A Study of Legible Braille Patterns on Capsule Paper: Diameters of Braille Dots and Their Interspaces on Original Ink-printed Paper

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Abstract: A legibility experiment was conducted using eleven braille readers in order to determine the suitable ranges of braille dot diameters and their interdot spaces on the original image for capsule paper braille. The obtained result shows that the reading of capsule paper braille with few mistakes in the dot diameter range of 1.17 to 1.43 mm and interdot space range of 1.05 to 1.15 times the standard Japanese interdot space took a short time and was rated high. On the other hand, the reading of braille with many mistakes at a large dot diameter and a narrow interdot space took a long time and was rated low. The three-dimensional measurement of braille dot shapes clarified that difficulties in reading braille under these conditions stem from the fusion of dots due to the expansion characteristic of capsule paper.

Key Words: Stereocopy, Braille pattern, Reading time, Tactile legibility, Three-dimensional shape

I. Introduction

Stereocopying is a type of tactile graphic used to convey graphical information, such as maps and charts, to blind people. Due to its simple preparation, it is widely used in schools (Rowell & Ungar, 2003). These tactile graphics can include a graphical image and braille as legends. However, braille on capsule paper, is not sufficiently legible. The reason for this is considered to be that people tend to prepare original ink-printed braille whose dot diameter is the same as that of ordinary embossed braille; swelled dots become larger than ink-printed black dots on original paper because of the expansion characteristic of capsule paper. Thus, it is heuristically said that “fonts for capsule paper should be larger than ordinary embossed braille and dots should be slightly smaller” (Misaki, 1994). However, quantitative data on this have not been obtained yet. Thus, we performed an experiment involving braille readers to determine the suitable ranges of braille dot diameters and their interspaces on the original image for legible capsule paper braille. We also measured the shapes of braille dots on capsule paper produced from the same original ink-printed paper used in a legibility experiment using a laser shape measurement system to explore the effect of braille shape on legibility.

II. Stereocopying using Capsule Paper

Stereocopying is a method of producing tactile graphics using the heat foaming characteristic of capsule paper. Capsule paper, also referred to as microcapsule paper or swell paper, is coated with microscopic polystyrene capsules (Way & Barner, 1997). These capsules expand when exposed to heat. Their expansion rate depends on heat temperature; the higher the heat temperature, the higher their extent of expansion.

The following are examples of commercially available capsule paper to date: Capsule Paper by Matsumoto Yushi-Seiyaku Co., Ltd., Japan, Flexi-Paper by Repro-Tronics Inc., USA, Swelltouch Capsule Paper by American Thermoform Corporation, USA, and Swell Paper by Zychem Ltd., UK. Prices are around 100 yen per sheet when procured in Japan.

The first step in producing tactile graphics is to prepare original ink-printed or handwritten images. These images are then photocopied onto capsule paper using a standard or specialized copy machine (stereocopy machine). An alternative to the use of a copy machine is directly writing on capsule paper with black ink. A stereocopy production machine or heater, also referred to as a developing machine by its manufacturer and seller Konica Minolta Holdings Inc., is used to heat capsule paper to 120-125 ˚C to expand the black-printed portions of the paper. As black-printed microcapsules absorb more heat and expand more than other microcapsules, these black portions are raised from the background. The expansion requires only several seconds depending on the type of heater used.

Fig. 1 shows a stereocopy machine, and Fig. 2, a heater. Fig. 3 shows the picture of braille produced on capsule paper.

Fig. 1 Stereocopy machine.

Fig. 2 Stereocopy production machine (heater).

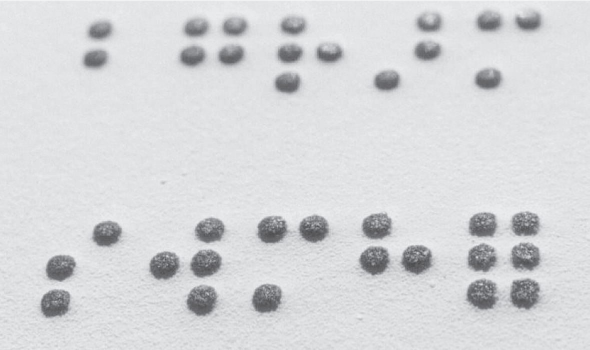


Fig. 3 Braille on capsule paper.

III. Experiment of Reading Braille on Capsule Paper

An experiment involving braille readers was conducted to determine the suitable ranges of braille dot diameters and their interdot spaces on the original image for capsule paper braille.

