Some Characteristics on Human Visual Sensitivity for Spatial Frequency of Digital Halftone Images

Shigeru Kitakubo and Yasushi Hoshino, Nippon Institute of Technology, Miyashiro, Saitama, Japan

Abstract

In this paper we show some experimental results of image recognition, and discuss them from the viewpoint of human visual sensitivity for spatial frequency. We have been interested in how we see digital halftone images which consists of halftone dots.

Introduction

Algorithms of converting a continuous-tone image into a binary high quality image are important in non-impact printing field. A great number of digital halftoning algorithms have been presented. Recently, FM screening has been extensively studied. In 1998 and 1999 we discussed the relationship between the minimum dot size and the print quality considering the human visual sensitivity. Through these results we recognized the importance of halftone screening method, which is one of the most widely-used binarization methods in printing and publishing industry. In 2000 and 2001 we discussed the stability of the shape of minimum dots and the merits of clustered dots. We presented many experimental results and their analyses with respect to the relationship between the size and the stability of clusters in 2002 and 2003.

In this paper we discuss the relation between the spatial frequency sensitivity and the contrast sensitivity on the basis of the experimental results. The experiment was done in 2004 and 2005, and a part of which was reported in 2004.

In the following, we describe an overview of special frequency and ordered dither method which we used in our experiment. Then we show the result of our experiment and discuss it. Finally we summarize the discussion.

Spatial Frequency Sensitivity

Research in both neurophysiology and visual psychophysics has led to the view that the early visual system consists of spatial frequency channels. Retinal images of objects are decomposed into spatial frequency components represented as channel activities. Object recognition is based on the further processing of this representation by later stages in the visual system. Even though the channel architecture of the early visual system is an important organizational principle in spatial vision, it is concerned only with the early stages of visual processing. Many important details have not been specified.

The spatial resolution of the visual system is usually assessed using a simple measure of static visual acuity. A typical visual acuity test consists of a number of high contrast, black-on-white targets of progressively smaller size. Recent research has demonstrated that visual spatial processing is organized as a series of parallel, but independent, channels in the nervous system. As a result of this parallel organization of the visual nervous system, visual acuity measurements no longer appear to adequately describe the spatial visual abilities of a given individual. Contrast sensitivity testing complements and extends the assessment of visual function provided by simple acuity tests.

Contrast sensitivity tests use sine-wave gratings as targets. Sine-wave gratings possess useful mathematical properties and researchers have discovered that early stages of visual processing are optimally tuned to such targets. This leads to determine the spatial frequency sensitivity.

Clustered-Dot Ordered Dither

Ordered dithering techniques can be divided into two classes by the nature of the dots or clusters of dots produced, clustered and dispersed. In this paper we use clustered-dot dither because it is the most widely used hafltoning technique in the printing process.

Clustered-dot ordered dither method can be characterized by the following four aspects; screen angle, screen frequency, dot pattern, level assignment. The original image is divided into cells. Each cell we used has 16 × 16 vertical and horizontal pixels, thus the screen angle is 0°. We denote each cell A[i, j], where a pixel A[i, j] has an integer value I in the interval [0, 255]. We prepare another 16 × 16 dither matrix B[i, j], whose dot pattern is shown in Fig. 1. This is a kind of threshold matrix and each will be compared with repeatedly to generate an output binarized image.

0	8	20	39	47	55	63	71	67	59	51	43	35	23	11	3
4	12	31	79	87	95	127	135	131	123	99	91	83	27	15	7
16	24	72	104	116	139	159	167	163	155	143	119	107	75	30	19
32	80	100	108	144	171	187	195	191	183	175	151	111	103	86	38
40	88	112	145	176	199	207	223	219	211	203	179	150	115	90	46
48	96	140	172	200	212	231	239	235	227	215	198	170	138	94	54
56	120	152	180	208	224	247	242	244	251	230	206	186	158	126	62
64	128	160	188	216	232	250	255	253	246	238	222	194	166	134	70
68	132	164	192	220	236	243	252	254	245	234	218	190	162	130	66
60	124	156	184	204	228	248	241	240	249	226	210	182	154	122	58
52	92	136	168	196	213	225	233	237	229	214	202	174	142	98	50
44	84	113	146	177	201	209	217	221	205	197	178	149	114	82	42
36	76	101	109	147	173	181	189	193	185	169	148	110	102	78	34
17	25	73	105	117	141	153	161	165	157	137	118	106	74	29	18
5	13	28	77	81	97	121	129	133	125	93	89	85	26	14	6
1	9	21	33	41	49	57	65	69	61	53	45	37	22	10	2

Figure 1. Dither Matrix B

There is a trade-off between the reproductivity of gray-levels and that of spatial resolution. It is said in general that the optimal size of halftone cell is around 4 × 4. However, we used 16 × 16 matrix B because we need to reproduce 256 gray-levels.

