Review of Legibility Relationships Within the Context of Textual Information Presentation

HELMUT T. ZWAHLEN, MURALI SUNKARA, AND THOMAS SCHNELL

An extended review of the relevant legibility literature was conducted to provide normalized legibility performance data for a comparison and consolidation of past legibility research. The data were normalized by expressing the legibility performance in terms of visual angle subtended by the character height. The data revealed large variations in visibility performance among the reviewed studies, despite similar or even identical experimental treatments. The normalized data were grouped into sets, relating the visual angle to the width-to-height ratio W/H, the intercharacter spacing-to-height ratio S/H, and the stroke width-to-height ratio SW/H, for both negative and positive contrast. Second-order polynomial least-squares functions were established to obtain a proposed and tentative functional relationship between the visual angle and W/H, S/H, and SW/H. As expected the data indicated that positive-contrast characters generally require smaller stroke widths than negative-contrast characters and that more widely spaced characters show an increased legibility over closely spaced characters. The present investigation provides display designers with proposed analytical functional relationships between legibility performance (visual angle) and typographical properties.

Visual displays could be devices such as traffic signs, license plates, computer cathode ray tubes or flat panel displays, televisions, or even pages in a book. However simple or complex they are, visual displays are used to transmit visual information to a human receiver. For a display to be effective its message must be visible, distinguishable, and easily interpretable (*1*). For this reason it is important that the displayed material be maximally legible.

In one of the earliest studies Forbes (*2*) adopted the term *legibility* to indicate a subject's ability to read the characters on a traffic sign. In another early study Aldrich (*3*) indicated that the intrinsic legibility of license plates will depend on the combined effects of size and shape of the plate, height, width, style, stroke width, spacing, and grouping of characters.

Most studies reviewed in the present investigation agree that legibility is affected by factors such as but not limited to character height (H), character width (W), stroke width (SW), height-width ratio (H/W), height-stroke width ratio (H/SW), intercharacter spacing (S), interword spacing, and interline spacing, as well as possible interactions between those factors. Optimal legibility under given conditions may therefore be achieved by an arrangement of the stimulus material in which the typographical factors mentioned earlier are coordinated to produce optimal viewing conditions and easy and rapid reading with adequate comprehension. Designers generally increased the character size if better legibility was required in the past (not always possible because of aesthetics or limited space). There is still a large degree of uncertainty as to which fonts perform well in terms of legibility and which ones do not. Standard fonts have been established, especially for use on traffic signs on highways (*4*).

Many of the studies reviewed in the present investigation have focused their efforts on developing minimum or maximum permissible values for the various factors that affect legibility. However, most of those studies were generally concerned with the absolute size of the characters rather than expressing legibility performance as a function of the visual angle subtended by the characters.

Human Factors and Ergonomics Laboratory, Department of Industrial and Systems Engineering, Ohio University, Athens, Ohio 45701-2979.

STUDIES ON HEIGHT, WIDTH, STROKE WIDTH, AND SPACING OF CHARACTERS

Forbes et al. (*5*) established the legibility distances of highway destination signs in relation to H, W, and reflectorization using black-on-white standard series B (narrow) and series D (wide) characters for six different character heights: 15.24, 20.32, 25.4, 30.48, 45.72, and 60.96 cm (6, 8, 10, 12, 18, and 24 in.). The wider series D characters were more legible. Legibility distances of 15.24 m (50 ft) and 10.06 m (33 ft) per inch of character height were obtained for the wide and the narrow characters, respectively, under daylight and normal vision (6/6) conditions (nighttime values were 15 percent lower). Forbes investigated pure legibility without considering limited viewing time (in the driving context, typically from 0.2 to 0.8 sec), compromised visual acuity, or reduced contrast sensitivity (mostly in elderly individuals). The data from Forbes could be adjusted with correction factors to account for these constraints.

In a field experiment Uhlaner (*6*) studied the effect of SW on the legibility of a black-on-white 7.62-cm (3-in.) block (height = width) capital characters. An SW of 18 percent of H (SW = H:5.5) was recommended. It was suggested by Uhlaner that SW needs to be reduced as H/W is reduced. Uhlaner's study was mainly limited to daylight legibility with illumination levels between 2690 and 5918 lx (250 and 550 fc). The use of seven different H/SW ratios in the study gives the reader a fairly good idea about the parabolic nature of legibility performance as a function of the H/SW ratio (see Figure 6).

Berger (*7*) experimented with H, W, SW, form, and horizontal S of black numerals on a white background (negative contrast) and white numerals on a black background (positive contrast). Berger recommended SW/H ratios of 1:8 for a positive contrast and 1:13 for a negative contrast. Positive contrast was better recognized than negative contrast. In another experiment conducted by Berger (*8*) five different numeral widths (1.5, 2.0, 2.75, 3.3, and 4.15 mm) for a numeral height of 6 mm were investigated by using the two black-on-white numerals 0 and 5. The legibility distance increased with increasing W. Berger (*9*) described the effects of varying both H and W on character legibility. Reportedly, legibility increased with increasing H and also with increasing W. Berger's experiments provide valuable quantitative information on the effects of the SW, H, and W of characters on legibility and were therefore used in the present investigation.

Kuntz and Sleight (*10*) established the H/SW ratio that was optimal for reading black-on-white and white-on-black numerals. The seven different H/SW ratios of 1:3.5, 1:4, 1:4.5, 1:5, 1:5.5, 1:6, and 1:6.5 were used. Kuntz and Sleight recommended an optimal H/SW ratio of 1:5 for reading both positive- and negative-contrast stimuli. It should be noted that the authors found no significant contrast polarity effect. This result is in conflict with the results of other researchers (*7,11*), who found an influence of contrast polarity on legibility performance. However, the lack of a contrast polarity effect may be attributed to a low display luminance.