1. Method

Subjects were eleven blind people who used braille on a daily basis. Their ages ranged from 26 to 68, the average being 44.2. They have been using braille for 11 to 52 years, and 34 years on the average. They usually read braille of the Japanese and/or international size and on refreshable braille displays.

Braille dots with three different diameters were printed on the original paper. The Japanese standard diameter is 1.43 mm (Kizuka, 1998). The other two sizes are 1.17 mm, which is less than the standard, and 1.67 mm, which is larger than the standard. In addition, five interdot spaces were selected: 0.9, 1.0, 1.05, 1.10 and 1.15 times the Japanese standard interdot space. The combination of dot diameters and interdot spaces produced fifteen conditions for original ink-printed braille. Table 1 shows these conditions, and Fig. 4, the types of braille interdot spaces. The line spacing was set to be 11 mm for all the conditions.

Table 1 Diameters of braille dots and their interdot spaces on original image used in experiment. [unit: mm]

	Distance between dots 1 and 2	*Distance between dots 1 and 4*	*Distance between dots 4 and 1*
0.9 times	2.13	1.92	2.94
standard size (1.0 times)	2.37	2.13	3.27
1.05 times	2.49	2.24	3.43
1.10 times	2.61	2.34	3.60
1.15 times	2.73	2.45	3.76

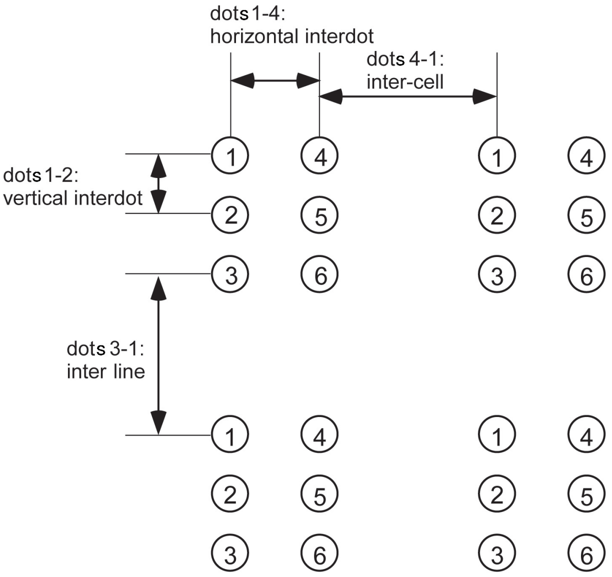


Fig. 4 Braille cells and types of interdot space. A full braille cell consists of six raised dots arranged in two parallel rows each having three dots. The positions of the dots are numbered one through six (cited from AFB's web page). Japanese braille, in essence, uses dots 1, 2, and 4 for presenting vowels and dots 3, 5, and 6 for presenting consonants.

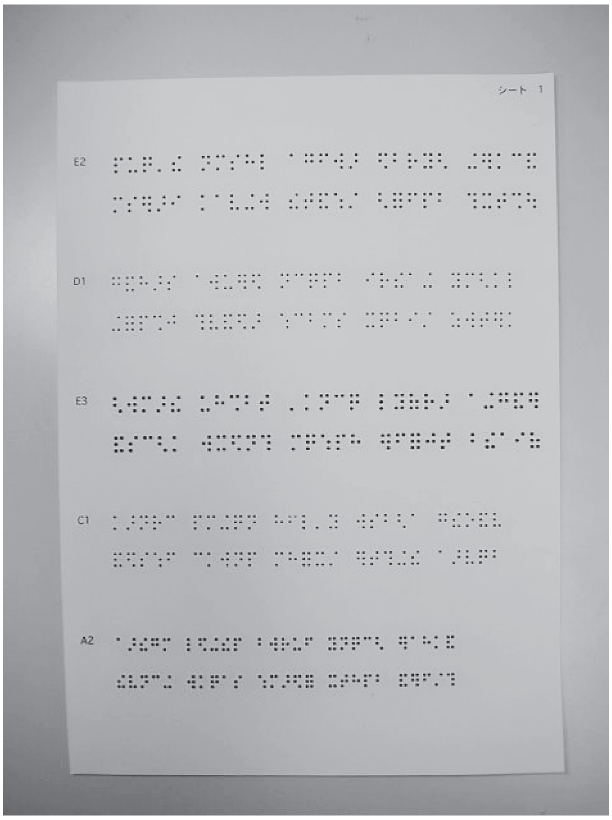


Fig. 5 Stimulus sentences used in legibility experiment.

The interline spaces produced using braille embossers generally range from 8 to 9 mm (Kamoda & Fujimoto, 2001). We added extra 2-3 mm to this range to prevent readers' fingers from touching the next line while reading.