Experiment

First we prepare 6 patterns of sample images BC1, SC1, BT1, ST1, BS1, and SS1, representing Big Circle, Small Circle, Big Triangle, Small Triangle, Big Square, and Small Square, respectively. The number '1' of every image name represents the difference of the brightness value from the background. For example, 'BC1' is an image of a circle with a diameter of 15 cm and brightness value of 64, aligned in the center of a square with sides 18 cm and brightness value of 63, and 'SC1' is an image of a circle with a diameter of 6 cm and brightness value of 64, aligned in the center of a square with sides 18 cm and brightness value of 63. The resolution of every image is 400 dpi.

Second we change the brightness value of each figure and get BC2, BC3, ..., BC10, SC2, SC3, ..., SC10, ..., SS2, ..., SS10. For example, ST10 is an image of a triangle with sides 6, 7, 7 centimeters long and brightness value 73 aligned in the center of a 18 cm × 18 cm square with brightness value of 63, as in Fig. 2.

Third we binarize each of above 60 original images in three different manners; (1) an original image is divided into cells of 16 × 16 pixels and our dither matrix B is applied to determine the output values, (2) an original image is divided into cells of 32 × 32 pixels and for each cell brightness values of 2 × 2 = 4 pixels are averaged and then our dither matrix B is applied to determine the output values, where the same output value, 0 or 255, is assigned to these 4 pixels, (3) an original image is divided into cells of 80 × 80 pixels and for each cell brightness values of 5 × 5 = 25 pixels are averaged and then our dither matrix B is applied to determine the output values, where the same output value, 0 or 255, is assigned to these 25 pixels. We show three binarized images of ST10 in Fig. 3(1), (2), (3), respectively. Note that binarized images consist of many clustered dots and its frequency is about (1) 1 dot/mm, (2) 0.5 dot/mm, and (3) 0.2 dot/mm, respectively. Thus we get 180 sample images after all.

