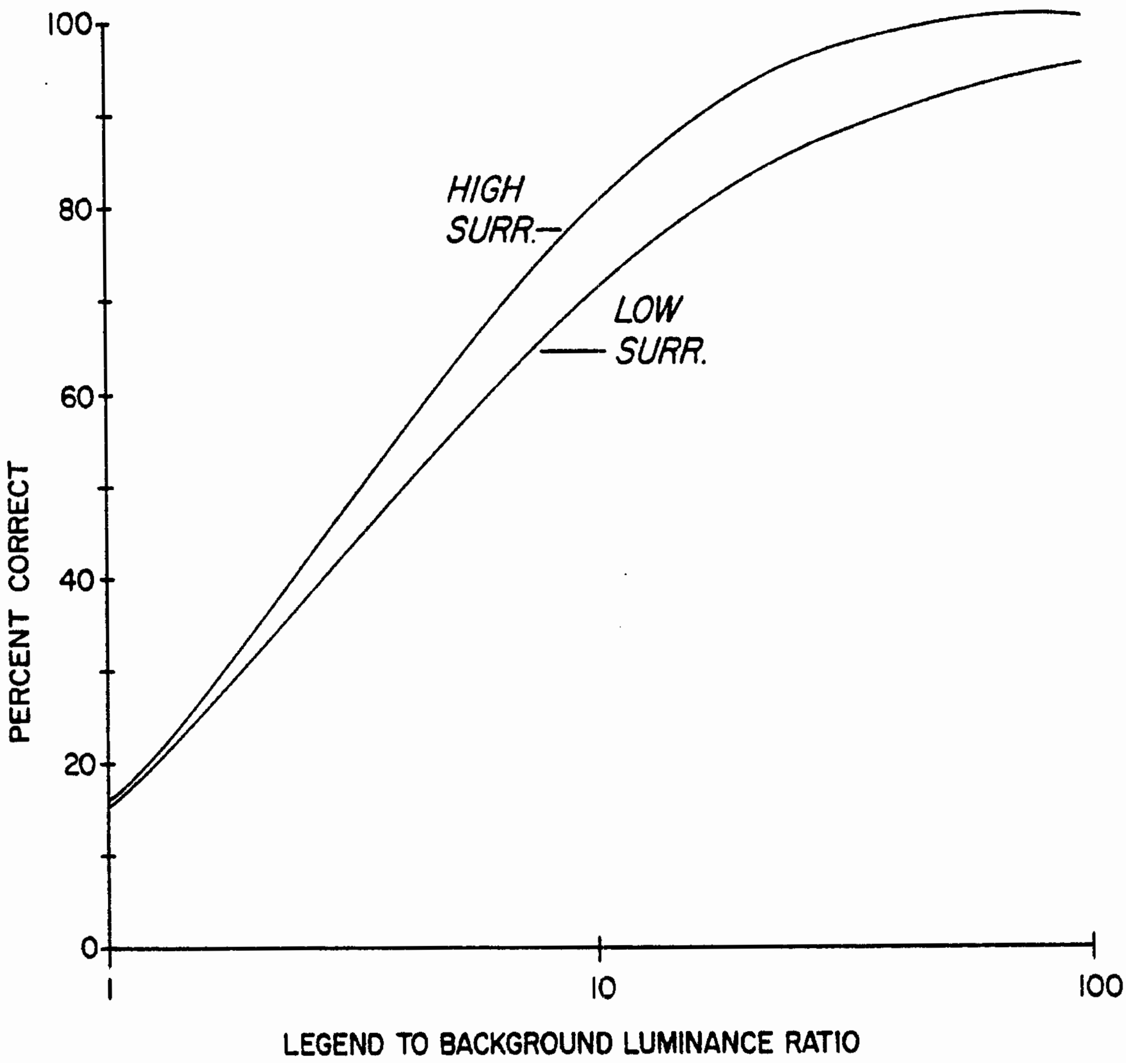


Figure 1-15. Percent correct responses as a function of legend luminance contrast and surround luminance. Maximum glare, 0.7° angle, 6 m/cm legend, 0.41 cd/m^2 green background. Young subjects.

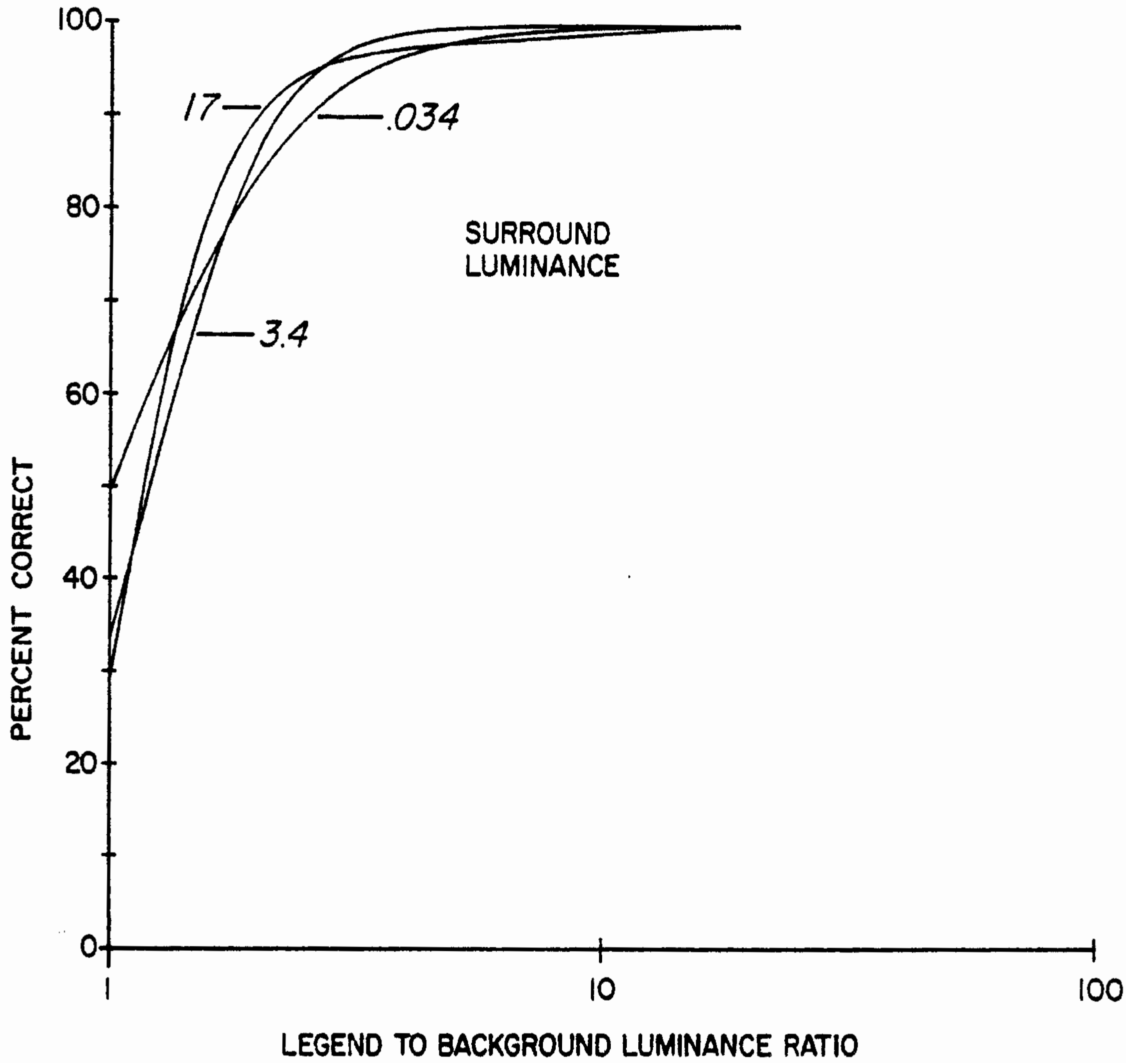


Figure 1-16. Percent correct responses as a function of legend luminance contrast and surround luminance. Green, 6.0 m/cm legend, 34. cd/m^2 background. Young subjects.

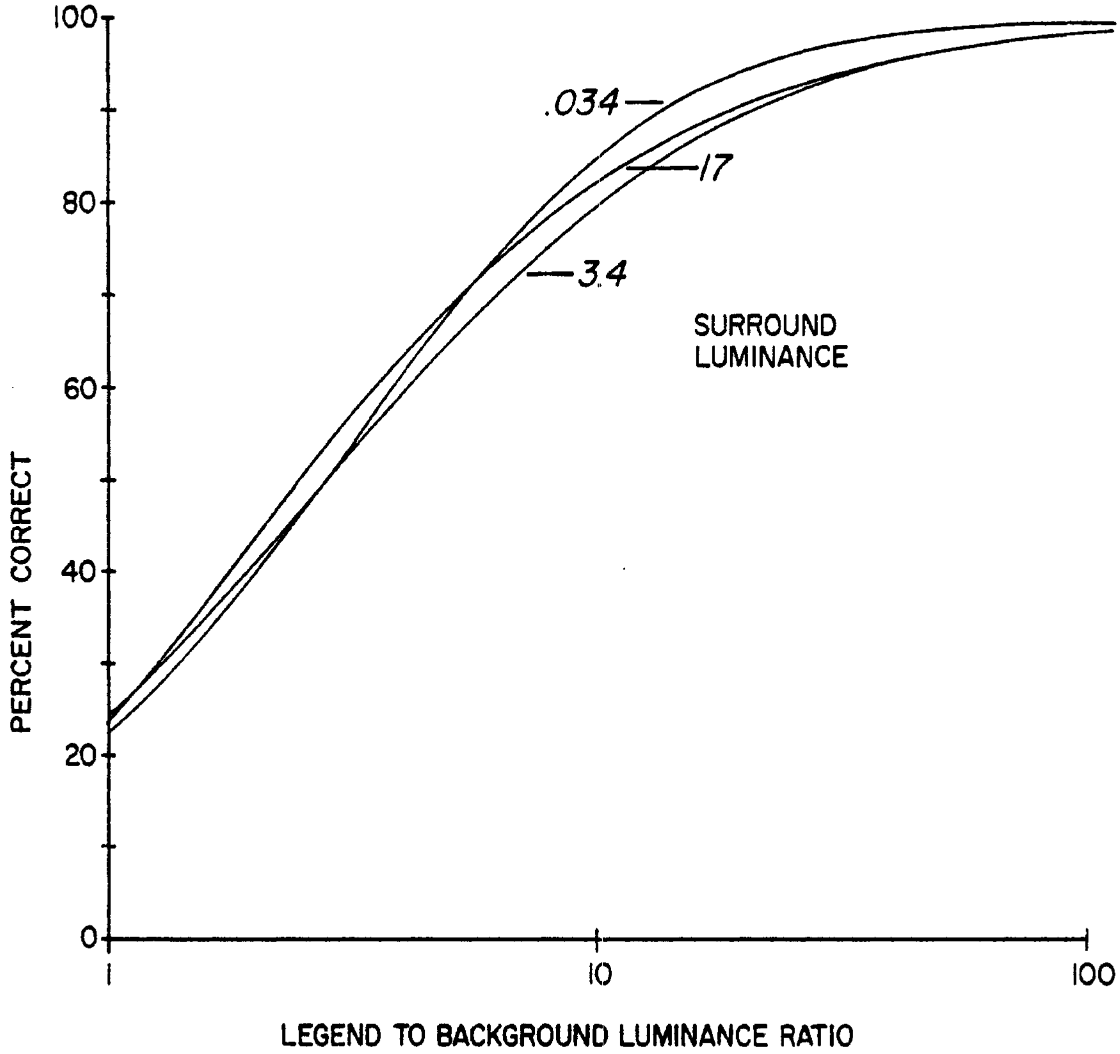
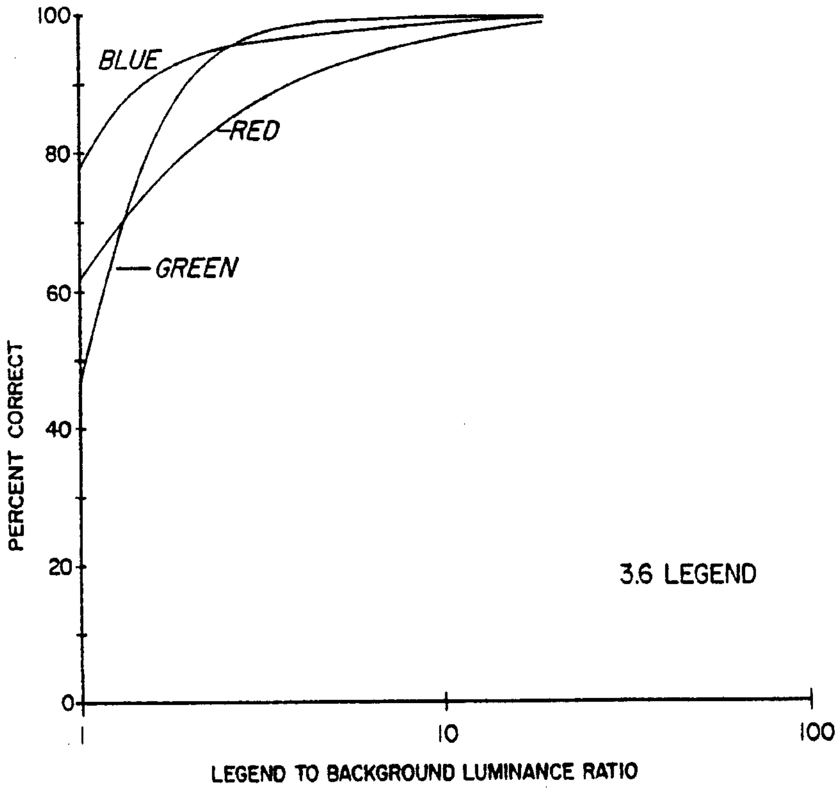


Figure 1-17. Percent correct as a function of legend luminance contrast and surround luminance. Green, 6.0 m/cm legend, 0.41 cd/m^2 background. Young subjects.



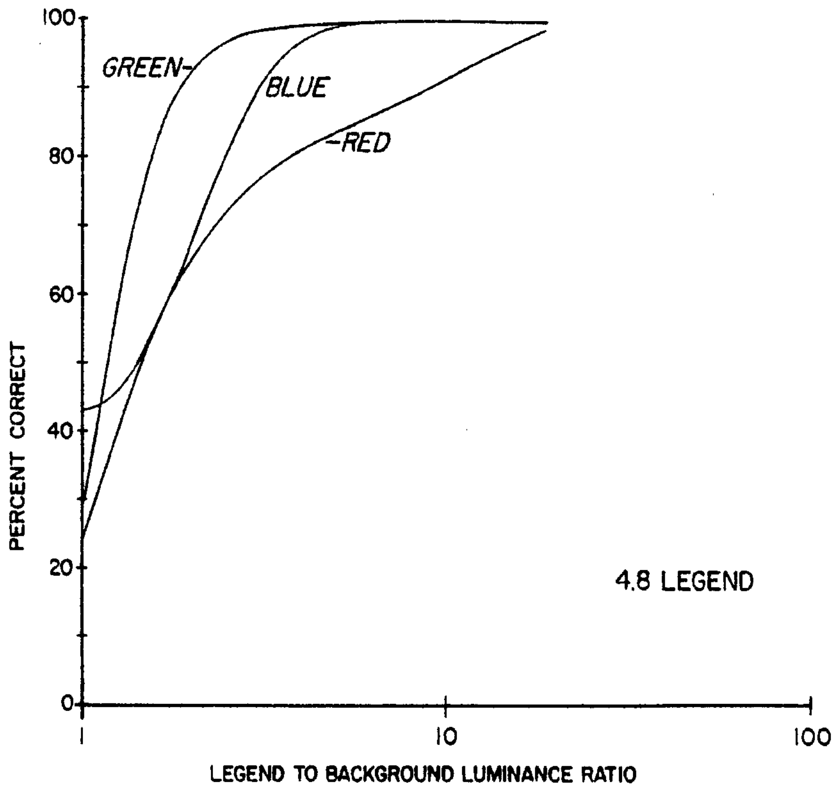
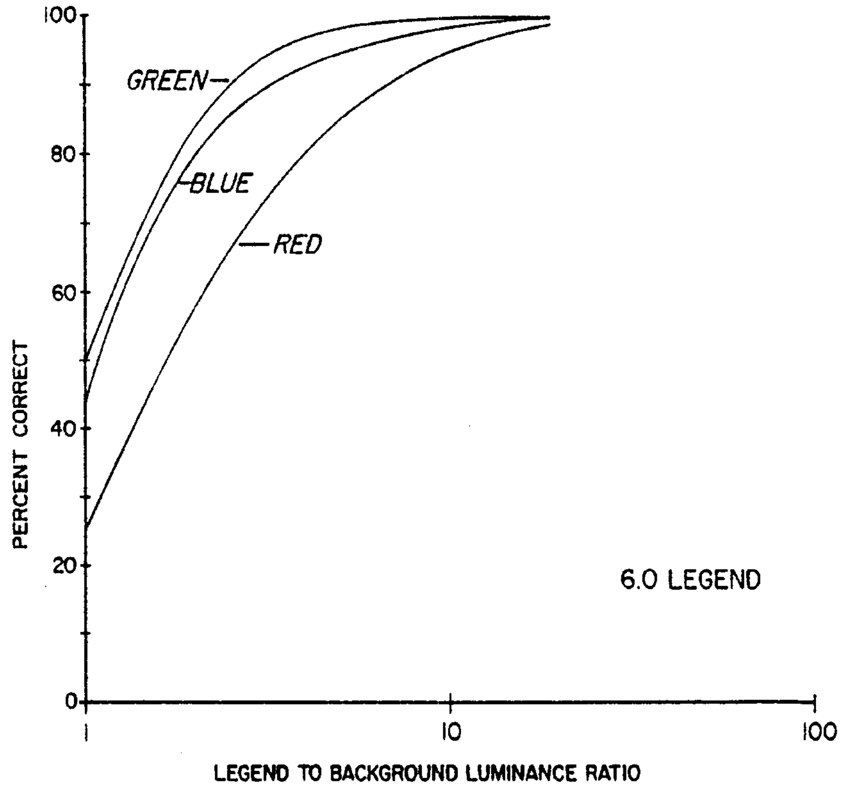
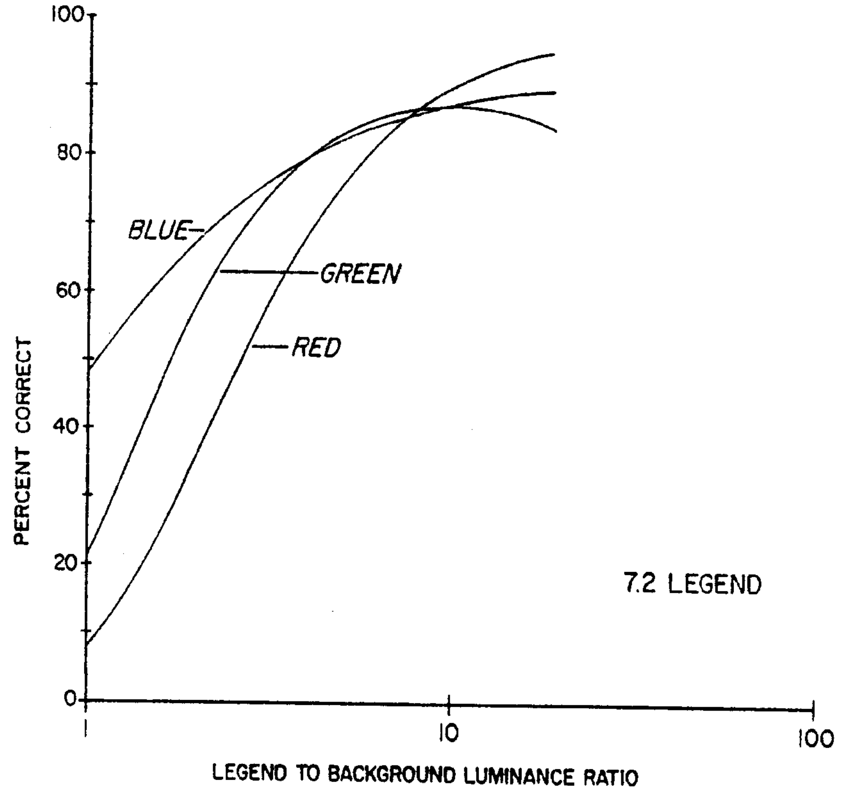


Figure 1-18. Percent correct response as a function of legend luminance contrast for green, red, and blue backgrounds, and each legend size. Dark surround (0.034 cd/m^2), 34.4 cd/m^2 backgound. Young subjects.


GREEN
BLUE
RED
6.0 LEGEND
PERCENT CORRECT
0
20
40
60
80
100
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO


BLUE
GREEN
RED
7.2 LEGEND
PERCENT CORRECT
0
20
40
60
80
100
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

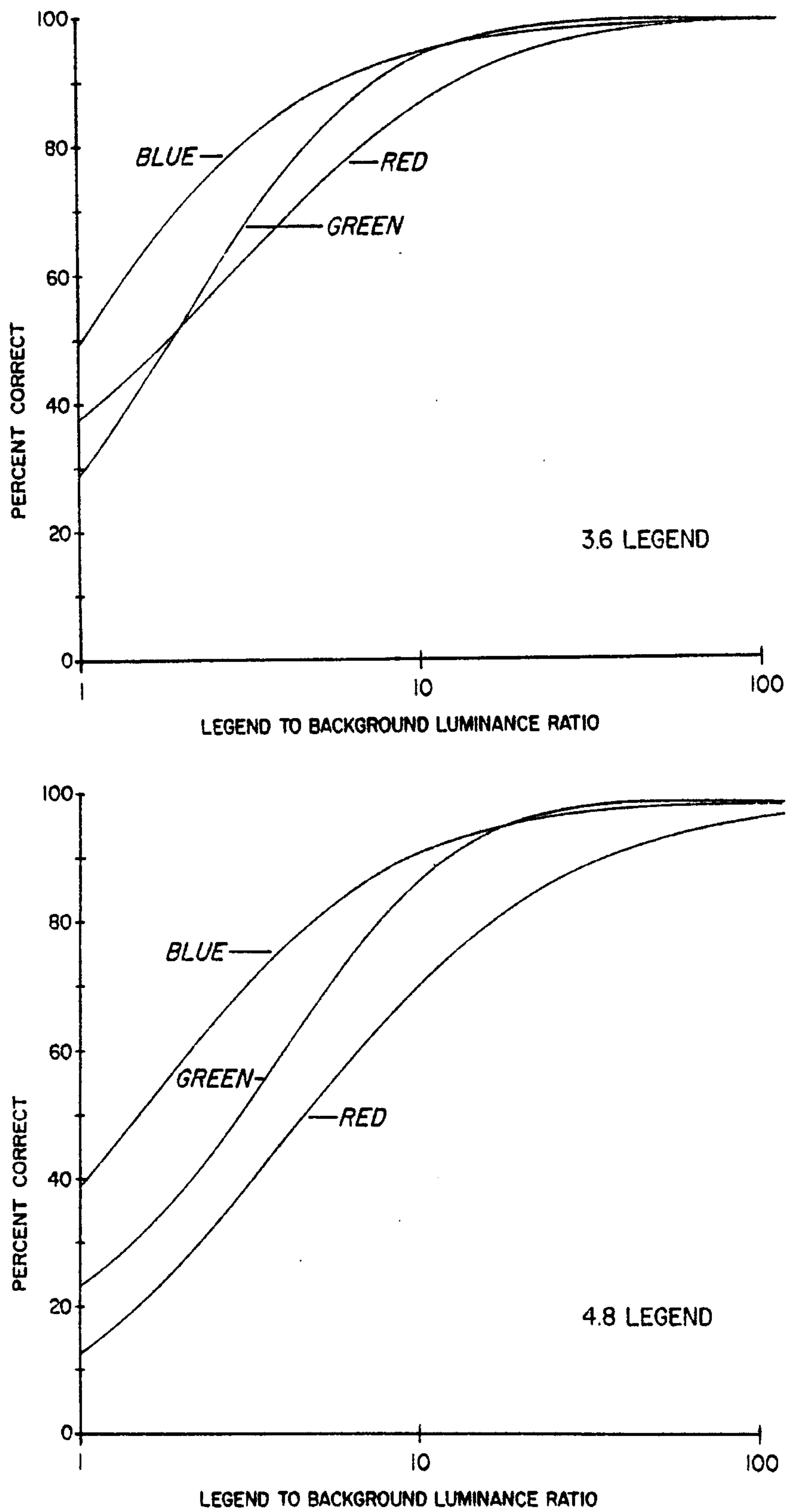
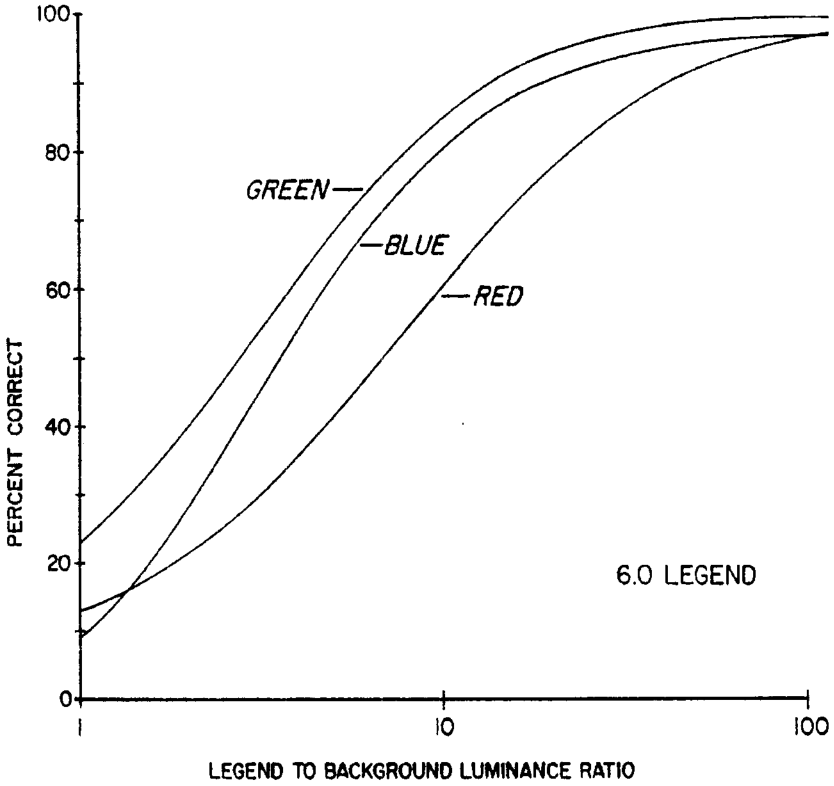
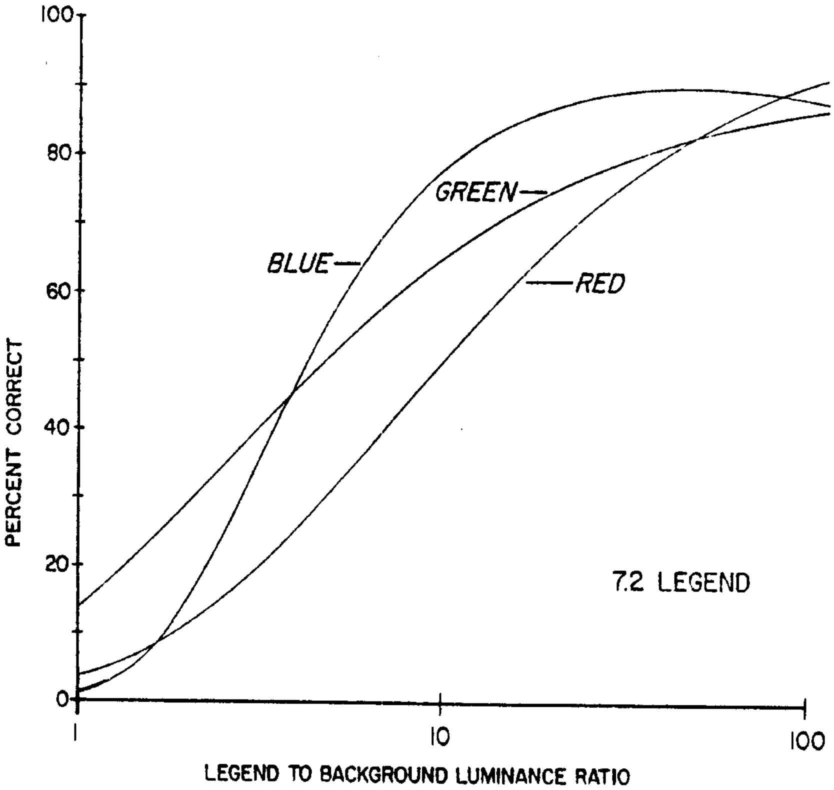


Figure 1-19. Percent correct response as a function of legend luminance contrast for green, red, and blue backgrounds, and each legend size. Dark surround (0.034 cd/m^2), 0.41 cd/m^2 background. Young subjects.