Stimulus sentences were a series of meaningless words formed with five letters in a chunk. Original meaningless words were collected from the appendix "Non-association rate of two-syllable *SEION* (having voiceless consonant)" of "Experiment and Test" (SIG on Psychological Experiment, 1972). Three two syllable words which do not include the same syllables were selected and concatenated to make a six-syllable word. Deleting the last letter from it produced a meaningless word formed with five letters. Ten chunks of five letters produced a stimulus sentence. The produced sentences differed from each other. Each sentence was laid out in two lines, each of which had five chunks, i.e., 25 letters (Fig. 5).

The original image of each condition was prepared with illustration software (Adobe Illustrator ver. 10) on a personal computer (Macintosh G4, Apple Computer) and printed out using a laser printer (LP 8200C, Epson) with a resolution of 600 dpi. This image was then copied onto sheets of capsule paper (ZY-TEX Swell Paper A4, Zychem) using a stereocopy machine (Partner Vision 2051, Minolta), and the ink-printed parts of the paper were foamed by heating with PIAF, Quantum Technology. The time for the sheets to pass through the heat source of the heater (width: approximately 15 cm) was 6.30 - 6.40 s. One of the stimulus sheets used in the experiment is shown in Fig. 5.

The experiment was conducted in a room. One subject was tested at a time. The subject sat on a chair and read stimulus sentences placed on the desk in front of him/her. He/she was instructed to read braille in the same hand manipulation manner as that in their daily life, that is, using only one hand (right or left) or both hands. Before each trial, the subject was instructed to place his/her index finger at a standby position, expressed as a raised letter, on the left-hand side of the first line of each subject sentence (Fig. 5). When one of the experimenters signed the subject to start, he/she started to read the stimulus aloud. The reading time was measured with a stopwatch. After each trial, the subject was asked to rate the legibility of stimulus braille on a five-point separate scale: "very difficult to read" (score: 1), "rather difficult to read" (score: 2), "difficult to say" (score: 3), "rather easy to read" (score: 4), "very easy to read" (score: 5). The judgment should be made without comparing with the preceding stimuli. The subject was instructed to read the stimulus as fast as possible without making mistakes. Eighteen stimulus sentences were prepared and shown in a random order. The order of presentation was the same for all subjects. The data from the first three stimuli were discarded and the data from the remaining fifteen stimuli were used for analysis. The hand movements of the subject while reading were videotaped. Reading errors were

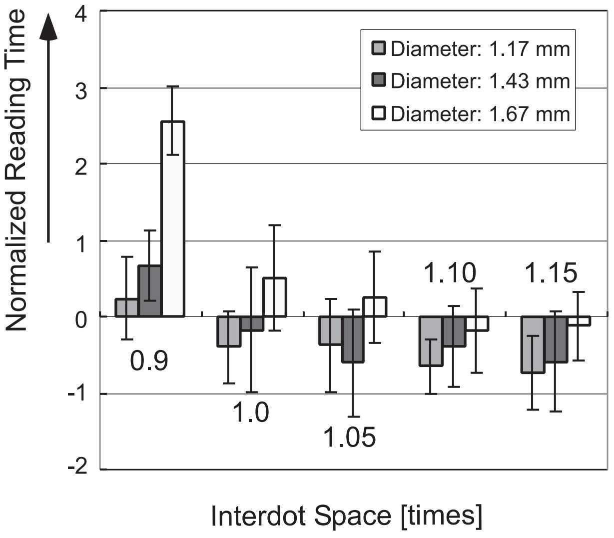


Fig. 6 Mcan and SD of normalized reading time.

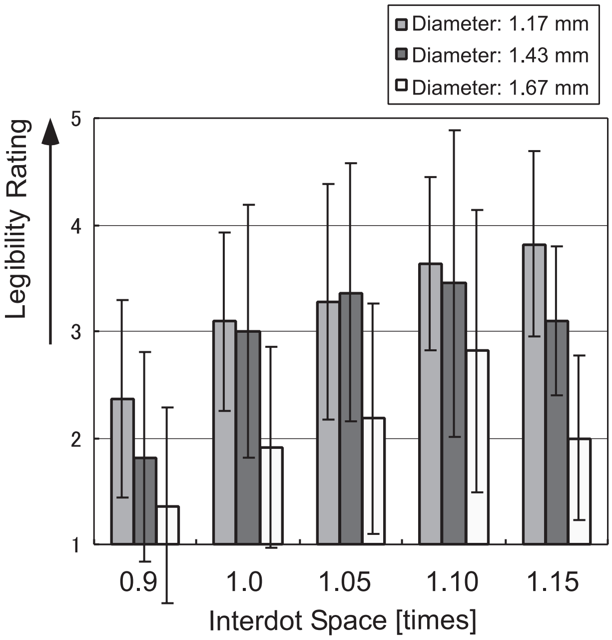


Fig. 7 Mean and SD of legibility rating.

noted during the experiment and reconfirmed using the videotape after the experiment. After reading all the stimuli, the subject was asked to answer which characteristcs made braille easy or difficult to read.