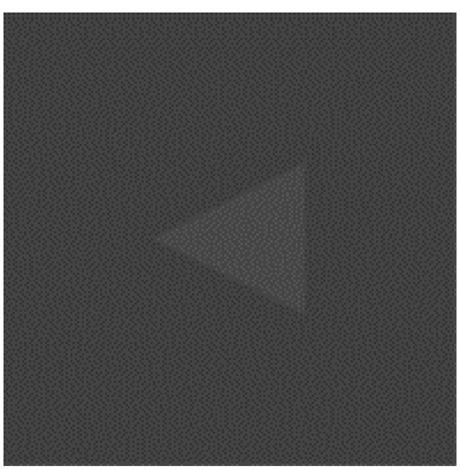

Figure 2. Original image ST10

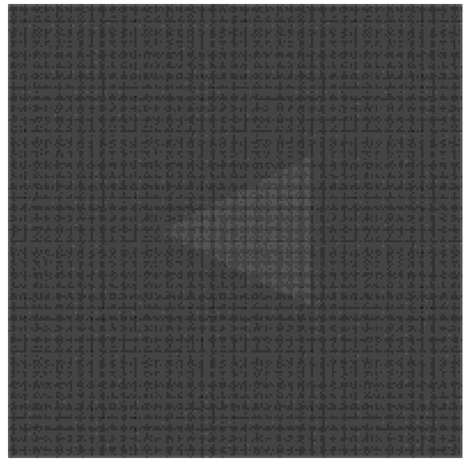

Figure 3(1). Binarized image of ST10 with frequency 1 dot/mm

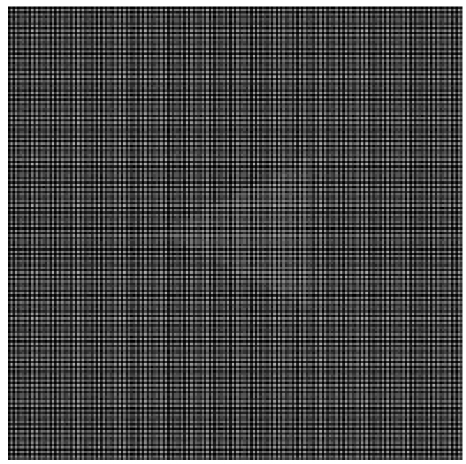

Figure 3(2). Binarized image of ST10 with frequency 0.5 dot/mm

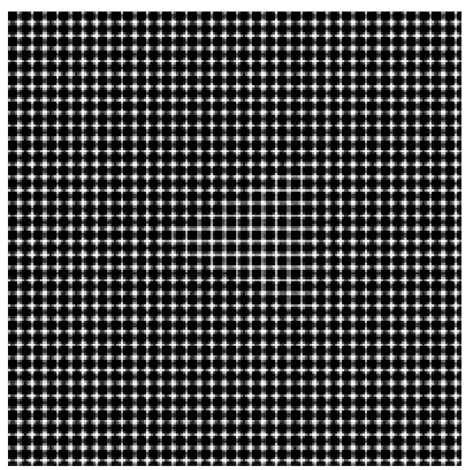

Figure 3(3). Binarized image of ST10 with frequency 0.2 dot/mm

Fourth we print the sample digital images on plain papers by using an inkjet printer with maximum resolution 600 dpi which are widely used for personal usage. After that we start the test for human recognition of a figure in gray background. Ten students in Nippon Institute of Technology with normal or corrected-to-normal vision, naïve to the purpose of the experiment, served as observers in the experiment. An observer looks at each printed image and tells whether he/she can recognize a figure in it or not. Repeat these processes at a distance of 0.5 m, 1 m, 2 m, and 5 m, respectively as in Fig. 4.

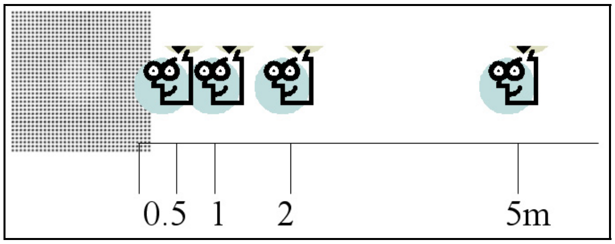

Figure 4. Object (figure) recognition test

Results

The results of experiments are shown in Fig. 5(a) and Fig. 5(b), when the distance between an image and an observer is 0.5m and 5m, respectively.

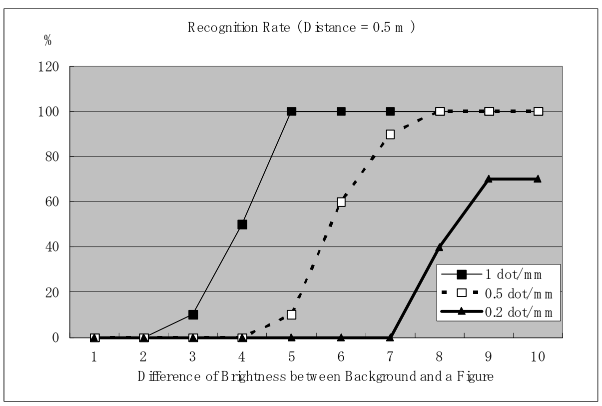

Figure 5(a). Recognition rate of a small triangle at the distance of 0.5 m

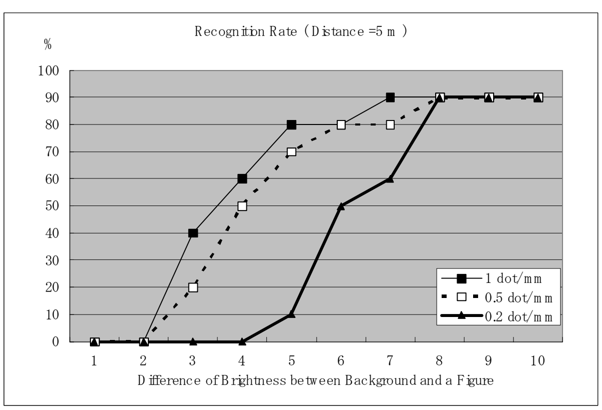

Figure 5(b). Recognition rate of a small triangle at the distance of 5.0m

Discussion

From the result the recognition rate is highest in the case of 1 dot/mm. Here, let us consider human visual sensitivity for contrast. Figure 6 shows a characteristic of human visual system; the relation between the spatial frequency and contrast sensitivity or MFT (Modulation Transfer Function). There is a peak around 10 cycles per degree. Next we translate 1 degree to mm. When we define the standard viewing distance as 50 cm, then the 1 degree at 50 cm translates to 500tan(1 degree)=8.7 mm. Thus the spatial frequency of maximum contrast sensitivity is around 10 cycles/8.7 mm=11.46 cycles/mm at the viewing distance of 50 cm.

We then translate each viewing condition of our experiment to the number of cycles per degree and get Table 1. We can explain the result of distance 5m, for example, in the following way; in this case the contrast sensitivity for the images of 1.0 dot/mm (87.3 cpd) and of 0.5 dot/mm (43.6 cpd) is too low to perceive each dot in these images, thus observers pay more attention to the whole images than dots and can find a triangle in each images. On the contrary, observers can perceive each dot in the image of 0.2 dot/mm (17.5 cpd), that disturbs them to perceive contrast.

