THE EFFECT OF STROKE WIDTH, ILLUMINATION LEVEL, AND FIGURE-GROUND CONTRAST ON LEGIBILITY OF NUMBERS

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

INTRODUCTION

Alpha-numerical codes are used in essentially three contexts; namely, in printed copy (such as in a book or newspaper), in tabular form (such as telephone directories and tables of numerical data), and as identification labels (such as on control devices, traffic signs, license plates). The problem of how to design numerals which will be read most rapidly and accurately has received attention in the past with reference to such uses as highway signs, automobile license plates, and time tables. Research is also being conducted to improve the visibility of numerals on instrument dials and other equipment.

Generally, if better legibility is required, the size of numerals is increased. Sometimes, however, an increase of size is not desirable, either because of a lack of space or because it would appear ugly. Furthermore, it is not necessarily true that the legibility of symbols increases by increasing the area of the number. Many big signs are less legible than others presenting smaller but differently constructed symbols.

The design of numerals should take into consideration both their legibility and their aesthetic quality. While these two need not be mutually exclusive, it is quite likely that numerals which are designed solely to be legible may not always be aesthetically pleasing, so that some compromise may be necessary.

The practical interest in this problem has produced a number of interesting contributions to the factors determining the legibility of symbols on highways and printed material for reading purposes. These investigations suggest a wide practical interest in the problem, but it also has theoretical implications which deserve attention. It is usually difficult, if not impossible, to draw conclusions from experiments made under refined laboratory conditions and to apply them to complex every day situations which rarely are sufficiently constant to permit reproducible results.

LITERATURE SURVEY

The general factors which govern the legibility of numerals may be listed as follows: the numeral design, stroke width, variability of stroke width within the numeral, color and contrast of figure-ground, illumination, height to width ratio, and the numeral size.

Numeral Design

Berger (1944) and Kuntz (1950) agreed that there is considerable variation in the legibility of numerals. Kuntz (1950) inferred that the numeral "1" yielded an average legible distance nearly twice as great as the numeral "8". There appears to be a consistent tendency for those numerals having most straight lines with least configurations to be most legible. Conversely those numerals having most curved lines or most configuration are least legible.

In an often cited study, Mackworth (1944) devised some new numerals and letters that simplified the components and curvature of conventional forms. The new angular digits were readable at significantly greater distances than conventional ones.

Atkinson, Crumley and Willis (1952) studied the legibility of the following numeral designs: Berger Numerals (a design developed by Berger (1944) for possible use on automobile licenses or on traffic signs), United States Air Force-Navy Aeronautical Design Standard, and Navy Aeronautical Medical Equipment Laboratory proposed numeral form (abbreviated NAMEL).

The various numerals of the three different forms were presented to subjects under both transillumination and simulated daylight conditions, with varying amounts of illumination for each type of condition. It was found that the NAMEL form had a lower percentage of errors than either of the other two.

In letter and numeral design, various other experimental forms have been established. One set of numerals, developed by Lansdell (1954) was tested by Foley (1956). These numerals were compared for legibility with those of Bartlett and Mackworth (1950). Legibility of Lansdell numerals was significantly better, both under straight-ahead viewing conditions and at different angles of views.

Stroke Width

The stroke width of numerals typically is expressed as the ratio of the thickness of the stroke to the height of the numeral. Uhlaner (1941) found that "the optimal stroke of three-inch block letters is, on the average, closest to 18% of the width or height of letter."

Berger (1944) conducted an experiment with two subjects and three numbers, 2, 5, and 8, designed by Berger himself. The area covered by the numerals was 42 mm x 80 mm. The numerals were made of paper and pasted on cardboard on a wooden frame, and were moved slowly towards the subject and away again. Observations were made outside, in the morning under diffuse daylight. The subject stood upright on his feet upon a lawn of 100 meters length. The threshold of legibility or recognition was determined by increasing the distance between the subject and test object until the particular characteristic observed could not be recognized. If the subject could just recognize the number, or could just not recognize them any longer, he raised his hand. At this point the distances were checked. Berger (1944) reported as optimal a stroke width/height ratio of 12% for black on white, and 8% for white on black. No statistical tests were reported by Berger in support of the above conclusions.

Kuntz and Sleight (1950) used a dolly, carrying the reading material and the tubular lamps to illuminate it, which moved back and forth inside a two-feet square tunnel eight feet long. The position of the dolly in the tunnel was controlled by the experimenter from his position at one end of tunnel, while subjects binocularly viewed the reading field from the opposite end. The brightness of the field was adjusted by lamps of variable voltage giving levels of brightness of 3, 10, and 31 foot-lamberts. Fourteen reading cards were divided into two groups, half with black numerals on white ground and half white on black. The numerals, made with a modified LeRoy lettering set, had seven different s.w/h ratios. Each card contained two rows of 15 numerals, each numeral appearing three times. Order was assigned by chance; except that no numeral appeared more than twice in a single row and no numeral appeared in immediate sequence. The first distance of presentation was 200 mm from the subject's corneas. The card was moved forward until the subject could read all numerals correctly. The criterion of legibility was the maximal distance of correct reading. The optimal stroke width to height ratio was between 14 and 20%. The effect of background was not significant.

Additional studies of stroke width were carried out by Brown and Lowery (1949), and Brown, Lowery, and Willis (1951). While these and other studies have resulted in some inconsistencies, none the less there seems to be at least a range of ratios which generally have turned out to be reasonably acceptable in terms of legibility. For black numerals on a white ground, this range of ratios is from 12% to about 18%; for white numerals on a black ground the ratios between 8% to 10% generally are more favorable.

To the author's knowledge no investigations have been made to determine the optimal s.w/height ratio of white numerals on a green background and white numerals on a blue background. These combinations of numerals and backgrounds are used extensively on United States highways, in addition to black numerals on a white background.

As far as the optimal s.w/h ratio of letters is concerned, Hodge (1962) compared the legibility of upper and lower case letters read individually, and determined the optimal s.w/h ratio for each letter case. The letters used in this study were 0.14 inches in height. The distance of recognition technique was used in that study, and upper case letters were found to be recognized at significantly greater distances than lower case letters. The optimal s.w/h ratios were 16% and 18% for the upper and lower cases, respectively.

Variability of Stroke Width Within Numerals

Soar (1958) developed new sets of arabic digits in which part of numerals were distorted in form and/or stroke width to emphasize a difference between them. The common elements were minimized and the unique elements were emphasized. Six of the experimental digits had less errors and proved to be significantly more visible than the usual arabic digits. The relative readability of different digits depends on the criterion used as a legibility measure, the stroke or form of numerals, and the stroke width. The digits 0, 3, 6, and 9 are most often confused with each other. They usually have curved rounded outlines.

Hughes (1961) varied the stroke width within a set of digits. He used eight types of digit configurations plus conventional arabic numerals. The results indicated that the symbolic numerals could be read at a greater distance and were significantly more visible than the conventional digits. Form and stroke width showed a significant interaction, supporting the conclusion that stroke width could vary within a set of digits or even within a single digit so as to increase the discriminability.

While designing numerals, two factors have to be taken into consideration, their legibility and their aesthetic quality. While these two need not be mutually exclusive, it is quite likely that numerals which are designed solely to be legible may not always be aesthetically pleasing, so some compromise has to be made. Thus even if legibility of numerals improves by varying the stroke widths within the numeral itself it may not be aesthetically pleasing to use such type of numerals.

Color and Contrast of Figure-Ground

The results of various experiments on legibility of black print on a white background and of white print on a black background conflict with each other.

Krischmann (1908), employing the method of indirect vision, discovered that both geometric forms and block capital letters were recognized at a greater distance when printed in white type on a black background than when printed in black type on a white background. There was a 16% advantage found for the white on black.