TABLE 1 Studies Conducted on W/H Ratio of Characters

Author(s)/ Year	Ratios Investigated	Recommended Ratio	Polarity	Comments
*Forbes (1939)	0.43, 0.67	Not specified	Dark on Light	Legibility of highway destination signs
*Berger (1948)	0.25, 0.33, 0.46, 0.55, 0.69	Not specified	Dark on Light	Legibility of numbers
*Berger (1950)	0.25, 0.29, 0.36, 0.40, 0.45, 0.47, 0.57, 0.63, 0.73	Not specified	Dark on Light	Legibility of numbers and letters
*Forbes et al. (1951)	0.81	Not specified	Light on Dark	Legibility of highway signs
Soar (1955)	0.30, 0.45, 0.60, 0.75	0.60 or 0.75	Unavailable	Legibility of numbers
*Solomon (1956)	0.54, 0.73, 0.79	Not specified	Light on Dark	Legibility of highway signs
Brown et al. (1953)	0.55, 0.70, 0.85, 1	1	Light on Dark	Legibility of letters on aircraft control panels
Benson et al. (1988)	0.25, 0.41, 0.48, 0.56, 0.64, 0.72, 0.84, 1	Not specified	NA	Legibility of characters on visual display terminals
*Mace et al. (1993)	0.54, 0.67	Not specified	Dark on Light	Legibility of signs
*Mace et al. (1993)	0.79	Not specified	Light on Dark	Legibility of signs

The optimum width to height ratios were not specified in many studies because it was not the objective of these studies to determine the optimum ratio

In the Soar (1955) study no information regarding the polarity was found

The * indicates that the data from those studies were used in establishing the functional relationships shown in Figures 1 and 2

Forbes et al. (*12*) compared lowercase and uppercase characters displayed on highway signs. White-on-black series E capital characters and lowercase characters of approximately the same average W/H ratio were used. To approximate the effects of word patterns (as opposed to character legibility) and word familiarity, three sets of measurements were made by (a) using scrambled characters, (b) using California place names being viewed for the first time, and (c) using California place names being viewed for the second time.

In a field experiment Case et al. (*11*) analyzed the effects of intercharacter S and interline spacing on the legibility of 76.2-mm (3-in.)-high series E (SW/H ratio = 1:6) black-on-white and white-on-black characters. The two intercharacter spacings of 38.1 and 101.6 mm (1.5 and 4 in.) and two interline spacings of 50.8 and 101.6 mm (2 and 4 in.) were used. Widely spaced characters were much more legible than closely spaced characters. A significant interaction between contrast polarity and spacing was reported (the negative-contrast treatment was slightly more legible with close spacing; the positive-contrast treatment was considerably more legible with wide spacing). No conclusions were made regarding the interline spacing. The results are valid only for SW equal to 1:6.

Soar (*13*) studied the interaction between the W/H ratio and SW on numeral legibility. The four W/H ratios 3:10, 4.5:10, 6:10, and

TABLE 2 Studies Conducted on SW/H Ratio and S/H Ratio

A: Studies Conducted on the Stroke-Width to Height Ratio of Characters

Author(s)/ Year	Ratios Investigated	Recommended Ratio	Polarity	Comments
Aldrich (1939)	0.08, 0.125	0.125	Dark on Light	Legibility of license plates
*Uhlaner (1941)	0.08, 0.12, 0.16, 0.20, 0.24, 0.28, 0.32	0.18	Dark on Light	Legibility of letters
Berger (1944)	0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2	0.075	Light on Dark	Legibility of numbers
Berger (1950)	0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.3	0.125	Dark on Light	Legibility of numbers
Kuntz et al. (1950)	0.15, 0.17, 0.18, 0.20, 0.22, 0.25, 0.29	0.2	Light on Dark	Legibility of numbers
Kuntz et al. (1950)	0.15, 0.17, 0.18, 0.20, 0.22, 0.25, 0.29	0.2	Dark on Light	Legibility of numbers
Brown et al. (1949)	0.07, 0.1, 0.13, 0.17, 0.2	0.17	Light on Dark	Legibility of letters on aircraft control panels
Brown et al. (1951)	0.07, 0.12, 0.125, 0.14, 0.17	0.125	Light on Dark	Legibility of numbers on aircraft control panels
Soar (1955)	.0625, 0.1, 0.125, 0.2	0.1	Unavailable	Legibility of numbers
Baerwald et al. (1960)	0.08, 0.104, 0.125, 0.15	0.08	Dark on Light	Legibility of license plates
Baerwald et al. (1960)	0.08, 0.104, 0.125, 0.15	0.15	Light on Dark	Legibility of license plates
Hodge (1962)	0.08, 0.11, 0.14, 0.18, 0.22, 0.27	0.18	Dark on Light	Legibility of letters

The * indicates that the data from this study were used in establishing the functional relationships shown in Figure 6

B: Studies Conducted on the Spacing Between Characters to Height Ratio of Characters

Author(s)/ Year	Ratios Investigated	Recommended Ratio	Polarity	Comments
Case et al. (1952)	0.50, 1.33	NA	Light on Dark	Legibility of highway signs
Case et al. (1952)	0.50, 1.34	NA	Dark on Light	Legibility of highway signs
*Solomon (1956)	0.19, 0.228, 0.266, 0.286	0.28	Light on Dark	Legibility of highway signs
Baerwald et al. (1960)	0.08, 0.17, 0.28, 0.33, 0.42	NA	Dark on Light	Legibility of license plates
Baerwald et al. (1960)	0.08, 0.17, 0.28, 0.33, 0.43	NA	Light on Dark	Legibility of license plates

The optimum spacing between characters to height ratios were not specified studies because it was not the objective of these in many studies to determine the optimum ratio

The * indicates that the data from this study were used in establishing the functional relationships shown in Figures 1 and 3

