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Some Psychophysical Tests of the Conspicuities of Emergency Vehicle Warning Lights

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U.S. DEPARTMENT OF
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FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards (NBS) furnishes technical support to the National Institute of Law Enforcement and Criminal Justice (NILECJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

LESL is: (1) Subjecting existing equipment to laboratory testing and evaluation and (2) conducting research leading to the development of several series of documents, including national voluntary equipment standards, user guides, and technical reports.

This document is a law enforcement equipment report developed by LESL under the sponsorship of NILECJ. Additional reports as well as other documents are being issued under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles and clothing.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the author or to the Law Enforcement Standards Laboratory, National Bureau of Standards, Washington, D.C. 20234.

Jacob J. Diamond, *Chief*
Law Enforcement Standards Laboratory

CONTENTS

SOME PSYCHOPHYSICAL TESTS OF THE CONSPICUITIES OF EMERGENCY VEHICLE WARNING LIGHTS

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This is a report of some exploratory studies aimed at evaluating the conspicuities (attention-attracting powers) of a group of commercial warning lights meant for use on emergency vehicles. The main experiment used a novel technique of conspicuity matching. Each observer, in turn, fixated straight ahead and viewed two flashing lights peripherally, one located 20° to the left of the fixation point, and one 20° to the right. One of the two lights was always a reference light whose intensity could be adjusted by the observer until the two lights appeared equally conspicuous. All the lights were thereby ranked on a single scale of conspicuity, based on the adjustable-light intensities. There was a good correlation (r=0.90) between these ranks and the measured effective intensities of the lights. Another, very brief, pilot experiment ranked some of the lights according to the number of degrees into the left side of the visual field that the flashes could still be seen. This disappearance-angle rank also correlated well (r=0.86) with conspicuity rank. Problems encountered and suggestions for future improvements are discussed.

Key words: Color, lights; conspicuity, lights; effective intensity; emergency lights; intensity, effective; lights, flashing; lights, warning; perception, visual; peripheral vision; vehicles, emergency; visibility, lights; visual perception.

1. INTRODUCTION

This report results from a project on emergency vehicle warning lights which included the physical measurement (photometry) of the intensities of some of the lights, psychophysical (perceptual) tests of some of the lights for conspicuity (attention-attracting power), and the writing of several reports [6,8,10].[1]

This report summarizes the conspicuity studies and relates the results of the psychophysical tests to the physical measurements on the lights.

The experiment was a pilot study. The procedure used contained some novel features, and a primary purpose of this report is to discuss the methodology and its potential for further refinement. Although the experimental data are flawed, as will be discussed later, there were nevertheless clear indications of the reliability of the basic method, and good agreement of the data with some other measures, both physical and psychophysical. This is a progress report and is being issued at this time because there is no present assurance that this research will be continued.

The basic function of an emergency vehicle warning light (EVWL) is to attract attention. The light must serve this function under conditions that are frequently visually and cognitively complex, as well as dynamically changing. The ultimate test of the effectiveness of an EVWL is how well it performs under real-life conditions in alerting drivers well in advance that an emergency vehicle is approaching. The impracticality of testing every light through actual use makes it desirable to develop a simplified perceptual test that can be shown to correlate well with in-service effectiveness. However, the development of a realistic and reliable measure of effectiveness under actual operating conditions would itself be a formidable undertaking, which has not yet been accomplished. In the meantime, it is important to derive perceptual measures that appear likely to be good guides to operational effectiveness.

It has been known for a long time that the key variable in determining the distance at which a flashing light can be seen is its effective intensity. Most of the published data on the visibility of flashing lights were obtained in the contexts of maritime and aviation signaling. In these situations, the signal light is often seen against a largely or entirely dark background, and

[1] Numbers in brackets refer to the references given on page 18.

frequently the observer knows the approximate direction in which the light will appear. When ground-vehicle emergency warning lights are used, the background is often filled with a variety of other lights, and the observer rarely knows where or when the signal will appear. It was plausible that effective intensity might be the dominant factor in determining conspicuity under these conditions, too, but it was not known quantitatively how well effective intensity would correlate with conspicuity, or how much influence other factors would have. Thus, a test that had a reasonable chance of being correlated with on-the-road conspicuity was formulated and then applied to a selection of actual EVWLs.

In an ideal multivariate experimental design, each separate variable is assigned a set of values that span the range of interest for that variable. Then, all possible combinations of the values of all the variables are tested (factorial designs), or else some systematically chosen subset of all these combinations is examined (as in Latin-square designs). In experimentation on warning lights, the relevant physical variables include effective intensity, color, flash rate, and flash duration or duty cycle.

Any set of commercial EVWLs represents a nonsystematic sampling of the possible combinations of values of these variables. Moreover, some of the variables (such as the flash rate) cover a range of values too narrow to permit exploration of the effects of those variables. We assumed that, in our experiment, the contributions to conspicuity of all the physical variables other than effective intensity would be of a lower order of magnitude relative to the contribution of the effective intensity. Therefore, we anticipated that the influence of effective intensity would be revealed by the study, with all the other variables more or less "averaging out," or serving as statistical "noise" that would slightly mask the contribution of the effective intensity. No attempt was made to detect the influence of any of the other physical variables, with the exception of color, because of the combination of small effects and nonsystematic sampling of values. In the case of color, the availability of different colored domes and bulbs permitted a very limited systematic examination of this variable.

2. BASIC PHILOSOPHY OF THE TEST

Several approaches to the design of a psychophysical test (relating the psychological or perceptual variable of conspicuity to the values of physical parameters) have been discussed elsewhere [6]. A feasible approach for an initial study seemed to be some form of direct subjective rating of conspicuity. The basic assumption behind such a technique is that observers can estimate, from the appearance of a light in a simplified experimental situation, the conspicuity that the light would have under realistic conditions. In order to check this assumption, data would have to be taken on the same set of lights under both the experimental and realistic conditions, and no such study has ever been performed, to our knowledge.

Edwards [2] has demonstrated that whatever it is that observers may really be responding to when they are asked to judge conspicuity, at least they are able to make the judgments in a consistent manner and produce relatively smooth data. Edwards used a paired-comparisons design, in which the observers looked at two lights simultaneously and judged which was more conspicuous. From a large number of these judgments of relative conspicuity, quantitative measures of conspicuity for each light in the experiment could be derived by established computation procedures [5].

This sort of paired comparisons by simple choice is a very time-consuming design, because each light must be compared to a substantial fraction of all the other lights in order to derive a reliable set of quantitative ratings. No meaningful rating can be derived from any single comparison, and each of the many comparisons must be made by a large group of observers, or by a small group of observers making each comparison many times.

We used a different technique, in which each single judgment by one observer is already in quantitative form. This technique involves the use of an adjustable flashing light that the observer can vary continuously along some measurable dimension until it matches the particular light under test in perceived conspicuity. Each match setting then constitutes a scale value for the conspicuity of the matched light.

The setting of matches by a subject through manipulation of a continuous control is a classical psychophysical method, the "method of adjustment" [3]. Application of the method of adjustment to perceptual scaling is also well established, as in "cross-modality matching" [4]. However, we have been unable to locate any previous reference to the scaling of conspicuity by the method of adjustment.

The adjustable light provided in the experiment operated with all of its characteristics fixed except for its effective intensity, which could be continuously varied by means of an electrical control held in the observer's hand. Because the main concern with EVWLs is attracting the attention of drivers who are looking away from the light source, the experiment involved viewing the lights in the periphery of the visual field. The observer fixated his gaze directly ahead and saw in symmetrical peripheral positions the test light on one side and the adjustable reference light on the other. The observer then adjusted the intensity of the reference light until the two lights appeared to him to be attracting his attention equally strongly. The quantity recorded was an electrical measure that corresponded, in a fixed but nonlinear relationship, to the intensity of the light. In this way, the conspicuities of all the test lights, regardless of their individual characteristics, could be expressed on a single quantitative scale.