2. Results

Reading times differed greatly among subjects. Although seven out of eleven subjects took about 20 s on the average to read, two persons took about 30 s, and the remaining two persons, 37.2 and 47.7 s (Table 2). Nevertheless, the change in reading time based on the conditions used was the same in all subjects; the interdot spaces of 0.9 and 1.0 times the standard interdot space produced a long reading time and spaces larger than these produced a negligible change; under small interdot space conditions, the larger the dot diameter, the longer the reading time. Consequently, in order to eliminate the effect of the difference between subjects in the statistical analysis, reading times were normalized (or standardized) for each subject. Normalization was performed by the following formula for $X_1, X_2, ..., X_n$, where $\overline{X}$ denotes the average, and s, the standard deviation (SD).

Table 2 Mean reading time per subject. [unit: s]

Subject	*Reading time*
1	30.2
2	47.7
3	19.8
4	37.2
5	31.4
6	19.4
7	18.4
8	19.4
9	20.3
10	18.9
11	16.2

$$z_i = (X_i - \overline{X})/s$$

The mean of the normalized z's is 0 and the SD is 1. Fig. 6 shows the normalized reading times (the average and SD of all subjects) under each condition.

A two-way ANOVA (analysis of variance) of the normalized reading times demonstrates a significant effect of the change in interdot space ($F(4, 80) = 56.04$, $p< 0.01$) and that of the change in dot diameter ($F(2, 80) = 70.98$, $p< 0.01$). The interaction effect of both factors was also significant ($F(8, 80) = 4.62$, $p< 0.01$). According to Tukey's HSD test ($p = 1$ %) (Mori and Yoshida, 1990), the reading times at the interdot space of 0.9 times the standard were significantly longer than those at the other interdot spaces at all dot diameters. At the dot diameters of 1.67 mm, the interdot spaces of 1.10 and 1.15 times the standard yielded significantly shorter reading times than the standard. Let us focus on the effects of the diameter change at the same interdot space. At the interdot space of 0.9 times the standard, significant differences were observed between three dot diameters; the larger the dot diameter, the longer the reading time. At the interdot spaces of 1.0, 1.05, and 1.15 times the standard, the dot diameter of 1.67 mm yielded

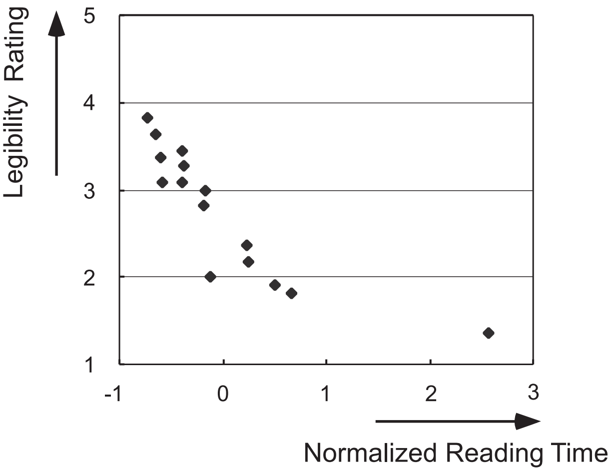


Fig. 8 Correlation between normalized reading time and lcgibility rating.

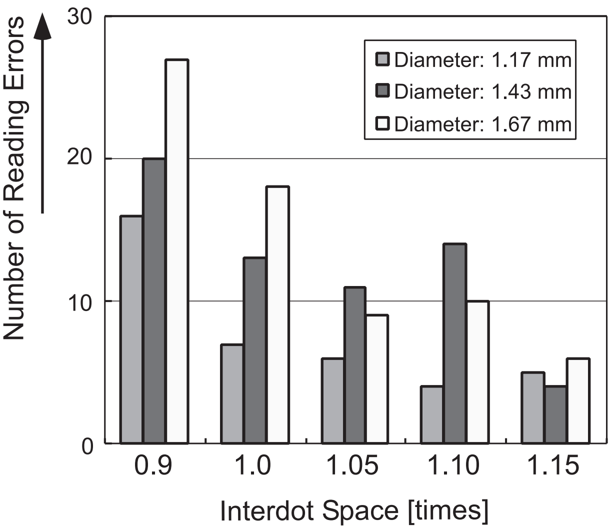


Fig. 9 Number of reading errors.