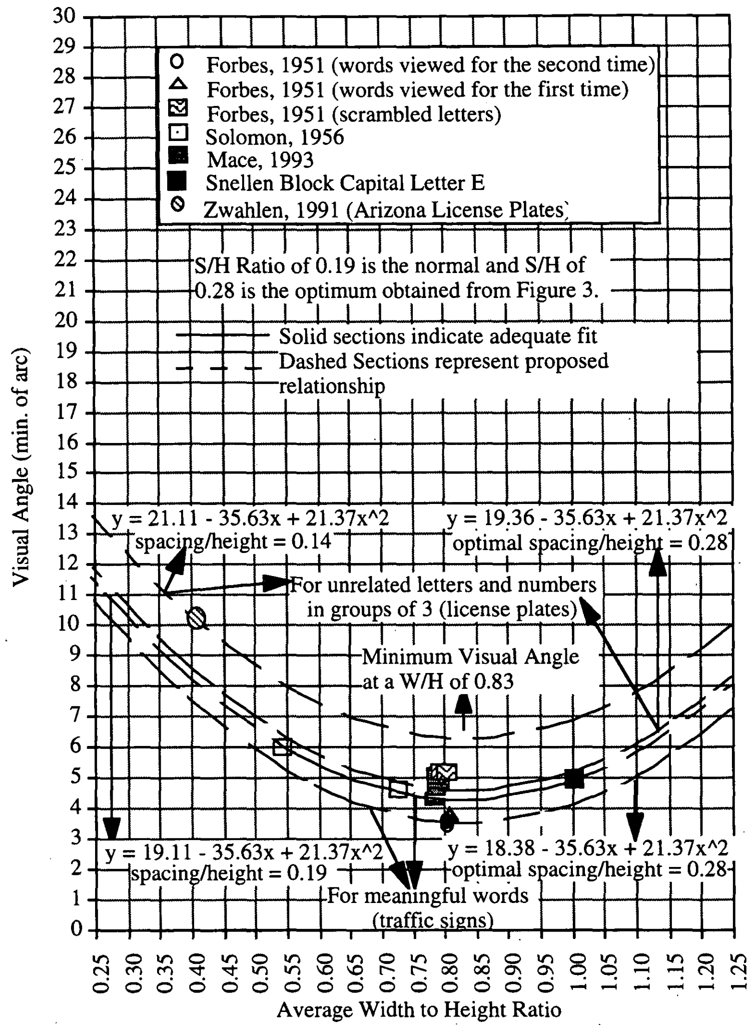

FIGURE 1 Visual angle as function of average W/H ratio for positive contrast.

7.5:10 at three different stroke widths were used. The SW/H ratios ranged from 1:5 to 1:8 for the widest SW and from 1:10 to 1:16 for the narrowest SW. A SW/H ratio of 1:10 was recommended to be optimal (no W/H and SW interaction). A W/H ratio of 10:7.5 was recommended for optimum legibility. However, Soar's experimental results suggest that most of the numerals showed consistent trends of increased legibility as W was increased.

Solomon (*14*) conducted a field experiment to determine the effects of W and intercharacter S on the nighttime legibility of highway signs with white-on-black characters. Characters with an H of 25.4 cm (10 in.), based on standard series C (narrow), series E (wide), and series ED (similar in form but slightly thinner than series E), were used in that study. S was increased from normal to 20, 40, and 60 percent above normal. Increasing S resulted in a legibility distance increase for all three font types up to the point where S was 40 percent above normal. The effects of increasing the H of a narrow series C character to the point where the area was equal to the area of a wide series E character were also studied. The two character types were equally legible for identical areas. This leads to the conclusion that a designer may use intercharacter S as an additional degree of freedom to compensate for constraints on H.

Baerwald et al. (*15*) investigated the factors affecting the legibility of automobile license plates using 76.2-mm (3-in.)-high standard series B numerals. A wide range of SWs was tested, and a significant interaction between SW and contrast polarity was found. An optimal SW of 11.113 mm (7/16 in.) or, alternatively, an optimal SW/H ratio of 1:6.8 was recommended for positive contrast. An optimal SW of 6.35 mm (1/4 in.) or, alternatively, an optimal SW/H ratio of 1:12 was recommended for negative contrast. Experiments conducted on S also indicated a significant interaction between S and the contrast polarity as well as between S and SW. Baerwald et al. concluded that the use of a thicker SW at a narrow internumeral S would have a greater effect on legibility than would a larger internumeral S. At a large internumeral S the positive-contrast numerals were more legible. However, when the internumeral S was decreased to a minimum, the negative-contrast numerals became more legible. These findings seem to confirm the previously described observations made by Case et al. (*11*).

Mace and Garvey (*16*) conducted a daytime study regarding the effects of increased H on sign legibility with a hypothesis that for a given color, contrast, and character series the legibility index will remain the same for different character heights. They further hypothesized that the legibility index would remain constant for different fonts, both contrast polarities, and different observer ages. They used two display groups with black series C and series D characters on a white background, respectively. Furthermore, they used one group with white characters on a green background and the modified series E font. Their results indicate that the legibility distance curves flatten between 30.48 and 40.64 cm (12 and 16 in.) of H for both young and older drivers and that extending H beyond 40.64 m (16 in.) might not be practical.

With the exception of the somewhat limited study conducted by Case et al. (*11*) (only two intercharacter S's and interline S's investigated) no other traffic sign-related studies dealing with intercharacter S and interline S were located. The visual display terminal legibility literature only provided the requirements of the Human Factors Society (*17*) (which state that "a minimum space of one character width shall be used between words and a minimum of two stroke widths or 15 percent of character height, whichever is greater shall be used for spacing between lines of text"). The *National Park Service Sign Manual* (*18*) provides some recommendations with regard to spacing, but no references were cited to support the recommended values.