100
80
60
40
20
0
PERCENT CORRECT
GREEN
BLUE
RED
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO


100
80
60
40
20
0
PERCENT CORRECT
GREEN
BLUE
RED
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

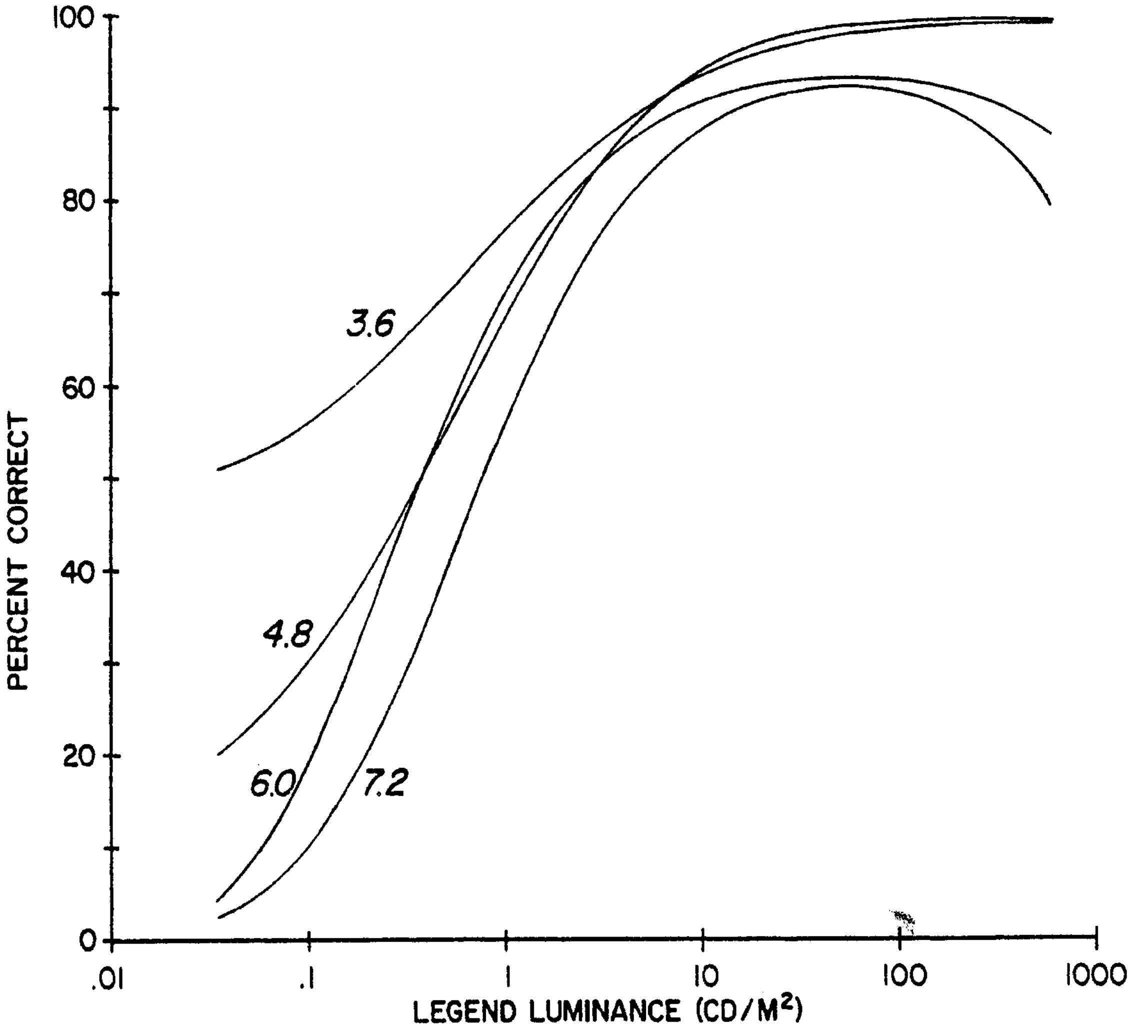


Figure 1-20. Percent correct responses to four legend sizes (in m/cm) seen against the black background as a function of legend luminance. Dark surround (0.034 cd/m^2). Young subjects.

Other research (e.g., Hind, Tritt, and Hoffman, 1976) suggests that white letters on a black background should be somewhat more legible than black letters on a white background. An examination of Figure 1-26 indicates support for this finding, at least for the 7.2 m/cm legend. It is also worth noting that Hind et al. found maximum legibility at about 34 cd/m^2, almost exactly the peak noted in Figure 1-26, 7.2 m/cm legend.

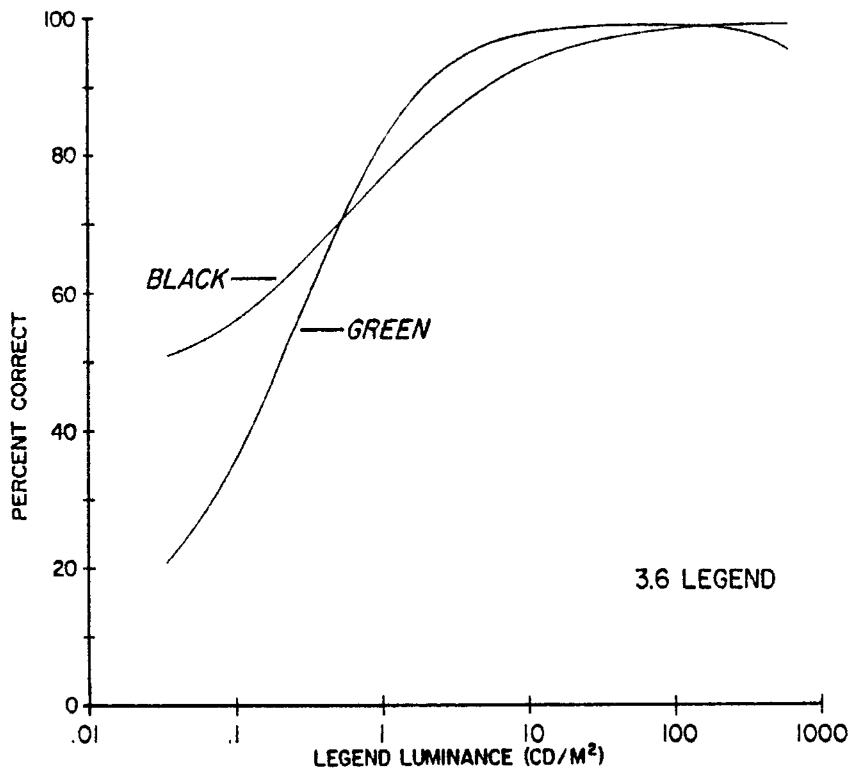
1.2.2 Older subjects.

1.2.2.1 Luminance and contrast characteristics. An important aspect of this study was a comparison of the performance of younger and older subjects. These data are summarized in the next series of figures. Specifically, Figures 1-27 through 1-30 compare performance of young and old subjects on green backgrounds; Figures 1-31 through 1-33 on combinations using a black legend. Three points are particularly worth noting:

1) While older subjects generally did poorer than younger subjects on white legend signs (i.e., required more legend luminance to achieve a given legibility level and had a lower maximum legibility distance), the relationship is not a simple one. Of particular interest is the effect of background luminance. Table 1-3 illustrates the effect of background luminance on the legend luminance contrast required to achieve a legibility distance of 6 m/cm (50 ft/inch letter height) for the younger and older subjects. For the brightest backgrounds, the contrast differences are relatively small, but they increase rapidly as background luminance decreases. These data strongly support the desirability of signing practices which result in backgrounds having high luminance characteristics. There is benefit to all drivers in terms of improved detection, legibility, and resistance to environmental glare. But, there is a special benefit to older drivers.

2) Older subjects were more likely to suffer a loss of legibility at high levels of contrast than were the younger subjects, and the loss was more severe. Thus, signing materials should be selected to provide optimum contrast but no more, since excessive contrast could prove disadvantageous to older drivers.

3) Differences between older and younger subjects are particularly dramatic with combinations using a black legend (Figures 1-31, 1-32, and 1-33). These data indicate that much higher background luminance levels are required by the older subjects to



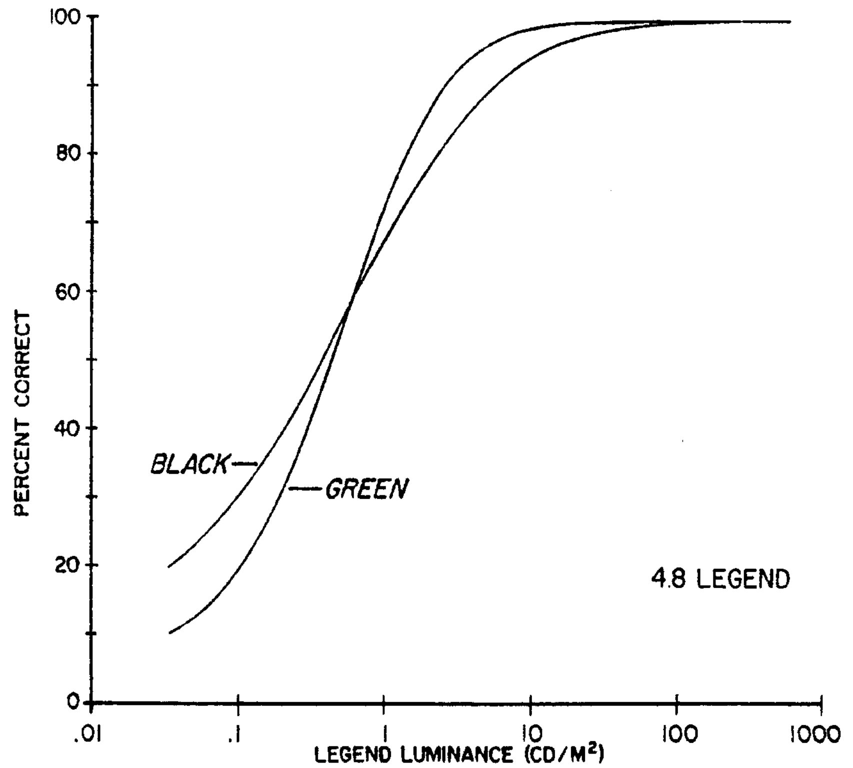
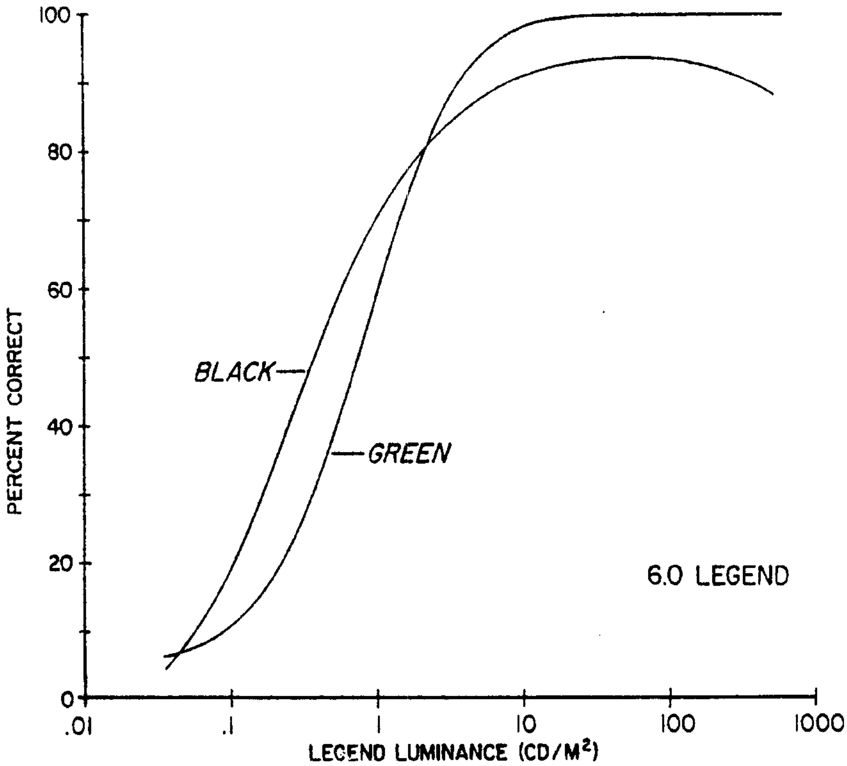
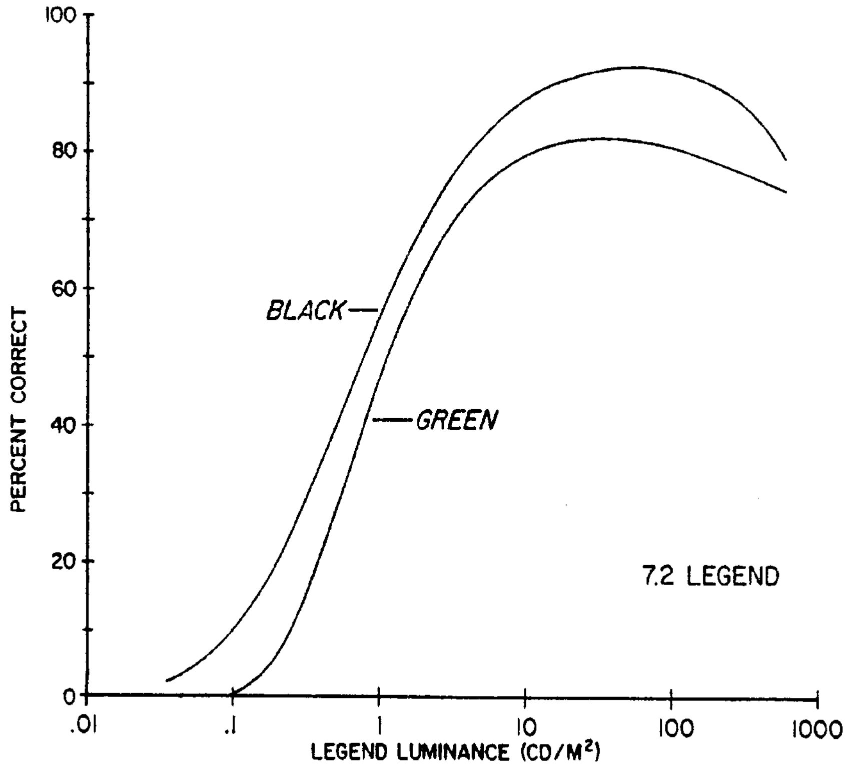


Figure 1-21. Percent correct responses to four legend sizes (in m/cm) as a function of legend luminance. Black versus 0.05 cd/m^2 green backgrounds. Dark surround (0.034 cd/m^2). Young subjects.



PERCENT CORRECT
100
80
60
40
20
0
BLACK
GREEN
6.0 LEGEND
.01
.1
1
10
100
1000
LEGEND LUMINANCE (CD/M²)



PERCENT CORRECT
100
80
60
40
20
0
BLACK
GREEN
7.2 LEGEND
.01
.1
1
10
100
1000
LEGEND LUMINANCE (CD/M²)

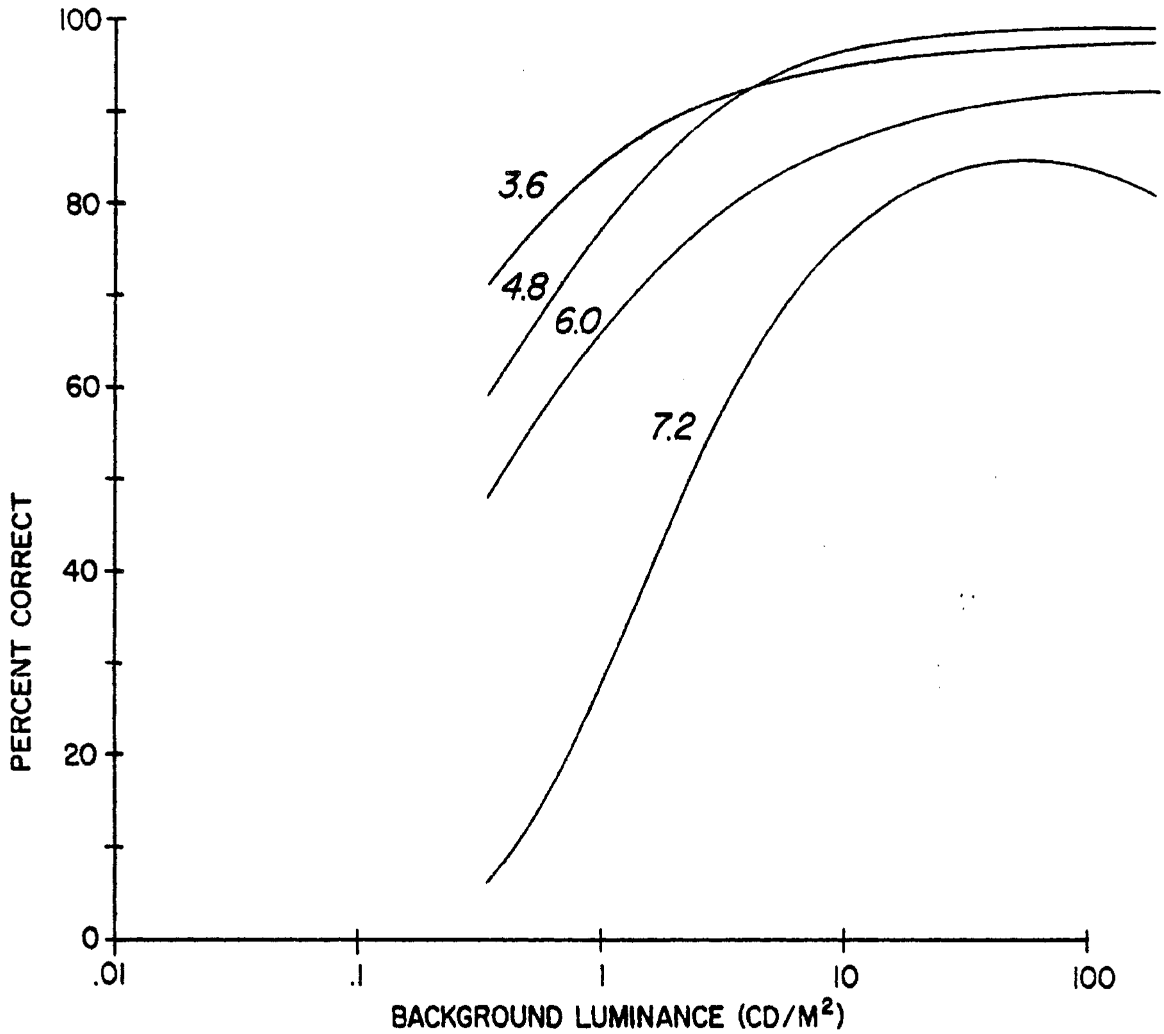


Figure 1-22. Percent correct responses to four legend sizes (in m/cm) as a function of background luminance. White background, dark surround (0.034 cd/m2). Young subjects.

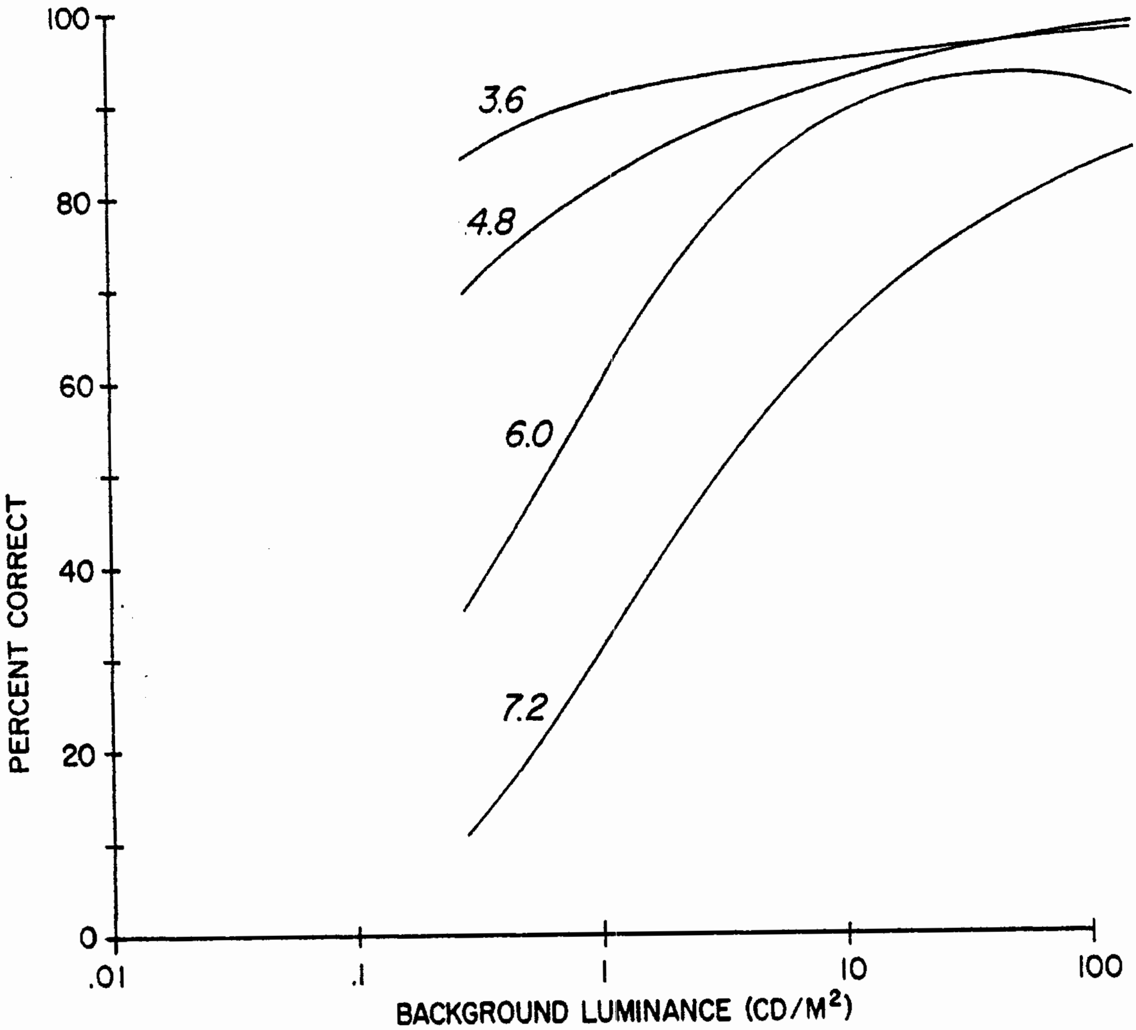


Figure 1-23. Percent correct responses to four legend sizes (in m/cm) as a function of background luminance. Yellow background, dark surround (0.034 cd/m^2). Young subjects.

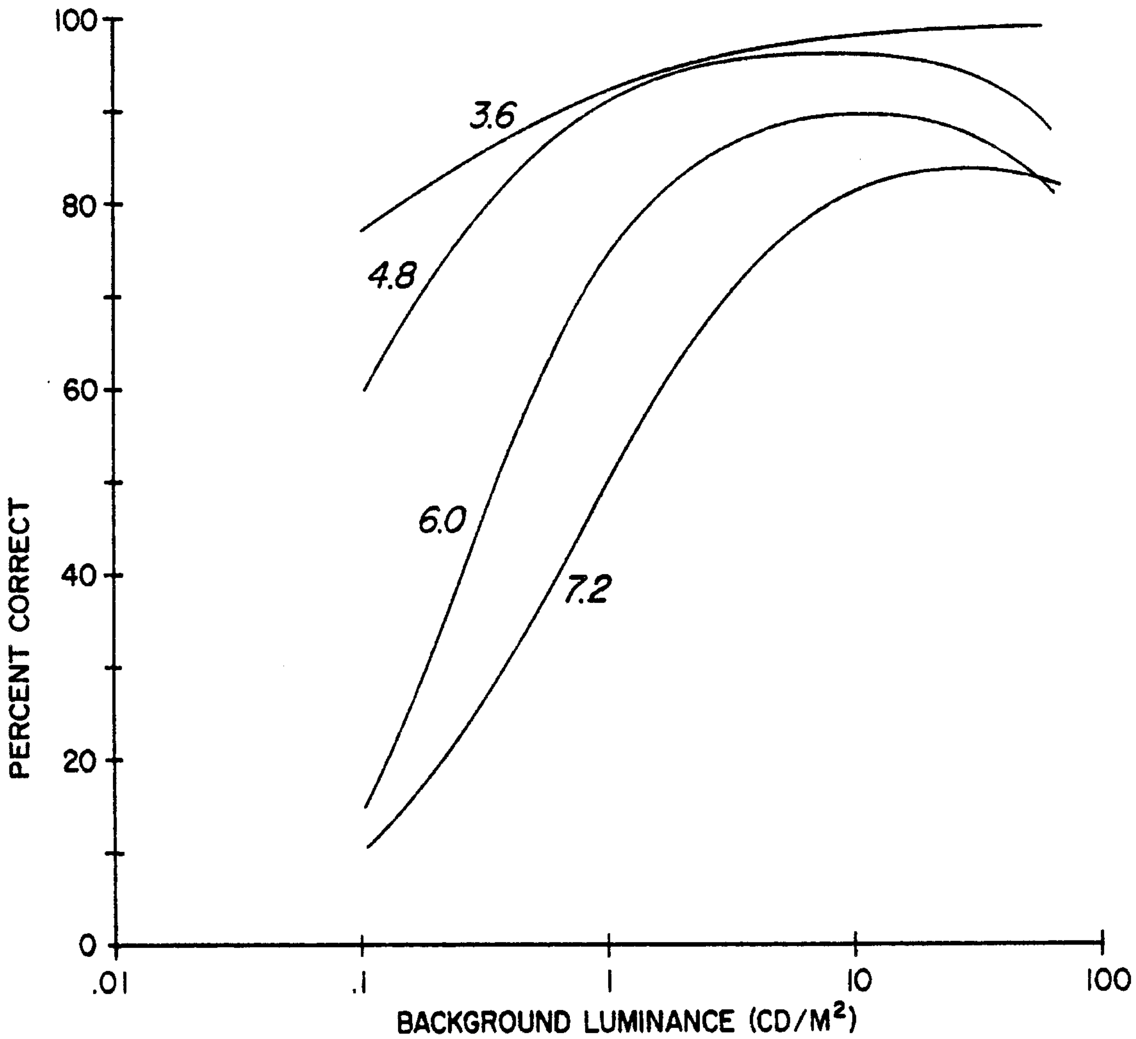


Figure 1-24. Percent correct responses to four legend sizes (in m/cm) as a function of background luminance. Orange background, dark surround (0.034 cd/m^2). Young subjects.

achieve performance comparable to the younger subjects. Indeed, in some instances, background luminance levels which result in improved legibility for older subjects are excessive for younger subjects.

Table 1-3

LEGEND LUMINANCE CONTRAST REQUIRED TO ACHIEVE 85% LEGIBILITY OF 6m/cm AS A FUNCTION OF BACKGROUND LUMINANCE AND SUBJECT AGE

BACKGROUND LUMINANCE (CD/M^2)	REQUIRED CONTRAST	
	YOUNG SUBJECTS	OLD SUBJECTS
34.26	2:1	5:1
3.82	5:1	9:1
0.41	10:1	x
0.05	60:1	xx

x 80% correct at 60:1
xx 75% correct at about 1000:1

Performance on blue background combinations is quite similar to the green. However, the older subjects did relatively much better with red background signs. This is illustrated by Figures 1-34 and 1-35, which compare young and old performance at all legend sizes and two levels of background luminance.

An explanation for the improved performance of the older subjects on red backgrounds may be found in the fact that the lens of the eye yellows with age. The lens thus becomes a color filter, having more effect on blue and green than on red.

1.2.2.2 Glare. Figures 1-36 and 1-37 summarize the principle glare data for the older subjects. As in the case of the younger subjects, only the highest glare level and smallest angle produced results of consequence, and the losses can be made up by increases in legend luminance contrast. Increases in sign background luminance mitigate environmental glare effects somewhat (Figure 1-38), as do increases in surround luminance (Figure 1-39).