If there is a "true" quantitative scale of subjective conspicuity, with meaningful difference (interval) and ratio properties [11], our scale was in all probability related to it nonlinearly. With only a few exceptions, it is well established that almost any physical stimulus scale is nonlinearly related to the corresponding subjective (ratio) scale [12]. Our ratings do not allow us to say that light A has twice the conspicuity of light B; or that light C is more conspicuous than light D by an amount equal to the difference between the conspicuities of lights E and F. What we measured constitutes an ordinal scale of conspicuity. All we can say is that if light G has a higher rating on our scale than light H, then light G is more conspicuous than light H. In terms of the actual observations made by a given observer, what we are then asserting is as follows: if the observer had to set the intensity of the reference light higher in order to match light G in estimated conspicuity than he had to set the intensity to match light H's conspicuity, then it is reasonable to assume that light G is more conspicuous than light H.

The reasonableness of this assumption follows from the fact that the lights were brighter than the background against which they were viewed, so that contrast increased with increasing intensity. The literature of vision research suggests that an increase in contrast should make an object stand out better against a fixed background, and, in this experiment, none of the observers ever reported any decrease in conspicuity of the reference light as its intensity increased.

3. APPARATUS AND PROCEDURE

Twenty-nine different basic light units were tested with clear (white) bulbs and domes. In addition, three of these units were tested with red, yellow, and blue domes, and one of the units was tested with red bulbs. In effect, therefore, there were 39 different units used in the experiment.

The study was carried out in a large, grassy field on the grounds of the National Bureau of Standards in Gaithersburg, Maryland. With the exception of a minor sub-study, the research was conducted during daylight hours. Stakes were driven into the ground at 5° intervals along a circular arc, laid out at a constant distance of 100 m (330 ft) from the point of observation. A light-colored, unpainted, wooden cross, used as a fixation point by the observers and representing the center of the stimulus configuration, was positioned at the point 5° east of due north. The limbs of the cross were two stakes, each about 5 cm by 50 cm (2 in by 20 in), oriented vertically and horizontally.

Because the inside rearview mirror of an automobile is often separated laterally by 30° or more from the driver's straight-ahead line of vision, and because the mirror is where the signal from an overtaking emergency vehicle is usually first noticed, it was originally intended that the conspicuity comparisons should be conducted with the lights being viewed about 30° into the periphery of the visual field.

Some initial exploratory observations revealed that under the viewing conditions we were using, many of the flashing lights were not sufficiently visible 30° into the periphery, or even at 25°, to allow for an acceptable degree of observer confidence in the conspicuity-matching task. As a result, the two lights used on each trial were placed on wooden platforms located 20° on either side of the cross (25° east of north and 15° west of north). This choice contrasts with Edwards' [2] use of lights less than 3° into the periphery in his study, which was conducted in the laboratory. A schematic plan diagram of the experimental layout is shown in figure 1.

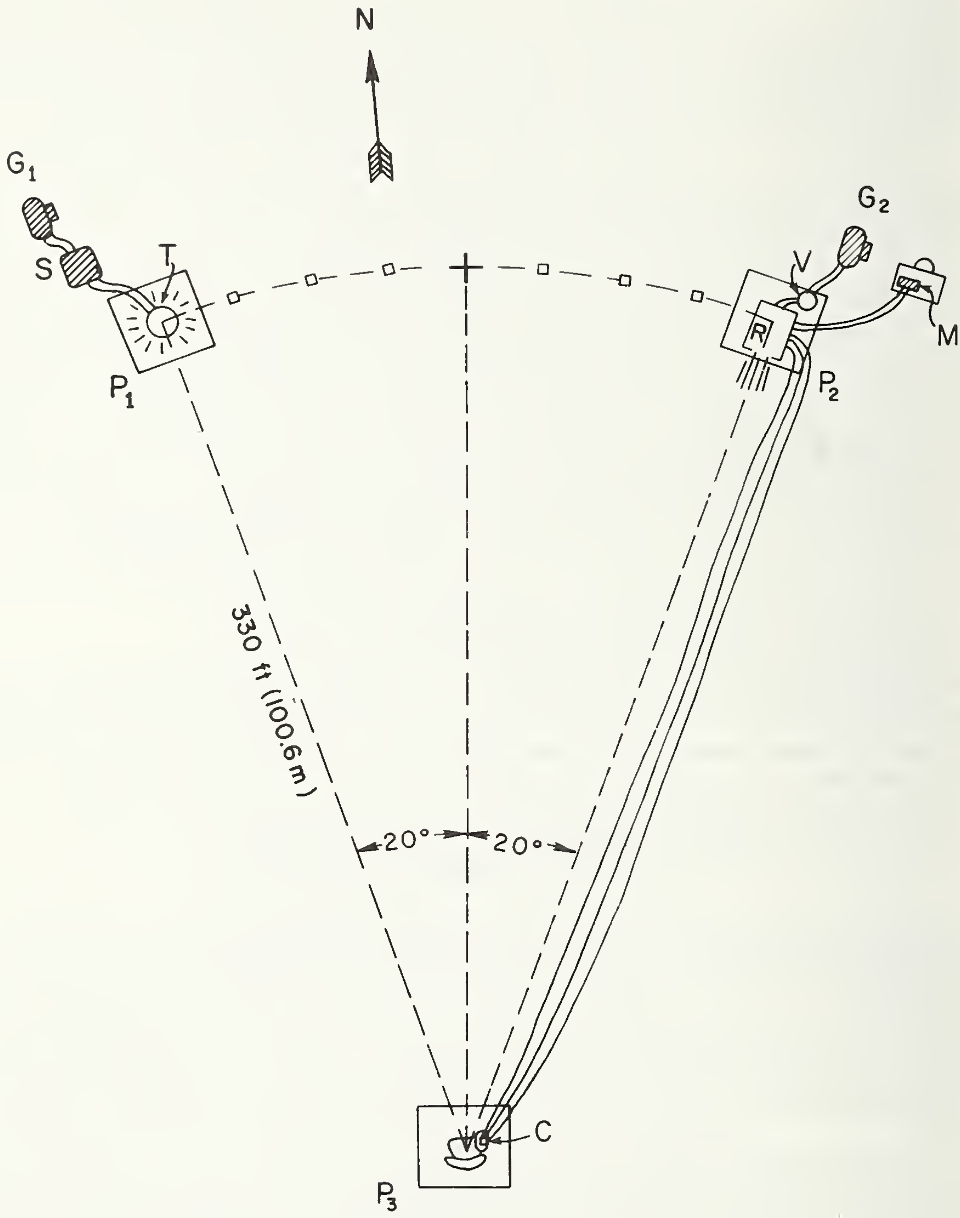

FIGURE 1. *Schematic diagram of the experimental layout.* The test light, T, and the reference light, R, were situated on level wooden platforms, P_1 and P_2. The observer sat in a chair on the platform P_3. Power for T came from the portable gasoline-powered generator G_1, which fed the stabilized power supply S, which maintained 12.8 volts DC into T. A second generator, G_1, powered R with 28 volts, monitored with a voltmeter (not shown) and adjusted through the variable transformer V. A single-pole, double-throw, spring-loaded center-off switch in the control box C permitted observer control of the intensity of R. The observer's switch manipulation controlled a motor-driven variable resistor, the resistance of which was read from the digital ohmmeter M at the experimenter's table.

We chose a nearly northward direction for the direction of observation in order to keep the sun away from the visual field of the observers throughout the day. In that position, too, there were no nearby trees directly behind either light. The background against which the lights were viewed consisted of grass and distant trees, with a grayish-buff building not far above the line of sight on one side. Because of the non-identical backgrounds on the two sides, and because some people might tend to be more sensitive to signals on one side or the other, every comparison was repeated with the adjustable reference light and the test light interchanged left for right. In any single experimental session, the reference light remained on one side. The reversed configuration was studied in a different session, usually on a different day.

The experimental subjects made their observations in turn, one at a time. The observer sat in a chair on a wooden platform at the fixed observation point. The heights of the platforms on which the test and reference lights were placed were such that the horizonal plane through the light source of a typical unit passed through the eyes of the observer of average height. In this way, the observer viewed all the lights close to their horizontal axes; that is, they saw the brightest part of the beam of each unit. Those units that were not uniform over 360° were rotated so that the brightest part of the beam pointed at the observer. One of the sources of variability introduced by doing a field study with full-size units was the difficulty of quickly positioning each unit so that its beam axis consistently pointed at the eyes of each observer, every time the light was set in place. The use of a bubble level permitted fairly accurate and rapid vertical alignment, but the horizontal pointing was less easy to control. It should be noted that a 1° error in orienting a light beam would move the axis almost 1.8 m (6 ft) away from the observer at a 100 m (330 ft) viewing range. For future reference, one way to assure repeatable positioning would be to mount each light unit on a separate base in such a way that the unit's orientation could be adjusted both vertically and horizontally, and so that once the unit was properly aligned, its base could be reproducibly mounted on the test light platform. Still greater precision could be achieved by having the observer's platform or chair adjustable in height, so that all observers would have their eyes at the same level.