Many other investigators, like Lauer (*19*), Aldrich (*3*), Mitchell and Forbes (*20*), Brown and Lowery (*21–23*), Schapiro (*24*), Crook et al. (*25,26*), Hughes (*27*), Hodge (*28*), and Benson and Farrell (*29*), have conducted studies dealing with either SW/H ratios or W/H ratios. These works were evaluated, and it was decided not to include the results in the present investigation because of the incompatibility or the incompleteness of the data presentation.

OBJECTIVES

The present investigation had a twofold objective: (a) to conduct an extensive literature review and to consolidate all of the relevant leg-

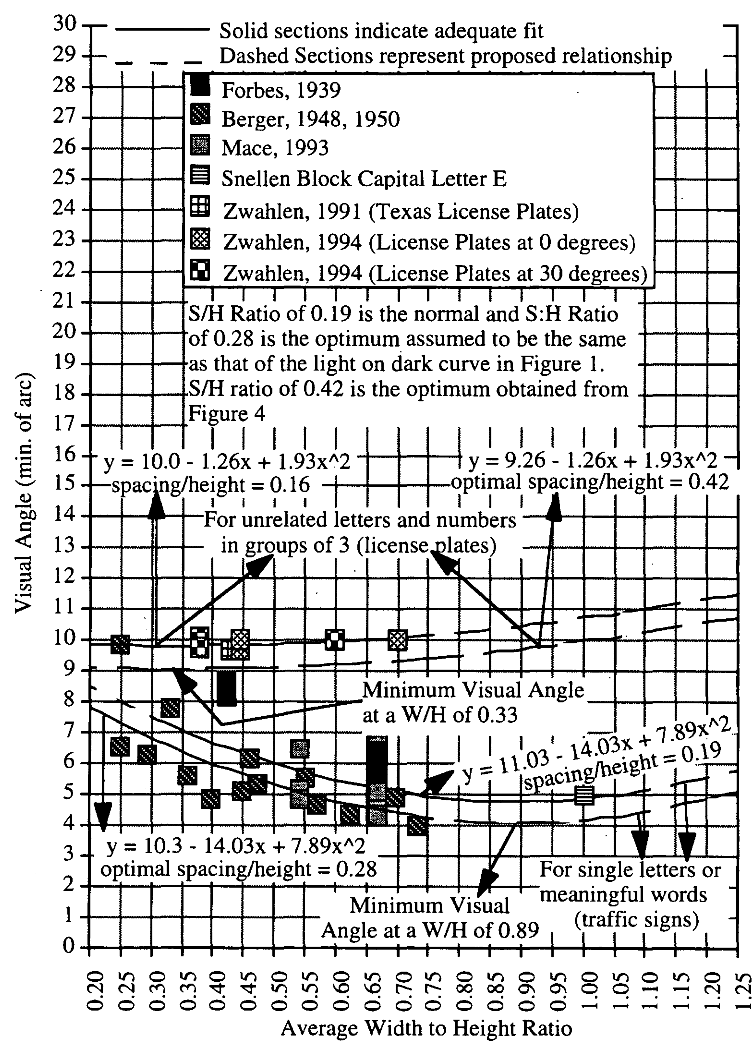

FIGURE 2 Visual angle as function of average W/H ratio for negative contrast.

ibility results from all the studies found in the literature and (b) to establish functional relationships based on least-squares curve-fitting techniques for legibility (in terms of visual angle subtended by H) as a function of the W/H ratio, intercharacter S/H ratio, and SW/H ratio for light on dark (positive contrast) and dark on light (negative contrast) characters.

METHOD

The studies discussed in the preceding literature review were first categorized into three major groups: (a) effects of W/H ratio on legibility, (b) effects of SW/H ratio on legibility, and (c) effects of intercharacter S/H ratio on legibility. Character dimensions and spacing dimensions were related to character height and were expressed in terms of dimensionless ratios (W/H, SW/H, S/H). Summary results of the previously reviewed studies are listed in Tables 1 and 2.

DEFINITIONS

Equation 1 shows the definition of contrast (c) as used in this investigation:

$$C = \frac{L_C - L_B}{L_B} \quad (1)$$

where L_C is the character luminance and L_B is the background luminance.

Equation 2 was used to calculate the visual angle (in minutes of arc) based on the character height and the legibility distance (in meters):

$$\text{Visual angle (minutes of arc)} = \frac{3438 \cdot \text{character height (m)}}{\text{Legibility distance (m)}} \quad (2)$$

The normalized visual angles expressed as a function of the W/H ratio, the intercharacter S/H ratio, and the SW/H ratio tended to be parabolically shaped (see Figures 1 to 6). Therefore, a second-order polynomial least-squares fit to the data is proposed as a method of obtaining a tentative functional relationship to express the legibility performance as a function of typographical properties for the given, limited data. The parabolas plotted in Figures 1 to 6 should therefore be considered proposed relationships. The dashed sections of these parabolas indicate extrapolated ranges (no data available) and are of a very tentative nature.