1.2.2.3 Surround luminance. It will be recalled that changes in surround luminance had no observable effect

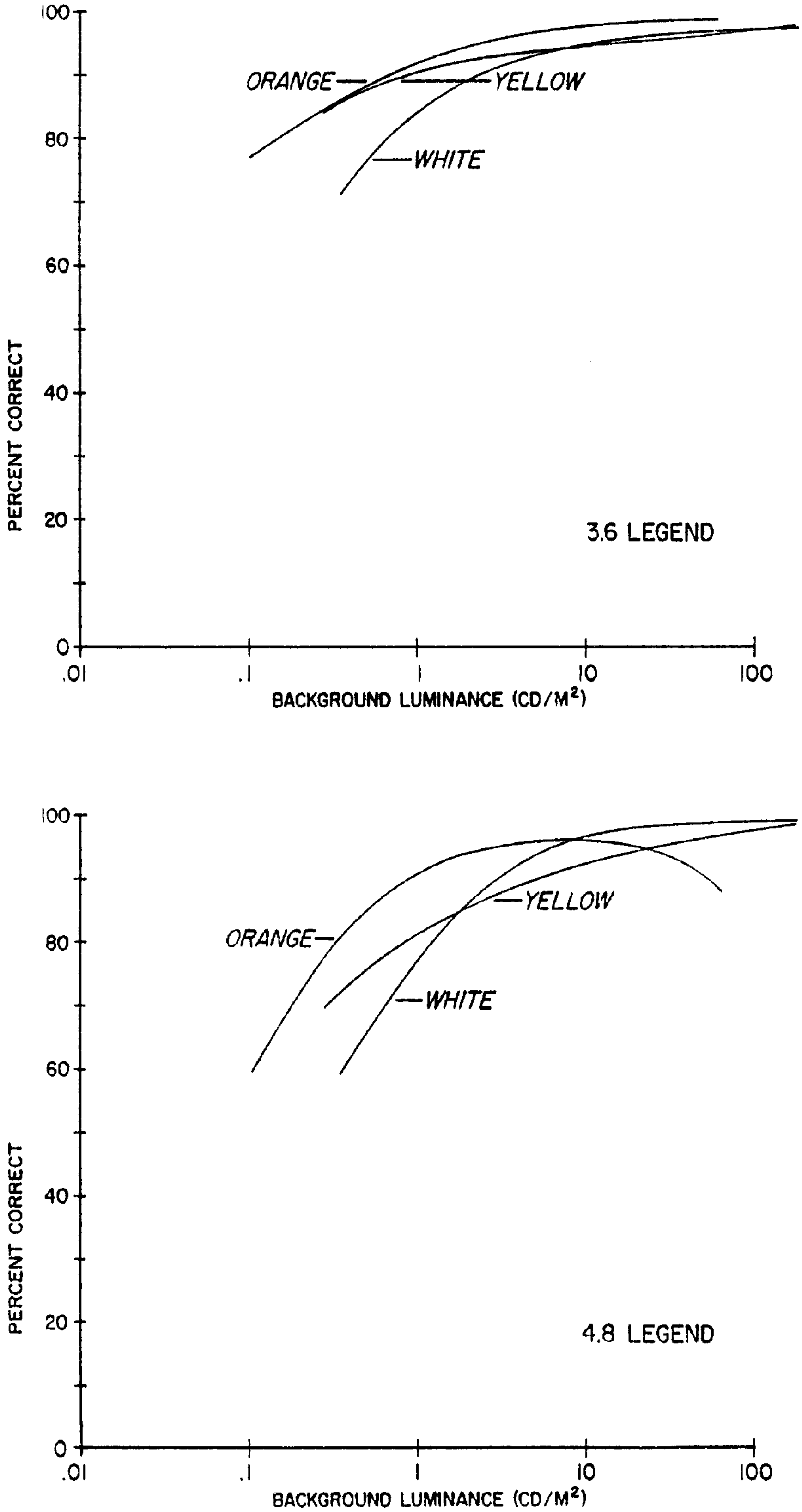
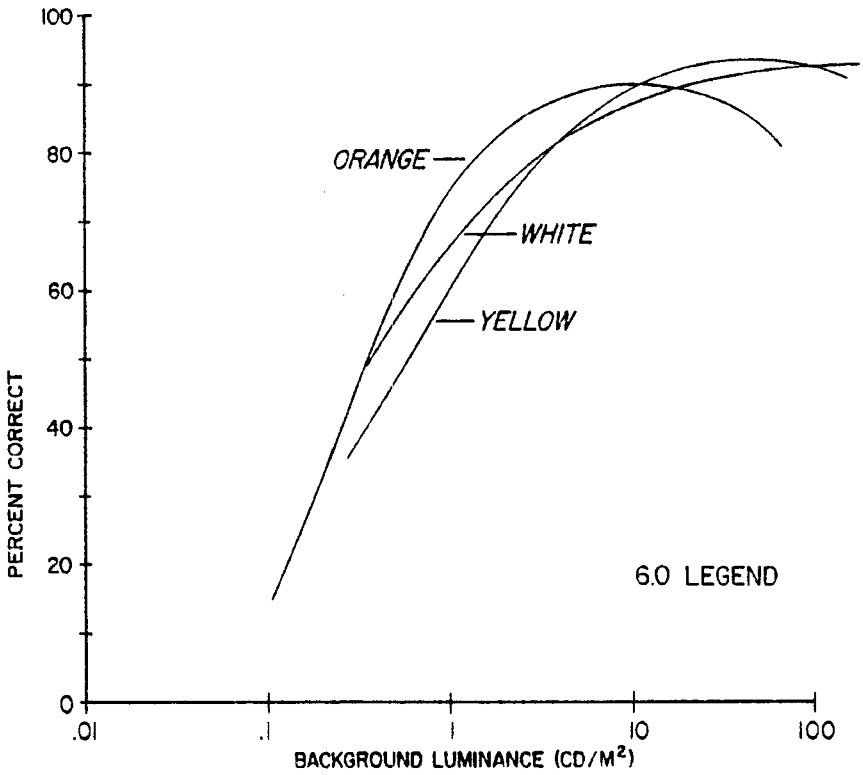
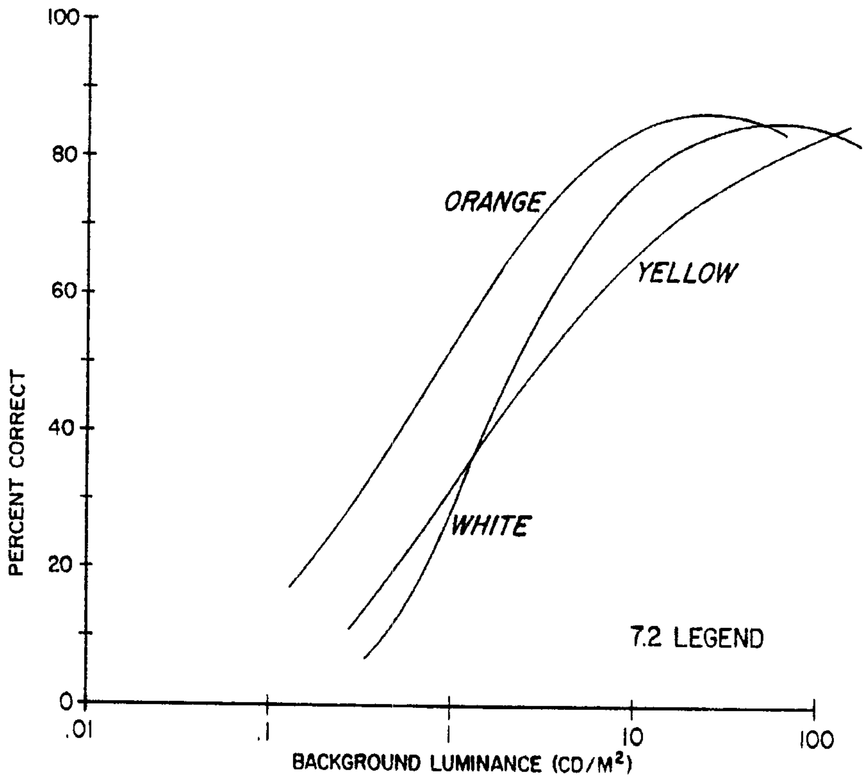


Figure 1-25. Percent correct responses as a function of background luminance and color. Dark surround (0.034 cd/m^2). Young subjects.


100
80
60
40
20
0
PERCENT CORRECT
ORANGE
WHITE
YELLOW
6.0 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)


100
80
60
40
20
0
PERCENT CORRECT
ORANGE
YELLOW
WHITE
7.2 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)

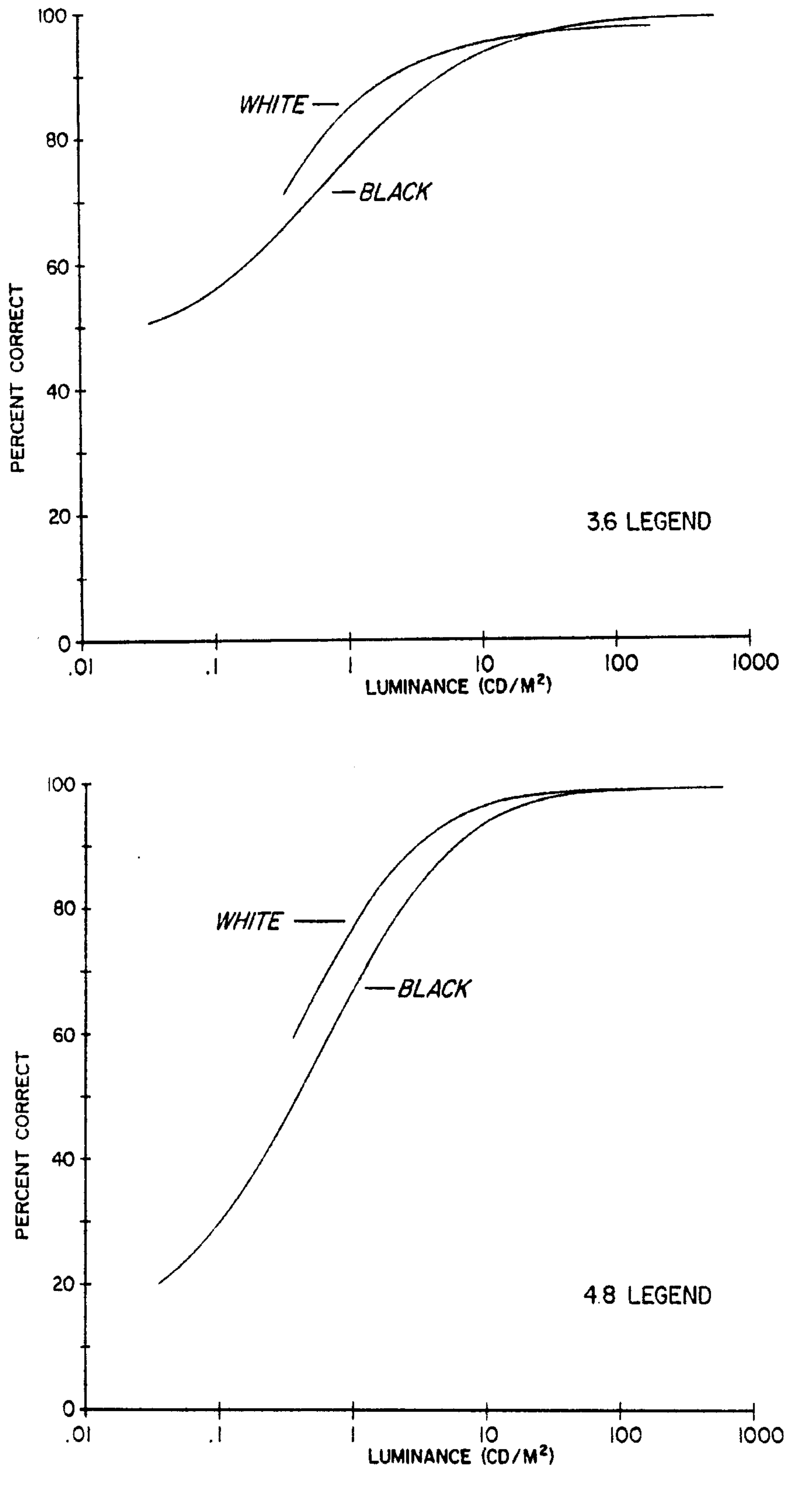
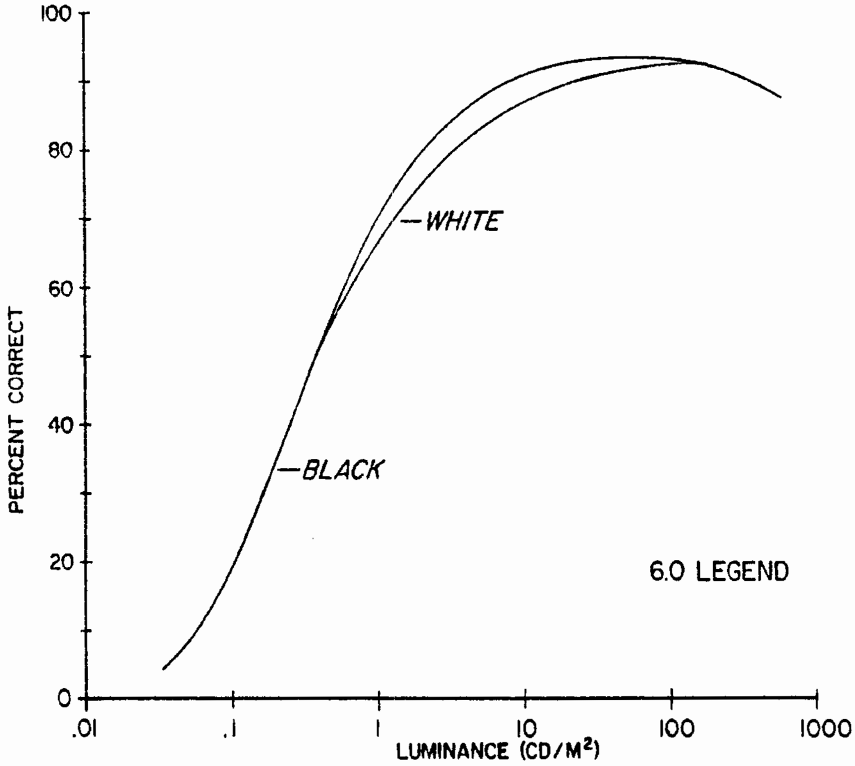
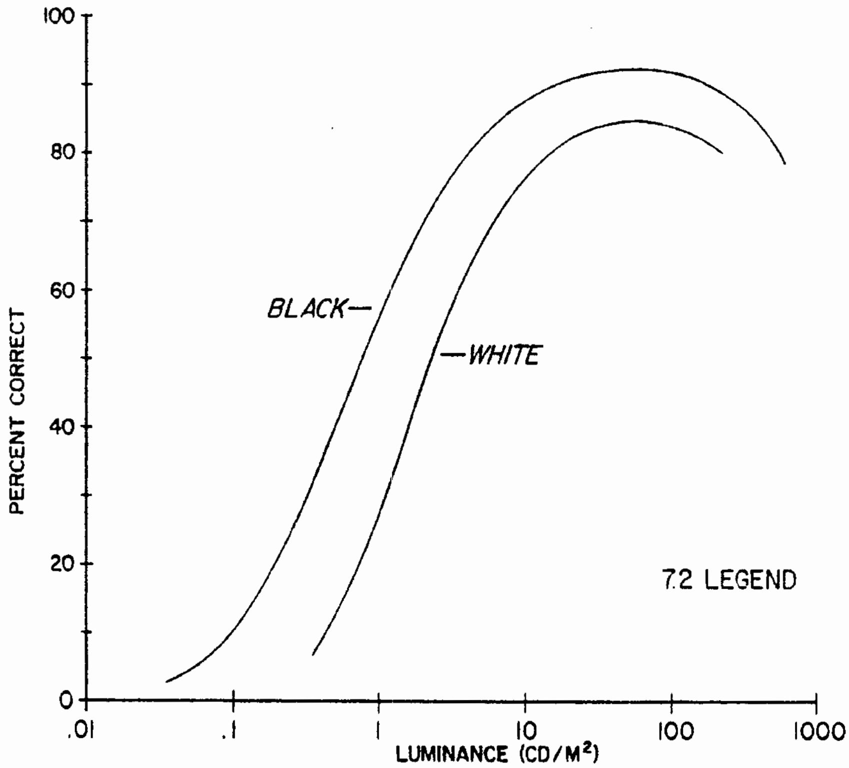


Figure 1-26. Percent correct responses as a function of sign luminance and legend size for black versus white backgrounds. Dark surround (0.034 cd/m^2). Young subjects.


100
80
60
40
20
0
PERCENT CORRECT
—WHITE
—BLACK
6.0 LEGEND
.01
.1
1
10
100
1000
LUMINANCE (CD/M²)


100
80
60
40
20
0
PERCENT CORRECT
BLACK—
—WHITE
7.2 LEGEND
.01
.1
1
10
100
1000
LUMINANCE (CD/M²)

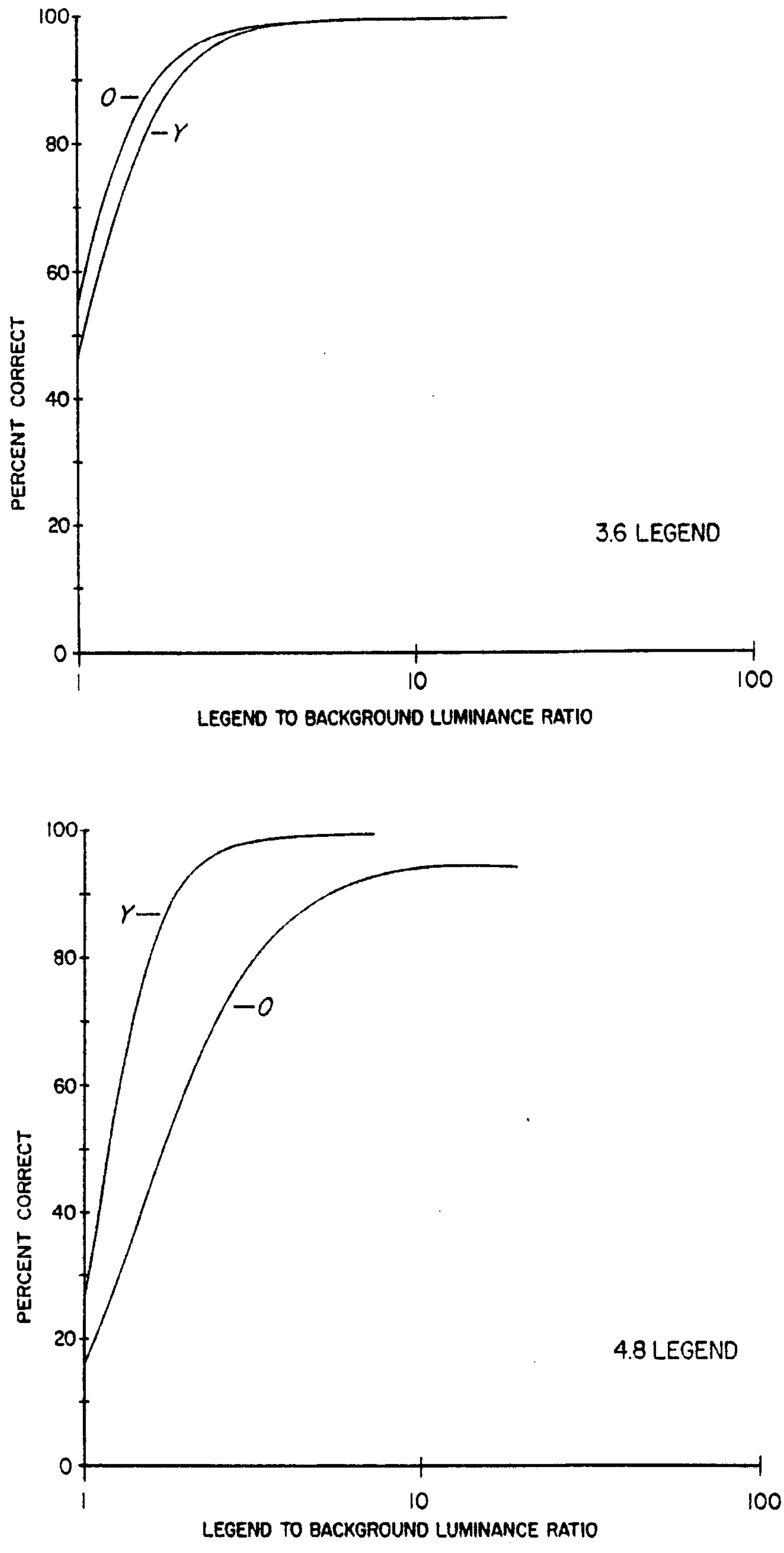
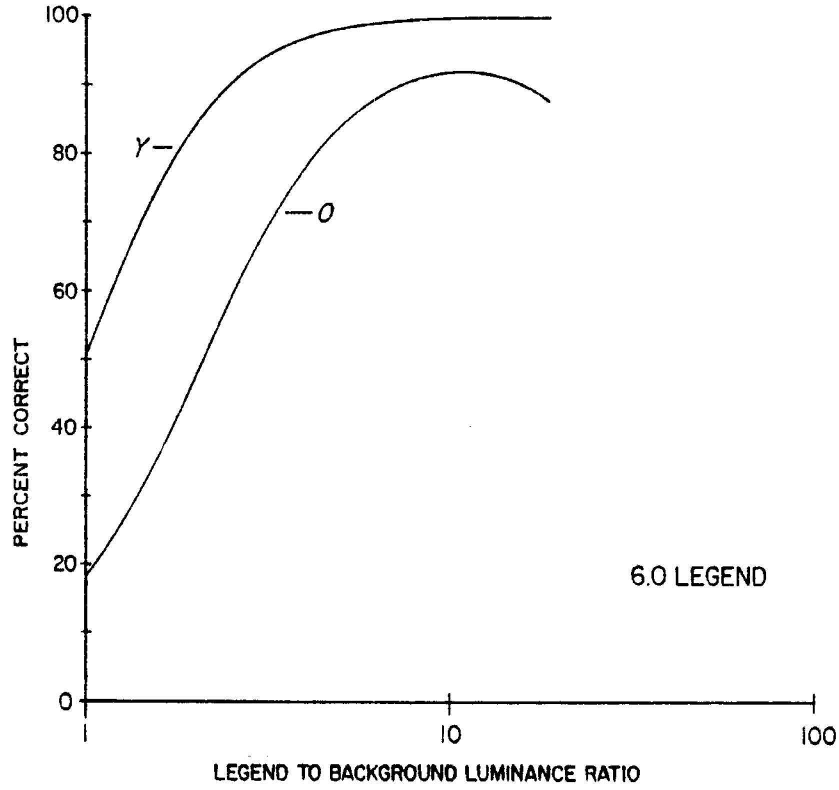
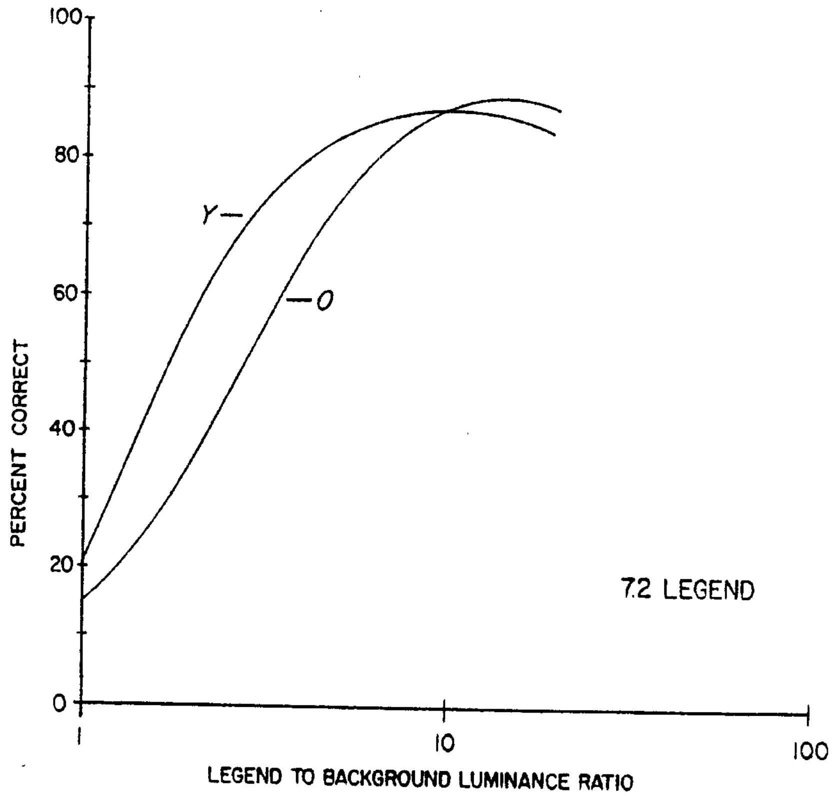


Figure 1-27. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Green background - 34.26 cd/m^2, dark surround (0.034 cd/m^2).



100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO



100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

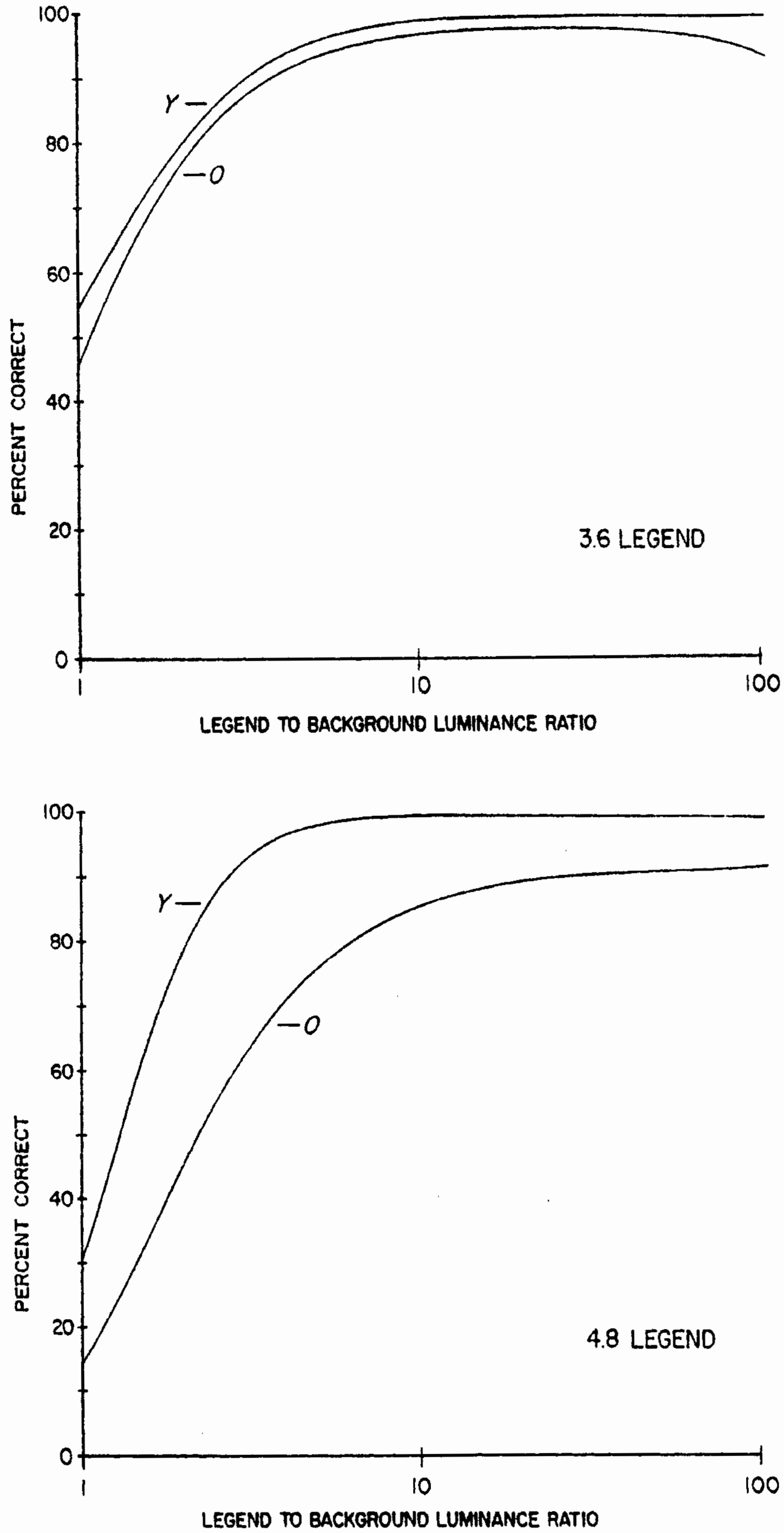
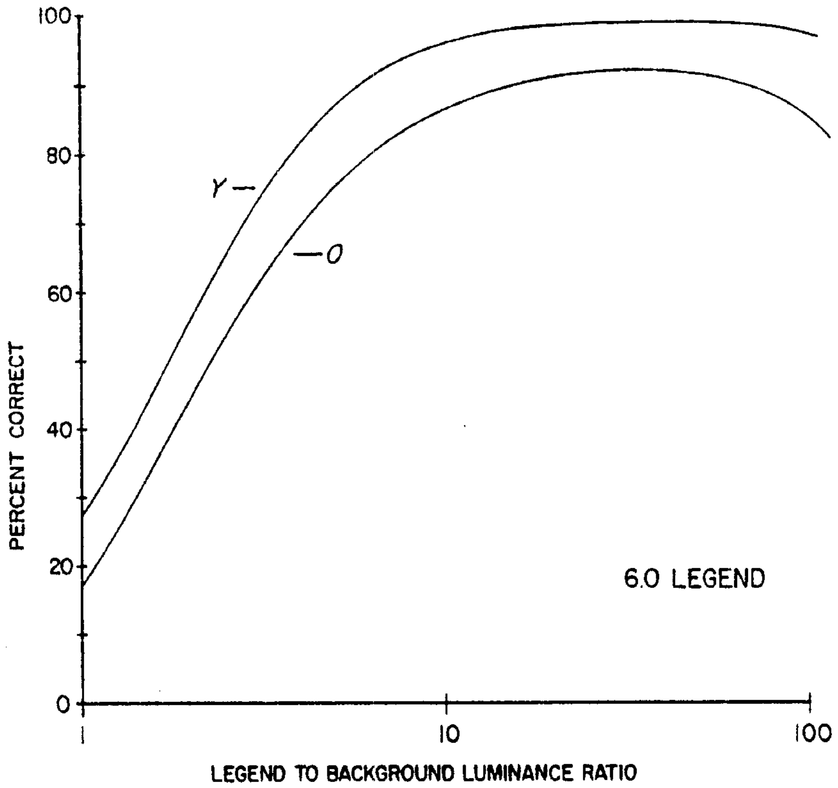
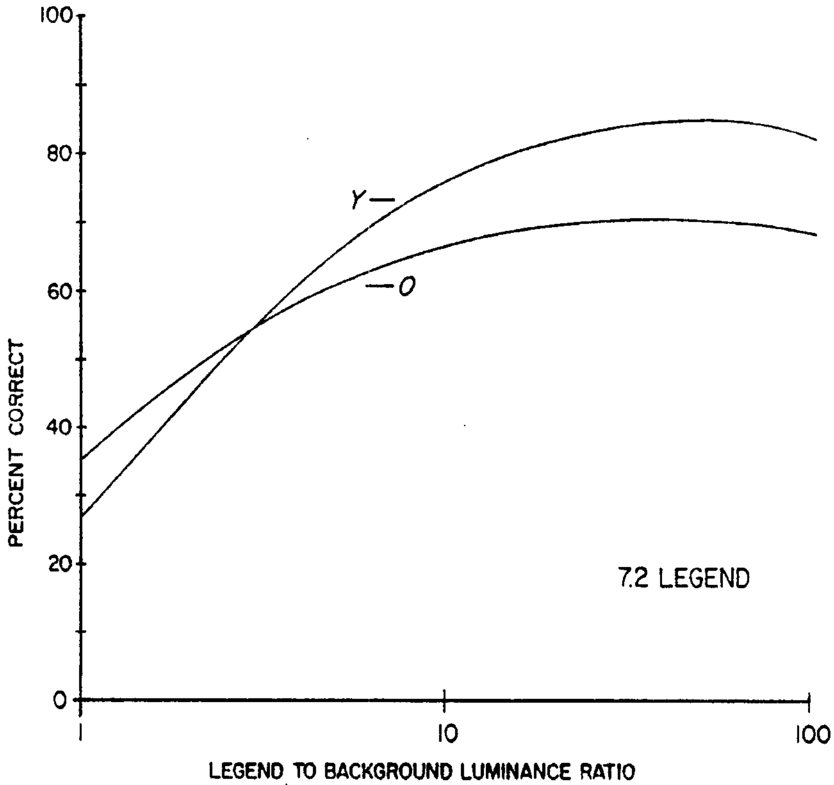


Figure 1-28. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Green background - 3.82 cd/m^2, dark surround (0.034 cd/m^2).