The instructions to the observers, reproduced in the appendix to this report, explain the procedure in considerable detail and should be read at this point. There were six observers, and each made three match settings for each test light. Thus, a particular test light was set up on the platform and each observer in turn made three consecutive matches to it before another light replaced it. The reference light was run at 28 V ac, supplied by a gasoline-powered 110 V ac generator and a variable transformer. A similar generator was used for the test lights, but the power was converted by an intervening stabilized power supply into 12.8 V dc. A schematic diagram of the adjustable reference light is shown in figure 2.

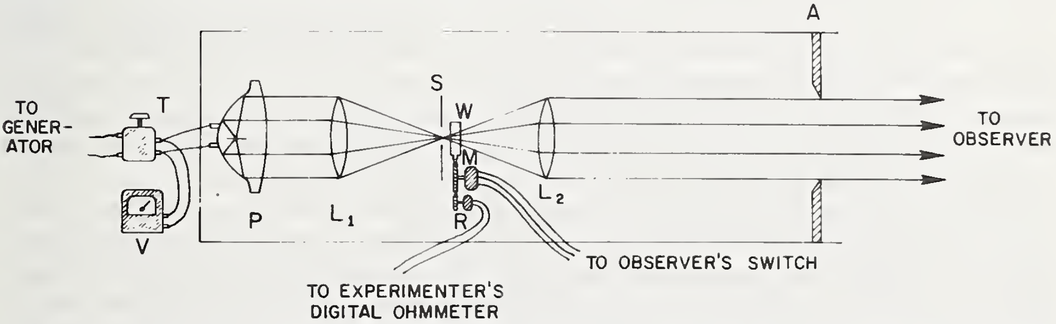

FIGURE 2. *Schematic diagram of adjustable reference light.* Voltage from a portable, gasoline-powered generator was adjusted by the variable transformer T, and monitored by the voltmeter V. The current lit the PAR lamp P (a 28-V aircraft landing light with a nominal 150,000 peak candlepower). The lens L_1 focused the beam from P in the plane of the rotating sector disk S, which had a single 20° open sector. The intensity of the light was then adjusted by passage through the linear neutral-density wedge W, which was driven back and forth by the motor M, through rack-and pinion gearing. A variable resistor R was geared into the same assembly. The resistance of R was an index of the density of W and thus of the intensity of the beam. The lens L_2 re-collimated the beam, which was projected toward the observer through the circular 5-in (12.7-cm) aperture A. The observer controlled the activation of the motor M, and its direction of rotation, through a cable leading to a double-throw center-off switch held in his hand.

The observation sequence used was highly wasteful of the observers' time, since each of the six observers was engaged in making matches less than one sixth of the time, but had to be present almost continuously in order to be ready to observe the next light. It would have been more efficient to have one observer make matches on a number of the lights before being replaced by another observer. However, because of the length of time required to change lights, the total elapsed time for the experiment would have been far greater if that procedure had been used.

3.1. Unexpected Problems

During the experiments two unanticipated problems arose that should be corrected in any future study that may be designed according to the same basic scheme. One of these was an apparatus problem, and one a procedure problem.

a. Apparatus: Insufficiently Bright Reference Light

During the course of the experiment, it was discovered that several of the test lights were more conspicuous than the reference light set at maximum intensity. To permit differentiation among these highly conspicuous units, a fixed neutral filter was placed in front of the test lights, and conspicuity matches made to the resulting dimmer lights. The filter was placed in front of a light when—and only when—an observer announced a need for it. There were borderline lights which some observers could match without a filter, but for which other observers required the filter.

The filter used was a dark gray Plexiglas (#2538), having a total luminous transmittance for CIE Source A (incandescent lamp at 2856 K) of 16.8 percent. The filter was somewhat biased toward longer wavelengths (10% transmittance at 400 nm and 20% at 700 nm), but the total transmittance for the bluer CIE Source C (resembling average daylight) was still 16.3 percent. (All figures are unverified manufacturer's specifications.) This particular product was satisfactory and was available locally, but no conclusion should be drawn that NBS considers it the best existing filter for the purpose.

In order to avoid darkening a significant portion of the background surrounding the lights, instead of only the lights themselves, the Plexiglas filter was cut down to the minimum size necessary to fully cover the largest dome (46 cm or 18 in square). For the units of smaller diameter, a certain amount of the immediate background of the lights was darkened by the filter. However, the entire filter subtended only about 16 minutes of arc at the observer's eye, so it was not expected that the angularly narrow margin of dark background around the smaller lights would have much effect, particularly with peripheral viewing. Nevertheless, the filter had a still unidentified effect on the observers' perception of at least some of the lights, beyond simply reducing the intensities of the lights. In future work of this kind, it would be highly desirable to avoid the use of any sort of filter. A reference light should be used that can produce flashes markedly brighter than those produced by the most potent unit to be tested.

One way to have brightened our reference-light flashes would have been to extend the duty cycle of the system. Instead of a 20° cut-out sector in the rotating sector disk, which provided a light pulse lasting 37 ms, or 5.6 percent of the cycle time, we could have cut out a larger sector. However, the 37 ms flash duration used is in the range typical of commercial rotating warning lights. Moreover, the location of the neutral-density wedge just past the focal point of the light beam (see fig. 2) resulted in a heavy heat load on the wedge that could have damaged it if the on-time of the pulse had been extended significantly. In fact, the first wedge installed had to be replaced because the glass cracked when the sector disk stopped for a brief period in the open position with the light on. The best solution, therefore, appears to be the use of a more intense lamp and a less heat-sensitive wedge. (Ours was of the absorption type; reflecting wedges are available.) Additional cooling can be provided by air blowers, water jackets, and infrared absorbing or reflecting glass.

b. Procedure: Fading of Visual Field

The procedure used required the observers to maintain their gaze steadily on the fixation cross. Some people are able to fixate so rigidly that a partial fading of the entire visual field occurs (but particularly the periphery), due to the uninterrupted stimulation of a fixed set of photosensitive visual cells. Several of our observers were occasionally troubled by such fading, and one observer was a frequent victim of the condition. The fading, in which both the test and reference lights became too dim to be seen at all in their locations 20° into the periphery, could be broken by looking around for a few seconds, but it sometimes returned almost as soon as fixation was resumed.

In future work a more limited, nonrigid kind of fixation might be used. Perhaps an extended fixation target embodying internal change or motion would induce enough continual shifting of fixation to prevent the fading effect. One possibility would be a rear-projection movie screen (about a meter wide) with an endless film loop of a changing scene projected on it. Although the fixation target is supposed to orient the observer's eye direction, his attention must be focused on the test and reference lights; the projected scene should therefore not be of intrinsic interest. The image could, perhaps, contain a single focal object, like a bouncing ball that hops randomly around to all parts of the screen. A 1 m (3.3 ft) screen at a distance of 100 m (330 ft) subtends more than half a degree at the observer's eye, so that if the observer visually followed such a ball, the images of the lights on his retina would also vary over half a degree. The light images themselves mostly subtend less than one fifth of a degree at 100 m (330 ft), so that no particular spot on the retina would be stimulated very long with this arrangement. It remains to be seen experimentally whether this hypothetical system would, in fact, forestall the fading problem.

4. RESULTS

The major result desired from this experiment was the practical one of rating the tested commercial light units for conspicuity. These ratings are given in section 4.2. Because of difficulties that arose in connection with the use of the filter, the nature of the scores by which the ratings are expressed had to be changed. This is discussed in section 4.1.

A second purpose for the experiment was to obtain information on the new conspicuity-rating method itself: its feasibility, its reliability, and its relationship to other measures. The reliability is discussed in section 4.3, and the relationship to other measures in chapter 5.

Finally, the results of the very limited study of the effects of color are described in section 4.4.