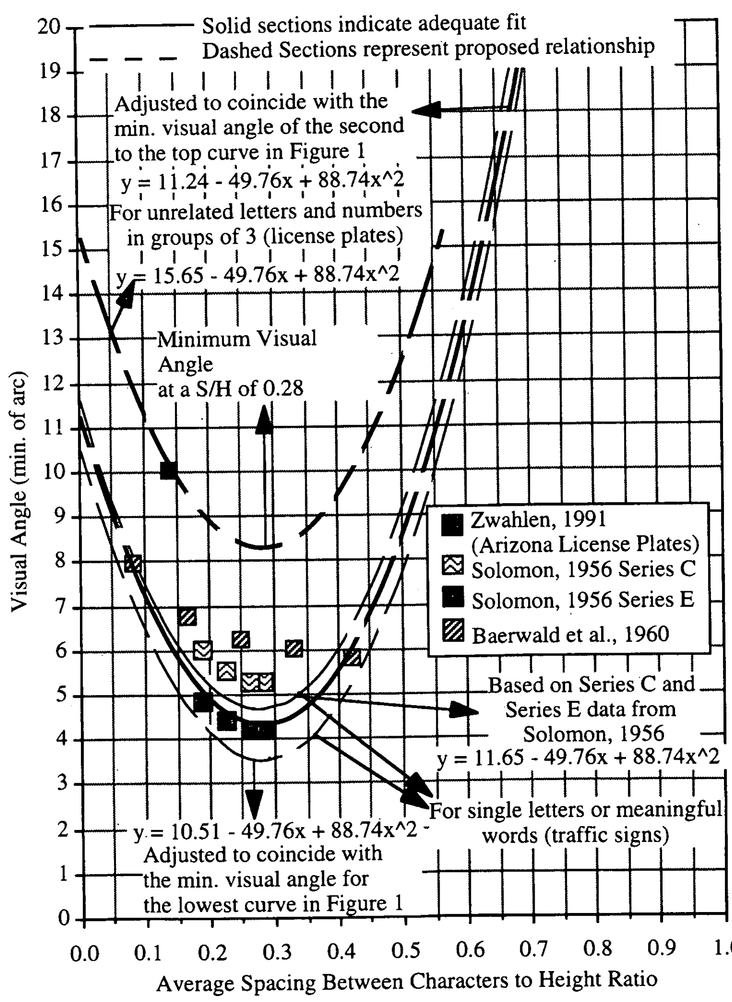

FIGURE 3 Visual angle as function of average intercharacter S/H ratio within a word for positive contrast.

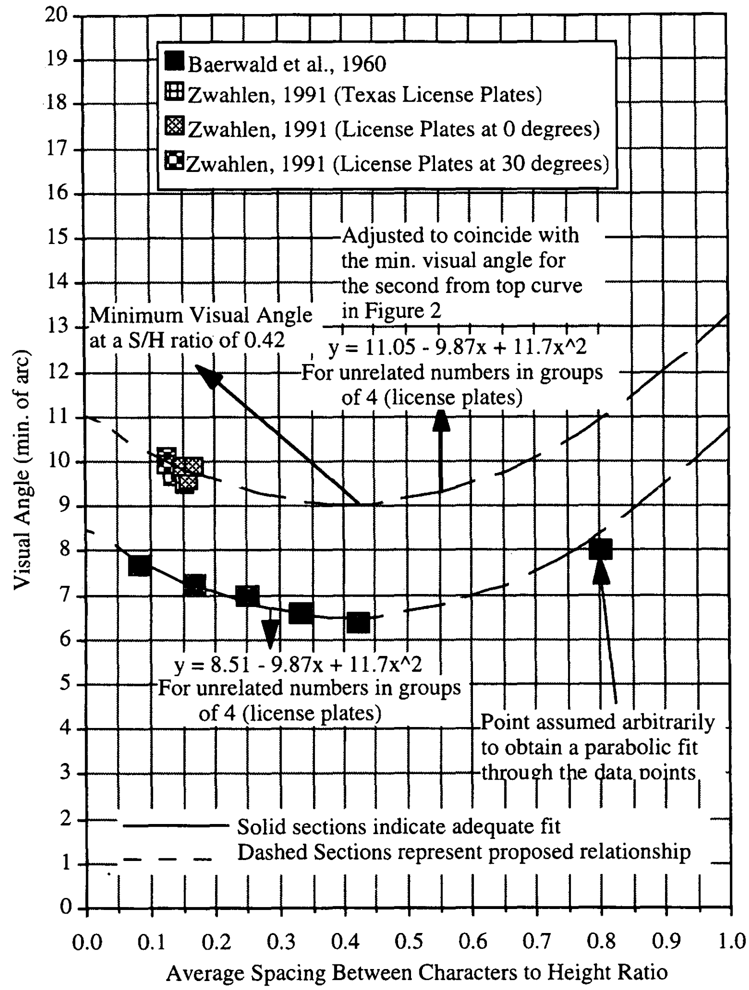

FIGURE 4 Visual angle as function of average intercharacter S/H ratio for negative contrast.

RESULTS AND GENERAL COMMENTS

It should be noted that the functional relationships and the optimal values obtained in this review are based on the information available in the literature, which was sometimes incomplete and most likely valid only for a limited set of conditions. Therefore, a number of assumptions and adjustments had to be made in almost all data sets to correct for experimental artifacts. In some cases it was not possible to establish the second-order polynomial fit because of incomplete experimental descriptions. Certain unknown and unspecified experimental conditions may be responsible for some of the rather large variations between the results of some of the studies. The use of a second-order polynomial least-squares fit to relate legibility to the W/H ratio, the S/H ratio, or the SW/H ratio is certainly not primarily justified by the presence of many and well-dispersed datum points. On the other hand the availability of relatively simple mathematically based functional relationships provide the opportunity to examine legibility trade-offs in an analytical manner.

Figure 1 shows the functional relationship between the visual angle (legibility measure) and the average W/H ratio for positive contrast. The Snellen E (block capital character in which the W/H ratio is 1) was added to have at least one average W/H ratio beyond 0.83. The bottom parabola and the second parabola from the top are based on an optimal S/H ratio of 0.28 (from Figure 3). The top parabola is based on an S/H ratio of 0.14. With the exception of the Snellen block capital E the second parabola from the bottom is based on an average S/H ratio of 0.19, which is fairly representative of series D characters. The remaining parabolas were vertically offset to fit the corresponding datum points. From Figure 1 it can be seen that meaningful words (traffic signs) appear to be more legible than unrelated characters (license plates) for positive contrast.