100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO


100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

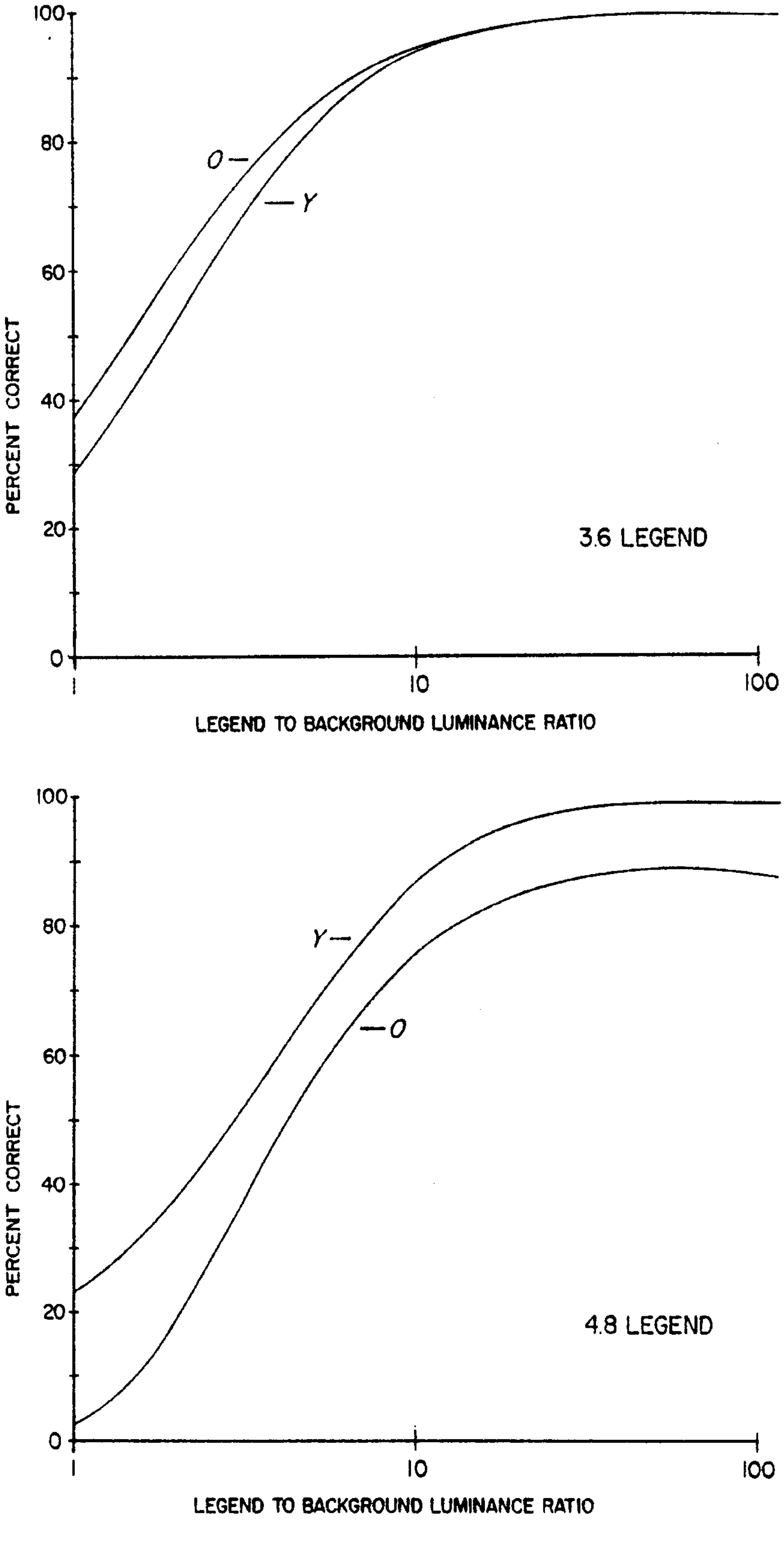
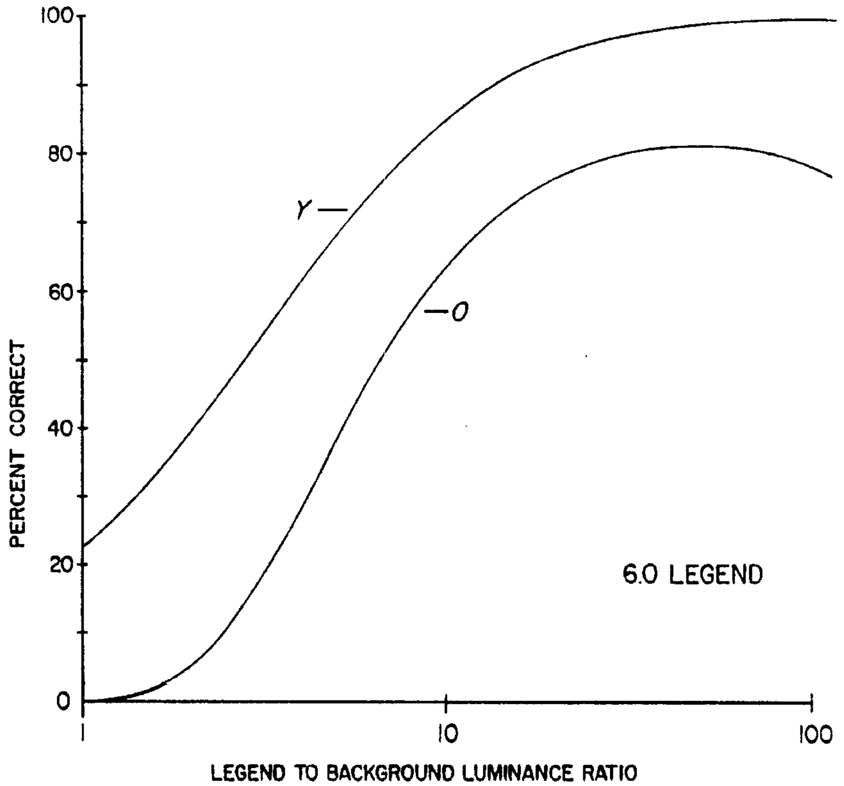
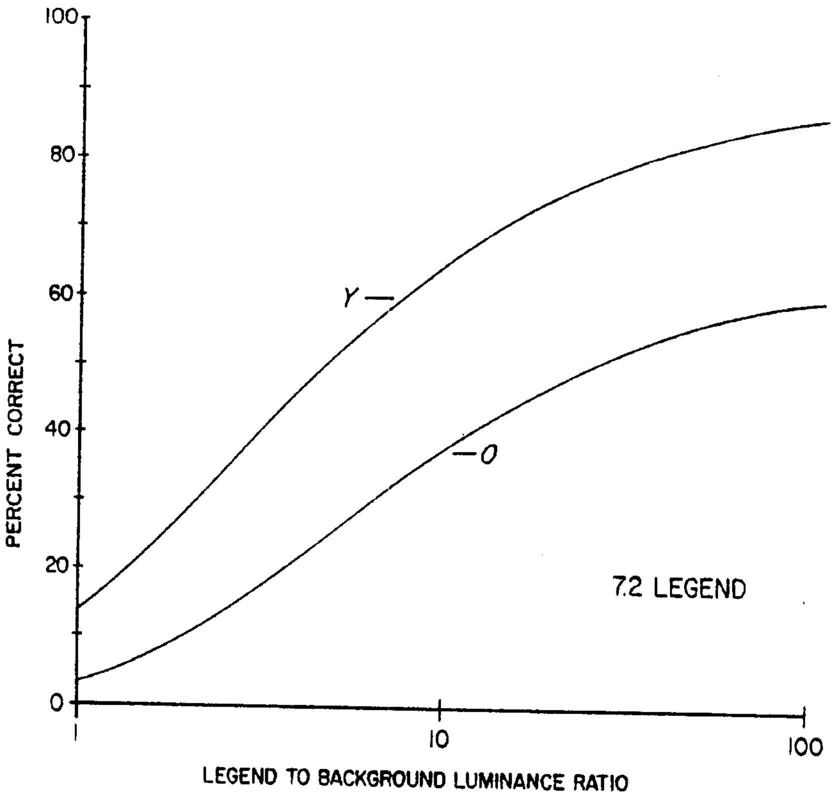


Figure 1-29. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Green background - 0.41 cd/m^2, dark surround (0.034 cd/m^2).


100
80
60
40
20
0
PERCENT CORRECT
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO
Y
O
6.0 LEGEND


100
80
60
40
20
0
PERCENT CORRECT
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO
Y
O
7.2 LEGEND

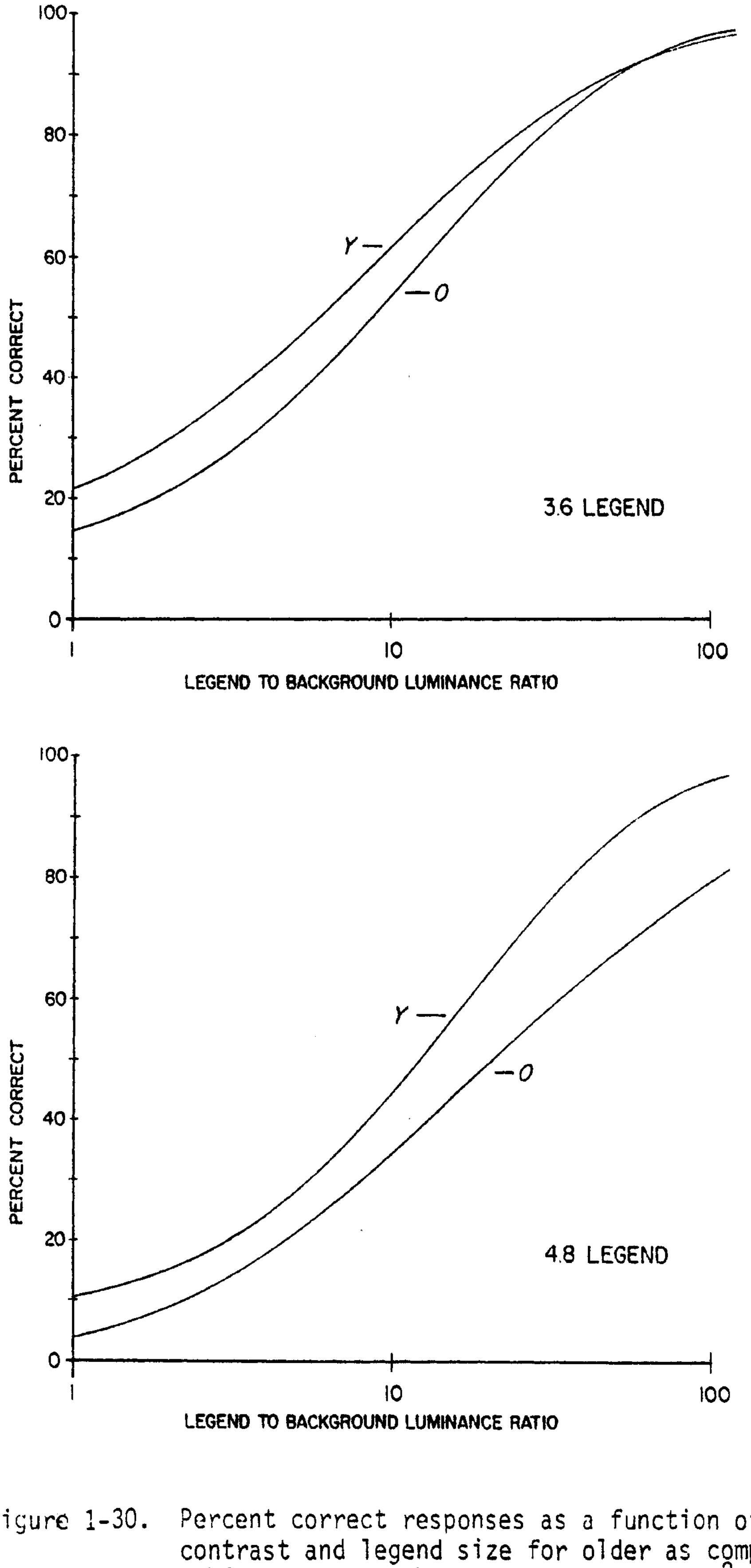
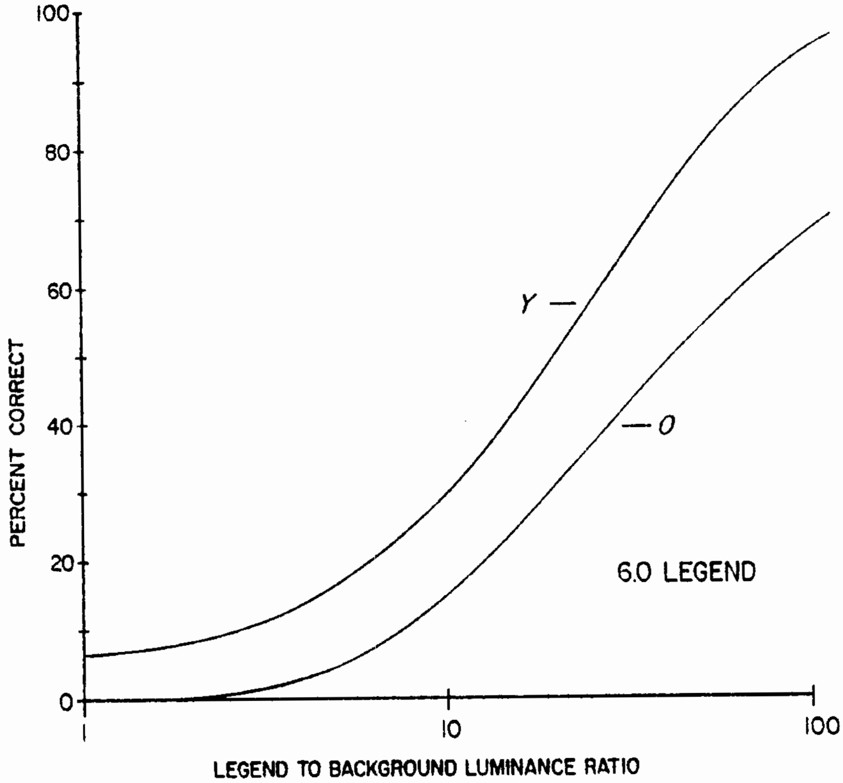
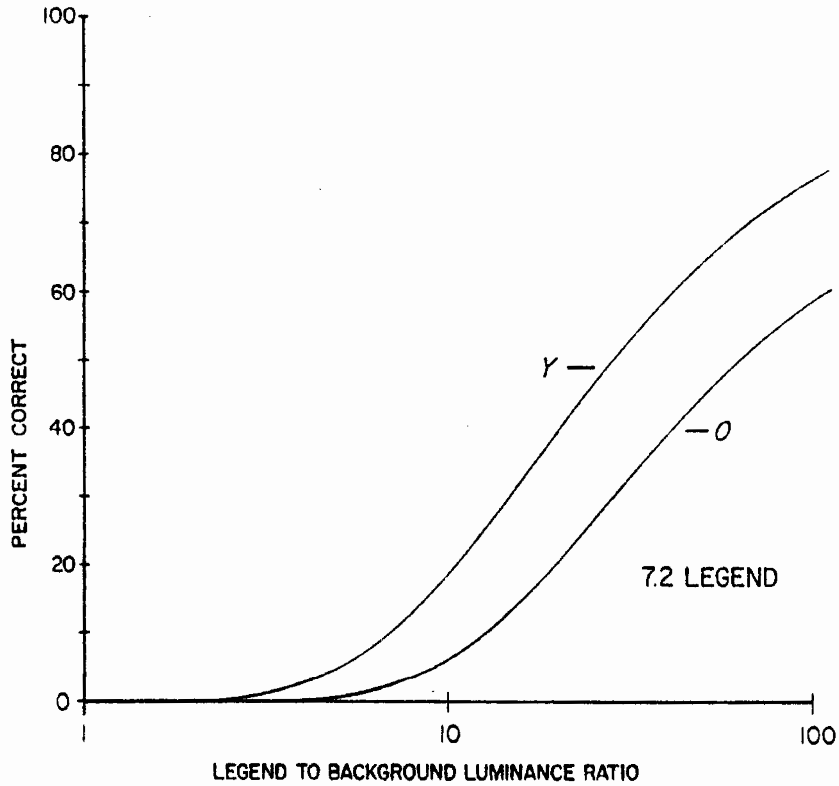


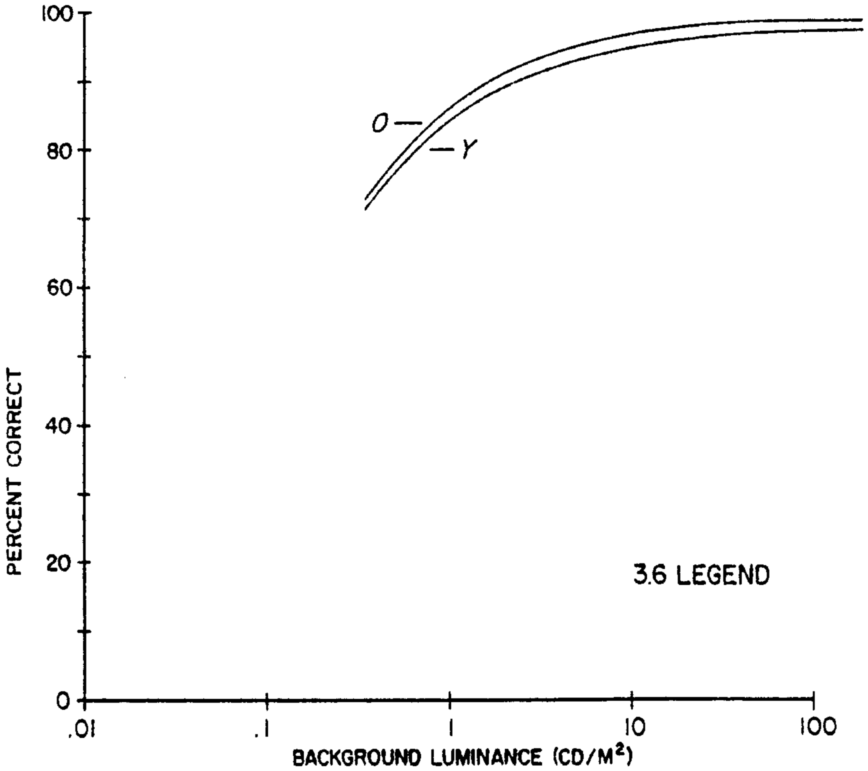
Figure 1-30. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Green background - 0.05 cd/m^2, dark surround (0.034 cd/m^2).



100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO



100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO



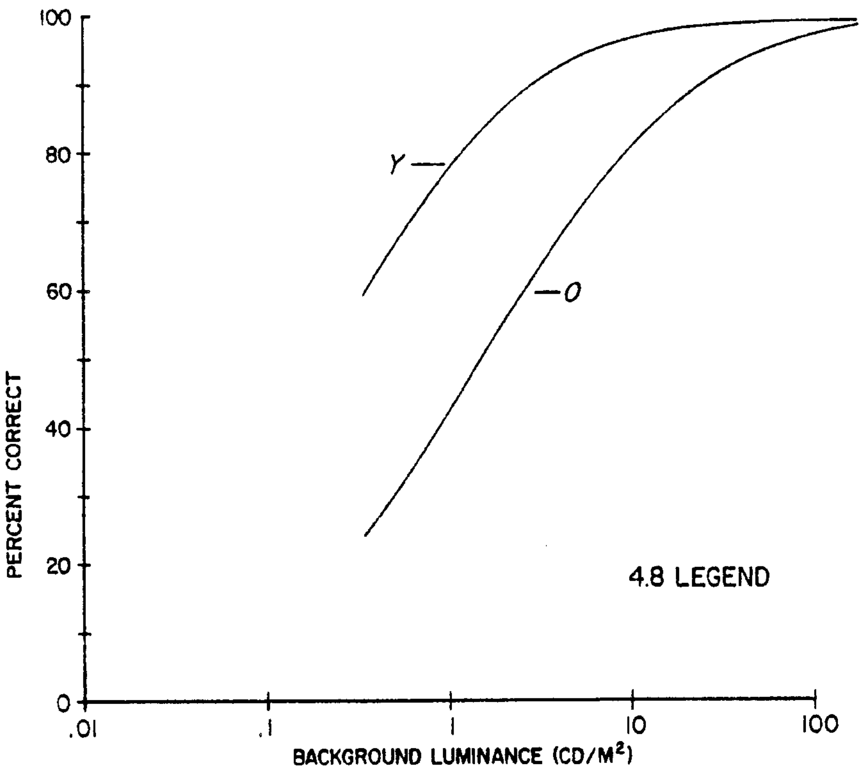
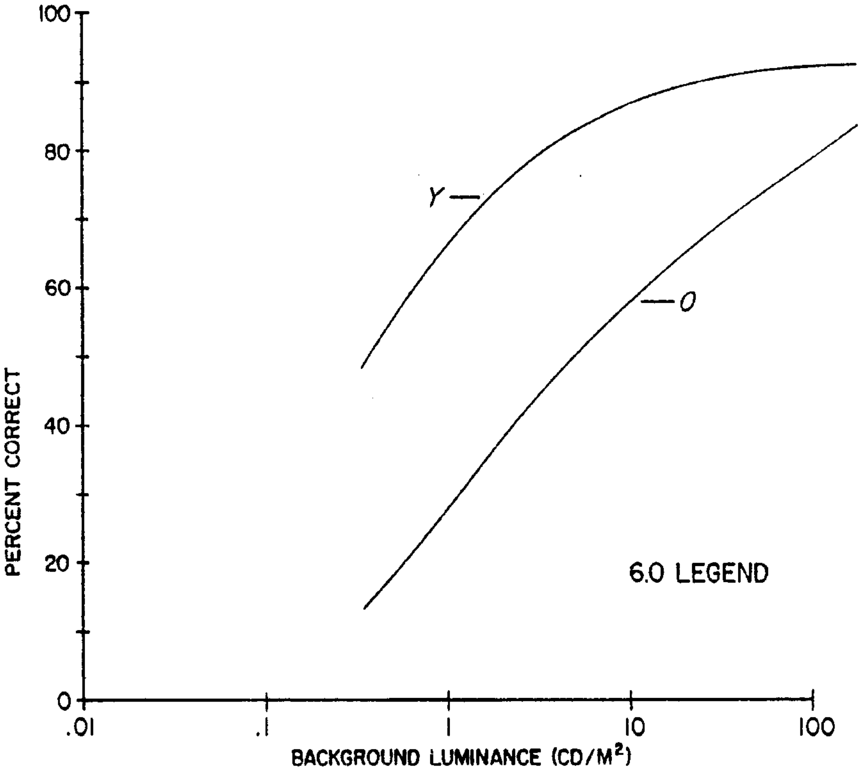
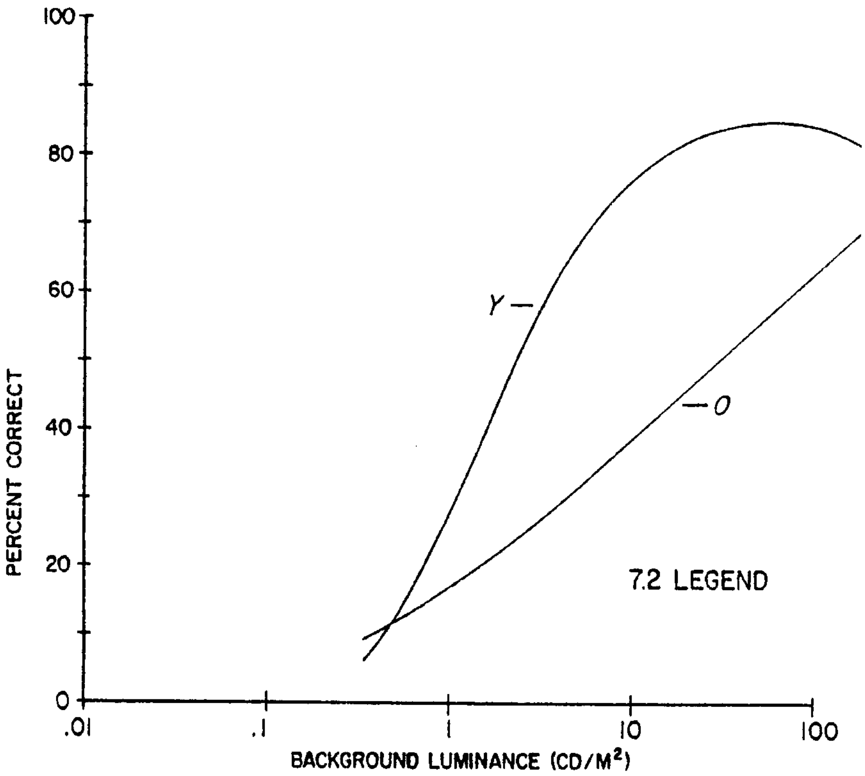


Figure 1-31. Percent correct responses as a function of background luminance and legend size for older as compared with younger subjects. White background, dark surround (0.034 cd/m^2).