On the other hand, Scott (1903) stated that there is a tendency for black letters on a white background to be more readily perceived than white letters on black. Starch (1914) likewise found a 42% speed advantage in favor of black type on a white background when compared with white type on a dark grey background. Holmes (1931), using ten point type, found that words printed in black type on a white background were identified at a 14.7% greater distance than white type on a black background. Taylor (1943) contended that all of the four methods used by him in reckoning relative legibility of black and white print (6, 8, 10, 12, 14 point type) showed support of the black print on a white background. However, he reported in the same study that a "serifless style (Kabel Lite) was as legible as black on white or as white on black, except for the smallest-type size used."

Berger (1944) concluded that white single numerals with optimal stroke width can, on an average, be recognized at an 8.8% greater distance than black numerals on a white background with optimal stroke width. This conclusion should not be applied to groups, consisting of more than one single number, because then the spaces between the numbers must be considered separately.

From an experiment designed to settle the relative merits of black and white and using 11 point type, Crook (1947) found that "under conditions of the experiment, comparing white on black with black on white lettering, there was no significant difference in legibility for two conditions." Kuntz and Sleight (1950) found mean legible distances as follows: black numerals on a white background, 1.420 meters; white numerals on a black background, 1.419 meters; the difference was not statistically significant.

Case, Michael, Mount and Brenner (1952) used letters which appear in the American Optical Company Snellen Chart for visual acuity. Forty randomly selected groups of eight black and eight white letters could be read. The orders of appearance of the letters was not the same for both the black and white card of a particular pair. In addition, all of the eight different letters used did not necessarily appear on any single card, since the selection method resulted in some letters appearing more than once in a specific group. The matched pairs of letter groups were then fastened on black or white matte boards, twenty by thirty inches. Eight letters appeared on each board in two rows of four letters each. Ten of the twenty paired groups were placed on the boards so that there was one-and-a-half inches (half the letter height) between each of the letters in a row of four, and two inches between the two rows. The other ten pairs were spaced four inches between letters and four inches between the two rows.

In the analysis of data, a highly significant F was obtained for the interaction between letter-background arrangement and spacing, which means that the legibility of the two letter-background arrangements was not independent of the letter spacing. Black letters on a white background were readable at a greater distance when the letters were closely spaced, but this was not true when the letters were widely spaced.

Shurtleff, Botha and Young (1966) compared the brightness contrast of letters and concluded that the surrounding brightness for light letters significantly affected legibility.

These inconsistent results with regard to legibility of black and white may be of considerable interest because they raise the question of the effects of irradiation which conventionally has been explained in visual perception as "the apparent excess in size of a visual stimulus of relatively high intensity, e.g. of a white figure on a black ground compared with an equal black figure on white." It seems important to remember that there may be two different aspects involved in the phenomenon of irradiation:

1. the apparent difference in size when stimuli are well above visual threshold; and

2. the threshold of visibility for figures yielding the same contrast but with opposite figure and ground relationships.

There seems to be a paucity of information concerning the effects of the irradiation in these two situations. Again, if irradiation is to be used as an explanatory concept for certain problems in legibility, then the basic problem of figure-ground relationship may be of considerable importance.

Preston, Schwankl, and Tinker (1932) studied the effect of variations in color of print and background on legibility. The purpose of this experiment was to investigate the effect of variations in color of print and paper on perceptibility of isolated words, by determining the farthest distance from the eyes at which five-letter words could be read correctly. The stimulus material consisted of 64 easy five-letter words printed in 10-point, Scotch Roman, lower case type with Ruxton's colored ink on Rainbow coverstock. The trade names of various combinations of ink and paper used were: black jobbing on white, grass green on white, lustre blue on white, black jobbing on yellow, tulip red on yellow, tulip red on white, grass green on red, chromium orange on black, chromium orange on white, tulip red on green, and black jobbing on purple. The apparatus for determining legibility by the distance method consisted of an extended bench, along which moved a sliding carriage with the words to be read. The reading material was uniformly illuminated with an intensity of 34 foot-candles. The stimulus material was moved successively nearer the subject by eight-inch steps until every word was read correctly.

Blue print on white paper was found most legible, and red on green least legible. The color combinations that ranked high in legibility were the ones which had marked brightness contrast between print and background. Those which had poor legibility had comparatively little brightness contrast between print and paper.

McLean (1965) investigated the effects of color and brightness contrast, direction of contrast, and six contrast values upon the legibility of a circular dial. The brightness of four chromatic hues (yellow, blue, red, and green) was matched with four achromatic hues (gray 1, gray 2, gray 3, and gray 4). Hues were combined in all possible combinations excluding chromatic with achromatic, resulting in six contrast values. For both dark on light and light on dark contrast directions, the contrast values were equal. Half of the twenty-four subjects had pilot training and half did not. A Dodge type tachistoscope was used to present the stimulus conditions. Reading time results indicated that the addition of color contrast to a dial of a given achromatic brightness contrast value, with a light on dark contrast direction, will not degrade and may improve the legibility of that dial. Legibility was also found to increase as contrast value increased.

Williams (1967) agreed with Preston, Schwankl, and Tinker (1932) and McLean (1965) that contrast is an important variable affecting legibility. He used nine contrast conditions consisting of black or white lettering on white, black, or gray, and three levels of illumination, 0.06, 0.60, and 6.0 foot-candles. Eighteen subjects were asked to search a stimulus array for a particular stimulus and then indicate its relative position among other stimuli. Reaction time and errors were recorded. Illumination proved to be the single most important factor. Significant differences in performance were observed between the contrast conditions at 0.06 and 0.60 levels of illumination. Varying contrast had little effect on speed and accuracy of performance as long as illumination was 6.0 foot-candles. Black lettering on a white ground and white lettering on a black ground did not differ significantly and were associated with the shortest reaction times and the least number of errors at all light levels.

Illumination

Loucks (1944) and Brown, Lowery, and Willis (1951) have reported data suggesting an interaction of illumination level and stroke width, but did not test it. Loucks (1944) used different brightness levels, but did not quantify them. Brown, Lowery, and Willis (1951) used a range of illumination and brightness from 80 foot-candles to .35 millilamberts.

Kuntz and Sleight (1950) tested the interaction of illumination level and stroke width. They used brightness ranging from 3 to 31 foot-lamberts, and found that there is a consistent trend for legible distance to increase with increase in illumination from 3 to 31 foot-lamberts. Thus they inferred that there was no interaction of illumination level and stroke width. Shapiro (1951) also suggested that there was no interaction, but he did not specify the brightness employed.

Soar (1955) concluded that illumination level showed a highly significant influence on numeral visibility. The three variables used were stroke width, color and contrast of figure-ground, and illumination at 0.5 and 500 foot-candles. The interaction of stroke width and illumination level was significant with wider stroke widths being optimal under low illumination. Illumination level did not interact with figure-ground contrast.

Allen (1958) conducted his study in the field on a straight flat section of rural highway near the University of Virginia. An overhead sign was mounted near one end of the section, and a road sign near the other. Both the signs used were positioned to be representative of sign positions on the Interstate System. The overhead sign was located over the travelled line, with the center of the sign twenty feet above the pavement. The center of the roadside sign was twelve feet above the level of pavement and twenty feet to the right of the pavement edge. Four-letter words, using only ten letters of the alphabet, ACEIKORSTY, were used as messages on the signs. The stroke width of the letters was 20% of letter height. The four levels of artificial illumination used were 0.1, 1, 10, and 100 foot-lamberts. Subjects sat in the front seat beside the driver, and had no task but reading the signs. The car approached the test sign at about fifteen mph. As soon as the observer could read the test sign he spoke the message word. When the sign was read correctly, a recorder seated in the back seat read the distance from an odometer or from stakes at the side of the road.