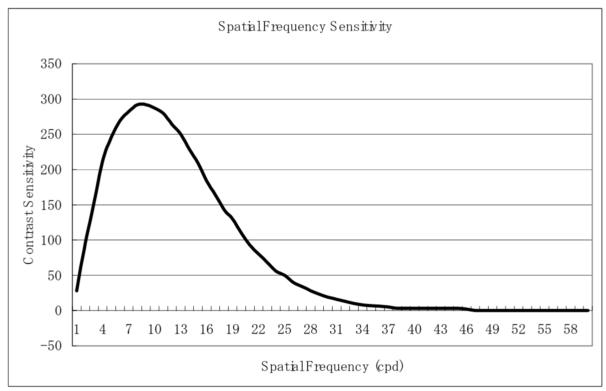

Figure 6. Spatial frequency sensitivity of human visual system

Table 1: Spatial Frequency (cycles/degree)

dots/mm	Distance between the image and the observer			
	0.5m	1m	2m	5m
1.0	8.7	17.5	34.9	87.3
0.5	4.4	8.7	17.5	43.6
0.2	1.7	3.5	7.0	17.5

As for the difference of brightness value between the figure's and background's, recognition rate gets higher as the difference gets bigger, which is predictable. We can say, however, there is a certain value of difference at that the recognition rate changes radically. For example, in Fig. 5(a) the recognition rate for the 1.0 dot/mm image raises from 50% to 100% when the difference of brightness value increases from 4 to 5. Since the spatial frequency sensitivity is high in this case (8.7 cpd), it is expected that there exists a critical value of brightness which sharply stimulates human visual sensitivity.

As future works, the following items will be remained;
1) consider the influence of light level, and
2) consider the eyesight of observers.

Conclusion

We made 180 different binarized images with three different spatial frequencies. We then did some tests using them in order to find the critical point where our attention is attracted more to the image as a whole than to the dots. We can explain the results by considering the spatial frequency sensitivity of human visual system.

References

1. L. Maffei, (1978). Spatial frequency channels: neural mechanisms. In Held, R., Leibowitz, H. W., and Teuber, H.-L., (Eds), Handbook of sensory physiology: Perception, p. 39-68. Springer-Verlag, Berlin, 1978.
2. Robert Ulichney, Digital Halftoning, The MIT Press, Cambridge, Massachusetts, London, England, 1987.
3. Reiner Eschbach, Recent Progress in Digital Halftoning II, IS&T, Springfield, VA, 1999.
4. S. Kitakubo and Y. Hoshino, Digital Halftoning Algorithm Characterized by the Merits of FM and AM Screening Method, Proc. IS&T's 11th International Congress on Advances in Non-Impact Printing Technol., pg.473-474, (1995).
5. S. Kitakubo and Y. Hoshino, Modified Error-Diffusion Methods and its Comparison with Halftone Method, Proc. NIP12, pg.77-78, (1996).
6. S. Kitakubo and Y. Hoshino, Relation Between Some Characteristics on Errors Caused by Binarizations and Print Quality, Proc. NIP13, pg.550-553, (1997).
7. S. Kitakubo and Y. Hoshino, Dependence of Print Quality on Minimum Dot Size and Binarization Method, Proc. NIP14, pg.607-610, (1998).
8. S. Kitakubo and Y. Hoshino, Dependence of Print Quality on Minimum Dot Size and Binarization Method II, Proc. NIP15, pg.370-373, (1999).
9. S. Kitakubo et al., Error Diffusion of Clustered Dots, Proc. NIP16, pg.690-693, (2000).
10. S. Kitakubo et al., Shapes of Printed Dots and Image Quality, Proc. NIP17, (2001).
11. S. Kitakubo et al., Characteristics of the Shapes of Printed Dots, Proc. NIP18, pg.819-822, (2002).
12. S. Kitakubo et al., Effect of Dot Clustering on Stability of Printed Image, Proc. NIP19, pg.777-779, (2003).
13. S. Kitakubo et al., Evaluation of Graininess for Digital Halftone Images Based on Human Visual Sensitivity, Proc. NIP20, pg.435-438, (2004).
14. T. Itoh, "Color Noise of Various Printer Outputs", Proc. SPIE, Color Imaging: Device-Independent Color, Color Hardcopy and Graphic Arts VI, (2001) pg.314-325.
15. Z.-L. Lu, et al., "Characterizing the spatial-frequency sensitivity of perceptual templates", J. Opt. Soc. Am. A, 18, pg.2041-2053, (2001).

Author Biography

Kitakubo Shigeru is Associate Professor of Nippon Institute of Technology. He received his B.S., M.S. and Dr. degrees in Science from Tokyo Institute of Technology in 1986, 1988, and 1992, respectively. Since 1993 he has worked in Nippon Institute of Technology. His work has primarily focused on digital processing theory, including halftoning technique and image quality issues. He participates in NIP conference every year since 1995.