PERCENT CORRECT
100
80
60
40
20
0
Y
O
6.0 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)



PERCENT CORRECT
100
80
60
40
20
0
Y
O
7.2 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)

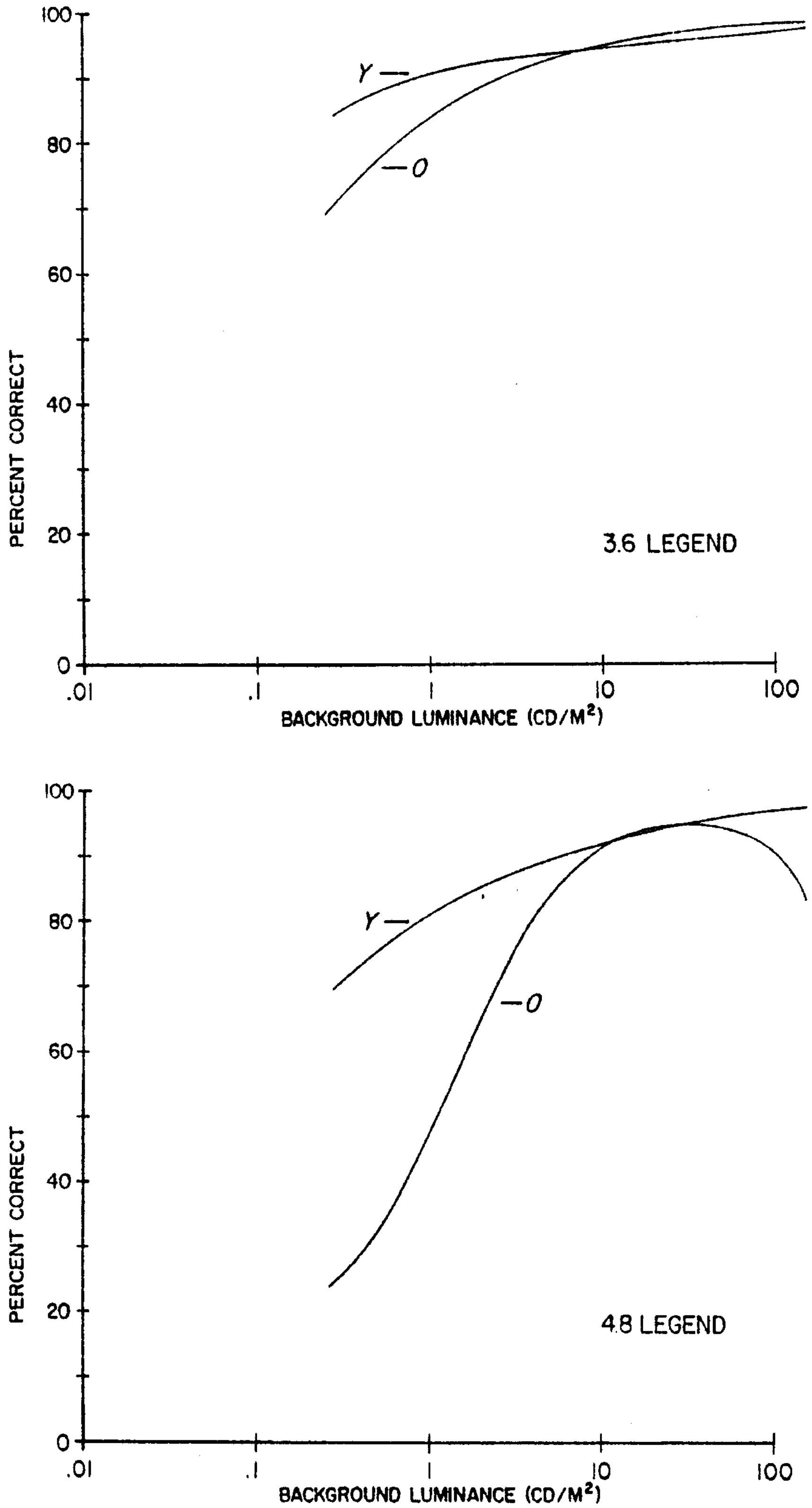
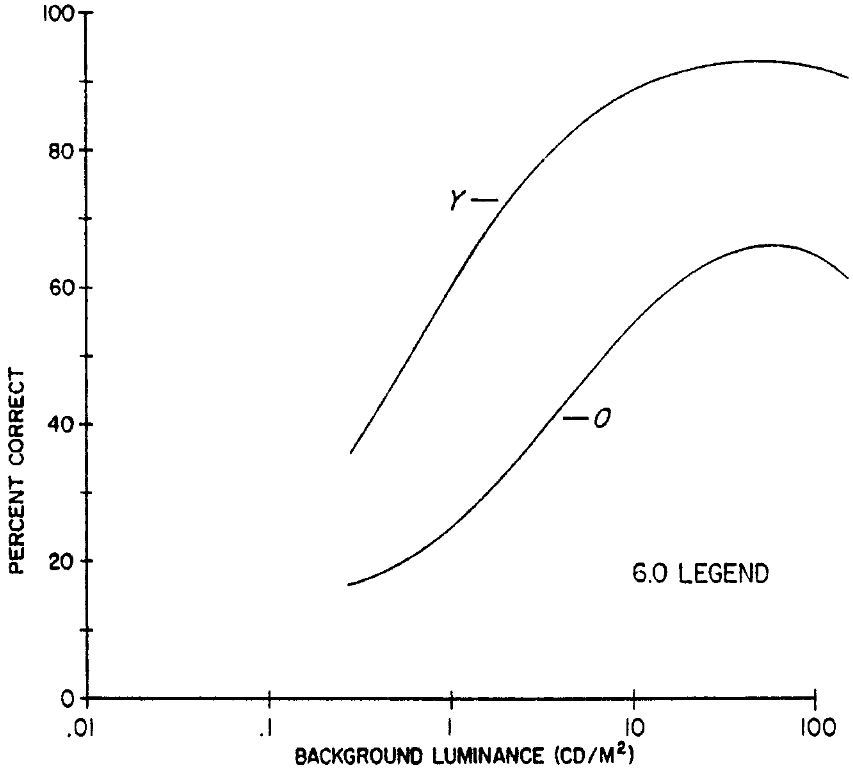
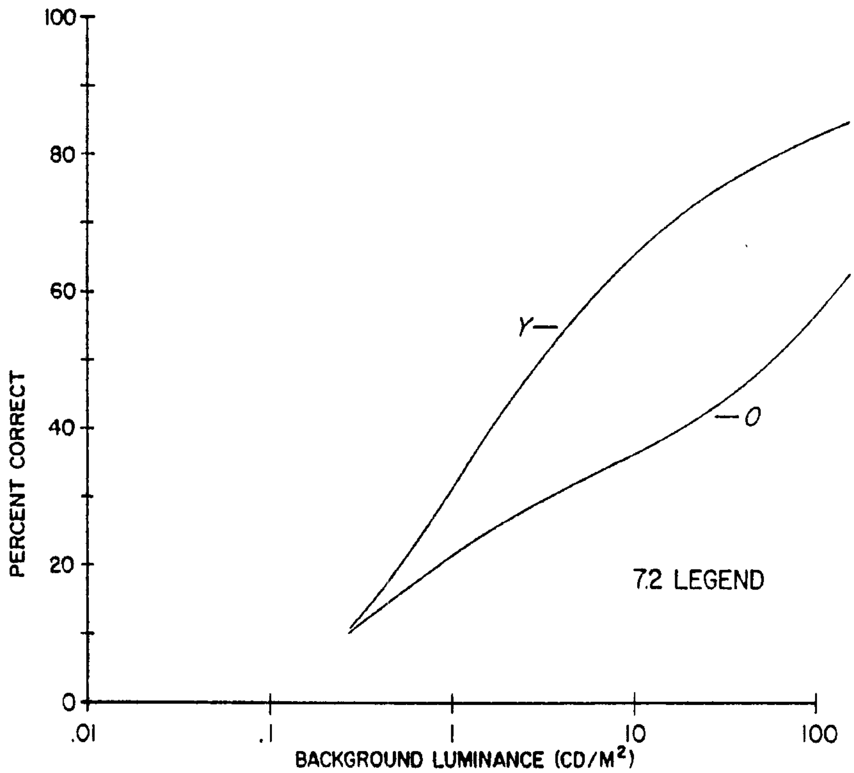


Figure 1-32. Percent correct responses as a function of background luminance and legend size for older as compared with younger subjects. Yellow background, dark surround (0.034 cd/m^2).


100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)


100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)

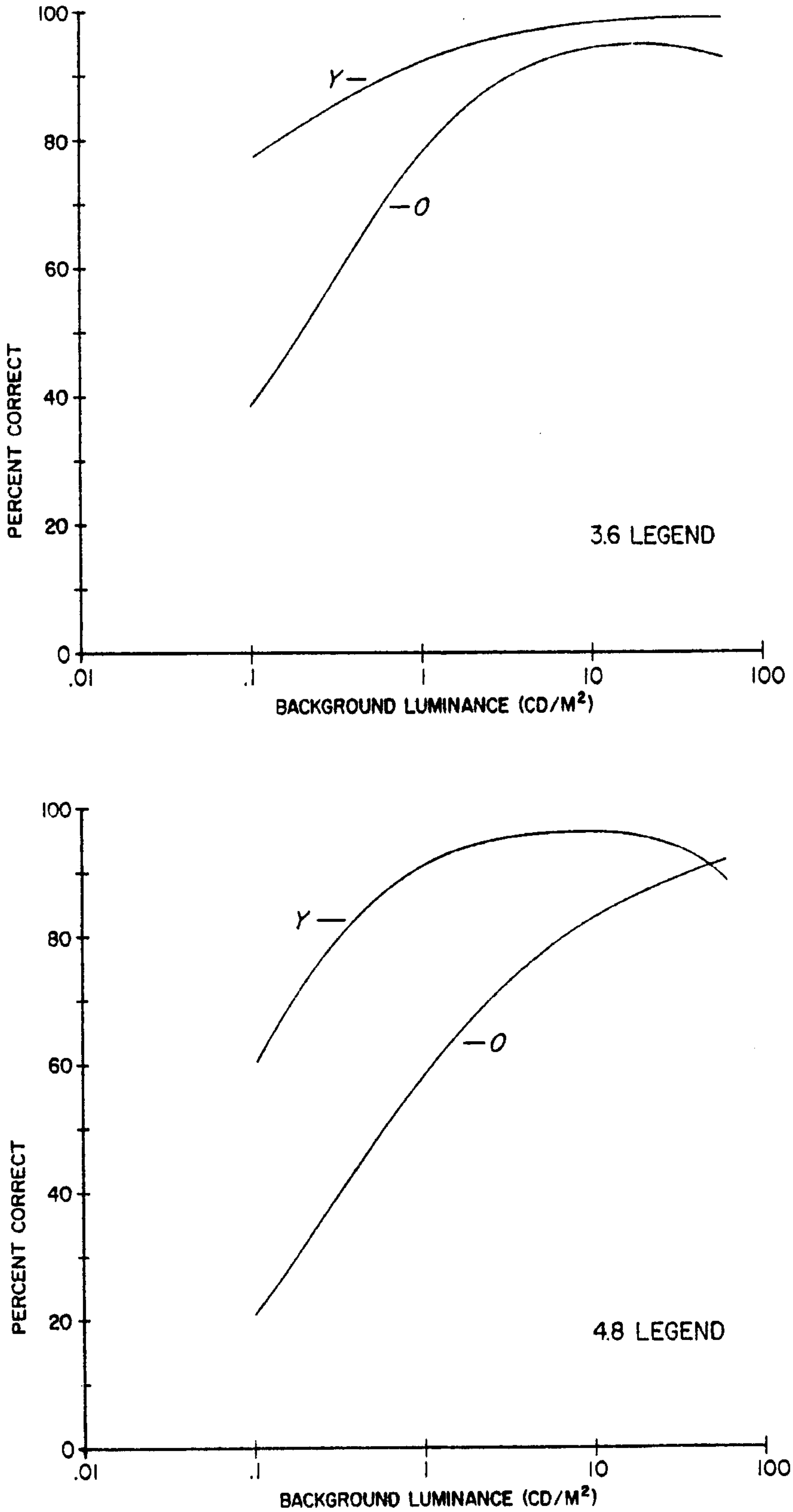
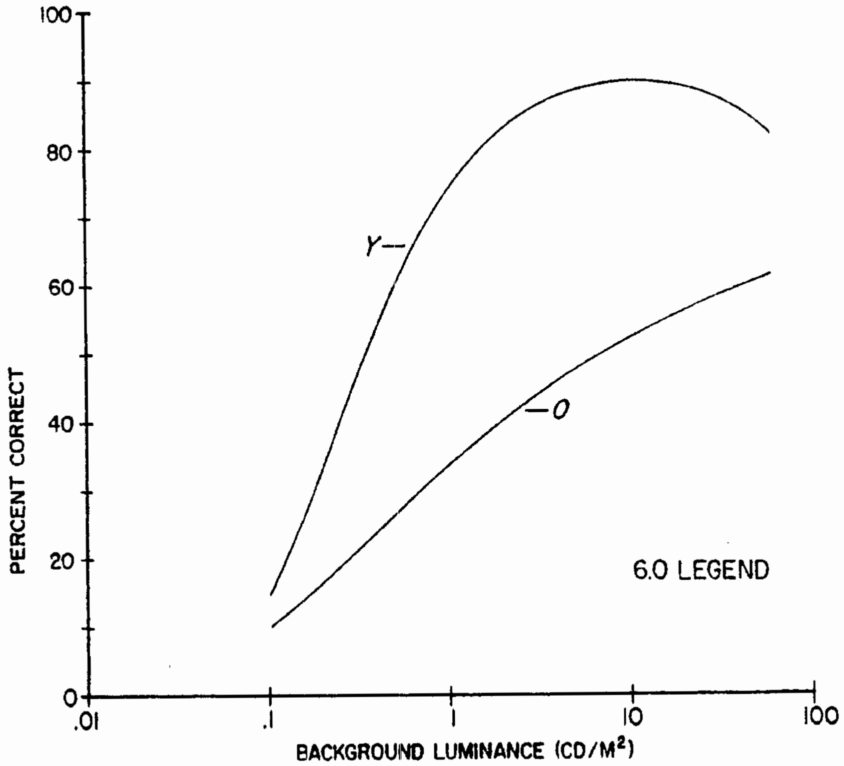
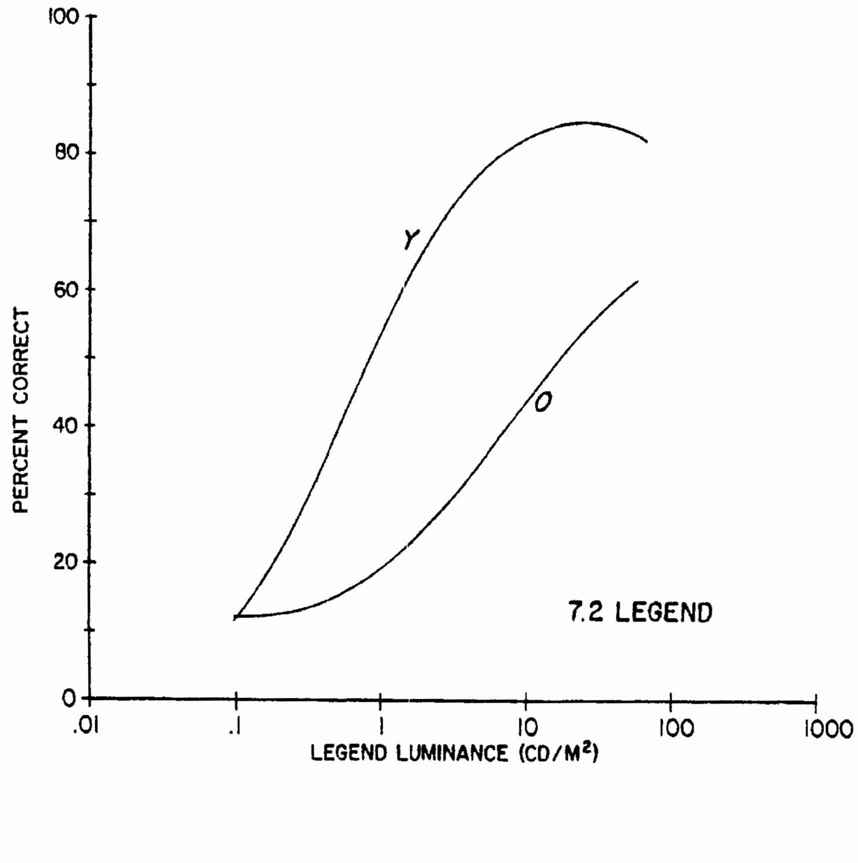
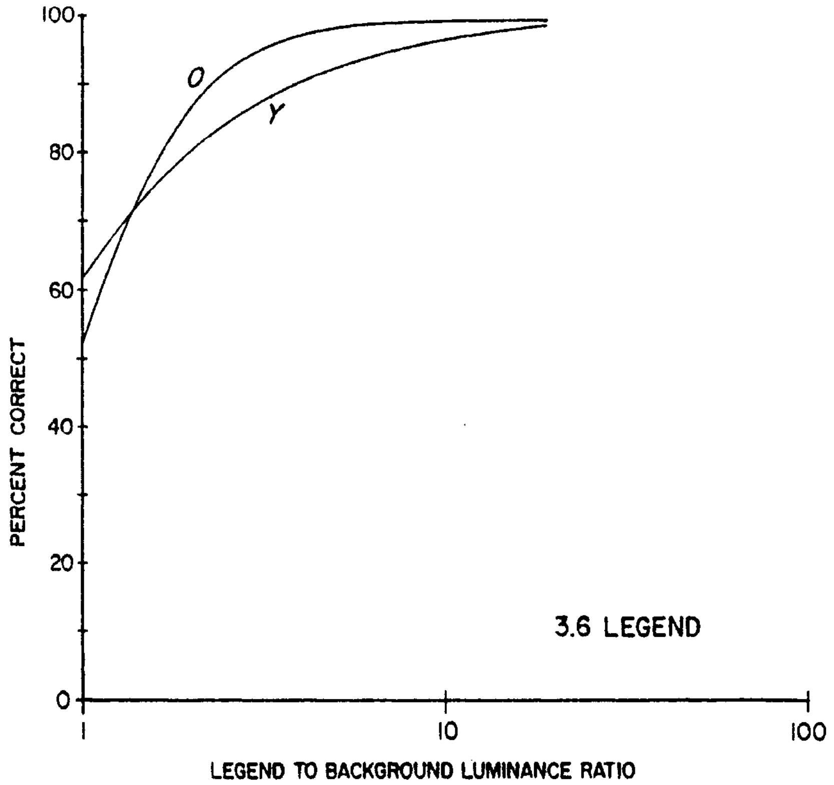


Figure 1-33. Percent correct responses as a function of background luminance and legend size for older as compared with younger subjects. Orange background, dark surround (0.034 cd/m^2).


100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
.01
.1
1
10
100
BACKGROUND LUMINANCE (CD/M²)


100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
.01
.1
1
10
100
1000
LEGEND LUMINANCE (CD/M²)



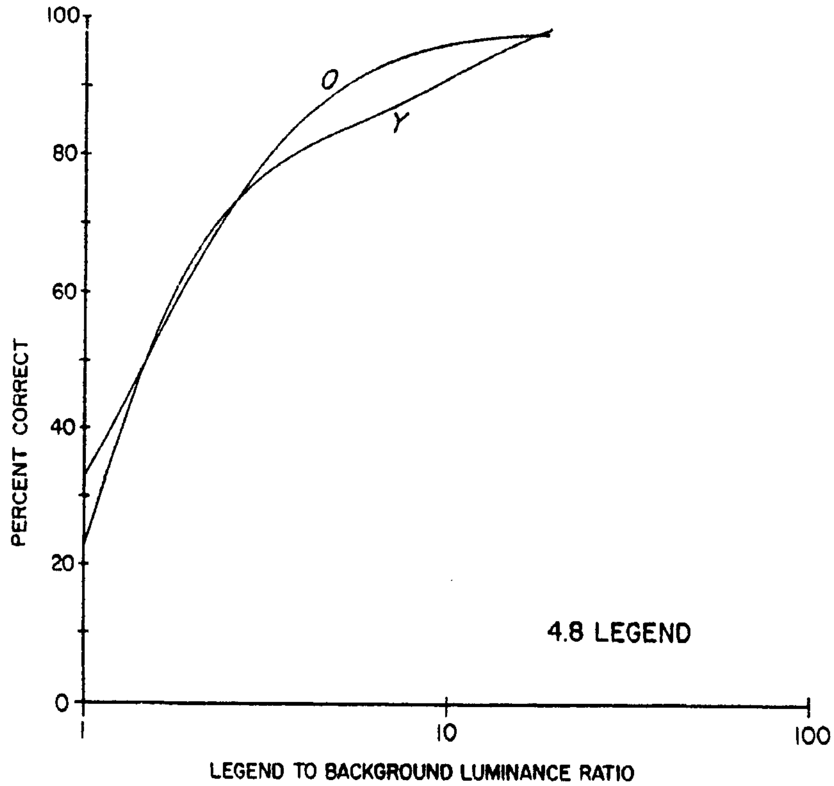
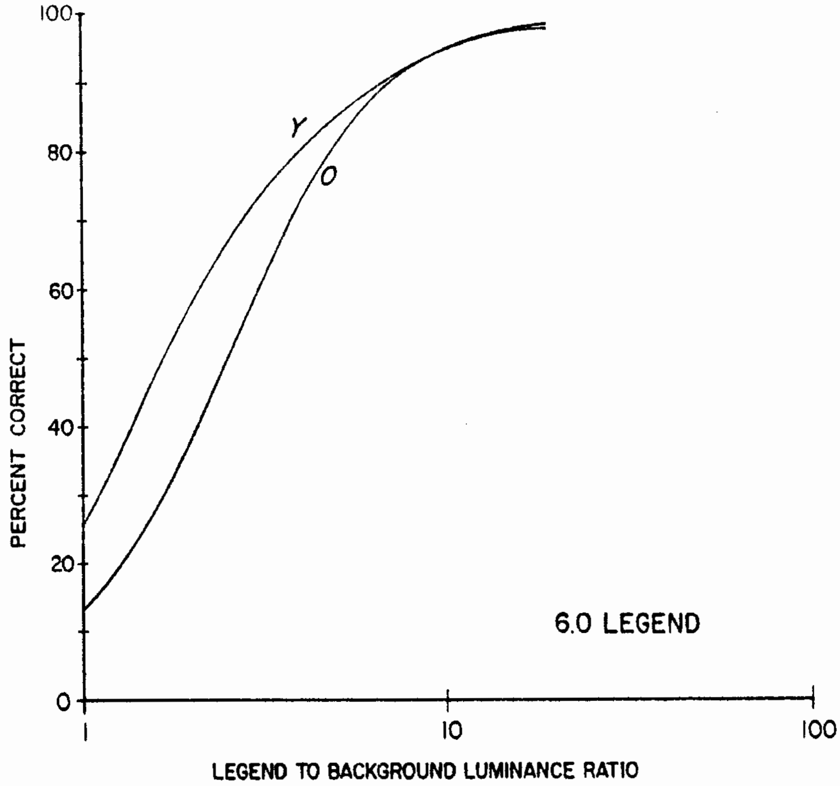
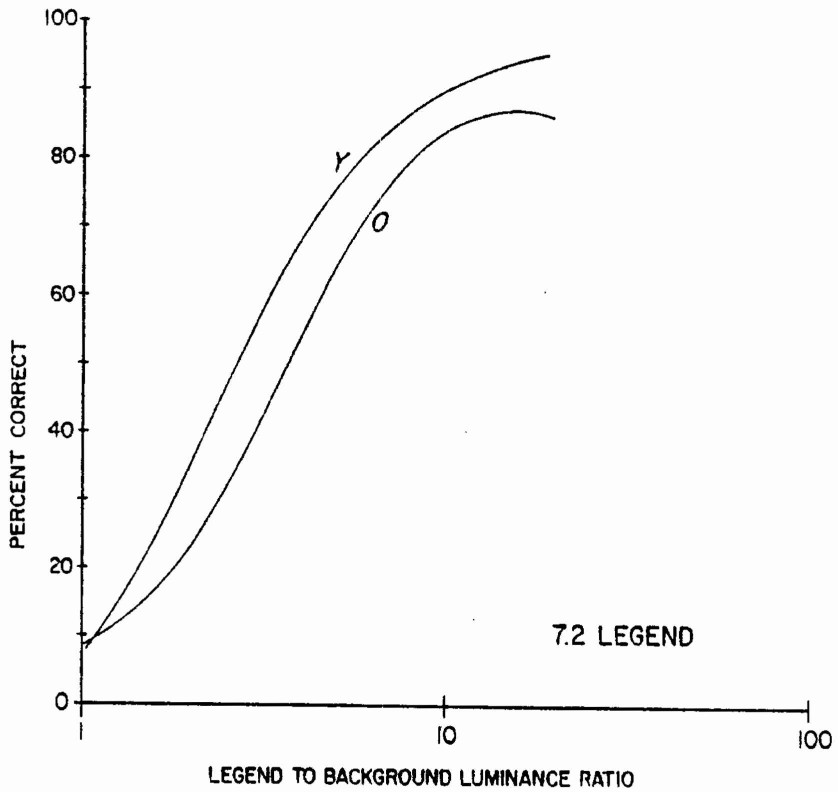


Figure 1-34. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Red background at 34.4 cd/m^2, 0.034 cd/m^2 surround.



100
80
60
40
20
0
PERCENT CORRECT
Y
O
6.0 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO



100
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PERCENT CORRECT
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7.2 LEGEND
1
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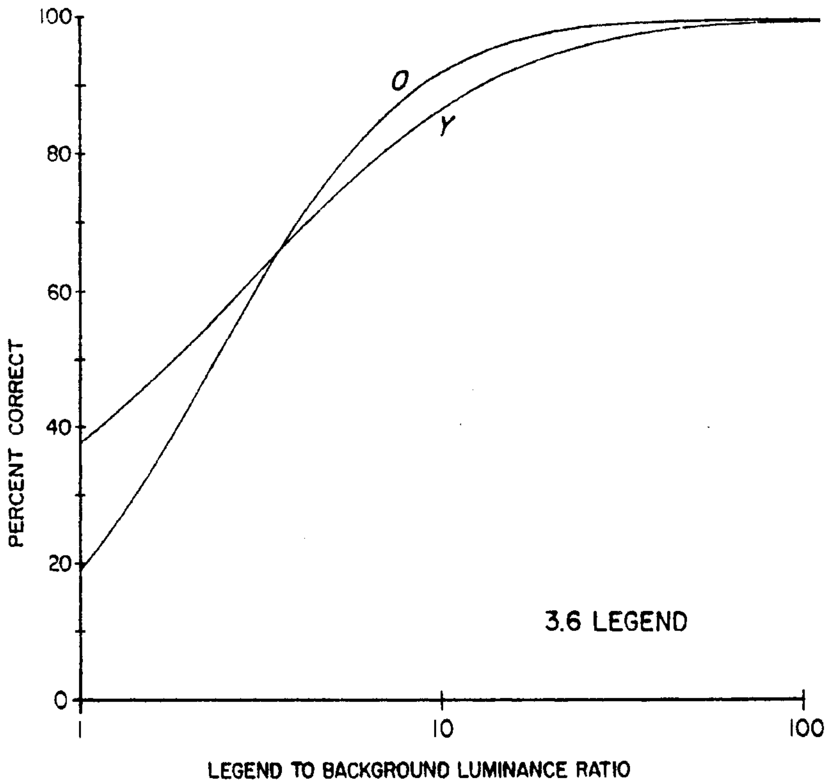
LEGEND TO BACKGROUND LUMINANCE RATIO



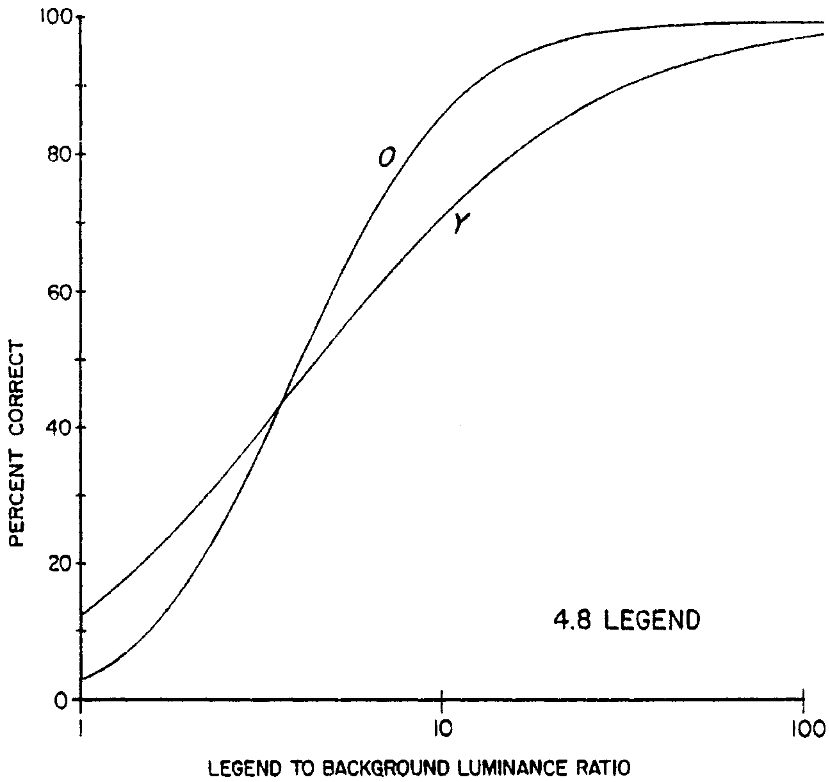
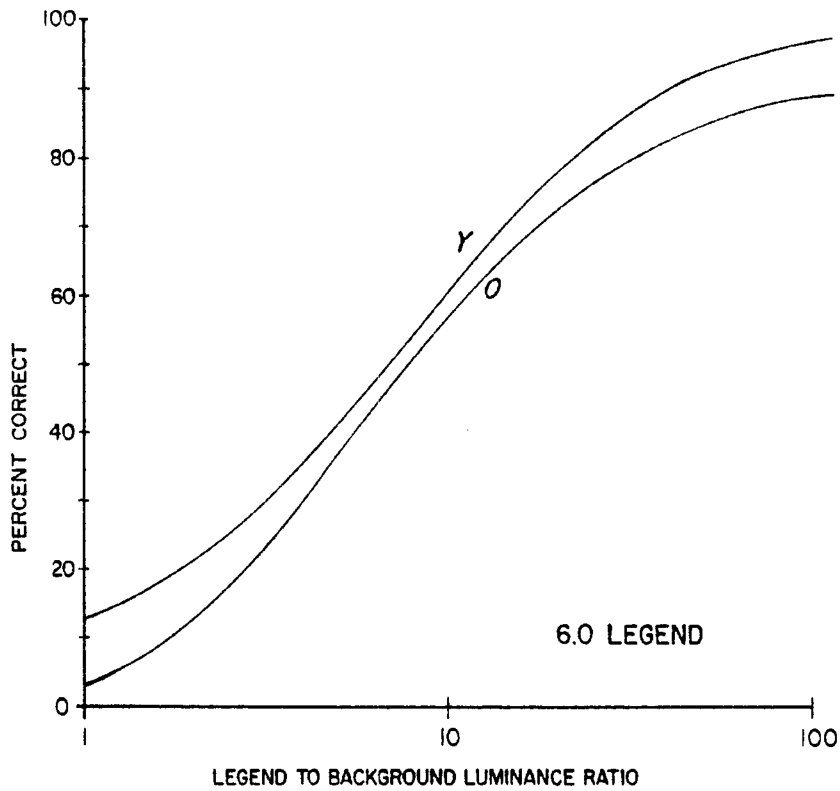


Figure 1-35. Percent correct responses as a function of legend luminance contrast and legend size for older as compared with younger subjects. Red background at 0.41 cd/m^2, 0.034 cd/m^2 surround.