The results obtained in this study showed that when illumination was too low, legibility distance was low; as illumination increased to an optimum value of 10 foot-lamberts, the legibility distance reached a maximum; when illumination was 100 foot-lamberts legibility was less.

Allen, Smith, Janson and Dyer (1966) used illuminated letters which were made to specifications for Interstate guide signs. The signs permitted only three-letter words, which did not differ greatly in legibility distance. The forty-eight-inch square sign was mounted on a hydraulically lifted platform on a truck. In addition, messages could be quickly changed for either white letters on a dark background or dark letters on a light background. Five levels of sign luminance were used: 0.2, 2, 20, 200, and 2000 foot-lamberts. Observers seated in the front seat with the driver were instructed to read the sign messages as soon as possible, and to continue reading until told their response was correct. The experimenter recorded the fifth wheel odometer readings at the instant of correct response. The vehicle speed was maintained at approximately fifteen mph.

Without headlight glare, the sign at 0.2 foot-lamberts was read at over twice the distance in the lowest ambient illumination (dark open road) than in high ambient illumination (downtown). The reverse was true for the sign at 2000 foot-lamberts; it was read about ten per cent farther away at the high ambient illumination. Legibility distances for the medium ambient illumination (typical luminaires) were intermediate between those for the extremes.

Contradictory results of the above studies indicate that further research should be accompanied by specification of the illumination level employed since the results obtained at one illumination level will not transfer to widely different illumination levels. Conversely, the optimal stroke width for each mode of figure-ground will need to be determined for a wide range of illumination. Application can then be made in terms of the level of illumination and mode of figure-ground which is to exist in practice.

<u>Height to Width Ratio</u>

The effect of height to width ratio on legibility of numerals was explored by Berger (1944); he found that a ratio of 1·9:1 was optimal. Bartlett and Mackworth (1950) found that numerals with height to width ratio of 1·4:1 were most legible.

Lauer (1947) concluded that block letters of equal height and width have best legibility. Brown (1953) used capital block letters of various height to width ratios. The letters were presented under transillumination conditions and also under simulated daylight conditions to one hundred and twenty Navy enlisted men. Each man was shown twenty groups under various controlled illumination and time conditions. Errors in reading were recorded. It was found that capital block letters with height to width ratio of

1·4:1, 1·2:1, and 1:1 were distinctly superior to the narrower ones, those with the height to width ratio of 1·9:1. From the above studies it seems that range of ratios from 1:1 to 1·4:1 are likely to be most satisfactory and practicable.

Numeral Size

Forbes and Holmes (1939) suggested a numeral height of 0.020 in/ft of reading distance. Bartlett and Mackworth (1950) inferred that a reasonable numeral height was 0.032 in/ft. Smith (1952) conducted an experiment on outdoor signs in daylight illumination, and agreed with results of Forbes and Holmes (1939). These figures seem to be too low. The typing on this page is 0.1 inch high; at a typical reading distance of 18 inches, the ratio would be 0.07 in/ft. Brown (1953) suggested a numeral height of 0.060 in/ft of reading distance.

The factors which should be taken into consideration in selecting the size of numerals for use as labels or markings are: illumination, reading conditions, distance, and the importance of accuracy. A formula has been developed by Peters and Adams (1959) that takes into account all the above factors. The formula is given below:

H (height of the numerals in inches) = $0.0022\ D + K_1 + K_2$

where

D = viewing distance in inches

K_1 = correction factor for illumination and viewing conditions in inches ($K_1 = 0.06$ above 1.0 fc, favorable reading conditions; $K_1 = 0.12$ above 1.0 fc, unfavorable reading conditions)

K_2 = correction for importance (for important items such as emergency labels, $K_2 = 0.075$ inches; for all other conditions, $K_2 = 0.0$)

THIS BOOK CONTAINS NUMEROUS PAGES WITH MULTIPLE PENCIL MARKS THROUGHOUT THE TEXT.

THIS IS THE BEST IMAGE AVAILABLE.

PROBLEM

From the literature survey it was observed that some work has been done pertaining to legibility of numerals. This thesis investigated legibility of "NAMEL" numerals under three levels of illumination, six levels of s.w/ height, and four different colors of figure-ground.

METHOD

Apparatus

The four colors of figure-ground used in this study were:

1. Black numerals on white ground. Munsell color specifications for the white ground were: Hue number 20.0, hue symbol 10.0 YR, value 9, and chroma 0.
2. White numerals on black ground. Munsell color specifications for the black ground were: Hue number 35.0, hue symbol 5.0 GY, value 1, and chroma 0.
3. White numerals on blue ground. Munsell color specifications for the blue ground were: Hue number 77.5, hue symbol 7.5 PB, value 2, and chroma 2.
4. White numerals on green ground. Munsell color specifications for the green ground were: Hue number 40.0, hue symbol 10.0 GY, value 5, and chroma 2.

The three illumination levels were:

1. 90 foot-candles.
2. 45 foot-candles.
3. 10 foot-candles.

The six different S.W/H ratios were:

8, 9, 10, 12, 15, and 18%.

Twenty-four reading cards (27 x 11 inches) were divided into four groups: six with black numerals on a white ground, six with white on a black ground, six with white on a green ground, and six with white on a blue ground. Each card contained one row of ten numerals with a particular ratio, each numeral appearing one time (Plate No. 1). The numerals were of "Navy Aeronautical Medical Equipment Laboratory proposed numeral form" (abbreviated NAMEL) and were 3 inches in height with 1.2 inches spacing between them. The sequence of ten numerals on the reading cards was assigned from a random numbers table. The sequence of numbers on each reading card is given in Table 1.

The reading card was mounted on a wooden frame, which in turn was mounted on a tripod (Plate No. 2). The reading cards were illuminated at 90, 45, and 10 foot-candles respectively with cool white fluorescent lamps. The illumination level was determined by a General Electric foot-candle meter, Model 213 (color and cosine corrected), on the surface of the reading card. This method of determining illumination level on the surface of reading card was very crude. Another point which the experimenter wishes to make is the equipment (lamps) which were used to provide illumination were not sophisticated enough, and the condition of constant illumination was not achieved on the surface of reading card at any stage of the experiment.

Task

The initial card-to-subject distance was two hundred and forty-six feet. The subject walked towards the card in steps of three feet, and the maximum distance from which subject was able to read correctly any five

PLATE 1

Cards Containing One Row Of Ten Numerals With
A Particular Ratio, Each Numeral Appearing One Time.


4189253067
3076924851
7452163089
6095473218

THIS BOOK CONTAINS NUMEROUS PICTURES THAT ARE ATTACHED TO DOCUMENTS CROOKED.

THIS IS AS RECEIVED FROM CUSTOMER.

PLATE 2

Reading Card Mounted On A Wooden
Frame Which In Turn Is Mounted On A Tripod.


1084275639
3076924851
4697815023

Table 1

Sequence of Numbers On Each Reading Card

S.W/Height	Black On White	White On Black	White On Blue	White On Green
8%	1508723946	2140378965	5032496718	3076924851
9%	9127350846	6281407593	0826395741	0387516924
10%	7452163089	4697815023	6257049381	1086374295
12%	2895640217	6095473218	4189253067	6523807194
15%	1084275639	3812570964	8541629037	2481973650
18%	0428635971	8659142730	9284371560	9134278506

digits on the card was recorded. This distance served as one of the criteria. After recording this distance, the subject continued to walk towards the card, and the maximum distance from which the subject was able to read correctly all ten digits was recorded. This distance served as the second criterion. After reading correctly all the ten numerals on the card the subject told the experimenter which particular numeral was most difficult to read; this number was recorded.