4.1. The Effect of the Filter

In order to tie together the results obtained with and without the Plexiglas filter, four lights that were not conspicuous enough to require use of the filter were run with the filter as well as without it. These lights were chosen to cover a range of conspicuities. It was hoped that these duplicate determinations of conspicuity (with and without filter) would serve to calibrate the filter so that its psychophysical effect could be stated mathematically. Unfortunately this turned out to be impossible. The results were highly inconsistent. The calibrations differed between observers, varied in a nonsystematic way for most individual observers, and were often different for left-hand and right-hand viewing of the test lights. If the variations of the calibration data for each observer was assumed to be due to random error and the calibration factors obtained for the four lights were averaged, the results turned out to be of no value. If applied to the highly conspicuous lights that could be run only with the filter, they resulted, in most cases, in scores lower than those of the most conspicuous lights that had not required the use of the filter.

It was thus not possible to relate the numerical ratings of the lights judged with the filter to those judged without the filter. The lights were therefore simply ranked in the order of their rating scores, with the most conspicuous lights (i.e., those which had to be rated with the filter) at the top of the list.

4.2. The Conspicuity Rankings

Table 1 lists the units studied, ranked in order of decreasing conspicuity. The rank numbers ("rank-scores") listed are average reverse rankings, in which a low rank number corresponds to an inconspicuous light. Each observer's individual rankings of the lights on the left side and on the right side (each based on the average of three settings) were averaged; and then these average within-observer ranks were in turn averaged over all six observers. Because the filter was used for some lights by some observers and not by others, it was not possible to average the numerical settings for all observers and then perform a single ranking. In fact, some observers needed the filter when viewing some lights on one side, but not on the other. The pair of columns to the right of the conspicuity rank-scores indicates how many of the six observers required the filter for each light, when viewed in each direction.

4.3. The Reliability of the Judgments

The reliability (correlation on repeated tests) of any rating procedure is an important indicator of the potential usefulness of the method. Figure 3 shows the left-side rank-scores (reverse ranks averaged for all observers) plotted against the right-side rank-scores. Since the lights were judged on the left side and on the right side in different experimental sessions (often

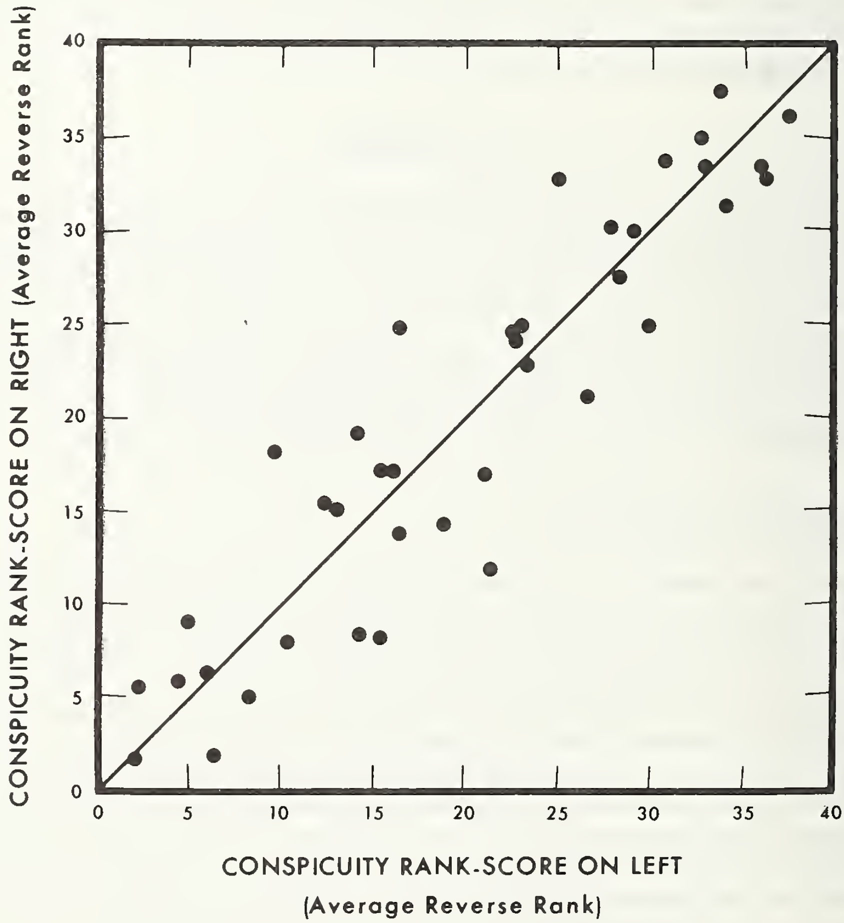

FIGURE 3. *Scatter diagram showing the correlation between the conspicuity rank-score (average reverse rank) of a light when viewed on the left of the observers and the corresponding rank-score of the light when viewed on the right of the observers.* The trend line is the line of equality (through the origin with a slope of unity).

Table 1. *Some emergency vehicle warning lights, in order of conspicuity*

Conspicuity rank-score[a]		Filter use L	Filter use R[b]	Unit identification: Unit code[c]	Unit identification: Source type[d]	Effective intensity (cd)[e]	Effective-intensity rank-score[f]	Disappearance-angle rank-score[g]
Most	36.7	5	4	22	S	2600	14	20.2
	35.5	5	6	23	S	-	-	24.8
	34.6	4	6	9	I	3211	15	24.8
	34.6	6	6	21	I	-	-	22.8
	33.9	6	5	6	I	-	-	20.2
	33.2	4	5	34	I	-	-	24.8
	32.6	4	5	24	I	1585	12	10.5
	32.2	5	6	37W	I	-	-	15.8
	29.6	3	4	26	I	2173	13	23.5
	29.0	2	5	3	S	-	-	20.2
	29.0	1	4	4	I	-	-	15.8
	28.0	5	3	11	I	-	-	16.2
	27.4	4	3	2	I	-	-	20.2
	23.9	-	1	18W	S	840	10.5	15.8
	23.8	1	2	1	I	780	9	15.8
	23.4	-	3	18B	S	-	-	-
	23.4	-	3	46Y	I	-	-	-
	23.0	-	1	5	I	-	-	20.2
	20.6	-	3	46W	I	840	10.5	15.8
	18.9	-	-	33	S	350	6	7.8
	16.6	-	-	27	I	-	-	11.8
	16.6	-	-	46R	I	-	-	-
	16.6	-	-	25	I	590	7	17.8
	16.6	1	-	16	I	602	8	12.2
	16.3	-	-	18Y	S	-	-	-
	15.1	-	-	12	I	159	4	4.5
	14.0	-	-	15	S	-	-	14.0
	14.0	-	1	37R	I	-	-	-
	14.0	-	-	20	I	322	5	5.5
	11.7	-	-	41	I	-	-	8.2
	11.4	-	-	18R	S	-	-	-
	9.0	-	-	10Y	I	-	-	-
	7.0	-	-	46B	I	-	-	-
	6.6	-	-	10W	I	116	3	4.8
	6.0	-	-	14	I	46	1	3.0
	5.2	-	-	30	I	96	2	2.2
	4.0	-	-	43	I	-	-	1.0
	4.0	-	-	10B	I	-	-	-
Least	1.9	-	-	10R	I	-	-	-

[a] The rank-score is the average reverse rank (in which the score 1 is assigned to the least conspicuous unit). The average is over 12 separate rankings by 6 observers.

[b] These columns indicate how many of the six observers needed the filter when the unit was viewed toward the left of the observers (L), and toward the right (R).

[c] The numbers are arbitrary codes for the units. Letters, indicating flash color, follow the numbers of those units that were tested with domes or lamps of more than one color. All units without letter suffixes were tested with white flashes only (clear domes and white lamps). Color code: W=white, R=red, Y=yellow, B=blue.

[d] Code: I=incandescent source, S=strobe (xenon discharge) source.

[e] Effective intensity measurements were confined to some of the rotating incandescent units and gaseous-discharge flashers, all with white (clear) lenses and bulbs.

[f] See footnote a for definition of rank-score. In this case, there was no averaging; the rank-scores are the reverse ranks of the effective intensities in the preceding column.