Figure 2 shows the functional relationship between the visual angle (legibility measure) and the average W/H ratio for negative contrast. For the bottom parabola an optimal S/H ratio of 0.28 was adopted from the positive-contrast data set (Figure 1). The second parabola from the bottom is based on an average S/H ratio of 0.19 (except for Snellen block letter). The top parabola in Figure 2 is based on an average S/H ratio of 0.16. For the second parabola from the top, an optimal S/H ratio of 0.42 was adopted from the data in Figure 4. From Figure 2 it can be seen that meaningful words (traffic signs) appear to be more legible than unrelated characters (license plates) for negative contrast.

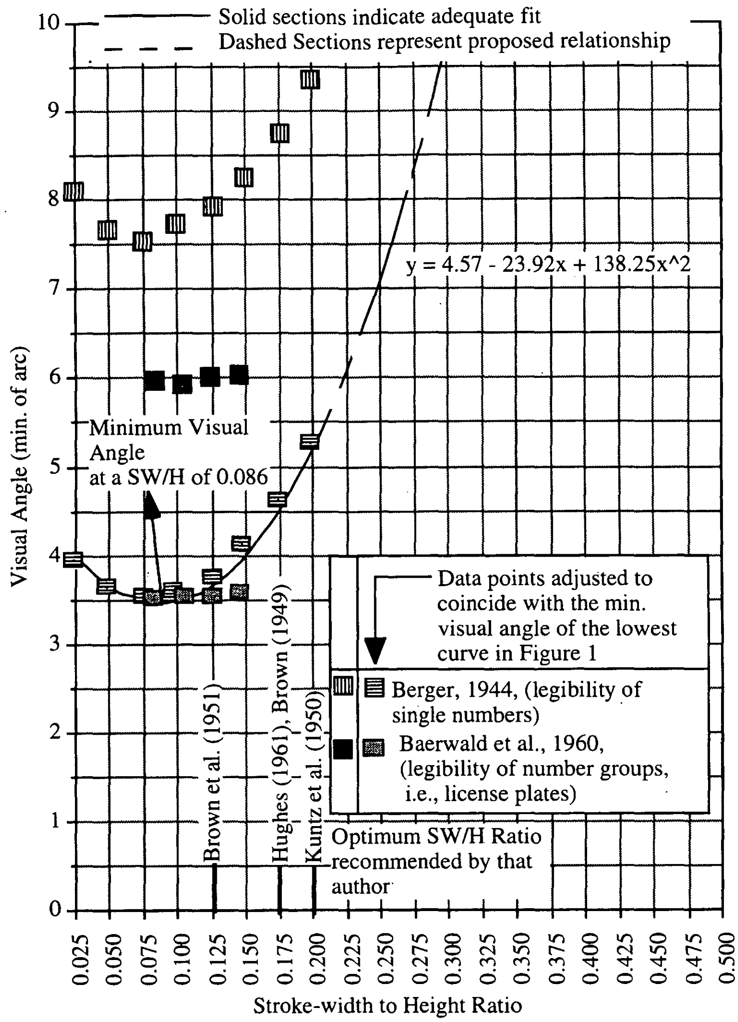

FIGURE 5 Visual angle and adjusted visual angle as function of SW/H ratio for positive contrast.

Figure 3 shows the functional relationship between the visual angle (legibility measure) and the average S/H ratio for positive contrast. The bottom parabola in Figure 3 was vertically adjusted to the minimum visual angle obtained from the bottom parabola in Figure 1. Similarly, the second parabola from the bottom was vertically adjusted to the minimum visual angle obtained from the second parabola from the top in Figure 1. The shape of the top parabola was assumed to be the same as that of the second parabola from the top (constant offset upward to 15.65 min of arc), because only one datum point was available.

Figure 4 shows the functional relationship between the visual angle (legibility measure) and the average S/H ratio for negative contrast based on data from Baerwald et al. (*15*) and Zwahlen (*30,31*). The top parabola was obtained by assuming the minimum visual angle to be equal to the minimum visual angle of the second parabola from the top in Figure 2.

Figure 5 shows the visual angle (legibility measure) and the derived functional relationships as a function of the SW/H ratio for positive contrast. As shown in Figure 5 the visual angle data obtained from Berger (*7*), which provides an optimum SW/H ratio of 0.075, is significantly different from the visual angle data obtained from Baerwald et al. (*15*), which provides an optimum SW/H value within a range of 0.075 to 0.15. Figure 5 also shows the recommended optimum SW/H ratios by

1. Brown and Lowery (*21*): SW/H ratio of 0.17 for the legibility of uniform stroke capital characters viewed in three character groups used on transilluminated control panels in military aircraft;
2. Hughes (*27*): SW/H ratio within a range of 0.125 to 0.17 for the legibility of single numbers;
3. Brown and Lowery (*22*): SW/H ratio of 0.125 for the legibility of uniform stroke capital characters viewed in three character groups used on transilluminated control panels in military aircraft; and
4. Kuntz and Sleight (*10*): SW/H ratio of 0.2 for the legibility of numbers.

The datum points presented in Figure 5 were then adjusted to coincide with the minimum visual angle of the bottom parabola in Figure 1.