The three different levels of illumination on the reading card were achieved with the help of overhead and table lamps. The position of the overhead lamp was fixed at all times, while the distance, and inclination of the table lamp to the reading card was changed in order to achieve the necessary level of illumination. By lowering the height of tripod on which the reading card was mounted, the distance between the reading card and the overhead lamp was changed, which also helped in achieving the desired level of illumination. Thus by manipulating the height of the tripod and the distance between it and the table lamp, the desired level of illumination on the reading card was achieved.

The subjects were given instructions not to give a response until they were reasonably confident or could see the digit well. Incorrect responses were not scored, and the experimenter told them that a mistake had been made, and asked them to walk further towards the card and give a new response.

Each subject was given oral instructions about the task before the commencement of experiment.

Subjects

Six male engineering graduate students at Kansas State University were paid $1.50/hour. All had normal vision, or optically corrected normal

Table 2. Sequence of Illumination Level Followed by the Subjects.

Subject	Illumination Level in Foot-Candles
1	45, 10, 90
2	90, 10, 45
3	10, 45, 90
4	90, 45, 10
5	10, 90, 45
6	45, 90, 10

vision. Average age of the subjects was 25 years. The experimenter intentionally selected engineering graduate students as subjects, because they know the importance of these kinds of experiments, and therefore take the experimentation seriously. Every student was also free to drop out from the experiment after the completion of the first trial, if he thought that the reading task was too fatiguing for his eyes. Out of the six students who were originally to serve as subjects, two dropped out after the completion of the first trial. Two new students were added, who completed the experiment successfully.

Experimental Procedure

The experiment was conducted in the hallway of the third floor of the Physical Science building at Kansas State University. The length of the hallway was approximately 250 feet. The reading cards were mounted on a wooden frame, which in turn was mounted on a tripod. The tripod was placed at one end of the hallway (Plate No. 3), and its position on the floor was marked. From this position, distances at the interval of three feet were marked off on the floor of the hallway for two hundred and forty-six feet.

One subject was tested at a time at an illumination level. For every card, the initial card-to-subject distance was two hundred and forty-six feet. A trial for a subject consisted of one round through the entire set of reading cards. The subject was not given more than one trial on the same day. The subject was asked to read at each condition twice. The sequence of illumination level followed by the subjects is given in Table 2. The reading cards were reassembled in random order for each trial; the sequence at which they were shown to subjects is given in Tables 3, 4, and 5.

The experiment was originally scheduled to last for six days, each

PLATE 3

View Of The Hallway.

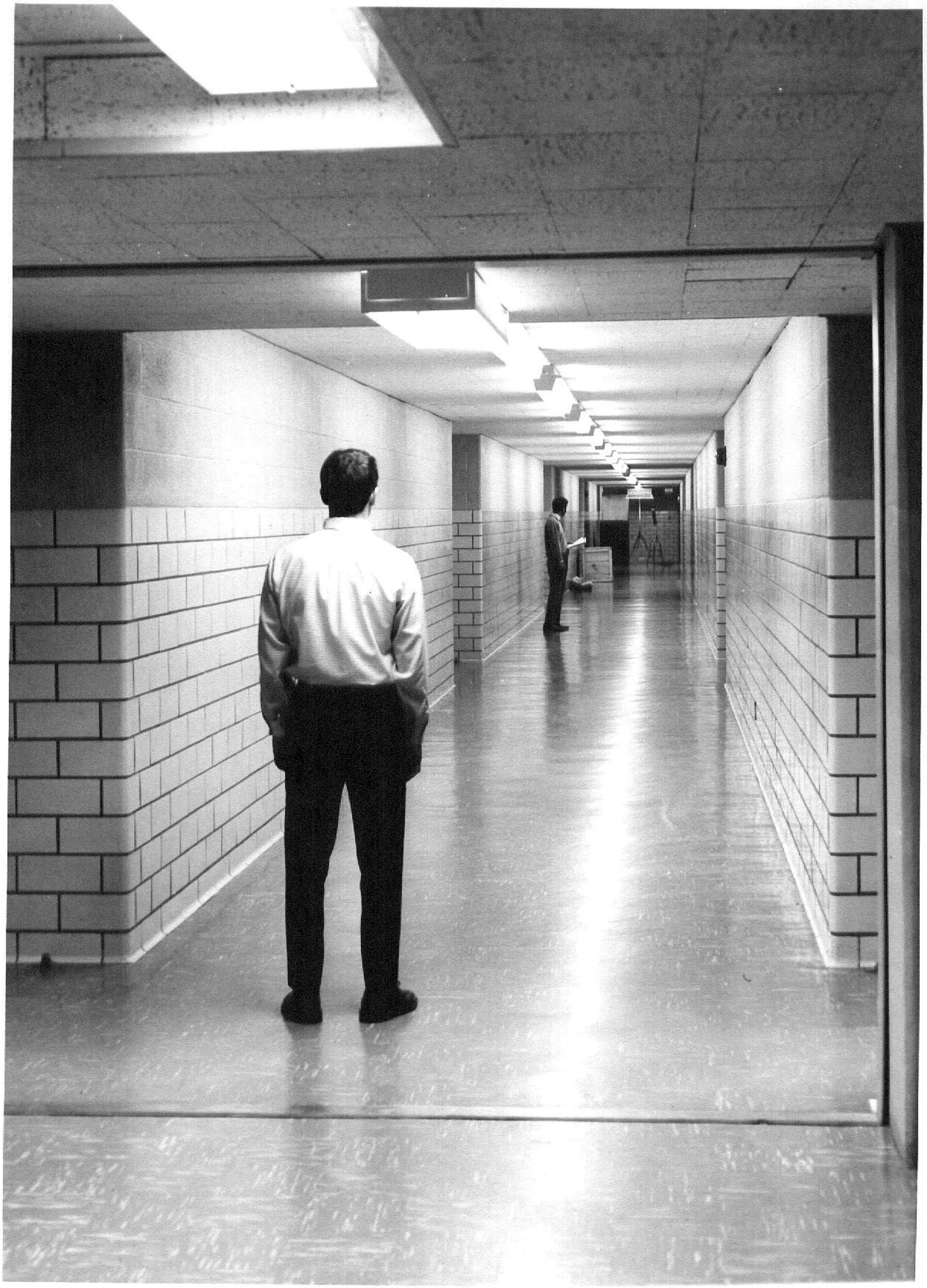

Table 3. Sequence Of Presentation Of Reading Cards To Subjects At Illumination Level Of 90 Foot-Candles.

		STROKE WIDTH TO HEIGHT RATIO																							
Sub-ject	Trial	Black On White						White On Black						White On Green						White On Blue					
		8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%
1	1	5	1	17	2	4	16	3	20	23	18	11	7	24	12	15	10	22	9	21	6	19	13	8	14
	2	11	24	9	15	12	6	5	3	21	17	8	14	10	13	1	18	4	20	2	7	22	16	23	19
2	1	6	21	8	16	24	10	12	17	3	20	1	13	11	2	23	15	5	9	14	22	7	19	4	18
	2	24	6	10	7	2	19	15	9	4	21	13	1	22	11	8	18	16	14	3	5	17	20	12	23
3	1	18	12	1	10	11	23	9	14	4	6	22	2	13	5	7	15	8	16	3	17	19	24	21	20
	2	19	7	8	22	16	2	12	23	11	5	17	21	18	6	20	3	13	14	1	4	10	9	15	24
4	1	12	4	5	18	9	11	1	7	8	24	21	19	14	2	10	15	3	23	13	17	6	16	20	22
	2	10	12	5	17	20	7	1	11	18	19	15	24	9	8	2	16	14	13	21	23	3	22	6	4
5	1	2	17	23	9	11	24	6	10	19	4	21	20	12	7	5	22	1	8	14	16	13	3	15	18
	2	19	10	4	22	3	14	17	5	16	6	24	11	9	7	2	13	8	23	18	1	21	12	20	15
6	1	12	1	14	19	15	8	3	13	20	24	11	9	4	22	21	2	17	16	23	6	10	5	18	7
	2	8	19	24	15	10	22	6	2	14	23	5	13	12	18	11	9	1	21	4	7	3	16	20	17

Table 4. Sequence Of Presentation Of Reading Cards To Subjects At Illumination Level Of 45 Foot-Candles.