[g] See footnote a for definition of rank-score. In this case, averaging was over rankings by two observers.

run on different half-days and sometimes on different days), the good correlation (product-moment r=0.92) illustrated in the scatter plot is an indication of good test-retest reliability. In fact, the differences shown in the figure between left-side and right-side rank-scores reflect not only the intrinsic variability of the conspicuity-matching task, but also whatever systematic differences may have existed between viewing on the two sides (differences in the effects of the backgrounds in the two directions, and the observers' left-right perceptual asymmetries). Therefore, it would be expected that the correlation shown in figure 3 would represent a lower limit to the true (population) reliability of this conspicuity-ranking procedure.

4.4. The Effect of Color

Table 2 summarizes the very limited results on the influence of color obtained in the main experiment (daytime), as well as in a subsidiary study carried out at night. The data are not

TABLE 2. *Effect of dome-color and lamp-color changes on conspicuity*

Conspicuity rank-score, comparison of 12 lights[a]	Dome color varied[b]			Bulb color varied	Conspicuity rank-score, comparison of 39 lights[d]
	Unit #18 strobe	Unit #10 incand.	Unit #46 incand.	Unit #37 incand.[c]	
		Daytime			
-				W	32.2
10.4	W				23.9
10.4			Y		23.4
10.2	B				23.4
8.8			W		20.6
8.3			R		16.6
7.5	Y				16.3
-				R	14.0
5.6	R				11.4
5.2		Y			9.0
4.2		W			6.6
3.4			B		7.0
2.5		B			4.0
1.5		R			1.9
		Nighttime			
11.2	W			This	Full
10.9			W	unit	set
10.2	B			not	of
8.6			B	tested	39
8.1	Y			at	lights
6.3			Y	night	not
5.2		W			tested
5.0	R				at
4.3			R		night
4.2		B			
2.5		Y			
1.4		R			

[a] These rank scores are the average reverse ranks for eight observations (four on the left and four on the right) in daytime and nighttime. The daytime data for the 12 lights (3 units with 4 dome colors each) tested at night by 4 observers were separated from the main daylight experiment.

[b] Throughout the table, the color code for the light signals is: W=white (clear dome), B=blue Y=yellow, and R=red. The light sources in units 18, 10, and 46 were never changed; only the domes were varied.

[c] Unit 37 was the only unit in which two colors of bulbs (lamps) were employed. It was not tested at night, and therefore was also not included in the daytime rankings given in the first column of this table. The red lamps differed from the white only in the bulb coloration, and consequently the red lamps had considerably lower intensity.

[d] These are rank-scores from table 1, which gives the results of the main daytime experiment on 39 lights. The correspondence between the daytime ordering of the 12 key lights (those tested in both the daytime and nighttime) by these scores (derived from six observers) and those of the first column (derived from four of the six observers) is perfect.

relevant to the fundamental question of whether some colors are more conspicuous than others when intensity is held constant. Rather, the data relate to the more immediately practical issue of the effect on conspicuity of placing domes of various colors over the same source of white light, or of replacing the white lamps in a given EVWL by otherwise identical lamps with differently colored bulbs. Because filters of different colors have quite different transmittances, the intensity of a light is strongly dependent on the dome (or bulb) color.

In producing a filter of a given nominal color (such as "blue"), each manufacturer may introduce a different set of colorants, or different amounts of the same set of colorants, into his melt of clear glass or plastic. Hence, one manufacturer's "blue" dome may have a somewhat different blue color and a somewhat different transmittance from the "blue" dome of another producer. Accordingly, the conclusions that can be drawn from the data of table 2 are of only a rough, qualitative nature.

The daytime data in table 2 were extracted from the results of the main experiment; the column at the right of the table repeats the conspicuity values given in table 1. The scale at the left of the table represents rank-scores recomputed from the original data to apply only to the observations made on the 12 lights (unit/color combinations) also studied at night, by only those four observers who served at night.

Of the four units listed in the table, three—units 10, 46, and 37—used incandescent sources. For such lights, the data suggest that the use of white or yellow filters in a given light leads to a higher level of conspicuity than the use of either red or blue filters. This result is just what would be expected on the basis of intensity; white (colorless) and yellow filters transmit high fractions of the light from an incandescent lamp, whereas red and blue filters transmit relatively low fractions of such light. The apparent superiority of yellow to white, if real, represents the influence of a factor other than intensity, since typical yellow filters transmit only about 55 percent as much incandescent lamp light as clear filters do (about 50% transmittance for the former, against 90% for the latter). Perhaps the color contrast between the predominantly green background and the yellow light was greater than the contrast between the background and the white light.

The strobe unit listed in table 2 (unit #18) had a xenon-discharge source, which produces light that is considerably bluer than incandescent light. For such strobe sources, it is generally true that a blue filter transmits a fraction of the generated light considerably greater than the fraction of incandescent light that the same blue filter transmits; and typical red and yellow filters have lower transmittances for xenon-discharge light than for incandescent light. The conspicuity ordering of the colors for the strobe unit in the table presumably is again largely a reflection of the effective intensities of the emitted flashes. Since the effective intensities of only white lights were measured in the NBS program, and the luminous transmittances of the domes were not determined, this presumption cannot be quantitatively confirmed.

The same three units that were studied in the daytime with different colored domes were similarly matched for conspicuity in a brief exploratory study carried out at night by four of the observers that served in the main experiment. The observers reported some difficulty in making the matches at night, because all the lights were fairly dazzling at the 100 m (330 ft) viewing distance used. Nevertheless, reasonably consistent data were obtained, and the result was the same for all three lights: at night, the order of increasing conspicuity was red, yellow, blue, white. This finding can be summarized by saying that at night, incandescent light sources seem to behave, with respect to color, as if they were xenon-discharge sources. (Actually, of course, it is not the light source that changes, but people's perceptions.) Both in daylight and at night, the strobe light (unit #18) yielded highest conspicuity with white and blue domes, lowest conspicuity with the red dome, and intermediate conspicuity with the yellow dome. At night, the two incandescent lights followed this same pattern. The basic phenomenon appears to be that blue becomes considerably more conspicuous at night, relative to other colors, than it is in daylight; and red becomes considerably less conspicuous at night, relative to other colors, than it is in daylight. Conversations with police officials indicate that this phenomenon has been previously noted. In fact, the California Highway Patrol has made a motion picture film in an attempt to demonstrate the effect directly.

These changes in color effectiveness are consistent with the shift toward shorter wavelengths of the sensitivity function of the eye in going from day (cone) to night (rod) vision (the Purkinje shift). It is sometimes stated that the dark-adapted eye is most sensitive to blue light; actually, the peak sensitivity under dark adaptation is to light with a wavelength of 507 nanometers, a slightly bluish green. Nevertheless, it is true that the ratio of blue to red sensitivity is considerably greater in night vision than in day vision.

The main problem with the Purkinje shift as an explanation of the effectiveness reversal of red and blue warning lights at night is that the rods do not see color at all; only the cones can distinguish one color from another. A plausible explanation is that in relative darkness the blue-sensitive rods more easily detect the blue light, which is recognized as blue by the cones.

5. CORRELATIONS WITH OTHER MEASUREMENTS

5.1. Another Perceptual Measure: Flash-Disappearance Angle

Prior to the main study that is the primary subject matter of this report, a few pilot observations of the lights were carried out on the roofs of two adjacent buildings. Since the ability of EVWLs to attract attention in the periphery of the visual field is crucial, it was natural to think about determining how far out (angularly) in the visual field the various lights could be distinctly seen.

In the laboratory and the ophthalmological clinic, an instrument called a perimeter is used to determine how far out in the visual field various objects can be seen. The observer fixates straight ahead while the objects are moved inward toward and outward from the fixation point. The disappearance point is read off from an angle scale.

In our work, a much greater scale of size was involved. The EVWLs being tested were bulky and required electrical connections, so it was impractical to carry the lights back and forth while the observer stared straight ahead. Consequently, we adopted a procedure that is an inverse form of the kind of perimetry conducted in the laboratory. As shown in figure 4, the roof of the building on which the lights were displayed was laid out as a giant perimeter. The direction 20° to the left of the normal to the roof edge (the normal being due north) was defined as 0°, and angles at 5° intervals were laid out along the roof parapet by means of a surveyor's transit and marked on the side of the building with adhesive tape. The angle positions at 10° intervals were labeled by large signs hanging over the roof edge. The light to be tested was located in a fixed position at 0°.