Figure 6 shows the visual angle (legibility measure) and the derived functional relationships as a function of the SW/H ratios recommended by various investigators for negative contrast. The

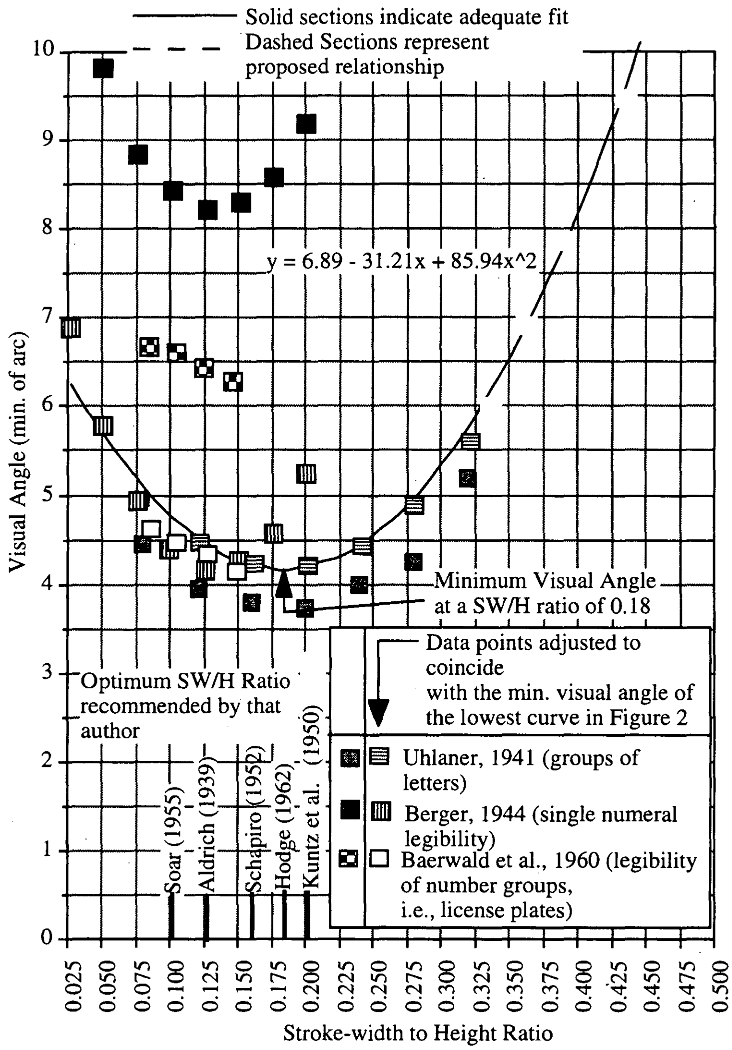

FIGURE 6 Visual angle and adjusted visual angle as function of SW/H ratio for negative contrast.

wide variation in these recommendations could be attributed to different experimental conditions. The datum points plotted in Figure 6 were adjusted to coincide with the minimum visual angle of the lowest parabola in Figure 2 to obtain the second-order polynomial functional relationship. Figure 6 also shows the optimum values recommended by other investigators, which are as follows:

1. Aldrich (*3*): SW/H ratio of 0.125 for the legibility of alphanumeric license plates with varying number of characters and numbers on each plate,
2. Berger (*7*): SW/H ratio of 0.125 for the legibility of single numbers,
3. Kuntz and Sleight (*10*): SW/H ratio of 0.2 for the legibility of numbers,
4. Soar (*13*): SW/H ratio of 0.1 for the legibility of single numbers,
5. Baerwald et al. (*15*): SW/H ratio of 0.15 for the legibility of license plates (four numbers on each plate),
6. Schapiro (*24*): SW/H ratio within a range of 0.125 to 0.2 for the legibility of single numbers, and
7. Hodge (*28*): SW/H ratio of 0.178 for the legibility of unrelated five- or six-character words.

SUMMARY AND CONCLUSIONS

Only a few studies that contained the necessary information to calculate the visual angles (legibility measure) as a function of either a character dimension or a spacing dimension were considered in the present investigation. Intercharacter spacing has been a subject of much controversy and has been studied by many researchers as a function of contrast polarity and a concept known as irradiation (for positive contrast). Irradiation may be highly dependent on the luminance.

It should be noted that the second-order polynomial functions Figures 1 to 6) extend in some cases into ranges of W/H, S/H, or SW/H, for which no data from the studies were available (tentative proposal by the authors). Until more appropriate values become available these proposed functional relationships could be helpful for display designs in which the overall available display space is limited or when displays are being designed for elderly individuals. For a fairly simple font a designer may want to optimize legibility by minimizing the visual angle on the appropriate parabola (Figures 1 to 6) and by selecting the corresponding optimal typographical factors (W/H, S/H, SW/H).

It was found that single characters and meaningful words are more legible than unrelated characters and numbers, both for positive and negative contrast. Although the recommended SW/H ratios varied considerably from study to study, it was generally found that characters displayed with a positive contrast require smaller SWs than characters displayed with a negative contrast. This may partially be attributed to irradiation, which may become a more and more serious problem as the display luminances increase. Furthermore, the reviewed data indicated that more widely spaced characters provide improved legibility over closely spaced characters. A possible explanation for this improved legibility was provided by Case et al. (*11*) in terms of eye fixation shifts.