		STROKE WIDTH TO HEIGHT RATIO																					
		Black On White						White On Black						White On Green						White On Blue					
Subject	Trial	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%
1	1	6	21	8	16	24	10	12	17	3	20	1	13	11	2	23	15	5	9	14	22	7	19	4	18
	2	24	6	10	7	2	19	15	9	4	21	13	1	22	11	8	18	16	14	3	5	17	20	12	23
2	1	18	12	1	10	11	23	9	14	4	6	22	2	13	5	7	15	8	16	3	17	19	24	21	20
	2	19	7	8	22	16	2	12	23	11	5	17	21	18	6	20	3	13	14	1	4	10	9	15	24
3	1	12	4	5	18	9	11	1	7	8	24	21	19	14	2	10	15	3	23	13	17	6	16	20	22
	2	10	12	5	17	20	7	1	11	18	19	15	24	9	8	2	16	14	13	21	23	3	22	6	4
4	1	2	17	23	9	11	24	6	10	19	4	21	20	12	7	5	22	1	8	14	16	13	3	15	18
	2	19	10	4	22	3	14	17	5	16	6	24	11	9	7	2	13	8	23	18	1	21	12	20	15
5	1	12	1	14	19	15	8	3	13	20	24	11	9	4	22	21	2	17	16	23	6	10	5	18	7
	2	8	19	24	15	10	22	6	2	14	23	5	13	12	18	11	9	1	21	4	7	3	16	20	17
6	1	18	22	11	16	24	20	18	19	13	15	1	2	19	5	23	21	3	14	12	16	6	4	7	10
	2	23	9	10	11	16	18	4	3	15	13	24	21	20	19	17	14	22	12	7	2	5	8	6	1

Table 5. Sequence Of Presentation Of Reading Cards To Subjects At Illumination Level Of 10 Foot-Candles.

		STROKE WIDTH TO HEIGHT RATIO																							
Sub-	Trial	Black On White						White On Black						White On Green						White On Blue					
ject		8%	9%	10%	12%	15%	18%	3%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%	8%	9%	10%	12%	15%	18%
1	1	18	12	1	10	11	23	9	14	4	6	22	2	13	5	7	15	8	16	3	17	19	24	21	20
	2	19	7	8	22	16	2	12	23	11	5	17	21	18	6	20	3	13	14	1	4	10	9	15	24
2	1	12	4	5	18	9	11	1	7	8	24	21	19	14	2	10	5	3	23	13	7	6	16	20	22
	2	10	12	5	16	20	7	1	11	18	19	15	24	9	8	2	16	14	13	21	23	3	22	6	4
3	1	5	1	16	2	4	16	3	20	23	18	11	7	24	12	15	10	22	9	21	6	19	13	8	14
	2	11	24	9	15	12	6	5	3	21	17	8	14	10	13	1	18	4	20	2	7	22	16	23	19
4	1	6	21	8	16	24	10	12	17	3	20	1	13	11	2	23	15	5	9	14	22	7	19	4	18
	2	24	6	10	7	2	19	15	9	4	21	13	1	22	11	8	18	16	14	3	5	17	20	12	23
5	1	18	22	11	17	24	20	18	19	13	15	1	2	19	5	23	21	3	14	12	16	6	4	7	10
	2	23	9	10	11	16	18	4	3	15	13	24	21	20	19	16	14	22	12	7	2	5	8	6	1
6	1	9	6	7	22	18	15	3	14	13	19	21	24	4	1	8	20	17	10	12	16	2	5	11	23
	2	20	19	10	24	11	5	13	3	23	21	18	15	14	4	16	16	2	6	19	1	7	8	12	22

subject going through one trial every day for six days. But since all the subjects were busy students and the experimenter had to take into account their convenience, it took thirteen days to complete the experiment.

No instructions were given as to the rest periods or means of reducing eye strain. The subjects were free to view the signs in whatever manner they chose. Nor were they told the exact nature of the experiment; however, this was obvious to most of them after a few of the reading cards were shown.

RESULTS

A total of 1728 scores were obtained, 288 from each of the six subjects. Of the total scores, 864 were obtained when the criterion of legibility was the distance at which any five numerals on the reading card were read correctly. The remaining 864 scores were obtained when the criterion of legibility was the distance at which all the ten numerals on the reading card were read correctly. The total distance for all conditions for all ten numerals for trial 1 for subject 1 was 13059 feet; the total for trial 2 was 13509 feet; the ratio was 98%. The ratios for the remaining 5 subjects were 99.5, 99.5, 97.5, 92, and 95%. Therefore the distances for trial one and trial two were totaled for each condition for each subject to give 432 distances for the "five numeral" distance and 432 for the "ten numeral" distance.

The first analysis was the two analyses of variance as summarized in Table 6. The criterion for the first analysis of variance was the mean legibility distance of two trials at which any five numerals on the reading card were read correctly. Similarly the criterion for the second analysis of variance was the mean legibility distance of two trials at which all ten numerals on the reading card were read correctly.

Illumination level and figure-ground contrast were statistically significant ($p < .01$), but the stroke width/height ratio was not; this was true for both the analyses of variance. The various interactions were also nonsignificant. The error mean square term in both the analyses of variance table was very large; probably due to subject variability. The mean for five numerals was 202.7 feet, and for ten numerals was 187.4 feet.

Table 6

Analyses of variance where the criteria of legibility are the distance at which any five numerals were read correctly, and the distance at which all ten numerals were read correctly.

Source of Variation	DF	Five Numerals Mean Square	Five Numerals F	Ten Numerals Mean Square	Ten Numerals F
Illumination(I)	2	11921.13	11.95*	10690.54	10.90*
Figure-Ground Contrast(C)	3	13080.66	13.12*	14269.69	14.55*
Stroke Width to Height Ratio(R)	5	294.11	0.29	1000.38	1.02
I x C	6	388.59	0.38	243.47	0.24
I x R	10	201.64	0.20	335.77	0.34
C x R	15	401.54	0.40	345.42	0.35
I x C x R	30	114.19	0.11	124.92	0.12
Residual	360	996.97		980.15	
Total	431				

* $p < .01$

Since by visual inspection the distribution of the means and variances of the various conditions were approximately the same whether the distance for five or ten numerals was used, all the future analyses will use distances for ten numerals.

It was decided to normalize the data to reduce the subject variability. The mean legibility distance for the subject 1 of 184.5 feet was subtracted from the value for each condition for subject 1. The same procedure was repeated to normalize the data of the rest of the subjects. The statistical analyses were all done with normalized data to determine which conditions were significantly different from each other. The data, however, is reported as the actual distances at which the subjects read.

Table 7 gives the analysis of variance for the normalized data, where the criterion was the mean distance of the two trials at which all ten numerals on the reading card were read correctly. The variables were the same as in Table 6. From Tables 6 and 7, it can be seen that the mean square for the effects were approximately same, but the residual term was drastically reduced. Use of normalized data also makes the use of subjects as replications and as a fixed factor in the model for ANOVA more valid. The effects of illumination and figure-ground contrast were statistically significant at $p < .01$, while the effect of stroke width/height ratio was significant at $p < .05$. None of the interactions were significant.