The observer began by facing the light with both eyes open, and then turned his head gradually to the right until he reached an orientation at which the individual light flashes could just barely be distinguished. He then glanced down slightly and read off the angle corresponding to this critical direction, interpolating to the nearest degree. The observations, which were fully made by only two observers (and partially by a third), were thus equivalent to the perimetric determination of disappearance angles in the left half of the binocular visual fields of the observers. These tests were conducted in the daytime.

Actually, two different angles of disappearance were recorded. Lights of various colors were tested, and it was found that the color of any light became indefinite at an angle at which the flashes were still clearly visible. In a sense, it could be said that the light then appeared white, but the failure of color perception was really more complete than that. Even when the test light was in fact white, it was possible for each observer to decide upon an angle at which it appeared subjectively that color perception—as opposed to brightness perception—no longer existed. Thus, the color beyond this angle was not really white, but simply indefinite. As the angle of gaze was increased beyond this color-disappearance angle, the flashes were still seen, but as progressively less distinct events, until an occasional flash was completely missed at large enough angles. This point was fairly definitely delimited because the previously regular rhythm of the flashes was broken.

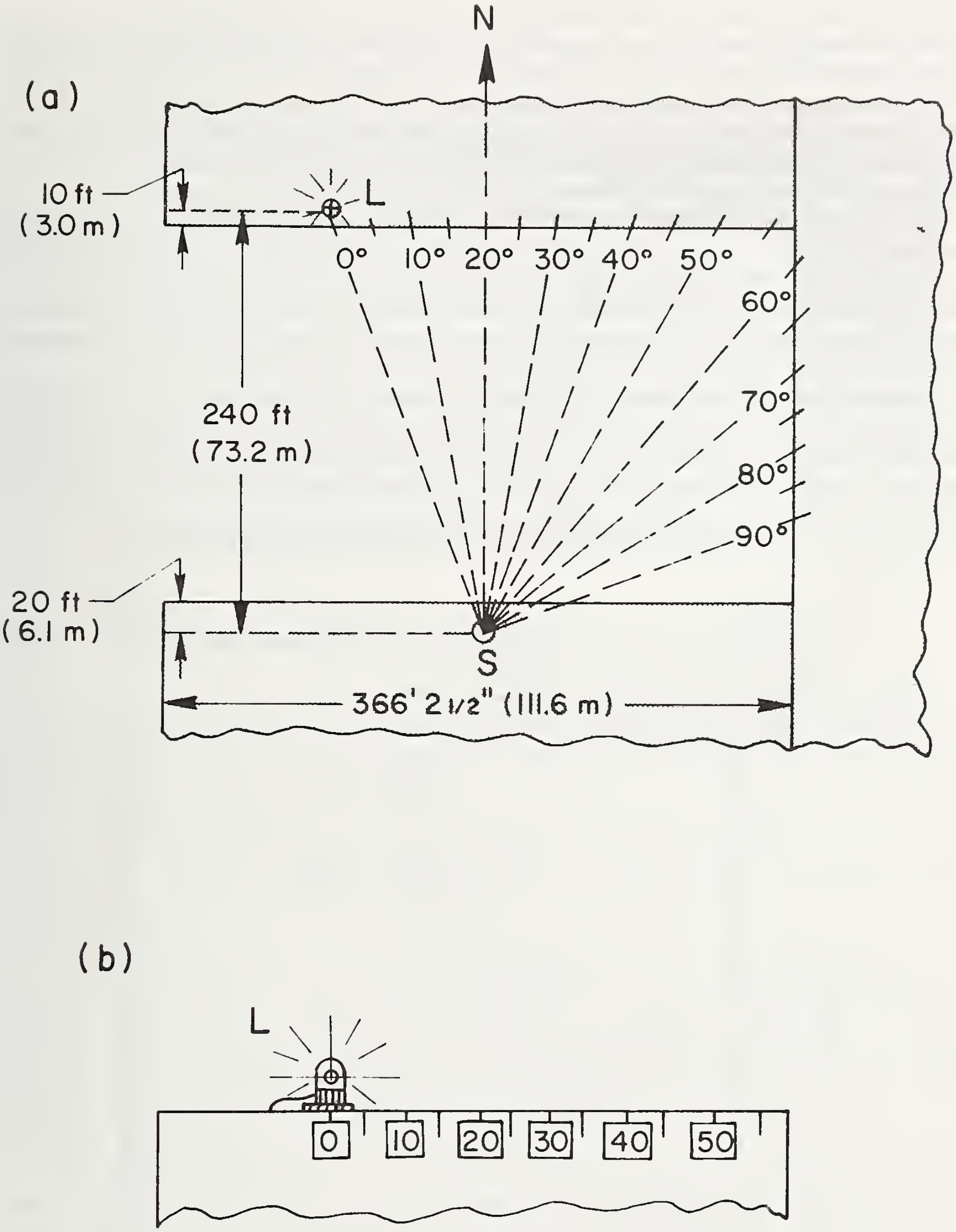

FIGURE 4. *Layout for rooftop observations to determine the flash-disappearance and color-disappearance angles.* (a) Plan view. Subject, S, made observations from one rooftop across to another roof on which the light, L, was located. Signs indicating angles of deviation from the line of view from S to L were hung from the parapets of the roof on which L was situated and on a roof adjoining to the side. N denotes due north. (b) Schematic diagram of S's view to the rooftop opposite.

With colored flashes, the flash-disappearance angle was commonly about five times the color-disappearance angle (for all three observers). With white flashes, the decision as to where color became unidentifiable was much more difficult, as would be expected. Each observer had to define for himself a criterion of color disappearance for white light as well as for colored light, and not all of the observers arrived at the same criterion for both. In fact, one of the two primary observers tended to go from a 5-to-1 angle ratio when he viewed colored flashes to about a 2-to-1 angle ratio when he viewed white flashes.

The critical element in EVWL effectiveness is the visibility of the light flashes in the periphery of the eye, since that is the mechanism for the initial attracting of attention. The ability to recognize color during this initial stage is secondary, since once attention has been attracted, the gaze is normally turned toward the flashes and color can then be easily identified. For this reason, and also because the flash-disappearance point was more easily recognized, the flash-disappearance angle was taken as the more significant measure.

Because one of the two observers who made a complete set of these observations consistently reported larger angles than the other, and because two readings are not enough to yield a stable average, the lights were rank-ordered separately for each observer (with reverse ranks), and a combined rank-score derived by averaging the two individual ranks. Figure 5 is a scatter plot

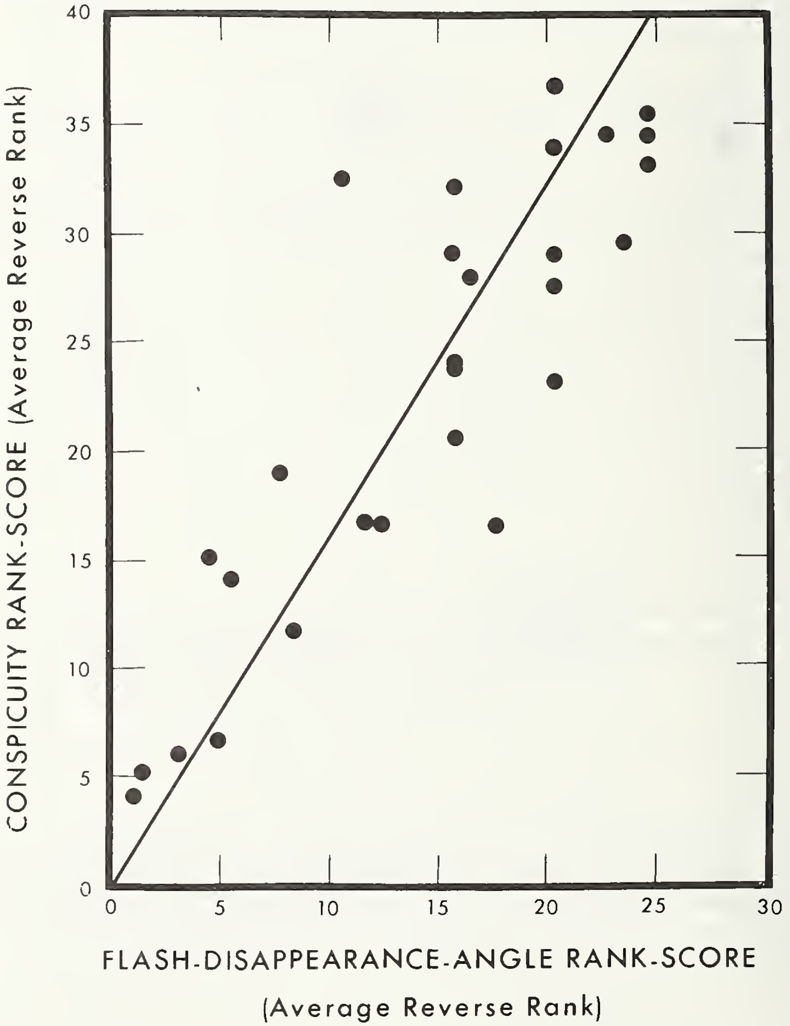

FIGURE 5. *Scatter diagram showing the correlation between average conspicuity rank in the main experiment and average flash-disappearance-angle rank.* Ranks are ordered in reverse. The straight trend line was fitted by eye, with the restriction that it pass through the origin.