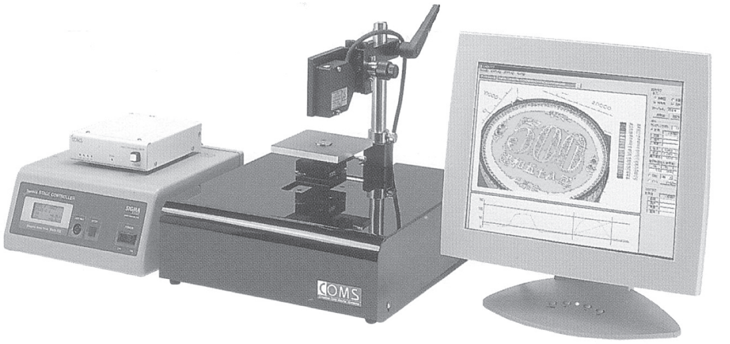


Fig. 10 Three-dimensional measurement system (from a picture in the brochure).

significantly longer reading times from the other two dot diameters. At the interdot space of 1.10 times the standard, a significant difference was observed only between the two dot diameters of 1.17 and 1.67 mm.

Since the rating of legibility was on an ordinal scale, its transformation was performed on an interval scale based on the law of categorical judgment (Nanba & Kuwano, 1998). As a linear correlation was observed between the original category values and the interval scale ($r = 0.999$), we considered the original category values to be on an interval scale.

Fig. 7 shows the legibility ratings (the mean and SD from all subjects) under each condition. A two-way ANOVA of the ratings of legibility revealed the significant effects of the changes in interdot space and dot diameter (interdot spaces: $F(4, 80) = 15.62$, $p< 0.01$, diameters: $F(2, 80) = 39.01$, $p< 0.01$). The interaction effect of these two factors was not significant ($F(8, 80) = 1.03$, $p> 0.1$). Tukey's multiple comparison test ($p = 1$ %) revealed that at the dot diameters of 1.17 and 1.43 mm, the stimuli with the interdot space of 0.9 times the standard were rated significantly lower than those with the other four interdot spaces. Additionally, at the dot diameter of 1.17 mm, the stimuli with the interdot space of 1.15 times the standard obtained significantly higher ratings than those with the standard. At the dot diameter of 1.67 mm, the stimuli with the interdot space of 1.10 times the standard gained the highest rating, and significant differences were observed between the interdot space of 1.10 times the standard and the other four interdot spaces. Here, let us focus, on the effects of the dot diameter change at the same interdot spaces. At the interdot space of 0.9 times the standard, the stimuli with the dot diameter of 1.17 mm obtained significantly higher ratings than those with the other two dot diameters. At the interdot spaces of 1.0, 1.05, and 1.10 times the standard, the stimuli with the dot diameters of 1.17 and 1.43 mm obtained significantly higher ratings than those with the dot diameter of 1.67 mm. At the interdot space of 1.15 times the standard, a significant difference was observed among all dot diameters and the stimuli with the dot diameter of 1.17 mm obtained the highest rating.

When all the trials were finished, the subjects were

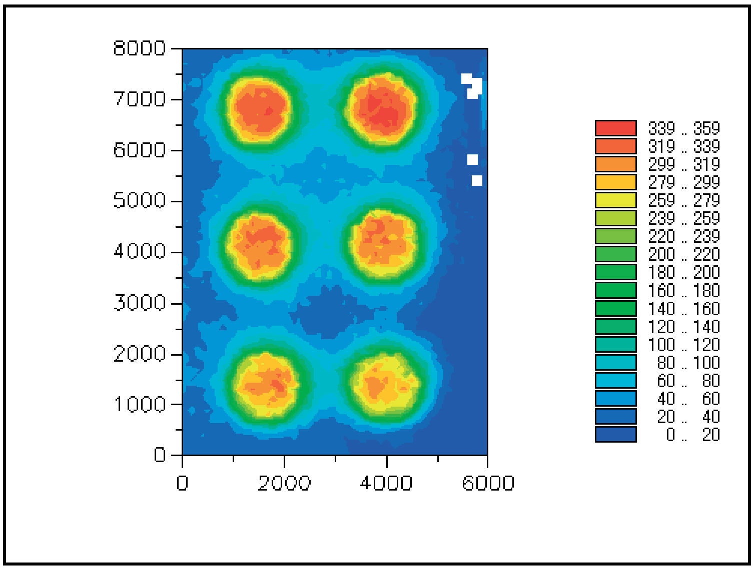


Fig. 11 Three-dimensional measurement of braille dots of “for” produced at dot diameter of 1.43 mm and interdot space of 1.15 times standard. Different colors represent different heights. Units in all axes are μm.