Duncan's New Multiple Range Test was used to test the differences between means. See Figure 1 and Table 8 for the effect of illumination. The mean distance of 192.4 feet at 90 foot-candles was significantly ($p < .01$) greater than the 185.3 feet at 10 foot-candles and the 184.6 feet at 45 foot-candles (a distance of 160 feet for these 3-inch numerals is equivalent to

Table 7

Analysis of variance for normalized data, where the criterion was the distance at which all ten numerals were read correctly.

Source of Variation	DF	Mean Square	F
Illumination(I)	2	10923.47	31.31*
Mode of Figure Ground Contrast(C)	3	13886.52	39.81*
Stroke Width to Height Ratio(R)	5	967.67	2.77**
I x C	6	198.56	0.56
I x R	10	368.14	1.05
C x R	15	353.08	1.01
I x C x R	30	111.81	0.32
Residual	360	348.78	
Total	431		

* $p < 0.01$

** $p < 0.05$

Table 8

Results of DNMR test as applied to illumination levels of 90, 45, and 10 foot-candles.

Illumination Level	Mean Legibility Distances in Feet
90	192.4
10	185.3
45	184.6

Mean legibility distances underlined by the same line are not significantly ($p < 0.01$) different from each other.

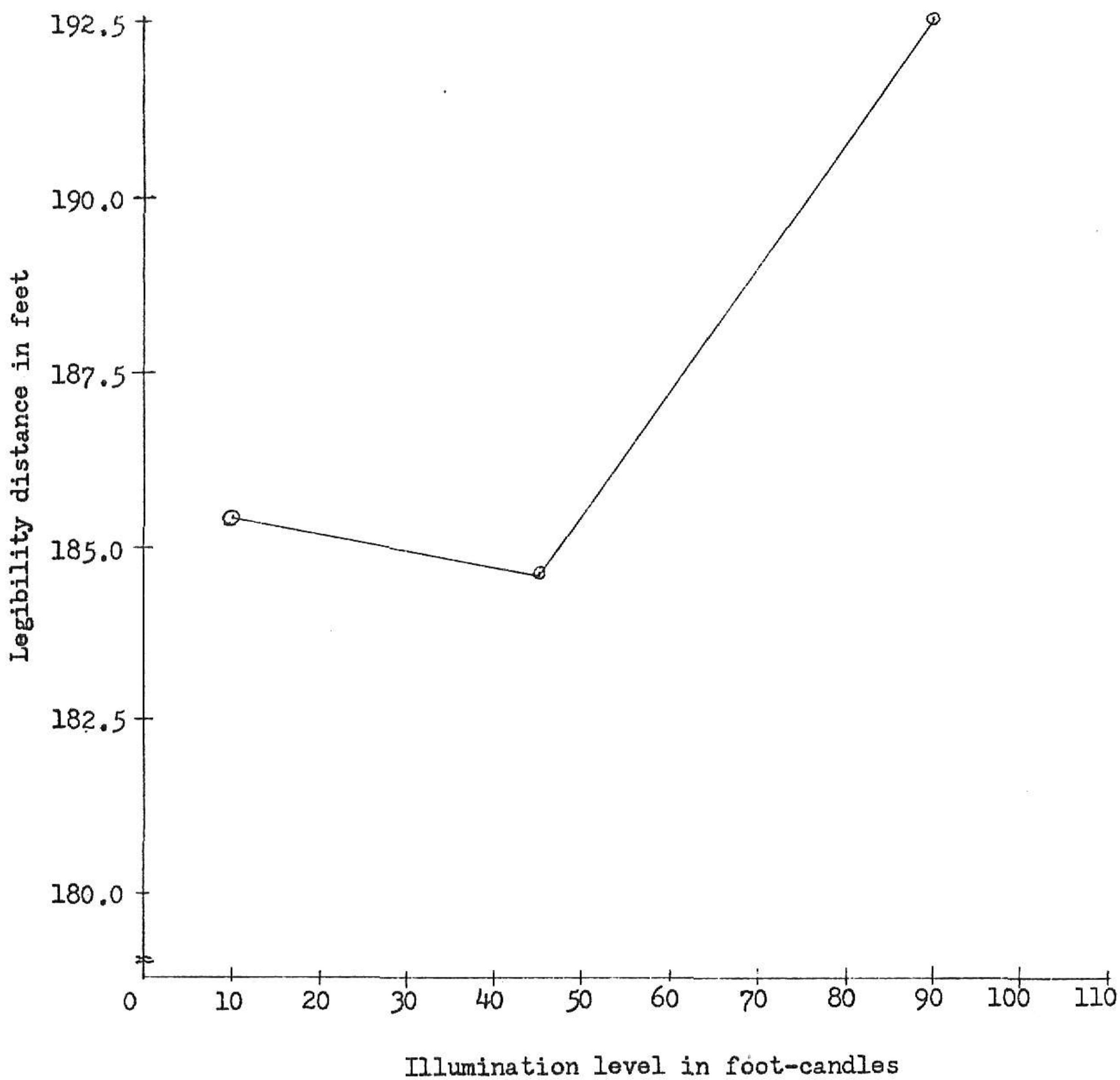

Figure 1. Illumination level vs mean legibility distance.

5.5 minutes of arc, 170 feet is 5 minutes, 180 feet is 4.5 minutes and 190 feet is 4 minutes). The difference between the 184.6 feet at 45 foot-candles and the 185.3 feet at 10 foot-candles was not significant.

Figure 2 and Table 9 show the means of the four figure-ground contrasts: black numerals on a white ground, white numerals on a black ground, white numerals on a blue ground, and white numerals on a green ground. The mean legibility distance of 193.9 feet for white numerals on a black ground was significantly better than the other three combinations. The 190.3 feet for white numerals on a blue ground was significantly ($p < .01$) better than the black numerals on a white ground and white numerals on a green ground. The 184.4 feet for black numerals on a white ground was not statistically better than the 181.1 feet of white numerals on a green ground.

Figure 3 and Table 10 give the effect of stroke width for the various backgrounds. There was no statistically significant difference found between the mean legibility distances for stroke width/height ratios of 8, 9, 10, 12, and 15%, but 18% was significantly ($p < .05$) worst.

Closer examination of individual curves indicated that even though ANOVA had indicated that s.w/height x figure-ground interaction was not significant, a paired comparison test should be used instead of an independent groups test such as ANOVA. A Wilcoxon Matched-Pairs Signed-Rank Test was used to test the difference between means of different stroke width/height ratios. See Figure 3 and Tables 11, 12, 13 and 14.

For black numerals on a white ground it seems that the optimal s.w/height ratio lies between 9% to 12%. For white numerals on a black ground, there seems to be a general decline in the legibility when stroke width/height ratio was increased from 8%. To determine the optimal stroke

Table 9

Results of DNMR test as applied to figure-ground contrast.

Figure-Ground Contrast	Mean Legibility Distances In Feet
White/Black	193.9
White/Blue	190.3
Black/White	184.4
White/Green	181.1

Mean legibility distances underlined by the same line are not significantly ($p < 0.01$) different from each other.

Table 10

Results of DNMR test as applied to different stroke width/height ratios (all figure-grounds combined).

Stroke Width/Height Ratio	Mean Legibility Distances In Feet
12%	189.1
8%	188.8
10%	188.3
9%	187.3
15%	187.1
18%	184.0

Mean legibility distances underlined by the same line are not significantly ($p<0.05$) different from each other.

Table 11

Results of Wilcoxon Matched-Pairs Signed-Rank Test as applied to different Stroke Width/Height Ratios of Black Numerals on a White Ground.

Stroke Width/Height Ratio	Mean Legibility Distances In Feet
10%	188.0
12%	186.7
9%	185.0
8%	184.4
15%	181.1
18%	181.0

Mean legibility distances underlined by the same line are not significantly ($p < 0.05$) different from each other.