showing the correlation between these disappearance-angle rank-scores and the conspicuity rank-scores from the main experiment, listed numerically in the last and first columns of table 1, respectively.

Inspection of figure 5 shows that the correlation is fairly high (product-moment $r=0.86$), and the relationship is approximately linear. The linearity is not surprising, since both scores are rank orders. On the basis of these data, it would appear that a quick, quantitative test of the relative conspicuities of any set of EVWL units could be made by the quite simple procedure of determining their flash-disappearance angles under fixed viewing conditions (background, night or day, etc.).

For daytime tests with the sun behind the observers, the 73.2 m (240 ft) viewing distance we used was not great enough to permit separation of the observers' responses to the most powerful lights. For each observer, all of these lights were visible out to the same maximum angle, which apparently represented the functional limit of his visual field under the particular test conditions. This angle was 77° to 79° for one observer and 85° for the other. In contrast, some of the flashes from the very weakest lights began to be missed beyond an angle of 3° or 4°, for both observers; these lights could not be used in the main experiment. Such lights are clearly of little use on the highway, so the disappearance-angle test should be designed to permit differentiation of the more powerful units. A daytime viewing distance of 300 m (980 ft) might serve the purpose. At night, still greater distances could be needed, since the visual signal-to-noise ratio is so much higher with a dark background.

5.2. Physical Measure: Effective Intensity

The instantaneous intensity of a flashing light varies cyclically over time. It is convenient to be able to assign a single numerical value to the output of a flashing light, and the quantity most commonly used, called the effective intensity, is defined as the intensity of the steady-burning light that disappears from view at the same distance as the flashing light in question. A formula, usually called the Blondel-Rey formula, is customarily used to predict effective intensity from a graph or table of the instantaneous intensity of a single flash as a function of time. The modern version of this formula was defined by Douglas [1]. The visual implications of the formula have been discussed by Projector [9], and the details of the calculations are presented in an IES publication [7].

As mentioned in the introduction, the effective intensities of some of the lights used in these perceptual experiments had been measured at NBS. Measurements were made in a photometric range, on most of those units for which the necessary equipment was already set up (namely, rotating incandescents and strobe lights). Because of special measurement problems that would have required unavailable time to overcome, no effective intensities were measured for electrically flashed incandescent lights, oscillating lights, multiple-light bar-mounted units, or lights of any color other than white.

The apparent success of the flash-disappearance angle in predicting conspicuity rank suggests that conspicuity is heavily determined by simple visibility, which is in turn known to be determined basically by the effective intensity of the flashes. Because effective intensity is a quantity derivable from physical measurements, it does not suffer from the sensitivity to subtle influences and the variability that characterize perceptual measurements, in which humans must serve as observers. For the routine testing of EVWL units, a physical measure such as effective intensity would be a great convenience, provided it could be shown to correlate well with a perceptual measure of conspicuity. It was of great interest, therefore, to compare the conspicuity ranks from our main experiment with the effective intensities of those units for which such data were available. The comparison is illustrated in figure 6, and shows that effective intensity correlates well with conspicuity rank-score, although the correlation is quite nonlinear (linear product-moment $r=0.90$). The nonlinearity is hardly surprising, since a perceptual ordinal measure (rank) is being compared with a physical ratio-scale quantity (effective intensity). Figure 7 shows the linear relationship that results when the same data are replotted with effective-intensity

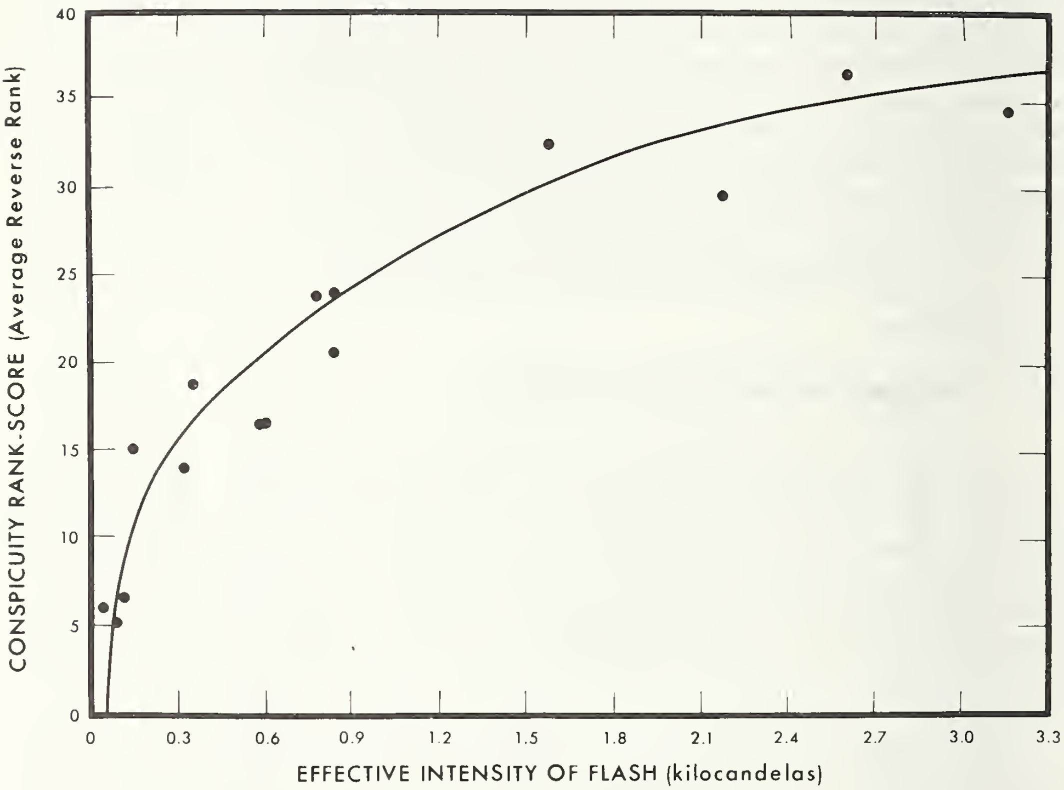

FIGURE 6. *Scatter diagram showing the (nonlinear) correlation between conspicuity rank-score (average reverse rank) in the main experiment and the effective intensity of the flashes.* The trend-curve was sketched by eye, and was deliberately directed away from the origin, since lights below a certain effective intensity have zero conspicuity (are invisible) at 20° into the periphery of a visual field.