asked about their criteria for rating legibility. Five subjects explained that the stimuli with large dots were difficult to read. Two of these subjects stated that the stimuli with large dots that were very close to each other were difficult to read. Moreover, one of these subjects expressed that the stimuli with large dots and narrow interdot spaces were difficult to read. In addition to these five subjects, another person stated that the stimuli with dots that were very close to each other were difficult to read. These two different expressions “large dots that were very close to each other” and “large dots and narrow interdot spaces” are considered to carry the same meaning. We presented the comments of the subjects as is. Four subjects explained that the stimuli with narrow interdot spaces were difficult to read. Two of these subjects claimed that the stimuli with both narrower and broader interdot spaces than the standard were difficult to read, and one explained that the stimuli with narrow interdot spaces were difficult to read when combined with large dot diameters, as mentioned above. On the other hand, as for legibility conditions, one subject supported braille of the Japanese standard size, and another subject stated that large interdot spaces are preferred to the extent that one has to move his/her finger in the vertical direction to read.

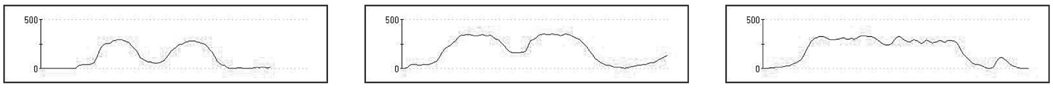
Fig. 8 shows the correlation between the normalized reading times and the legibility ratings. It was observed that short reading times lead to high legibility ratings; the correlation between these two factors was almost linear (correlation coefficient r = 0.843). When braille sentences have unligible parts, readers tend to move their finger on those parts repeatedly to read them correctly and the reading time increases as a result (Koyanagi, 1978). In this experiment, we did not only confirmed this phenomenon by videotaping but also demonstrated the linear correlation between the legibility rating and the reading time quantitatively.

The numbers of reading errors under each condition were added for all subjects (Fig. 9). As a whole, the number of reading errors increased as the interdot space decreased. In addition, at the interdot sapce of 0.9 and 1.0 times the standard, the number of reading errors increased as the dot diameter increased. These trends was the same as that of the reading time. No trade-off between speed and accuracy was observed; a long reading time did not lead to an increase in the number of reading errors.

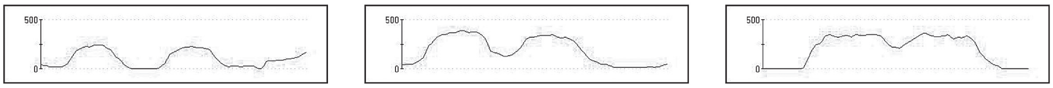
IV. Three-Dimensional Measurement of Braille Dot Shapes

The shapes of capsule paper braille dots produced from the same original ink-printed paper used in the legibility experiment were measured using a laser 3D shape measurement system. The system consists of an XY stage-controlling system, EMS98AD-3D, COMS, and a CCD laser displacement measurement unit, LK-030, Keyence (Fig. 10). The system enables the measurement of the displacement in the Z-direction with a resolution of 1 μm (according to the measuring conditions on the specifications) while moving the stage in the X- and Y-directions.

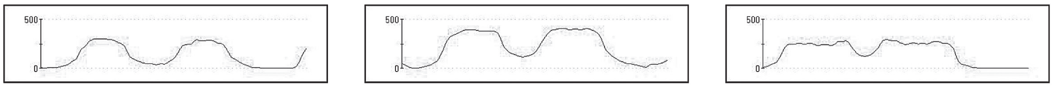
To focus on the fusion of braille dots caused by microcapsule foaming, the braille contraction of “for” was chosen as a sample since its six dots are raised. Braille



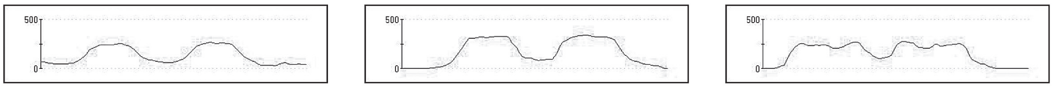
D: 1.17 mm, IS: 0.9 times. D: 1.43 mm, IS: 0.9 times. D: 1.67 mm, IS: 0.9 times.