Table 12

Results of Wilcoxon Matched-Pairs Signed-Rank Test as applied to different Stroke Width/Height Ratios of White Numerals on a Black Ground.

Stroke Width/Height Ratio	Mean Legibility Distances In Feet
8%	198.5
10%	195.4
9%	194.7
12%	194.0
15%	192.5
18%	188.1

Mean legibility distances underlined by the same line are not significantly ($p < 0.05$) different from each other.

Table 13

Results of Wilcoxon Matched-Pairs Signed-Rank Test as applied to different Stroke Width/Height Ratios of White Numerals on a Blue Ground.

Stroke Width/Height Ratio	Mean Legibility Distances In Feet
8%	192.5
12%	191.4
15%	191.2
9%	190.4
10%	189.5
18%	186.8

Mean legibility distances underlined by the same line are not significantly ($p < 0.05$) different from each other.

Table 14

Results of Wilcoxon Matched-Pairs Signed-Rank Test as applied to different Stroke Width/Height Ratios of White Numerals on a Green Ground.

Stroke Width/Height Ratio	Mean Legibility Distances In Feet
12%	184.2
15%	183.3
10%	180.5
18%	180.0
8%	179.6
9%	179.3

Mean legibility distances underlined by the same line are not significantly ($p < 0.05$) different from each other.

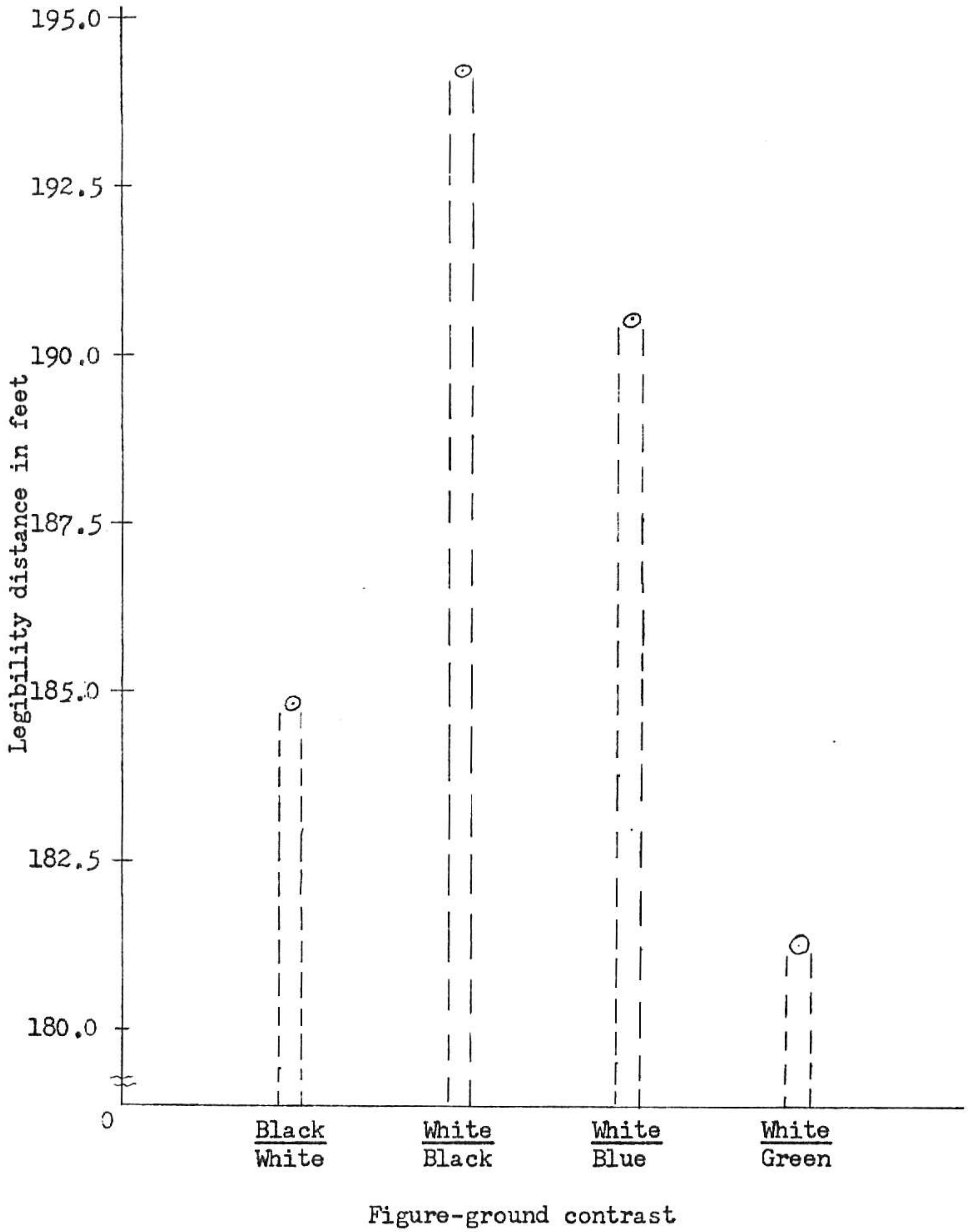

Figure 2. Figure-ground contrast vs mean legibility distance.