100
80
60
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20
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PERCENT CORRECT
Y
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6.0 LEGEND
1
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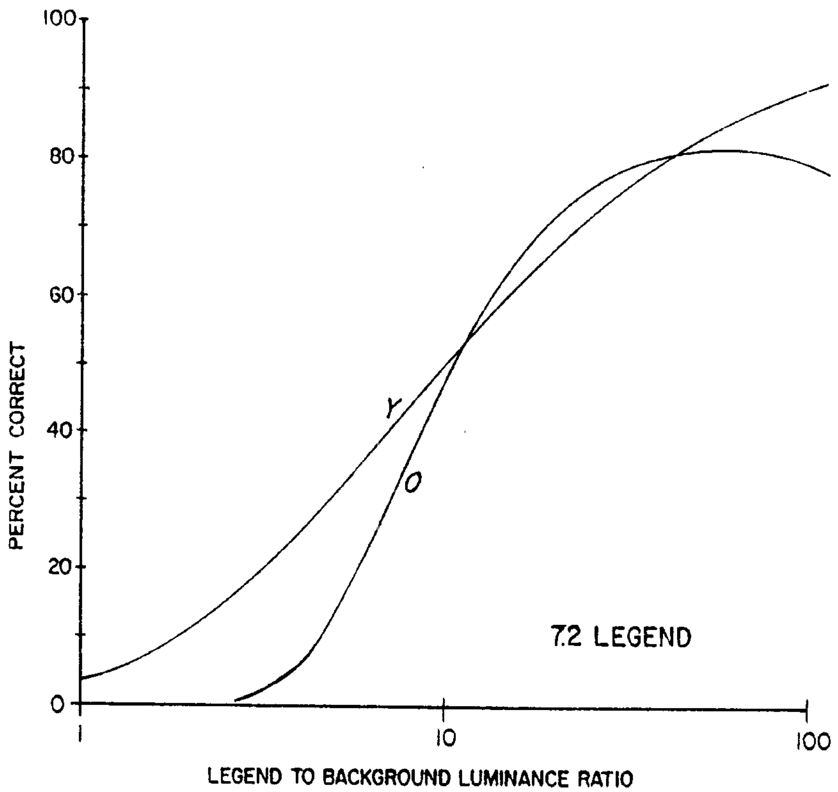
100
LEGEND TO BACKGROUND LUMINANCE RATIO


100
80
60
40
20
0
PERCENT CORRECT
Y
O
7.2 LEGEND
1
10
100
LEGEND TO BACKGROUND LUMINANCE RATIO

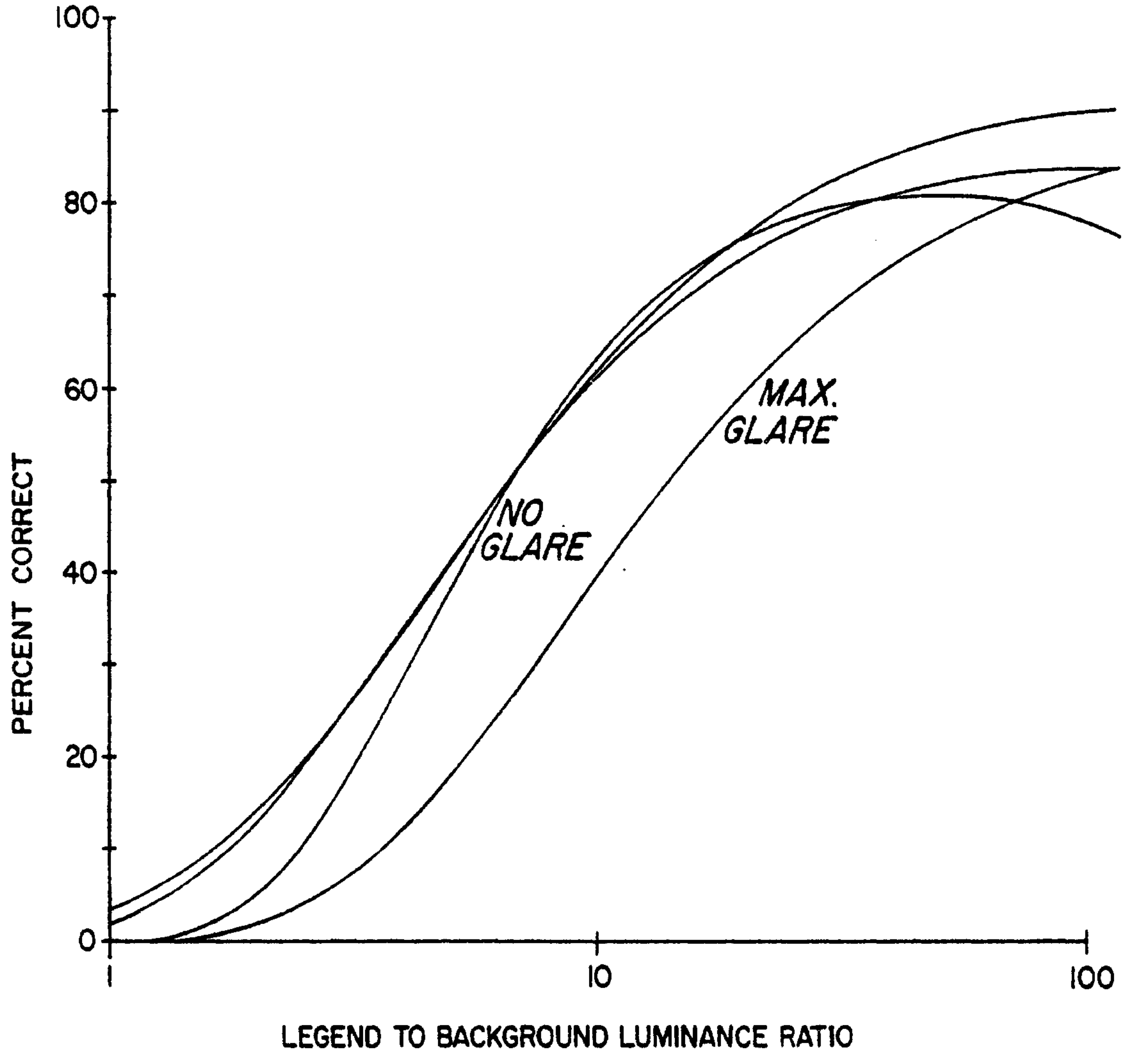


Figure 1-36. Percent correct responses as a function of legend luminance contrast and four levels of glare illuminance. Glare angle 0.7°, dark surround (0.034 cd/m^2), 6 m/cm legend, 0.4 cd/m^2 green background. Older subjects.

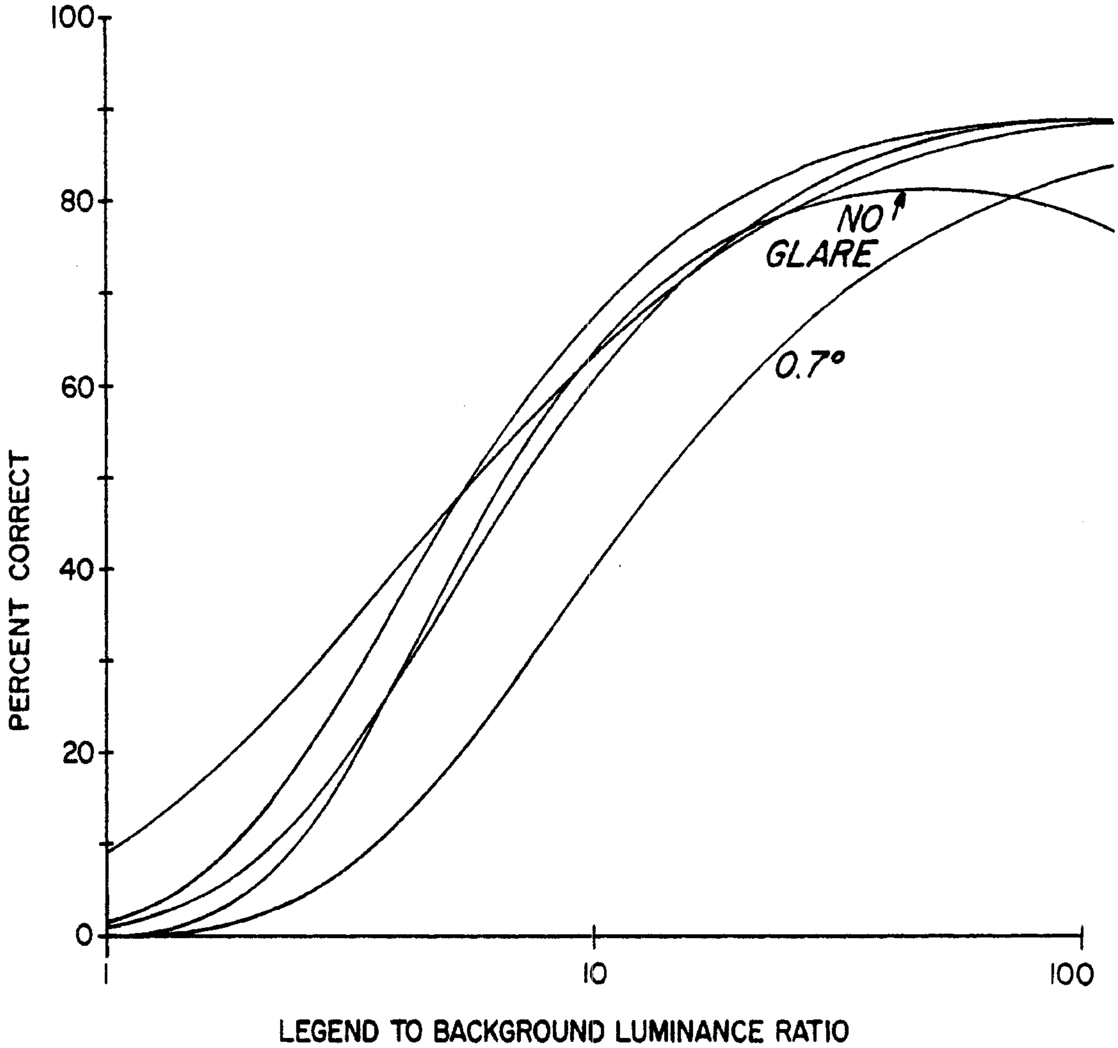


Figure 1-37. Percent correct responses as a function of legend luminance contrast and four glare angles. Glare illuminance 0.38 lux, dark surround (0.034 cd/m^2), 6 m/cm legend, 0.4 cd/m^2 green background. Older subjects.

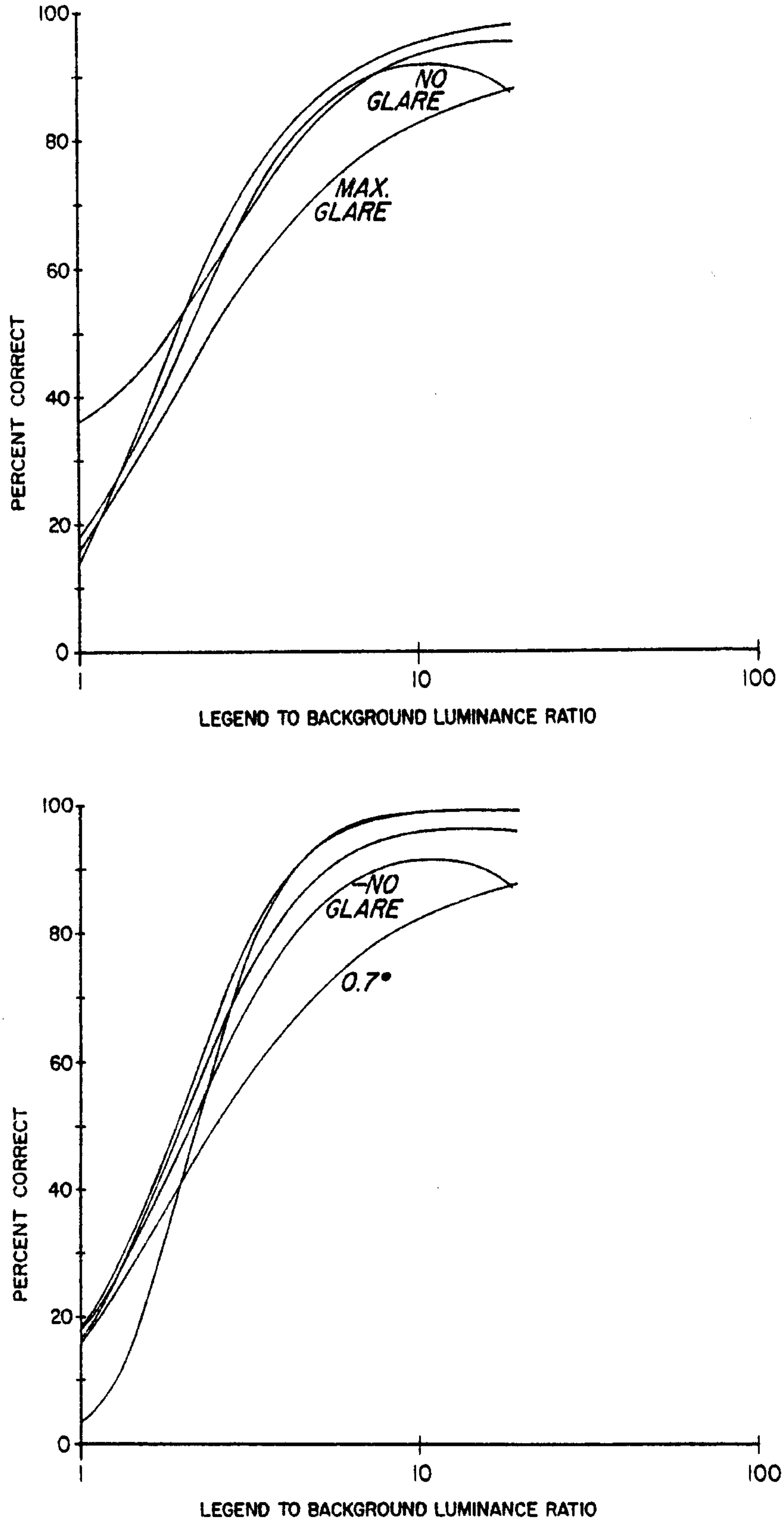


Figure 1-38. Percent correct responses as a function of legend luminance contrast and glare parameters. Dark surround (0.034 cd/m^2), 6 m/cm legend, 34.4 cd/m^2 green background. Older subjects.

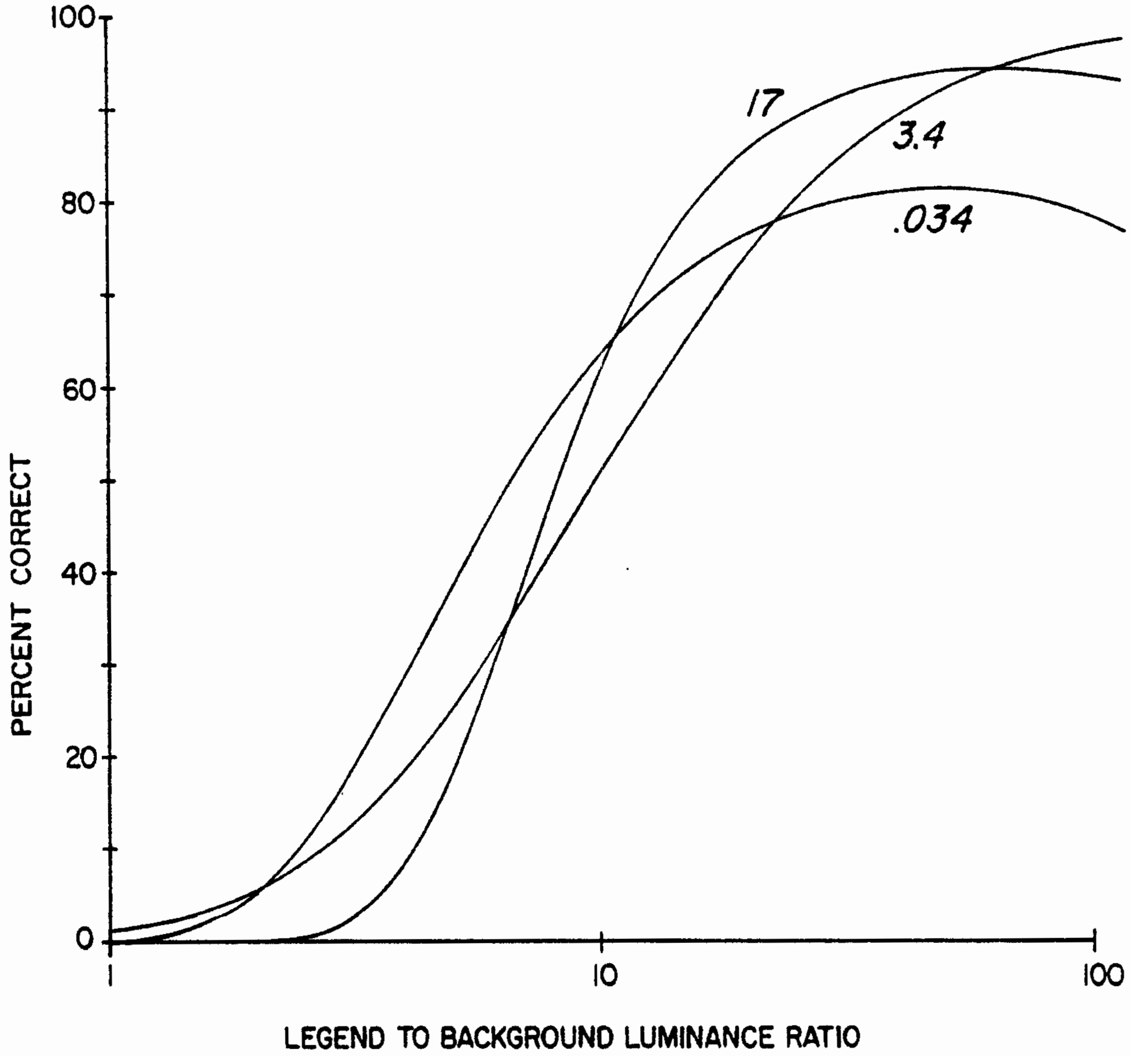


Figure 1-39. Percent correct responses as a function of legend luminance contrast and surround luminance. Maximum glare smallest angle. Dark surround (0.034 cd/m^2), 6 m/cm legned, 0.41 cd/m^2 green background. Older subjects.

on the performance of the younger subjects. A different result pertains to the older subjects (Figures 1-40 and 1-41), although the primary benefit to increased surround luminance seems to be in eliminating the loss of performance associated with high legend luminance contrast. However, the fact that the curves asymptote at or near 100% correct suggests that legibility distances greater than 6 m/cm are possible.

1.3 Conclusions

The most important single variable affecting the legibility of highway signs at night is luminance contrast. There are three conditions which must be considered:

1. For white legends seen against a background having a luminance of about 0.4 cd/m^2 or more: Legend luminance contrast is the most important factor in legibility. Contrast requirements depend on background luminance, decreasing as background luminance increases. For signs having background luminance levels typically associated with retroreflective guide signs today (i.e., about 3 to 0.4 cd/m^2), maximum legibility is achieved at contrasts of 30 to 60:1. (For highly reflective signs much lower contrasts are possible; about 5:1.) The higher contrast levels are especially helpful to older drivers.

Sign background luminance is also a significant factor in the legibility of white legend signs. High background luminance levels make possible greater legibility distances at lower contrast levels, reduce or eliminate the negative effects of excessive legend luminance contrast, reduce environmental glare effects, and aid color identification, and conspicuity. High background luminance levels are particularly helpful to older drivers.

2. For white legends seen against a non-retroreflective or black background: Legend luminance is the most important factor in legibility. Luminance values in the range from about 10 to 100 cd/m^2 are associated with optimum performance for young subjects, with the higher values being desirable to aid older drivers. Luminance levels beyond the range just indicated may reduce legibility.

Since luminance varies with a number of conditions over which the engineer has little control (e.g., headlamp beam, number of vehicles in the approach, pavement wetness), it is difficult to maintain it within the fairly narrow "optimum" range. Thus it is desirable to design signs having one non-retroreflective component (either legend or background) to a more liberal standard (i.e., less than the theoretical maximum legibility distance), under the assumption that it

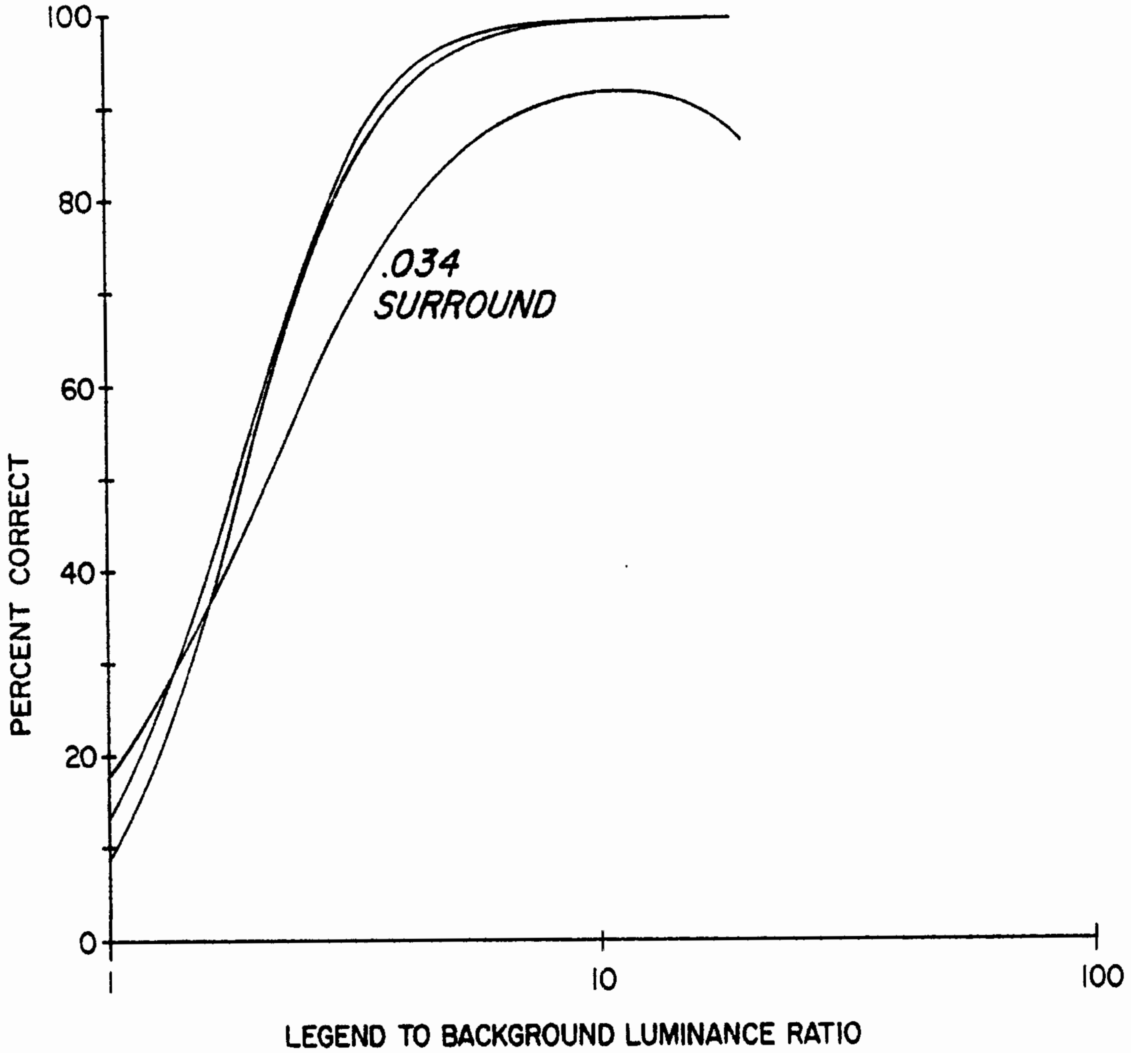


Figure 1-40. Percent correct responses as a function of legend luminance contrast and surround luminance. Legend - 6m/cm, 34.3 cd/m^2 green background. Older subjects.

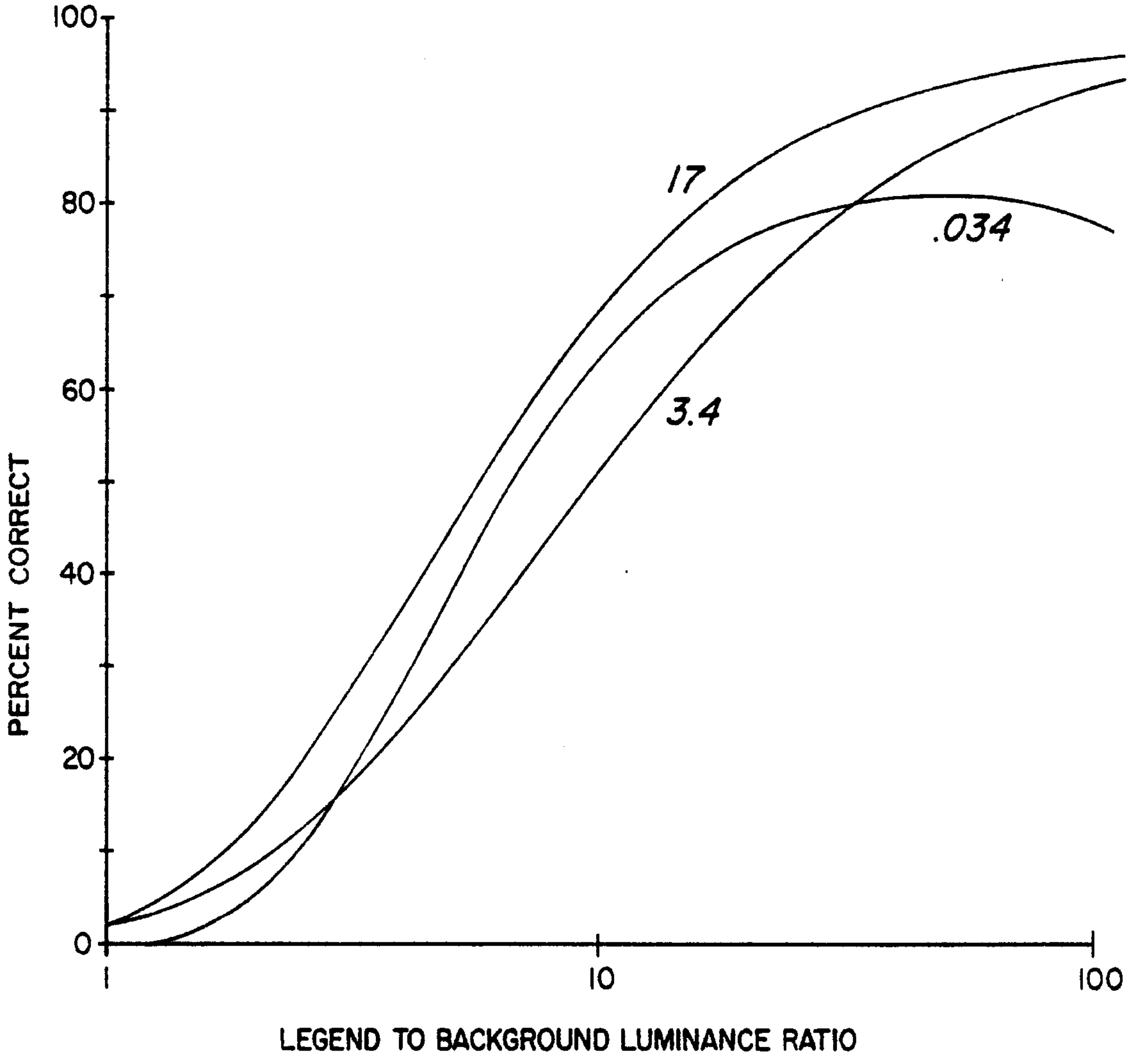


Figure 1-41. Percent correct responses as a function of legend luminance contrast and surround luminance. Legend - 6m/cm, 0.41 cd/m^2 green background. Older subjects.

will often be seen under other than optimum conditions. In this respect fully reflectorized signs have an advantage, since their contrast does not change with the conditions mentioned above.

3. For black legends seen against a background having a luminance of about 0.4 cd/m^2 or more: In terms of legibility characteristics, a black legend seen against a bright background follows the same general rules as a white legend seen against a black background. That is, the luminance of the retroreflective component (whether legend or background) determines legibility distance. The optimum range is from about 10 to 100 cd/m^2.

Evidence indicates that all other factors being equal, white on black signs will be somewhat more legible than black on white, yellow or orange. For both types, legibility at high luminance levels is limited by irradiation. Irradiation causes white letters to (apparently) grow larger and lose definition; it causes black letters to be "swallowed" by the background. This problem can be aided by altering the stroke width of the legend to suit the contrast direction. Thus, white letters should have a narrower stroke width than black letters. Hind, et al. (1976) recommends a stroke width to height ratio of 0.167 for black legends on light backgrounds, and about 0.083 for white legends on black backgrounds.