REFERENCES

1. Kantowitz, B. H., and R. D. Sorkin. *Human Factors: Understanding People-System Relationships.* John Wiley and Sons, Inc., New York, 1983.
2. Forbes, T. W.' *Human Factors in Highway Traffic Safety Research.* Wiley-Interscience, New York, 1972, pp. 95–109.
3. Aldrich, M. H. Perception and Visibility of Automobile License Plates. *HRB Proc.*, Vol. 17, 1939, pp. 393–412.
4. *Standard Alphabets for Highway Signs and Pavement Markings,* Metric Edition. Office of Traffic Operations, FHWA, U.S. Department of Transportation, 1977.
5. Forbes, T. W., and R. S. Holmes. Legibility Distances of Highway Destination Signs in Relation to Letter Height, Letter Width and Reflectorization. *HRB Proc.*, Vol. 19, 1939, pp. 321–355.
6. Uhlaner, J. E. The Effect of Thickness of Stroke on the Legibility of Letters. *Proc., Iowa Academy of Sciences,* Vol. 48, 1941, pp. 319–324.
7. Berger, C. Stroke-Width, Form and Horizontal Spacing of Numerals as Determinants of the Threshold of Recognition. *Journal of Applied Psychology,* Vol. 28, No. 3, 1994, pp. 208–231.
8. Berger, C. Some Experiments on the Width of Symbols as Determinant of Legibility. *Acta Ophthalmologica,* Vol. 26, No. 4, 1948, pp. 517–550.
9. Berger, C. Experiments on the Legibility of Symbols of Different Width and Height. *Acta Ophthalmologica,* Vol. 28, No. 4, 1950, pp. 423–434.
10. Kuntz, J. E., and R. B. Sleight. Legibility of Numerals: The Optimal Ratio of Height to Width Ratio of Stroke. *American Journal of Psychology,* Vol. 63, 1950, pp. 567–575.
11. Case, H. W., J. L. Michael, G. E. Mount, and R. Brenner. Analysis of Certain Variables Related to Sign Legibility. *Bulletin 60,* HRB, National Research Council, Washington, D.C., 1952, pp. 44–54.
12. Forbes, T. W., and K. Moscowitz. *A Comparison of Lower Case and Capital Letters for Highway Signs.* HRB, National Research Council, Washington, D.C., 1951, pp. 355–372.
13. Soar, R. S. Height-Width Proportion and Stroke-Width in Numeral Visibility. *Journal of Applied Psychology,* Vol. 39, No. 1, 1955, pp. 43–46.
14. Solomon, D. The Effect of Letter Width and Spacing on Night Legibility of Highway Signs. *HRB Proc.*, Vol. 35, 1956, pp. 600–617.
15. Baerwald, J. E., D. F. Karmier, and C. G. Herrington. The Functions and Design of Motor Vehicle License Plates. *University of Illinois Bulletin,* Vol. 58, No. 10, Sept. 1960.
16. Mace, D. J., and P. M. Garvey. The Effects of Increased Character Height on Sign Legibility, *Presented at 72nd Annual Meeting of the Transportation Research Board,* Washington, D.C., 1993.
17. *American National Standard for Human Factors Engineering of Visual Display Terminal Workstations.* Human Factors Society, 1988.
18. *National Park Service Sign Manual.* U. S. Department of Interior, 1988.
19. Lauer, A. R. Improvements in Highway Safety. *HRB Proc.*, Vol. 12, 1932, pp. 389–401.
20. Mitchell, A., and T. W. Forbes. Design of Sign Letter Sizes. *Proc., American Society of Civil Engineers,* Vol. 68, 1942, pp. 95–104.
21. Brown, F. R., and E. A. Lowery. *A Study of the Requirements for Letters, Numbers and Markings To Be Used on Trans-Illuminated Aircraft Control Panels. Part 1. The Effects of Stroke Width Upon the Legibility of Capital Letters.* Report TED NAMEL-609, ATI-205 706. Aeronautical Medical Equipment Laboratory, Naval Air Material Center, Philadelphia, 1949.
22. Brown, F. R., and E. A. Lowery. *A Study of the Requirements for Letters, Numbers and Markings To Be Used on Trans-Illuminated Aircraft Control Panels. Part 3. The Effect of Stroke-Width and Form Upon the Legibility of Numerals.* Report TED NAMEL-609, ATI-107 638. Aeronautical Medical Equipment Laboratory, Naval Air Material Center, Philadelphia, 1951.
23. Brown, F. R., and E. A. Lowery. *A Study of the Requirements for Letters, Numbers and Markings To Be Used on Trans-Illuminated Aircraft Control Panels. Part 4. Legibility of Uniform Stroke Capital Letters as Determined by Size and Height to Width Ratio and as Compared to Garmond Bold.* Report TED NAMEL-609, AD-10 211. Aeronautical Medical Equipment Laboratory, Naval Air Material Center, Philadelphia, 1953.
24. Schapiro, H. B. *Factors Affecting Legibility of Digits.* WADC Technical Report 127, Contract AF 33(038)18317, AD-1 117, 1952.
25. Crook, M. N., J. A. Hanson, and A. Weisz. *Legibility of Type as a Function of Stroke Width, Letter Width, and Letter Spacing Under Low Illumination.* WADC Technical Report 53–440, Contracts W33-038 ac-14559 and AF33(616)-2018, AD-43 309, 1954.
26. Crook, M. N., J. A. Hanson, and A. Weisz. *Legibility of Type as Determined by the Combined Effect of the Typographical Variables and Reflectance of Background.* WADC Technical Report 53–441, Contracts W33-038 ac-14559 and AF33(616)-2018, AD-43 309, 1954.
27. Hughes, C. L. Variability of Stroke-width Within Digits. *Journal of Applied Psychology,* Vol. 45, No. 6, 1961, pp. 364–368.
28. Hodge, D. C. Legibility of Uniform Stroke-Width Alphabet. I. Relative Legibility of Upper and Lower Case Letters. *Journal of Engineering Psychology,* Vol. 1–2, 1962–1963, pp. 35–46.
29. Benson, B. L., and J. E. Farrell. The Effect of Character Height to Width Ratio of CAT Display Legibility. *Society of Information Display: Digest of Technical Papers.* Palisades Institute of Research Services, Inc., New York, 1988, pp. 340–343.
30. Zwahlen, H. T. *Reflective License Plate Material—Evaluation of Conspicuity and Legibility Performance for a Standard License Plate Configuration Using Beads on Paint vs Reflective Sheeting.* Final Report FHWA-AZ91-358. Arizona Department of Transportation, Phoenix, 1991.
31. Zwahlen, H. T. Legibility and Conspicuity Performance of Dry and Wet Beads on Paint and Reflective Sheeting License Plates Under Low-Beam Illumination at Night. In *Transportation Research Record 1456,* TRB, National Research Council, Washington, D.C., 1994, pp. 112–124.

Publication of this paper sponsored by Committee on User Information Systems.