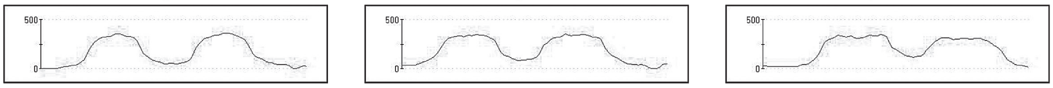
D: 1.17 mm, IS: 1.0 times. D: 1.43 mm, IS: 1.0 times. D: 1.67 mm, IS: 1.0 times.



D: 1.17 mm, IS: 1.05 times. D: 1.43 mm, IS: 1.05 times. D: 1.67 mm, IS: 1.05 times.



D: 1.17 mm, IS: 1.1 times. D: 1.43 mm, IS: 1.1 times. D: 1.67 mm, IS: 1.1 times.



D: 1.17 mm, IS: 1.15 times. D: 1.43 mm, IS: 1.15 times. D: 1.67 mm, IS: 1.15 times.

Fig. 12 Cross sections of braille dots “for” measured along horizontal line crossing either of centers of dots 1 and 4, dots 2 and 5. or dots 3 and 6. The unit of the vertical line is μm, and the width of each cross section is 6 mm long. D denotes the dot diameter, and IS, the interdot space. Tilt compensation and level cut were applied to the obtained data. Since it is difficult to determine the zero level, a comparison of dot heights lacks decisive power.

samples were produced under the same conditions as those in the legibility experiment. The cross-sectional shape of each sample was measured along the horizontal line crossing the center of dots 1 and 4, dots 2 and 5, or dots 3 and 6. Horizontal cross sections were chosen because the spaces between the dots in a row are narrower than those between the dots in a column and these adjoining raised dots are more inclined to fuse together. The sample measurement of the entire character “for” is shown in Fig. 11 (at the interdot space of 1.15 times the standard and the dot diameter of 1.43 mm). The cross sections obtained under all the conditions are shown in Fig. 12, where we can observe the fusion of two dots at the dot diameter of 1.67 mm. Fusion occurred markedly at the interdot spaces of 0.9 and 1.0 times the standard. It is reasonable to consider that fusion leads to the unlegibility of braille.

Swelling parts on capsule paper became larger than the original ink-printed dots because of the foaming of microcapsules. On the basis of the technical information from Matsumoto Yushi-Seiyaku Co, Ltd., microcapsules of 10-30 μm particle diameter expand a maximum of 70 times. The same principle applies to SwellPaper from Zychem, which was used in this experiment. Microcapsules expand not only in the normal direction to the paper surface but also in any lateral directions. Supposing that their extent of expansion is the same as that of vertical swelling, the particle diameter of these microcupsules increases to a maximum of 0.35 mm (Fig. 12) from the edge of the black ink-printed parts of the original image. This foaming of capsule paper should be explored in detail aside from legibility experiments.

V. Discussion

The results of this experiment clarified the unsuitable ranges of braille dot diameters and interdot spaces on the original image for stereocopying. Seven conditions of the dot diameter of 1.67 mm and the interdot space of 0.9 times the standard produced long reading times and legibility ratings lower than 3 (Fig. 8). On the other hand, the conditions of the dot diameter of 1.43 mm, which is the standard dot diameter, the dot diameter of 1.17 mm, which is smaller than the standard, and the interdot space range of 1.05 - 1.15 times the standard, which is broader than the standard, produced short reading times and high legibility ratings. Among these conditions, the interdot space of 1.15 times the standard and the dot diameter of 1.17 mm produced the shortest mean reading time and the highest legibility rating. Note that it does not necessarily indicate that these conditions are optimum for braille dots on the original image for stereocopying. Regarding the preferable braille size, subjects had different opinions; some preferred the standard braille size, but others, sizes larger than the standard. Moreover, variations in heating time, temperature, and type of capsule paper differentiated the degree of swelling. Accordingly, the suitable ranges of dot diameters and interdot spaces clarified in this experiment should be utilized as a reasonable guideline.