It should be noted that the above cautions do not apply to white legend signs when the background has significant luminance. So long as the contrast is set no higher than the levels recommended in this report (30-60:1), irradiation is no problem. Under these conditions, maximum legibility will be achieved by legends having a stroke width to height ratio of about 0.2.

4. Environmental glare appears not to be a serious problem in terms of sign legibility. It is probably much more significant as a negative factor in conspicuity. When significant glare sources are located near signs, the losses in legibility can be compensated for by increases in legend luminance contrast or background luminance. The latter approach has the additional advantage of increasing conspicuity as well.

5. The luminance of the sign surround has a minor effect on legibility, especially for younger drivers. High surround luminance levels do reduce the effects of environmental glare and excessive legend luminance contrast, however.

6. Sign background colors have only a minor effect on legibility. The effect is probably due to the change in

spectral sensitivity which the eye undergoes as part of the dark-adaptation process.

2.0 FIELD EXPERIMENTS

2.1 Introduction

Two experiments were performed to supplement the laboratory findings. They differed in the testing site, approach speeds, and glare angles that were investigated. The common features will be described first, followed by the aspects specific to each of the two experiments.

2.1.1 Method. These were nighttime investigations in which subjects either drove or rode in an automobile and at the same time watched for a retroreflective sign. The sign had been erected along the right side of the road, showing a left- or right-facing E. The measure of performance was the distance at which the subject could identify the orientation of the letter (E or Ǝ) with or without the presence of glare.

2.1.1.1 Test signs. The backgrounds of the test sign were 90 cm wide and 90 cm high. They were constructed by attaching retroreflective or non-retroreflective sheeting to aluminum panels. A ledge was fixed to each sign to support a 20-cm tall letter in the center of the background. The entire sign was placed on a flat-black supporting stand. With this arrangement, the center of the letter E was about 1.3 m above the pavement.

The background material was green, while the letter was white.

2.1.1.2 Glare source. Glare was provided by one of three 12v, 10 cm (in diameter) spotlamps (#4416). Using a 6v battery and neutral density filters, the lamps were calibrated to emit a maximum of either 140 cd or 1400 cd.

2.1.1.3 Test vehicle. The test vehicle was a standard, full-size station wagon. The vehicle has a distance-measuring system with a digital distance readout.

2.1.1.4 Procedure. The data were collected from three subjects concurrently (a driver and two passengers). The three were seated in the front seat of the car. Each subject held a push button switch. When depressed, each switch turned on a small light bulb in the rear compartment of the vehicle. The switches operated silently and thus subjects were unaware of the timing of each other's responses. The experimenter, who sat in the rear seat behind the subjects, also had a switch which turned on a fourth bulb. The experimenter pressed his switch when he passed the sign. This array of lights was viewed by a camera and videotaped simultaneously with the distance readout. For each run, then, three lights indicated when each subject had identified the orientation of the letter and the last light indicated the position of the sign. By subtracting the first three distance readings (corresponding to the onset of the lights) from the last, legibility distances were determined.

The instructions specified that the subjects were to press the button once for a right orientation of the letter and twice for a left orientation. After the instructions had been read, all questions were answered and four practice runs given. Two short breaks were permitted during the session. Any required make-up trials were given at the end of the regular sequence. The orientation of the letter E was varied randomly. All data were taken using standard low beams.

2.2 Experiment 1

2.2.1 Method

2.2.1.1 Sign materials. Five combinations of the letter and background material were used (see Table 2-1).

Table 2-1

PHOTOMETRIC PROPERTIES OF THE LETTER/BACKGROUND COMBINATIONS

COMBINATION (Letter Material on Background Material)	SPECIFIC LUMINANCE ($cd/lx/m^2$)		CONTRAST RATIO
	LETTER	BACKGROUND	
Enclosed Lens on Encapsulated Lens	115	36	3:1
Encapsulated Lens on Encapsulated Lens	325	36	9:1
Prismatic on Encapsulated Lens	1200	36	33:1
Prismatic on Enclosed Lens	1200	15	80:1
Enclosed Lens on Non-Reflective	115	0.06	1916:1

2.2.1.2 Glare sources. The glare sources were mounted on tripods at the same height as the letter E, but displaced 3.2 m laterally. The lamps were aimed so that the maximum output reached the driver's eyes at a predicted no-glare legibility distance of 122 m (400 feet). At the actual mean no-glare legibility distance (which proved to be 88.3 m), the glare angle was 2° and the illuminances at the subject's eyes (provided by the two glare sources) were .017 and .17 lux. The two glare levels correspond to the glare levels from oncoming low beams at approximately 300 m and 95 m, respectively.

2.2.1.3 Subjects. Subjects of two age levels participated. The younger subjects were between 20 and 30 years of age and the older subjects were between 63 and 75 years of age. Fifty potential subjects were screened with visual acuity and color vision tests. Six younger and six older subjects whose visual-acuity scores could be most closely matched were selected to participate. Their characteristics are described in Table 2-2. As is evident from Table 2-2, the two groups had comparable visual-acuity scores under three sets of conditions: high luminance/high contrast, high luminance/low contrast, and low luminance/high contrast. (From each age group two subjects participated as drivers and four as passengers.)

2.2.1.4 Facility. The test was conducted on a recently finished, but still unopened, limited-access highway with two lanes in each direction. The utilized section was dark, flat and straight, and about 1.6 km long. Two signs were erected opposite each other at the right edges of the two right-hand lanes in both directions.

2.2.1.5 Procedure. Each run began with the test vehicle proceeding in the right lane (at a speed of approximately 72 km/h), passing the sign placed on the right, and continued until the vehicle reached a median crossing, that was used as a crossover to the opposite direction of the highway. The 45 experimental trials (three replications, three glare levels, five signs) took about 1 1/2 hours to complete.

The order in which the letter/background combinations and glare intensities were presented was varied systematically.

2.2.2 Results

The mean legibility distances for the various letter/background combinations, glare levels, and age groups are presented in Table 2-3.

Analysis of variance revealed the following:

- Effect of age was statistically not significant; the mean legibility distances for the younger and older group were identical (93.9 m).

Table 2-2

SUBJECT CHARACTERISTICS

SUBJECT	AGE	SEX	VISUAL ACUITY HL HC	HL LC	LL HC	LL LC	COLOR VISION
1	21	M	20/22	20/35	20/60	20/100	Normal
2	30	F	20/22	20/50	20/50	20/150	Normal
3	21	M	20/25	20/35	20/35	20/100	Normal
4	20	M	20/18	20/20	20/25	20/60	Normal
5	27	M	20/14	20/25	20/22	20/60	Normal
6	21	F	20/18	20/25	20/27	20/60	Normal
7	66	M	20/22	20/40	20/35	20/60	Normal
8	75	M	20/20	20/35	20/40	20/150	Normal
9	59	F	20/22	20/35	20/40	20/80	Normal
10	70	M	20/20	20/35	20/40	20/150	Normal
11	63	M	20/18	20/40	20/40	20/60	Normal
12	72	M	20/18	20/40	20/40	20/100	Normal

Mean (younger): 20/20 20/32 20/36 20/88
Mean (older): 20/20 20/37 20/39 20/100

Note: HL - High Luminance (161 cd/m^2)
LL - Low Luminance (.2 cd/m^2)
HC - High Contrast (22.5:1)
LC - Low Contrast (1.3:1)

- Effect of seat position (driver, middle, and right passenger) was statistically not significant ($F<1$).

- Effect of letter/background combination was statistically significant ($F[4,24]=5.07$, $p < .005$). *Post hoc* pairwise comparisons, using Newman-Keuls range test (Hicks, 1973), showed that both the 1200/36 (33:1) and 325/36 (9:1) combinations yielded significantly longer legibility distances than either the 1200/15 (80:1) or 115/.06 (1916:1) combinations. Also, the 1200/36 (33:1) combination yielded significantly longer legibility distances than the 115/35 (3:1) combination.

- Effect of the glare level was statistically significant ($F[2,123] = 12.49$, $p < .005$). The mean legibility distances were 88.3, 95.3, and 98.1 m for the no-glare, .017 lux, and .17 lux conditions, respectively. *Post hoc* pairwise comparisons using the Newman-Keuls range test revealed that the legibility distances were shorter under the no glare condition than under either of the conditions with glare present ($p < 0.05$).

- Effect of subjects was statistically significant ($F[6,360] = 57.9$, $p < .001$).

- No other main effects or interactions were statistically significant (except some involving subjects as a factor).

2.2.3 Discussion

One of the most interesting findings of this study was the absence of an age effect. In our previous study (Sivak et al., 1979), matching older and younger subjects on high luminance/high contrast acuity did not prevent younger subjects from enjoying a 30-54% advantage in legibility distances. In the present study, on the other hand, the two age groups were also matched on low luminance/high contrast acuity. The implication of the results is that good low luminance/high contrast acuity assured good performance under the present conditions. Furthermore, this finding implies that the usually observed age-related decrement in nighttime legibility performance is due exclusively to visual deficits (deterioration of visual acuity with age) and not to any information-processing deficits.

The older subjects had a poorer low luminance/low contrast visual acuity than did the younger subjects (see Table 2-2). Therefore, it is not surprising that there was a tendency for a poorer performance by the older subjects on the letter/background combination providing the least contrast (see Table 2-3). On the other hand, the older subject showed a tendency to perform better than the younger subjects on the letter/background combinations providing the three highest contrast ratios. However, these differences were statistically not significant.

The longest legibility distances were provided by the letter/background combinations yielding contrast ratios of 9:1 and 33:1. Further increase in the contrast ratio (to 80:1)or a decrease (to 3:1) was accompanied by a performance decrement. This finding of essentially an inverted U-shaped function of the legibility vs. contrast ratio is in agreement with our previous data (Sivak et al., 1979). However, contrast levels remained partially confounded with background luminance levels.

Probably the most surprising aspect of the results is an apparent "glare enhancement" effect: the presence of a glare source resulted in longer legibility distances in comparison to the no-glare control condition. This effect

TABLE 2-3

MEAN LEGIBILITY DISTANCES (in meters) FOR THE TWO AGE GROUPS

LETTER/BACKGROUND SPECIFIC LUMINANCE (CONTRAST RATIO)	GLARE ILLUMINANCE (lux)						MEAN BY AGE		MEAN
	0		.017		.17				
	YOUNG	OLD	YOUNG	OLD	YOUNG	OLD	YOUNG	OLD	
115/36 (3:1)	94.6	82.3	92.9	89.2	99.8	81.6	95.8	84.3	90.1
325/36 (9:1)	98.3	92.2	105.8	101.9	105.0	109.2	103.0	101.1	102.1
1200/36 (33:1)	95.3	93.3	99.2	96.3	107.5	123.5	100.7	104.4	102.5
1200/15 (80:1)	78.5	82.7	91.6	101.5	82.9	86.4	84.3	90.2	87.3
115/.06(1916:1)	77.9	87.9	87.2	87.2	91.9	93.4	85.6	89.5	87.6
MEAN BY AGE	88.9	87.7	95.3	95.2	97.4	98.8	93.9	93.9	
MEAN	88.3		95.3		98.1				93.9

was not the result of averaging across subjects and/or across legend/background combinations. The longest legibility distances were obtained from either of the two conditions with glare present (as opposed to the no-glare condition) for both age groups, 11 out of 12 subjects, and all five legend/background combinations. One can only speculate about the reasons for this effect. A possible explanation is as follows: In the present situation (dark rural road), the pupil size is close to maximum as a result of the pupil-light reflex (e.g., Crawford, 1936). However it is known that at low levels of background luminance, reducing the pupil size (while keeping the retinal illuminance constant) results in better visual acuity. The presence of a glare source would, in the present situation, lead to a decrease in the pupil size. Therefore, it is possible that at the glare angle of 2° the beneficial effect of the reduced pupil size (i.e., a reduction in the dioptric aberrations) more than compensated for the detrimental effect of the reduced pupil size (i.e., a reduction in the amount of light reaching the retina) and for the veiling luminance. Potentially beneficial effects of a low-level glare have been noted by other researchers [e.g., Fischer and Christie, 1965, Schober, 1965].

2.3 Experiment 2

2.3.1 Method

2.3.1.1 Sign materials. The background material was made of retroreflective sheeting (encapsulated-lens type) having a specific luminance of 36 cd/lx/m^2 (at 0.2° and -4°). The letter E was white and was made of retroreflective sheeting (encapsulated-lens type) with a specific luminance of 325 cd/lx/m^2. Thus, the contrast ratio between the letter and the background was approximately 9:1.

2.3.1.2 Glare sources. Each glare source delivered a maximum of 140 cd. The lamps were aimed so that the maximum output reached driver's eyes at the predicted no-glare legibility distance of 122 m (400 feet), resulting in illuminance at the subject's eye of .0098 lux.

2.3.1.3 Glare angles. Three glare angles were investigated (in addition to the no-glare control). At the mean no-glare legibility distance (which proved to be 119.3 m) the three glare angles (from the center of the letter E to the center of the glare source) were as follows: 0.2°, 0.6°, 1.5°. (The lamps at the two smaller glare angles were mounted on the sign-support panel, 0.43 and 1.14 m below the center of the letter E. The lamp at 1.5° was mounted on a tripod at the same height as the letter E but was displaced 3.2 m laterally.)

2.3.1.4 Subjects. Three subjects participated. Some of their characteristics are listed in Table 2-4.

Table 2-4

SUBJECT CHARACTERISTICS

SUBJECT	AGE	SEX	VISUAL ACUITY				COLOR VISION
			HL HC	HL LC	LL HC	LL LC	
1	19	F	20/10	20/16	20/22	20/40	Normal
2	21	M	20/10	20/20	20/25	20/50	Normal
3	27	M	20/14	20/25	20/22	20/60	Normal

Note: HL - High Luminance (161 cd/m^2)
LL - Low Luminance (0.2 cd/m^2)
HC - High Contrast (22.5:1)
LC - Low Contrast (1.3:1)

2.3.1.5 Facility. The test was conducted on a dark, private-access road. The road has two asphalt lanes, is 800 m long, and is flat and straight. Two signs were set up at the edge of the paved surface, facing in opposite directions, 400 m away from the ends of the road.

2.3.1.6 Procedure. Each run was started with the test vehicle at one end of the road. The driver proceeded in the right lane (at a speed of approximately 24 km/h) passing the sign placed on the right, then continued to the end of the road, turned around, and started the next run. The 40 experimental trials (10 replications per each glare angle and the no-glare condition) took about 1 1/4 hours to complete.

2.3.2 Results

The mean legibility distances for the various glare conditions are presented in Table 2-5.

Analysis of variance revealed that the effect of glare angle (treating the no-glare condition as a glare angle of infinity) was statistically significant, $F(3,6) = 8.42$, $p < .05$. *Post hoc* Newman-Keuls range tests showed that the legibility distance for the smallest glare angle (.2°) was significantly different from each of the other glare conditions ($p < .05$). However, no other pairwise differences were statistically significant. (The other statistically significant main effect and interaction in the analysis involved subjects as a factor.)

Table 2-5

MEAN LEGIBILITY DISTANCES AS A FUNCTION OF GLARE ANGLE

GLARE ANGLE	LEGIBILITY DISTANCE (m)
0.2°	96.1
0.6°	122.9
1.5°	117.9
(No Glare)	119.3

2.3.3 Discussion

The main finding of this experiment is that the detrimental effects of a .0098 lux glare (equivalent to the glare provided by low beams at about 400 m) are present only at very small angular separations between the legibility target and the glare source: The glare-angle conditions of .6° and 1.5° did not yield different legibility distances than the no-glare condition. Only at the glare-angle of .2° was there a statistically significant reduction in legibility distance.

The conditions in this experiment did not result in the "glare enhancement" evident in the findings of Experiment 1. While one can only speculate about the reasons for this difference, the following is a possible explanation: The effect of a given glare source on a dark-adapted observer is dependent on the angular separation of the glare source from the legend. At very small glare angles (.2° under the conditions of Experiment 2), the effect is negative, yielding the traditional disability-glare findings. At larger glare angles (.5° and 1.5° under the conditions of Experiment 2), the negative consequences (light scatter and veiling luminance) and positive consequences (reduced pupil size) balance out. At even larger glare angles (2° under the conditions of Experiment 1), the positive consequences might more than compensate for the negative consequences, resulting in the "glare-enhancement" effect.

3.0 THE SIGN AS A GLARE SOURCE

3.1 Method

In this phase of the project, laboratory data were collected to assess the effect of glare on the luminance required to maintain threshold detectability of a low contrast object. This was intended to address the question of whether there should be an upper limit to sign luminance; that is, a point were a sign begins to interfere with part of the basic visual task of a motorist.

3.1.1 Variables. Disability glare has been shown to be a function of glare illuminance (measured at the observer's eye in units such as lux), and angle from the point of regard (e.g., Fry, 1954). Thus, these were the variables considered in this study.

3.1.1.1 Glare illuminance. Five levels of glare were utilized. Measured at the subject's eye, these were:

1. 0.904 lux (0.084 ft-c)

2. 0.101 lux (0.0094 ft-c)

3. 0.0104 lux (0.00097 ft-c)

4. 0.0012 lux (0.00011 ft-c)

5. No glare

(Note: Examples of glare illuminance from signs under various conditions are provided in Table 3-3.)

The glare source was circular and subtended an angle of 1.15° at the observer's eye.

3.1.1.2 Glare angle. The glare angle was measured from the center of the target disc (which was 0.15° in diameter) to the nearest edge of the glare source. It should be noted that this is a departure from the usual way in which glare angles are measured in disability glare research (i.e., from the center of the glare source [e.g., Schober, 1967]). This was done in order to relate the results to the real-world situation of interest.

The angles tested were:

1. 0.25°

2. 0.75°

3. 1.5°

4. 3.0°

5. 5.0°

Data at 5° were taken only with the two highest glare illuminance levels.

3.1.1.3 Subjects. Five subjects participated in the study. All were young (18-25). They were part of the group screened using the procedure described in Appendix A, and were selected to be as homogeneous as possible on the low luminance variables. Their visual characteristics are listed in Table 3-1.

Table 3-1

SUBJECT CHARACTERISTICS

SUBJECT	AGE	SEX	VISUAL ACUITY				COLOR VISION
			HL HC	HL HC	LL HC	LL LL	
1	21	M	20/25	20/35	20/35	20/100	Normal
2	21	F	20/18	20/25	20/27	20/60	Normal
3	21	M	20/22	20/35	20/60	20/100	Normal
4	27	M	20/14	20/25	20/22	20/60	Normal
5	20	M	20/18	20/20	20/25	20/60	Normal

Note: HL - High Luminance (161 cd/m^2)
LL - Low Luminance (0.2 cd/m^2)
HC - High Contrast (22.5:1)
LC - Low Contrast (1.3:1)

3.1.1.4 Surround luminance. It was intended that the study include two levels of surround luminance, 0.034 cd/m^2 (0.01 ft-L) and 10.28 cd/m^2 (3.0 ft-L), to simulate two types of driving environment (Woltman and Youngblood, 1976). Lamps were placed behind the equipment to illuminate the back wall of the laboratory to the desired levels. However, data from a pilot subject were identical under the two lighting conditions. As a result, all data were taken under the lower level (0.034 cd/m^2) surround condition.

3.1.2 Equipment. A schematic of the equipment layout is provided in Figure 3-1. The glare source (A) was a 15-cm disc of white encapsulated-lens signing material. It was mounted on a background (B), which was covered with a black fabric. The disc was illuminated by a projector (P_1). The beam from P_1 was constrained by an aperture mounted behind the slide position so that it was just large enough to cover A. The beam from P_1 was reflected from a first surface mirror placed in front of the subject's eyes at C and directed toward A. The luminance of A was controlled by neutral density filters in P_1.

The luminance of the target disc (D) was controlled by another projector, P_2. The beam from P_2 was reflected by the mirror E and into the box at F. This is the sign simulator box used in the legibility study described in Section 1.0.

Target D was made of black, enclosed-lens retroreflective material. The beam from P_2 passed through the piece of glass (G), was retroreflected by D, and returned toward the projector. About 8% of this illuminance was reflected by G and directed toward the subject behind C.

The arrangement using the sign box was necessary in order to minimize the effect of stray light from P_1. Without it, the stray light was sufficient to make D always visible, except at the largest angles. The effect of the box was to reduce the additive luminance from P_1 onto D to less than 1/100th of what had been measured initially. There was still significant luminance contributed to D by P_1. Prior to the study, comprehensive photometric measurements were made so that the actual luminance of D was known for all conditions. A listing of the available luminance levels of D under no glare conditions is provided in Table 3-2.

Figure 3-2 is a close-up photograph of the sign box with the glare disc in position. The target disc, which is not visible in this picture, appeared midway between the vertical white lines on the box. Figure 3-3 shows how the equipment appeared to the subject. Figure 3-4 is a photograph of the area occupied by the experimenter (behind the table to the left) and the subject (behind the mirror at the top right). Projector P_2 is visible on the table. P_1 is under the box to the right of P_2.

3.1.3 Procedure. Subjects were run individually. When each reported to the laboratory, he/she was seated at the subject's station and the seat and chin rest adjusted so that their eyes were in the desired location relative to the top of the mirror (C in Figure 3-1). The instructions were read, any questions answered, and the laboratory lights extinguished to start the dark adaptation period.

During the time allotted for dark adaptation (ten minutes), a series of practice trials was given, to ensure

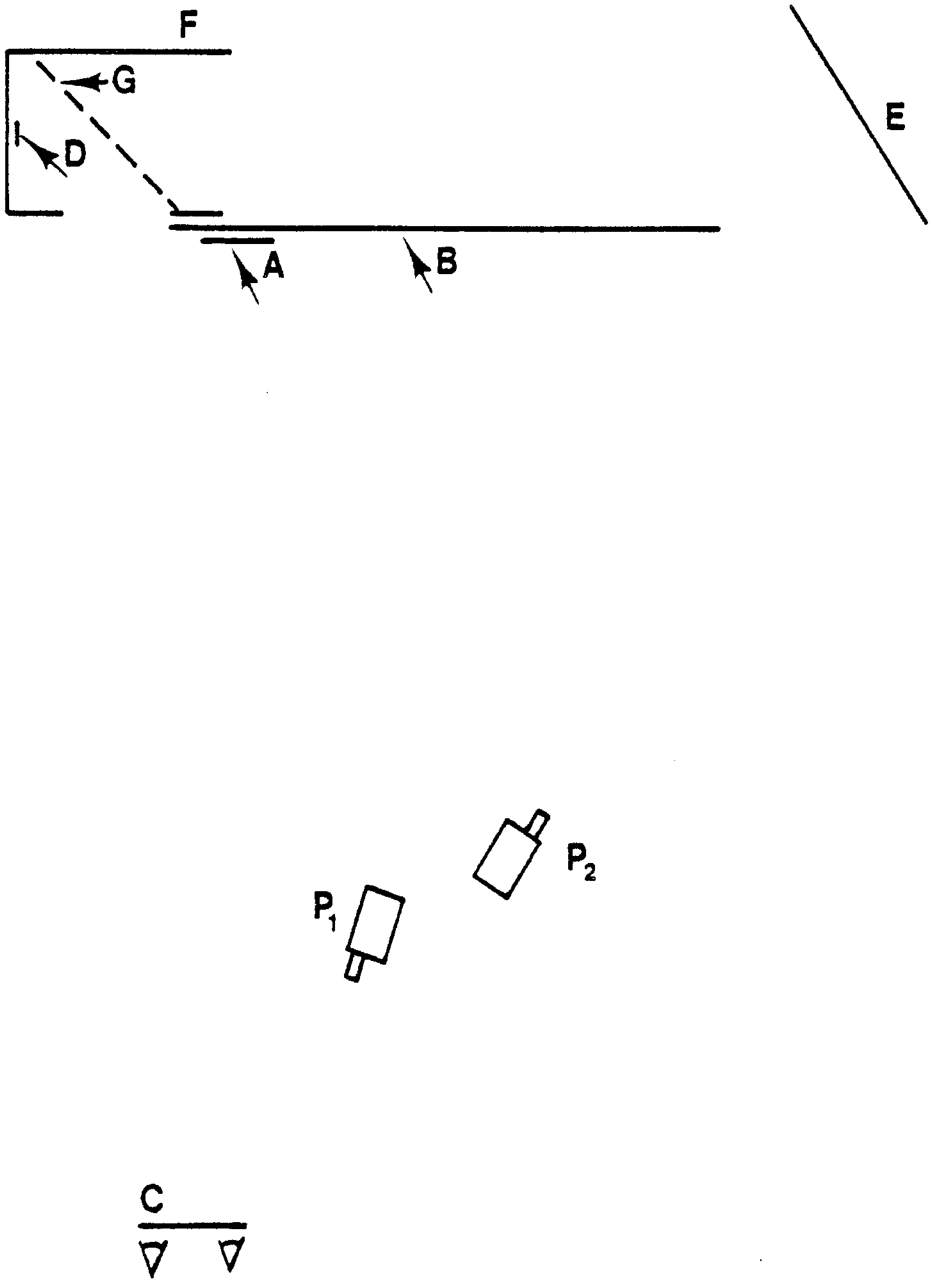


Figure 3-1. Schematic of laboratory set up.

Table 3-2

NO GLARE LUMINANCE VALUES OF TARGET DISC AVAILABLE WITH TEST EQUIPMENT

FILTER NUMBER	TARGET DISC LUMINANCE	
	cd/m^2	ft-L
No Filter	2.06	0.60
1	1.58	0.46
2	0.93	0.27
3	0.66	0.192
4	0.514	0.150
5	0.387	0.113
6	0.147	0.043
7	0.092	0.0268
8	0.062	0.0182
9	0.052	0.0153
10	0.0302	0.0088
11	0.0151	0.0044
12	0.0075	0.0022
13	0.0055	0.0016
14	0.0041	0.0012
15	0.0033	0.00096
16	0.0018	0.00054
17	0.00075	0.00022

that the subject fully understood the task requirements. At the conclusion of this period data trials commenced.

At the start of each series of trials, glare angle and illuminance levels were selected and the glare projector switched on. It remained on during the trial series. To initiate a trial the experimenter pressed a button. A tone sounded to alert the subject. Two seconds later the shutter on the target disc projector (P_2 in Figure 3-1) opened for one second. When it closed the subject was required to indicate, by pressing a button near his/her right hand, whether the target had been seen or not.

Data were taken using the "staircase" method (Dixon and Massey, 1969). That is, the luminance of the target disc was increased on trial n+1 if the subject reported "not seen" on trial n, or decreased if the subject reported "seen." In accordance with accepted practice, two staircase sequences were run simultaneously for each condition, the experimenter choosing the sequence for each trial on a random basis. This approach reduces the likelihood of the

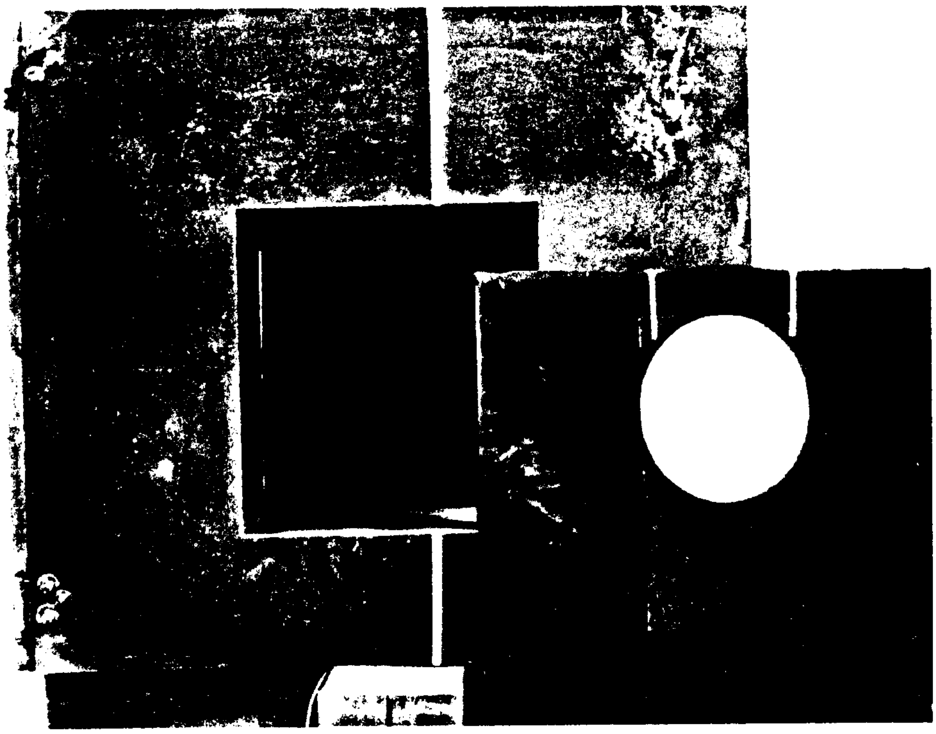
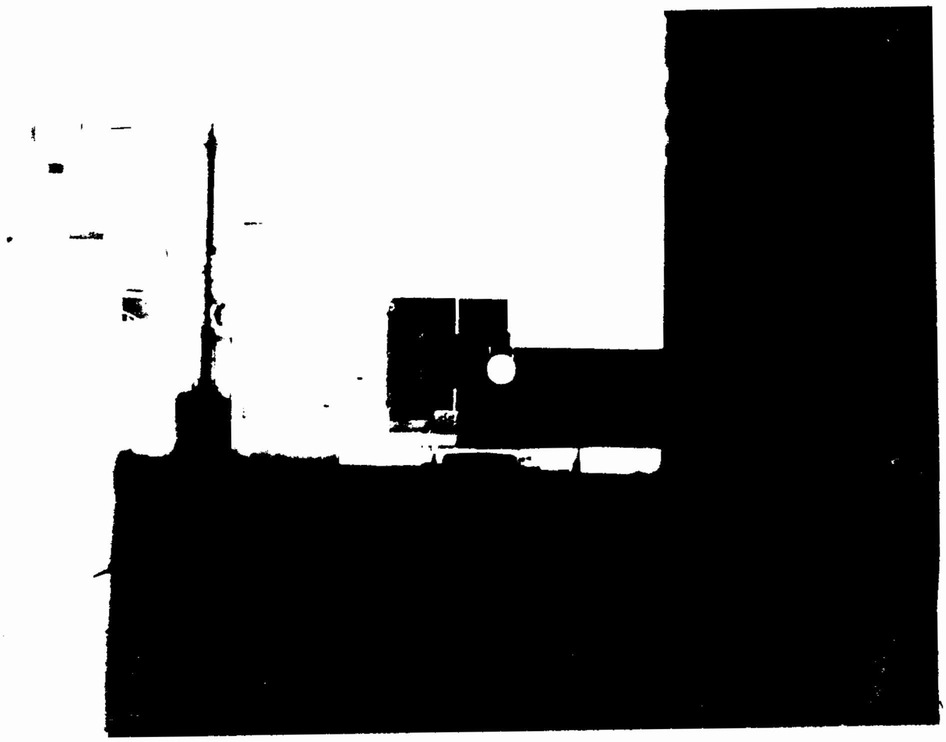


Figure 3-2. Close-up photograph of glare source (disc on right), and box which presented target disc.