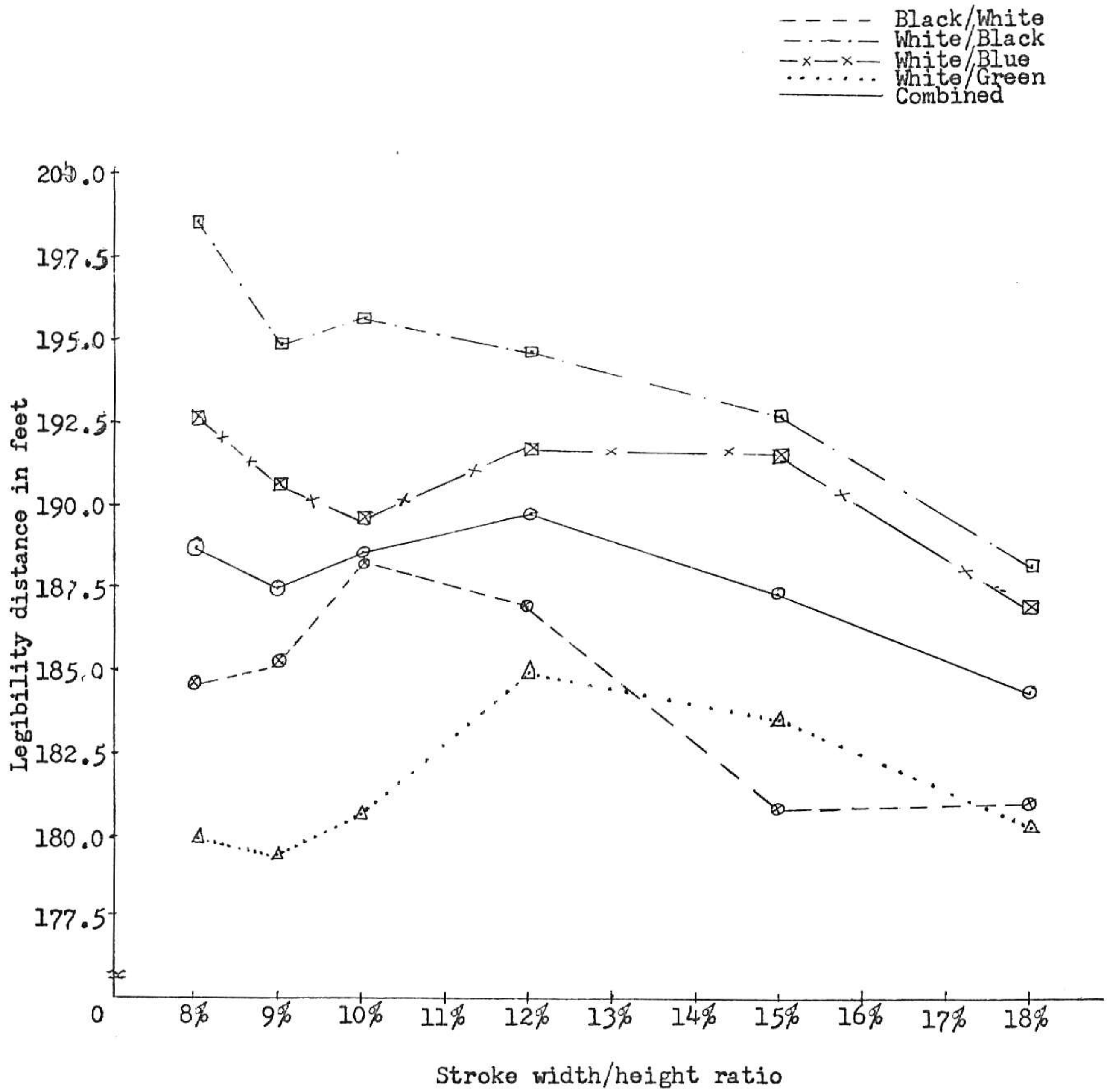

Figure 3. Stroke width/height ratio vs mean legibility distance.

width/height ratio for this figure-ground, investigation at stroke width/height ratios of 5, 6, and 7% probably would be desirable. For white numerals on a blue ground, the curve shape is generally similar to that of white on black. Optimum seems to be at low values, with a decline as the stroke width/height ratio increases. For white numerals on a green ground, the optimum is around 12 to 15% with legibility declining as stroke width/height ratio is increased or decreased from this.

Table 15 gives the frequencies of most difficult numerals on the 864 presentations of the reading cards grouped by figure-ground. For the reading cards which had black numerals on white ground, the numbers which posed maximum difficulty in reading were 8, 6, and 3 in that order. For reading cards which had white numerals on a black ground, the numbers which were most difficult to read were 8, 3, and 6. For white numerals on a blue ground and on green the difficult numbers were again 8, 3, and 6.

Table 16 gives the frequencies of most difficult numerals on the 864 presentations of the reading cards grouped by stroke width/height. For stroke width/height ratios of 8, 9, 10, and 15% the numbers which were most difficult to read were 8, 6, and 3. For a stroke width/height ratio of 12% the numbers which were most difficult to read were 8, 3, and 9. The numbers which were most difficult to read for a stroke width/height ratio of 18% were 8, 0, and 3.

Thus it seems that 8 is the "NAMEL" numeral that most needs redesign, with 3 and 6 also candidates. 1 and 7 seem quite satisfactory. If the five most difficult numerals could be made as readable as the five easiest, the mean distance of legibility could be increased from 187.4 feet to 202.7 feet or an improvement of 8%.

Table 15

Frequencies of most difficult numerals on 864 presentations of reading cards. (All illumination levels and stroke width/height ratios included.)

Number	Figure-Ground Contrast: Black/White	White/Black	White/Blue	White/Green	Total
0	9	14	8	13	44
1	0	0	0	0	0
2	4	13	18	11	46
3	32	60	33	54	179
4	7	8	17	9	41
5	14	8	15	11	48
6	39	35	30	24	128
7	3	0	0	0	3
8	90	68	85	82	325
9	18	10	10	11	50
Total	216	216	216	216	864

Table 16

Frequencies of most difficult numerals on 864 presentations of reading cards. (All illumination levels and figure-ground contrasts included.)

Number	Stroke Width/Height Ratio 8%	9%	10%	12%	15%	18%	Total
0	5	2	2	5	4	26	44
1	0	0	0	0	0	0	0
2	10	8	7	10	8	3	46
3	22	51	36	23	29	18	179
4	3	8	9	3	13	5	41
5	6	9	7	12	3	11	48
6	38	27	20	13	23	7	128
7	0	0	2	1	0	0	3
8	52	39	50	63	56	66	325
9	8	1	11	14	8	8	50
Total	144	144	144	144	144	144	864

DISCUSSION AND CONCLUSIONS

Illumination Level

Illumination level had a significant influence on numeral visibility. There was no significant difference in numeral visibility when illumination level was increased from 10 foot-candles to 45 foot-candles. However, numeral visibility increased significantly when illumination level was increased from 45 to 90 foot-candles. From these results, a level of illumination which will have optimal numeral visibility cannot be specified. Further research should be conducted using a wider range of illumination levels.

There was no significant interaction between illumination levels and figure-ground contrasts, which agrees with the results of Kuntz and Sleight (1950) and Shapiro (1951). This means that the same illumination levels can be used for optimal numeral visibility irrespective of figure-ground contrasts. The interaction was not significant between illumination level and s.w/h ratios, which implies that the optimal s.w/h ratio does not change with illumination level.

Figure-Ground Contrast

Figure-ground contrast had a significant influence on numeral legibility, which agrees with McLean (1965), and Williams (1967). White numerals on a black ground were read at a greater distance (statistically significant) than white numerals on a blue ground, black numerals on a white ground, or white numerals on a green ground. White numerals on a black ground and white numerals on a blue ground were significantly more legible than black numerals on a white ground. A possible explanation for this lies in the phenomena of irradiation; according to which a bright object on a dark background appears to be wider than a similarly-sized dark object on a bright background. Such irradiation was observed in the numerals used in this study. The white ones appeared to be considerably wider than the black ones. Conversely it may be that black numbers were affected in an opposite manner and seemed narrower due to irradiation of the white areas surrounding them.

Numerals with poor contrast such as white on green were inferior to numerals with greater contrast such as white on black.

Stroke Width/Height Ratios

The conclusion that there is interaction between stroke width/height ratios and figure-ground agrees with Berger (1944) and Brown and Lowery (1949). Thus for each figure-ground an optimal stroke width/height ratio should be determined. The optimal s.w/height ratios determined in this study will only hold good for the figure-grounds for which they have been determined.

Numeral Design

For the "NAMEL" design, the numerals which were most difficult to read were 8, 3, and 6. It is suggested that these numerals should be redesigned. Some of the possibilities are the variation of stroke width within the digit, use of symbolic digits instead of conventional arabic digits, and use of a thinner s.w/height just for the numeral eight.

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THE EFFECT OF STROKE WIDTH, ILLUMINATION LEVEL, AND FIGURE-GROUND CONTRAST ON LEGIBILITY OF NUMBERS

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ABSTRACT

Stroke width to height ratios of numerals 3 inches in height and of NAMEL form were studied at illumination levels of 10, 45, and 90 foot-candles. Twenty-four reading cards were divided into four groups, six with black numerals on a white ground, six with white numerals on a black ground, six with white numerals on a blue ground, and six with white numerals on a green ground. There were six different S.W/H ratios: 8, 9, 10, 12, 15, and 18%. Each card contained one row of ten numerals with a particular S.W/H ratio, each numeral appearing one time. Six male graduate students at Kansas State University served as subjects. The subject was asked to walk towards the card, and the maximum distance from which subject was able to read all ten digits correctly was recorded. The criterion was the maximum distance of correct reading.

The effects of illumination level, color and contrast of figure-ground, and S.W/H ratio were statistically significant. No interactions were significant. The distance to read all ten digits correctly was 192 feet for 90 foot-candles, 185 for 10 foot-candles, and 184 for 45 foot-candles. For figure-ground, the 194 of white on black was best; second was white on blue with 190; third was black on white with 184; and last was white on green with 181. Stroke width was optimum at 12% with a value of 189; worst was 18% with 184. 8, 3, and 6 were the numbers most difficult to read.