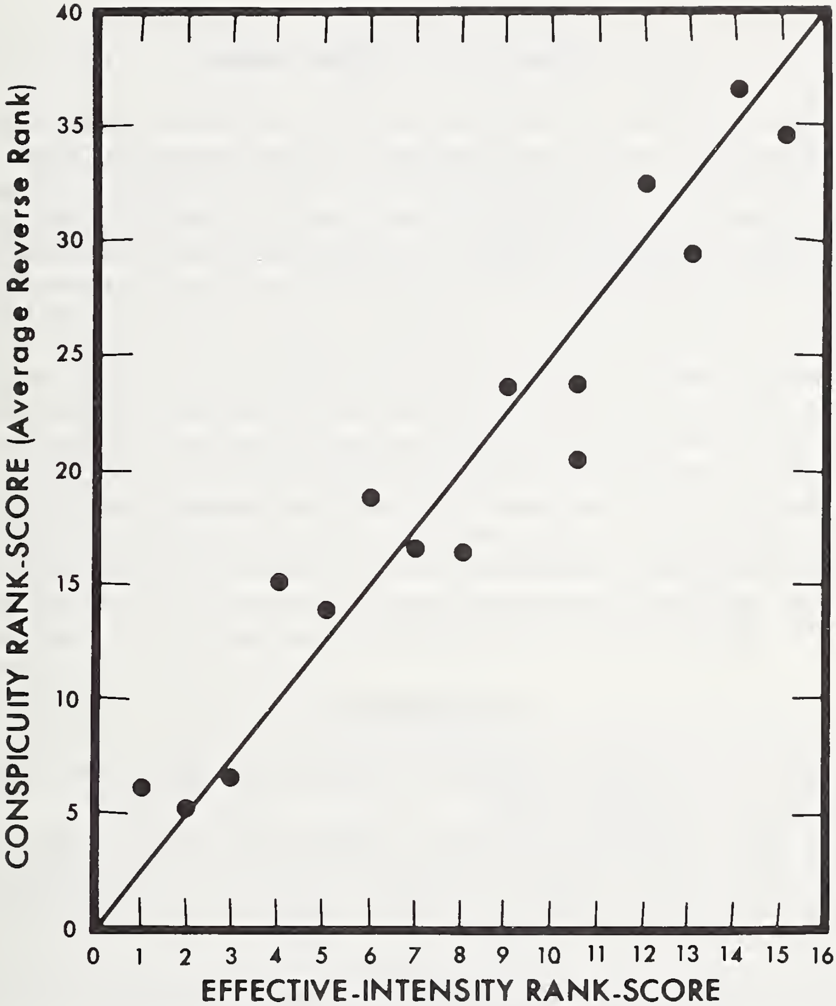

FIGURE 7. *Scatter diagram showing the correlation that results from replotting figure 6 with the abscissa variable converted from effective intensity to effective-intensity rank-score (reverse rank).* The trend line was fitted by eye, with the restriction that it pass through the origin.

rank-scores replacing the absolute effective intensities. The correlation in this scatter plot is seen to be quite high (product-moment $r=0.96$). To the extent that conspicuity rank from our experiment is an accurate gauge of true conspicuity in the real-life situation, it follows that effective intensity is a suitable measure on which to base the requirements of a standard for EVWLs.

6. SUGGESTED FUTURE WORK

The conspicuity-matching experiment described in this report was carried out under a single set of viewing conditions, namely in daylight with an immediate background of green grass and foliage. Moreover, most of the work was done with units emitting white flashes, whereas color is an important element of a visual signaling system. It would be useful to carry out comparable studies at night, at a much longer viewing range so that the lights would not be dazzlingly bright to the observers. It would also be of value to conduct daytime studies in which the lights were viewed against a variety of backgrounds, including such colors as black, earth brown, snow white, roadway gray, and sky blue, in addition to grass/foliage green.

More refined experimental exploration of the factors affecting the conspicuity of signal lights is still needed. We know that effective intensity is the major determinant of conspicuity, but other factors such as color, flash rate, and flash duration may have smaller but significant effects. An experiment that can evaluate the separate effects and the interactions of these variables requires systematic variation of the different parameters in a variety of combinations. Such control over the stimulus is not available in commercial EVWL units. Instead, the experiment must be conducted in the laboratory using fully controllable light sources. A laboratory simulation would also permit much more rigid uniformity of and control over the background and the ambient illumination level. Conspicuity will not be fully understood until such controlled experimentation is carried out.

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APPENDIX—INSTRUCTIONS TO OBSERVERS

Each subject in the experiment was asked to read the following written set of instructions.

INSTRUCTIONS

This experiment deals with the conspicuity of light signals—that is, their ability to attract your attention when you are not looking directly at them and are occupied with other matters. An example of the sort of situation in which we are interested is the appearance, in the inside rearview mirror of an automobile, of the flashing warning light of a police car overtaking from the rear. The driver is paying attention to the road ahead and the light in the mirror is well to the right (and perhaps somewhat above) the driver's line of vision.

We are going to show you a number of warning lights of the kind used by emergency vehicles, and you will be asked to estimate to yourself how strongly each light would tend to attract your attention if you were driving down a road looking straight ahead and the light appeared off to one side.

There is a wooden cross stuck in the ground half way in between the platforms out there on either side of you. The cross is almost on a line with the clump of two trees you see straight ahead of you. You will be asked to look always at the center of this cross when you are examining the lights, never directly at the lights themselves. As you look straight ahead at the cross, we will show you two lights, one on each side of you, on the platforms out there. The control box you will be holding will enable you to adjust the intensity of one of the lights. Your task is to run the intensity of the adjustable light up and down until you have the impression that the two lights are equally conspicuous or attention-attracting. Do not pay any specific attention to the brightness or colors of the lights, the rates at which they are flashing, or any other particular quality of the lights. Just form an overall impression of conspicuity and vary the adjustable light until it matches the fixed light in attention-pulling power.

The control box contains a switch that normally rests in the center position and is returned there automatically by a spring as soon as you let go of the handle. When the handle is centered, the adjustable light remains fixed in intensity. If you push the handle upward, the light will begin to increase in intensity and will grow brighter and brighter as long as you keep it in the upward position. As soon as the light is as bright as you want it, release the handle and the light will remain at whatever brightness it had at the moment you let go of the handle, which will snap back to the center position. Now if you want to make the light dimmer, you push the handle downward and keep it down until the light is at the intensity you want, then release the handle. If you want to switch directly from making the light brighter to making it dimmer, or vice versa, it is all right to push the handle right through the center position from one extreme to the other. Whenever you want to stop to compare the lights, though, the handle should be let go or held in the center position.

First try running the intensity down as far as it goes. Push the handle downward and hold it there until the light gets so dim you can't see it any more, then release the handle. Now increase the intensity by pushing the handle upward until the light doesn't seem to be getting any brighter any more. That is the brightest we can make the adjustable light.

At the beginning of each trial, you should set the adjustable light to be much less conspicuous than the fixed light. Then please make the adjustable light brighter until it is clearly more conspicuous than the fixed light. Then make it a little dimmer, and zero in on the equal-conspicuity setting by running the intensity up and down until you feel you have it just right for equal attention-attracting power of the two lights. When you are near the equality setting, you may find it desirable to just flick the switch up or down for an instant.

Some of the fixed lights will be very conspicuous. If you find that you cannot run up the intensity of the adjustable light so that it is definitely more conspicuous than the fixed light, even at the very top, please tell this to the experimenter. You should then try to set for equal conspicuity, and tell the experimenter either that you cannot even reach equality of conspicuity when the adjustable light is at its brightest, or else that you have succeeded in matching conspicuities, even though you can't make the adjustable light clearly more conspicuous than the fixed light.

You may also find a few lights that are so inconspicuous that you cannot clearly see the individual flashes when you are looking at the cross. When you try to match such a light, please tell the experimenter if you are very unsure of the settings. At first, you may find yourself unsure of all your settings, but as you go along this unfamiliar task will get easier. Simply do your best to match the conspicuities. There are no "right" answers, of course; we want to find out how things look to you.

Please look at the cross during the entire time you are making each match. You may find at first that your eyes tend to wander off to look directly at one light or the other, but you must fight this natural tendency. When you have completed your adjustment for equal conspicuity, tell the experimenter. Then stop staring at the cross and look around at nearby objects to relax your eyes. If you find during a trial that everything begins to fade out as you continue looking at the cross and adjusting the light, just look down at the ground in front of you and move your gaze around a little, and then look back at the cross and continue your adjusting. Do not look directly at the lights at any point during a trial.

When you have arrived at a match, take your hand away from the control box and tell the experimenter. Do not touch the switch again until the experimenter tells you to proceed. Usually, you will be asked to make several matches in a row on the same light and then leave the observer's chair and relax while other observers take their turns.

If there are any questions about what is expected of you, the experimenter will be glad to answer them.

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