Figue 3-3. Subject's eye view of test equipment.

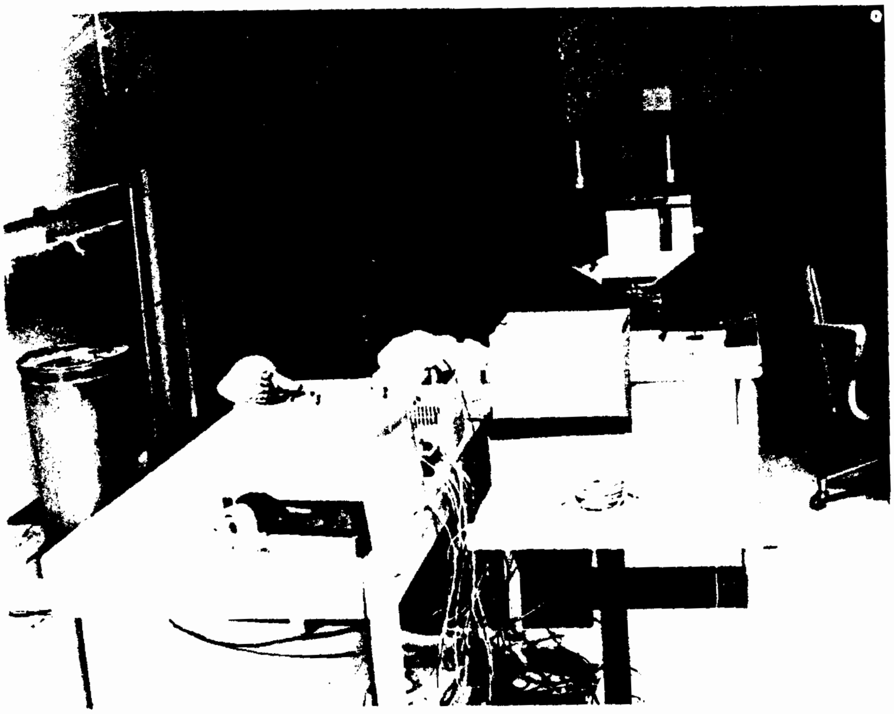


Figure 3-4. Photograph of experimenter's table (on left) and subject's station (behind mirror at right). Task projector (P_2) is visible at left, glare projector (P_1) is facing in opposite directions under box to the right of P_2.

subject becoming aware of the strategy being used by the experimenter.

Each series of trials always started with the presentation of a clearly visible target disc and continued as required by the method just described to the end of the prepared sequence.

Figure 3-5 is a reproduction of one of the score sheets used in the study. It is for subject number 1, a glare angle of 0.25° and a glare illuminance of 0.0322 cd/m^2. The numbers 0 through 20 represent neutral density filter slides, as described in Table 3-2. In this particular case, the first staircase sequence (left side) started with three "seen" responses (X's) before a "not seen" response was obtained on level 8. The second staircase sequence started with six "not seen" responses before a "seen" response was obtained at level 6. The percent of "seen" responses is determined for each level and the threshold (50%) point determined by interpolation. In this case the threshold lies between levels 7 and 8. For this combination of independent variables level 7 equals 0.230 cd/m^2 and level 8 equals 0.199 cd/m^2. The threshold was calculated as 0.223 cd/m^2.

Typically, about 40 individual trials were collected on each subject for each combination of glare intensity and angle. This took about five minutes. The subject was then given a short break while the experimenter set up for the next condition. The entire series required about 2.5 to 3 hours to complete.

3.2 Results and Conclusions

Figure 3-6 summarizes the results of this study. The figure shows the mean target disc luminance required to produce a threshold response at each of the levels of glare illuminance and angle tested. The no glare threshold is shown as well (dark horizontal line near the bottom of the figure). The smooth curves are visual best fits as determined by the authors.

The major question to be addressed is the implication of this study for signs. The illumination (in lux) produced by a sign at the eye of an observer can be calculated using the following equation:

$$I = LA/d^2$$

where:

L = average luminance of the sign in cd/m^2

A = area of the sign in square meters

SUBJECT # 1

SURROUND ____________

GLARE:

ANGLE 0.25

INTENSITY 2

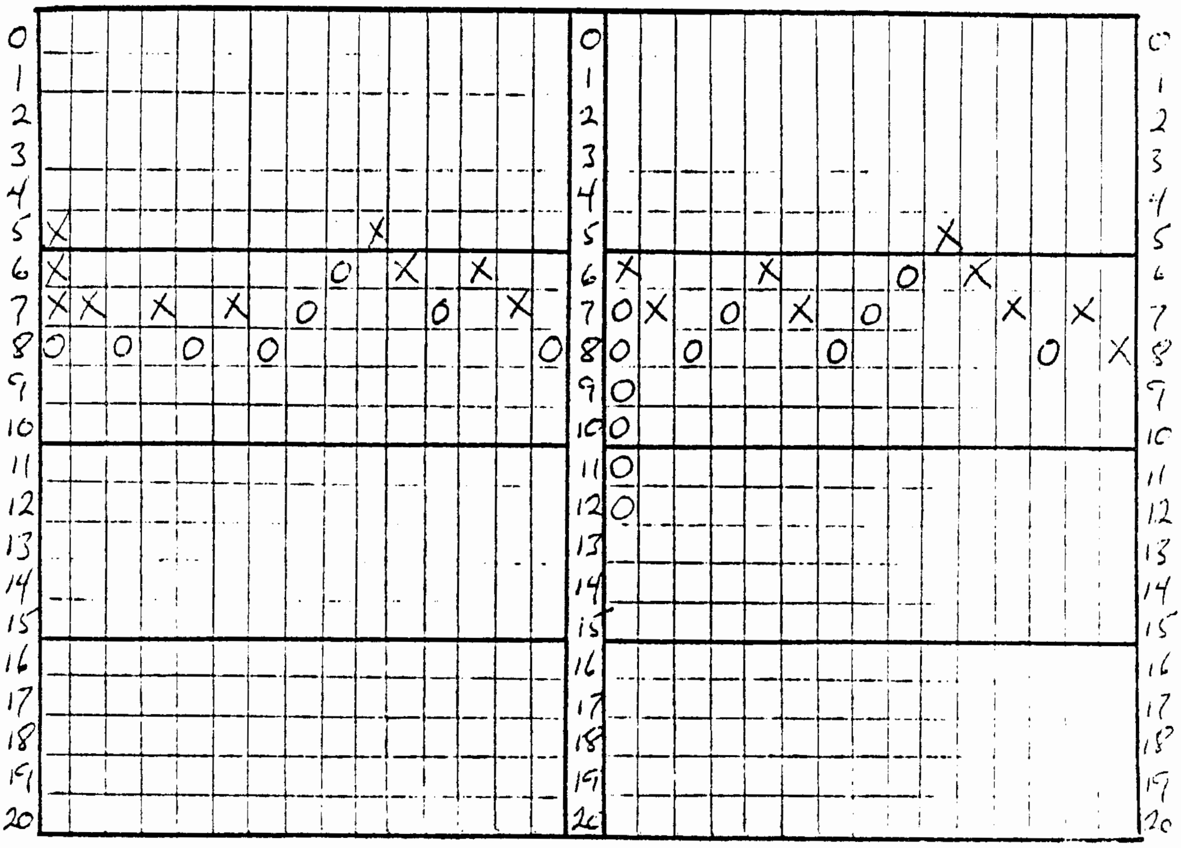


Figure 3-5. Reproduction of subject score sheet.

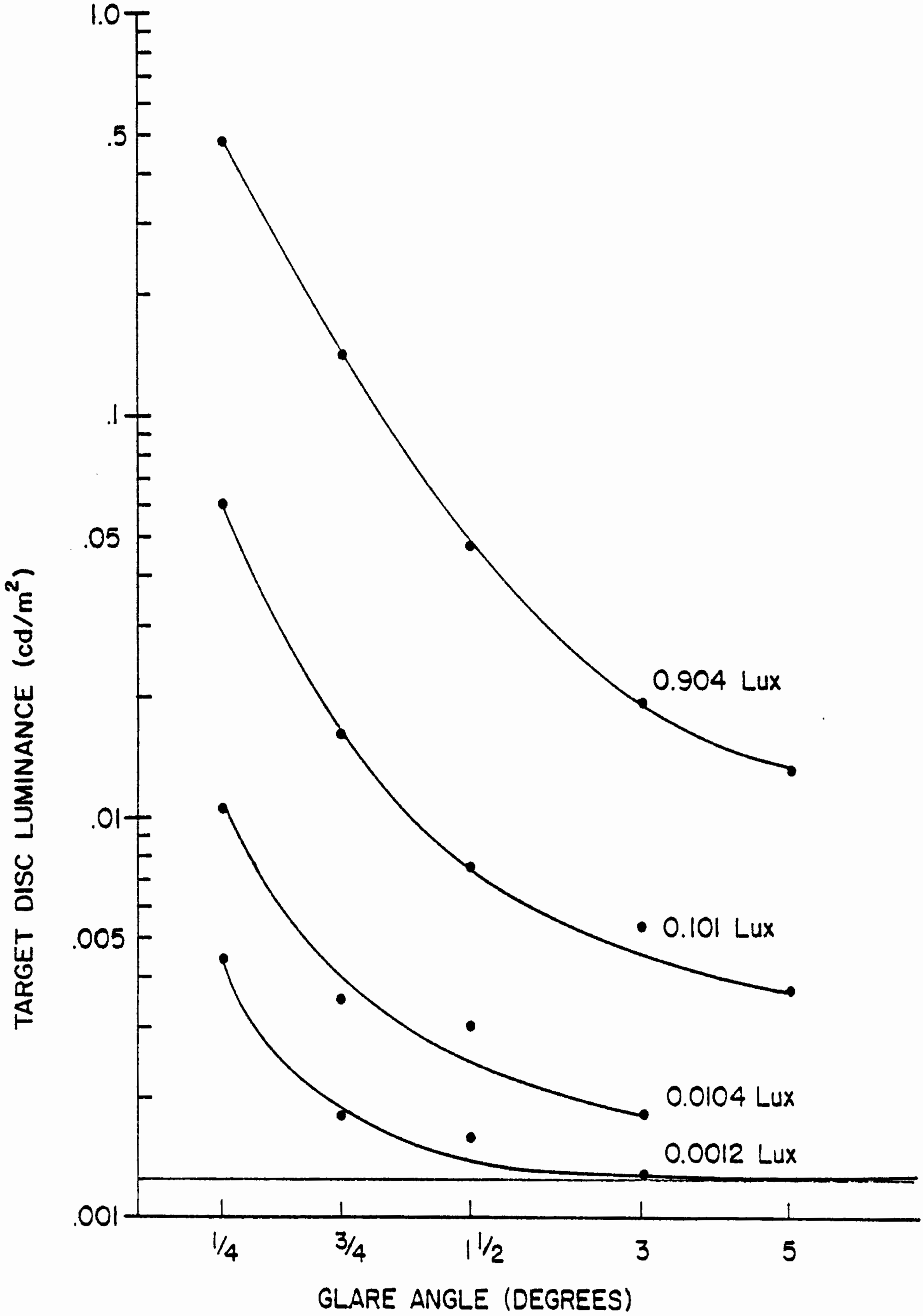


Figure 3-6. Threshold detection levels of target disc as a function of four levels of glare and five glare angles.

d = distance from the observer to the sign in meters.

Table 3-3 was prepared to provide examples of glare from three typical signing situations. It suggests, for example, that a large, fairly bright overhead guide sign would provide a very small disability glare effect if placed in a dark environment. On the other hand, the smaller ground mount would not produce any significant glare effect.

Certain classes of signs, warning and regulatory for example, are normally placed much closer to the roadway. Further, to enhance their attention-getting characteristics, high luminance levels are desirable. Construction zone warning signs, for example, are often placed in the roadway and the combination of efficient retroreflective materials and proximity to the headlamp beam can result in high luminance levels. Thus, for example, the warning sign in Table 3-3 has 1/32nd the area of the overhead guide sign, but the combination of higher luminance and smaller angle make it a more significant glare source. For example, the data suggest that the luminance of a low contrast object two meters from the edge of the sign would have to be approximately doubled to make up for the glare of the sign. In the real world this would be accomplished by decreasing the distance between the car and the object. Thus, if an object would have been detected at 100 meters under normal conditions the data suggest that it will be detected at about 70 meters with the sign present. This is an appreciable loss in visibility distance, and implies that signs and other construction zone warning devices must be placed to guide traffic clear of any potential conflicts in the zone.

The brightest signs in the highway environment are typically for advertising purposes. The last example in Table 3-3 is for a modest size but bright advertising sign. For the condition shown, the luminance of a target object would have to be increased by a factor of about ten to make up for the glare produced by the sign.

The results of this study suggest that highway signs at the highest luminance levels typically found normally do not constitute a significant glare source to drivers, even in very dark surroundings. Indeed, luminance levels could be substantially upgraded in many cases with no harm done. However, care must be exercised in dealing with very large signs or signs which must be placed very close to the path of the vehicle.

Only at luminance levels achieved by some internally illuminated signs is significant impairment possible. It

TABLE 3-3

EXAMPLES OF GLARE PRODUCED BY TYPICAL SIGNS

SIGN	SIZE IN (meters)	DISTANCE FROM OBJECTS OF CONCERN (meters)	AVERAGE LUMINANCE (cd/m^2)	VIEWING DISTANCE (meters)	GLARE ANGLE (degrees)	GLARE INTENSITY (lux)
Overhead guide	4x8	6	4	300	1.15	0.0014
				200	1.72	0.0032
				100	3.44	0.0128
Ground Mount Guide	3x4	10	4	300	1.91	0.00053
				200	2.86	0.0012
				100	5.73	0.0048
Warning	1x1	2	35	300	0.38	0.00039
				200	0.57	0.00088
				100	1.15	0.0035
Internally Illuminated Advertising Sign	3x4	10	350	300	1.91	0.467
				200	2.86	1.05
				100	5.73	4.2

Note: These calculations ignore losses due to atmospheric and windshield transmissivity.

appears there may be merit in controlling the installation of such signs.

4.0 SIGN MODEL VALIDATION

4.1 Introduction

The computer model developed as part of this project was designed to predict sign legibility distance for a variety of conditions. In this portion of the report we will describe the validation of this model.

The most comprehensive data set on sign legibility known to us is that produced by Olson and Bernstein (1977). In that study sign luminance and contrast were varied over a broad range by altering several parameters. These data were selected as a basis for the validation process.

4.2 Method

The Olson and Bernstein study was carried out on a straight, flat private road, using small (0.9 x 0.9 m) signs set close to the edge of the road. The criteria was the distance from the sign at which subjects could determine the orientation of a letter E (Ǝ or E). The independent variables were:

1. Sign background specific luminance, three levels: non-retroreflective, 10 and 30 cd/lux/m^2.

2. Legend specific luminance, four levels: buttons (assumed 600 cd/lux/m^2), 250, 70 and 45 cd/lux/m^2.

3. Legend size, three levels: 15.2, 25.4, and 38.1 cm.

4. Headlamp beam, two levels: low and high.

Not all possible combinations of these variables were tested. A total of 48 combinations were included, selected to provide a maximum range of luminance and contrast.

Eighteen subjects participated in the study. Their ages ranged from 18 to 35. All were subjected to a vision test prior to the study to be sure they fell within normal ranges.

4.3 Results and Discussion

The basic results of this study are shown in Table 4-1. This table lists all of the material combinations tested and the mean legibility distances recorded compared with those predicted by the model.

TABLE 4-1

VALIDATION RESULTS

Specific Luminance cd/lux/m^2		Legend Size (cm)	Low Beam Legibility Dist. (m)		High Beam Legibility Dist. (m)	
Bkgrnd	Legend		Measured	Predicted	Measured	Predicted
30	600	15	129	118	131	115
30	600	25	188	195	196	194
30	600	38	275	288	270	294
30	250	15	121	116	124	116
30	250	25	201	191	198	196
30	250	38	266	280	258	295
30	70	15	108	105	112	109
30	70	25	160	170	176	182
30	70	38	212	246	235	272
30	45	15	102	98	114	104
30	45	25	159	159	157	173
30	45	38	198	228	209	258
10	600	15	124	113	123	112
10	600	25	177	186	169	185
10	600	38	255	273	250	281
10	45	15	115	109	119	115
10	45	25	172	174	198	191
10	45	38	223	251	255	285
NR	600	15	96	97	82	66
NR	600	25	149	167	116	111
NR	600	38	262	258	202	187
NR	45	15	112	104	100	95
NR	45	25	171	171	176	164
NR	45	38	233	250	274	253

Figure 4-1 is a plot of the validation data. The product-moment correlation between the obtained data and the model prediction is r = .98.

An examination of Figure 4-1 reveals that the data break into three clusters. In most cases, these are associated with the three letter sizes. The model tends to overpredict at the greater distances and there appears to be more scatter in that area as well. However, when using linear scales, constant percentage variance will produce an illusion of greater scatter because actual variance increases as the means increase. The important point is that the very high correlation achieved indicates that the model is sensitive to differences in conditions and ranks them appropriately.

The results of this study indicate that the computer model has the ability to predict sign legibility to a useful degree of accuracy.

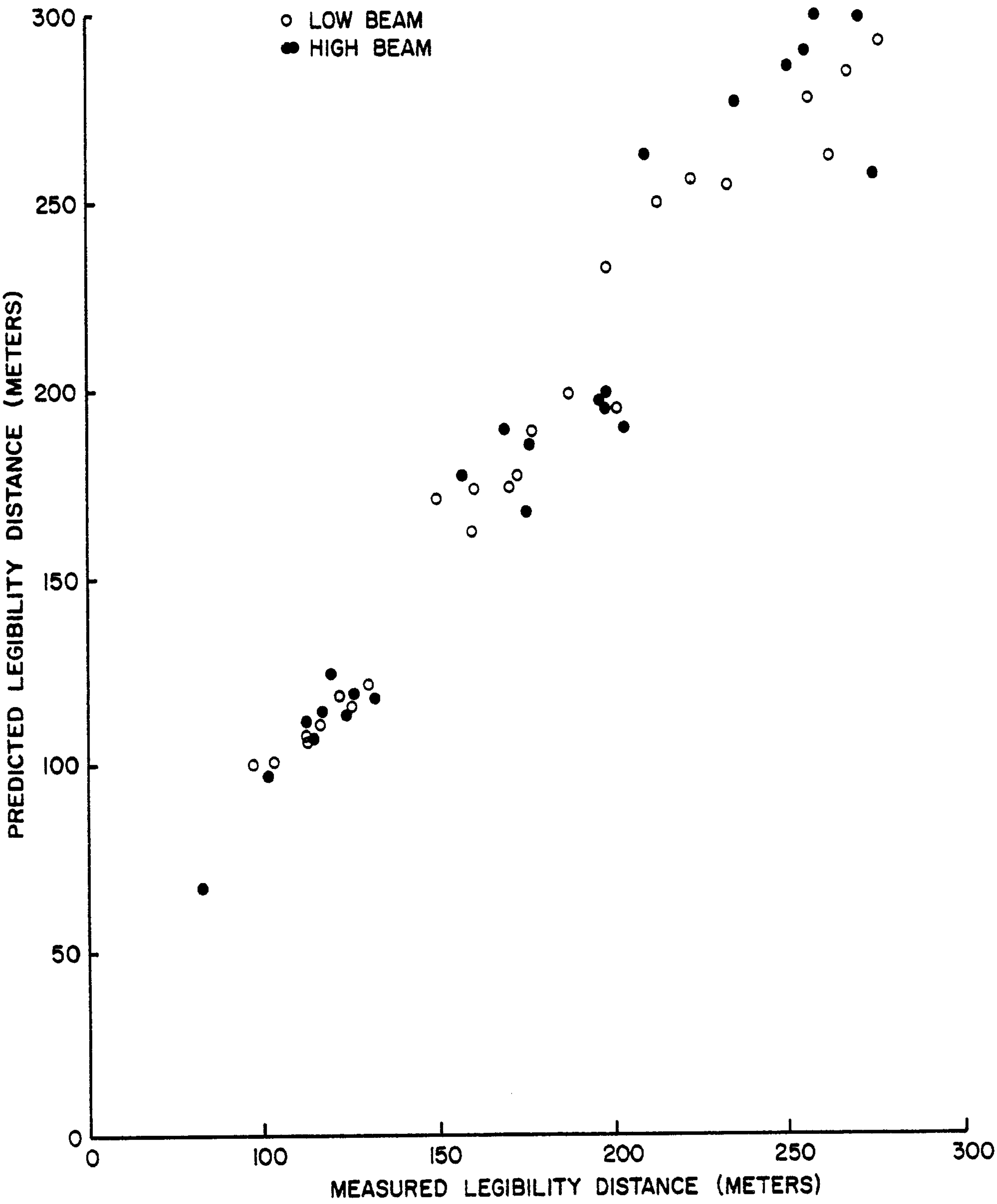


Figure 4-1. Model validation study. The relationship between measured and predicted legibility distance.

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APPENDIX A

Subject Screening Procedures

Subject screening for studies of this type has typically been rather casual, usually consisting of no more than simple far acuity at high luminance levels.

Given the complexity of this study, the fact that it was possible to use only a limited number of subjects, and the desire to more fully understand age effects in night driving, a more comprehensive visual screening was thought appropriate.

A nine-part test was put together for the screening process. The first five tests were given using a Titmus Tester. The Titmus is a compact vision tester commonly used in schools, industry, and driver licensing. The last four tests were for high and low luminance, high and low contrast visual acuity and were prepared by the project staff.

A screening form was prepared as illustrated in Figure A-1. The first page provided some general background to the potential subject and collected some basic information.

The reverse of the screening form provided a score sheet for each of the vision tests. First is the far acuity test, followed by stereo depth (SD), color (C), and vertical and lateral phoria (V and L), all from the Titmus test.

The last four tests were prepared using Landolt rings on 35-mm slides. These slides were then projected on a white paper background at a distance of 7.6 meters from the subject. The ring gap could appear in any of eight positions.

"High luminance" means the white background against which the rings were seen was 162 cd/m^2. Room lights were on; the wall on which the screen was mounted was illuminated to 115 cd/m^2. "Low luminance" means the background was 0.22 cd/m^2. Room lights were off; no reading could be taken from the wall. High contrast (HC) was 22.5:1, low contrast (LC) was 1.3:1. It should be noted that the high luminance, high contrast test was intended to be comparable to the Titmus acuity test and was used primarily to ensure a proper frame of reference.

The two high luminance tests were given first, just after the Titmus series. The low luminance tests followed after a dark adaptation period of about ten minutes.

A total of 53 young and 39 older persons were screened. All those having visual problems (e.g., color deficiency) or falling outside a range of 20/15 to 20/25 high luminance, high contrast far acuity were eliminated. Invitations to participate were then issued in an effort to build groups as similar and homogeneous as possible. Table A-1 lists the characteristics of the subjects who completed the testing

SUBJECT SCREENING FORM - SIGN GLARE STUDY

This summer we will be carrying out several studies relating to nighttime sign reading. These will be laboratory investigations and will be conducted here at HSRI. A great deal of data will be taken with each subject, so it will be necessary for those who participate to return a number of times. These appearances will be scheduled at the convenience of the subject. Pay rate is $2.50/hr. Payment will be made when each person's participation is ended.

Please provide the information requested below. You will be given a brief vision test today for which you will be paid $2. We will contact you later about participating in the studies.

- -

(Please print)

Name: ______________________________ Date of Birth: ___________

Sex: M F Do you have a drivers license? Y N

If yes, for how many years? _____________

Do you wear glasses or contact lenses? (please circle one option below)

always never sometimes (please explain below)

____

Would you prefer to participate in mornings or afternoons? __________

Best days to participate are (circle): M T W Th F

Telephone number(s) where you can usually be reached: _____________

Best time(s) to call? ____

Figure A-1.

	TITMUS							Hi Lum.		Lo Lum.	
	Far Acuity		SD	C	V	L		HC	LC	HC	LC
1	20/200	T	B	12	1	1	20/125	BR	T	TR	B
2	20/100	R	L	5	2	2	20/100	BL	TL	TL	BL
3	20/70	R	B	26	3	3	20/80	TR	R	BR	R
4	20/50	L	T	6	4	4	20/60	BL	B	TL	T
5	20/40	T	T	16	5	5	20/50	L	TR	L	BR
6	20/35	B	L	B	6	6	20/40	TL	R	BL	R
7	20/30	L	R		7	7	20/35	T	BL	B	TL
8	20/25	R	L			8	20/30	L	BR	L	TR
9	20/22	L	R			9	20/27	T	TR	B	BR
10	20/20	B				10	20/25	L	B	L	T
11	20/18	R				11	20/22	BL	BR	TL	TR
12	20/17	B				12	20/20	TL	TL	BL	BL
13	20/15	T				13	20/18	BL	L	TL	L
14	20/13	R				14	20/16	TR	R	BR	R
						15	20/14	T	L	B	L
							20/12	TL	TR	TL	TR
							20/10	BR	BR	BR	BR

Figure A-1 (continued).

program. It will be noted that the two age groups compare well on all measures except low contrast acuity.

TABLE A-1

Listing of Subject Characteristics for Sign Legibility Study.

SUBJECT	SEX	AGE	GLASSES	DRIVING YEARS	TITMUS					35 mm SLIDES			
										HIGH ILLUM. Contrast:		LOW ILLUM. Contrast:	
					PAR 20/	COLOR	STEREO 9*	VERT. PHORIA 4*	LAT. PHORIA 8*	HIGH 20/	LOW 20/	HIGH 20/	LOW 20/
1	M	24	Yes	8	17	OK	9	4	10	18	30	27	60
2	M	25	No	9	15	OK	5	4	9	16	27	25	50
3	F	24	Yes	8	25	OK	9	4	10	22	27	30	50
4	M	24	Yes	7	18	OK	4	4	9	14	25	25	80
5	M	22	Yes	5	22	OK	7	4	10	22	40	80	80
6	M	67	Yes	40	18	OK	1	5	4	22	30	40	125
7	F	69	Yes	50	20	OK	3	4	9	22	60	60	125
8	F	69	Yes	45	18	OK	9	3	8	16	40	30	80
9	M	73	Yes	50	17	OK	9	4	9	25	27	50	100
10	M	64	Yes	46	20	OK	9	5	10	20	30	40	50

* "Best" score.

APPENDIX B

Obtained Contrast Ratios

Illumination from the legend projector contributed to the background luminance. Thus, the realized contrast ratio was:

$$CR = \frac{L}{B'},$$

where

L = legend

B' = background + K (legend)

CR = contrast ratio

Measurements of K indicated that it was slightly more than .4% (less than the .6% estimate referred to in Section 1.1.2). Thus, we have:

$$CR = \frac{L}{B + .004\ L}$$

observe that:

$$\lim_{L \to \infty} \frac{L}{B + .004\ L} = \frac{1}{.004} = 250:1$$

In reality, the maximum CR was about 215:1.

Note that the plots presented in the results section reflect performance within the range of legend luminances not causing B' to differ from B by more than a factor of 2. Estimations of higher contrast ratios for the intended background values must be made by extrapolation.

For the model, the extrapolations were supplemented in the following manner:

1) For 0.05 cd/m^2 background estimate with black background performance at L = 300 - 600 cd/m^2.

2) For 0.41 cd/m^2 background estimate 200:1 CR by using data from 0.05 cd/m^2 background with L = 60 (then B' = 0.05 + 0.5, 20:.1 = 200:1).

3) For 3.82 cd/m^2 background similarly estimate with 0.5 cd/m^2 background at L = 600.

4) For 34 cd/m^2 background extrapolate with decline pattern for 0.05 to 3.82.