In addition to the above-mentioned heating conditions, the shape of the swelling parts of capsule paper changed in

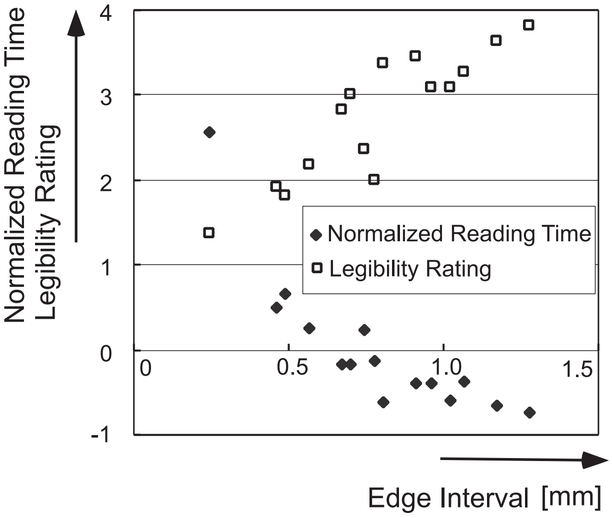


Fig. 13 Effects of edge interval on normalized reading time and legibility rating.

quality owing to finger pressure and abrasion. Regarding this issue, reading with a typical pressure does not rapidly wear the swelling parts away, as proven by our experience. Although we used the same stimulus capsule paper for all the subjects in the experiment, the trends in the changes in reading time and legibility rating under different conditions were in agreement for all the subjects. That is, within the limit of this legibility experiment, it can be considered that stimulus braille does not wear away so markedly that it affects the result. However, in future studies, it is necessary to measure the shapes of braille dots before and after reading to verify the finding.

In this study, the correlation between the braille size and its legibility on capsule paper was investigated. In addition, research studies on the legibility of braille embossed using braille printers were performed. For example, Kuroda et al. (1995) conducted an experiment using stimuli with different intercell and interline spaces, and concluded that either of large intercell or interline space improves legibility. Moreover, Nakano et al. (1997) showed that jumbo braille with increased vertical and horizontal intercell and interdot spaces can be read tactually even by visually impaired persons who suffered from diabetic retinopathy and had a low tactile sensitivity. If these experimental results are applied, an interdot space larger than 1.15 times the standard, which is the largest space used in this experiment, might also improve the legibility of braille on capsule paper. However, in this case, it is required to keep the dot diameter small, about 1.17 mm (Figs. 6 and 7).

The fusion of dots, which is considered to be the cause of unlegibility, can be expressed more directly by the edge interval of dots on the original image than by the dot diameter and interdot space. The edge interval was calculated by subtracting the dot diameter from the interdot space. The horizontal axis of Fig. 13 denotes the edge interval. The normalized reading time and legibility rating were expressed in the vertical axis. The chart shows that as the edge interval decreases, the reading time increases and the legibility rating decreases. Large correlation coefficients were found between the edge interval and the legibility rating (r = 0.840), and between the edge interval and the normalized reading time (r = 0.895). To the best of our knowledge, this is the first time to clearly demonstrate the linear correlation between the edge interval and the reading time, and between the edge interval and the legibility rating. Although this finding was derived from the experiment using braille on capsule paper, it would be applied to braille embossed using braille printers. New knowledge on the speed and difficulty of tactile reading may be acquired if future studies are conducted with a new index, the edge interval, other than widely used diameters and interdot spaces.

In this study, we explored the relationship between the 3D shape of a braille dot and the reading time, and between the 3D shape of a braille dot and the legibility rating focusing solely on dot fusion. We observed that the legibility rating depends not only on the occurrence of dot fusion but also on the shape of an individual dot (Kamoda and Fujimoto, 2001). The opinions of the subjects who participated in this experiment varied from “higher dots are preferable,” to “sharp and lower dots are preferable.” Koyanagi (1978) reported that braille with 0.4 - 0.6 mm high dots is the most legible. On the other hand, the braille dots on capsule paper used in this experiment were approximately 0.35 mm high (Fig. 11). As for the shapes of braille dots, braille dots embossed using braille printers generally had a shape of an upside down bowl and their tops were round, whereas large dots (diameter: 1.67 mm) on capsule paper had flat tops and they resembled a plateaux (Fig. 12). It is possible that these shapes contribute to the difficulty of reading. In future studies, it is necessary to discuss the relationship between the shape of a braille dot and the legibility rating more precisely using physiological data.

VI. Conclusion

The experimental results of reading capsule paper braille quantitatively demonstrated the suitable ranges of the dot diameters and interdot spaces of the original braille image for producing legible braille. One of the future tasks is to select appropriate braille fonts and sizes that keep original ink-printed braille dots in these suitable ranges. We hope that this research will provide useful information for persons who perform stereocopying in their daily job and life.

Acknowledgements: Authors would like to thank Yutaka Kitabayashi (Japan Vocational Development Center for the Blind) and Tetsuji Tanaka (Japan Braille Library) for helping with the conduction of the experiment, and the subjects for their participation in the experiment.

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—Recieved June 5, 2003; Accepted April 27, 2004—