Experimental Results on Human Visual Sensitivity for Spatial Frequency of Digital Halftone Images (II)

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Abstract

In this paper we add some new experimental results to our recent work and discuss them with respect to human visual sensitivity for spatial frequency. In our experiment, several dot pattern images and sinusoidal gratings are used to probe the capabilities of the visual system.

We can see some characteristics of human perceptual system when we analyze our experimental results from the viewpoint of halftone dot size, shape and frequency.

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.

In this paper we add some new experimental results to our recent work and discuss them with respect to human visual sensitivity for spatial frequency. In our experiment, several dot pattern images and sinusoidal gratings are used to probe the capabilities of the visual system. We can see some characteristics of human perceptual system when we analyze our experimental results from the viewpoint of halftone dot size, shape and frequency.

In 1998 and 1999 we discussed the relationship between the minimum dot size and the print quality. 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 2004 we focused on human visual sensitivity for graininess and presented a paper at ICISH'04. In 2005 through to 2007 we compared several halftone images and discussed whether we perceived an image as a set of small dots or we paid attention to some specific objects in the image.

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.

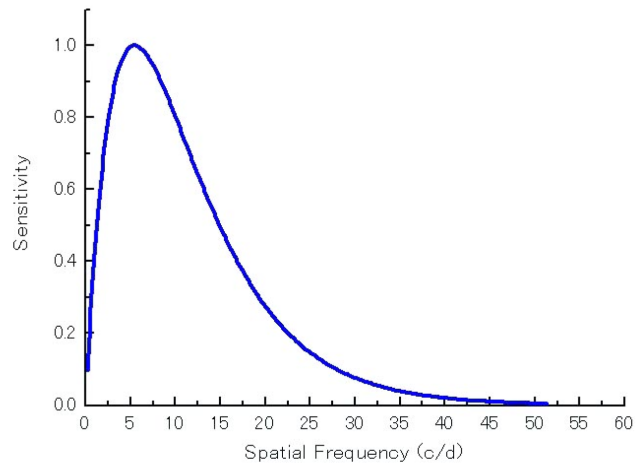

Figure 1. *Spatial frequency sensitivity of human visual system*

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. Fig. 2 shows an example schema for a frequency sensitivity experiment schema and some sample images.

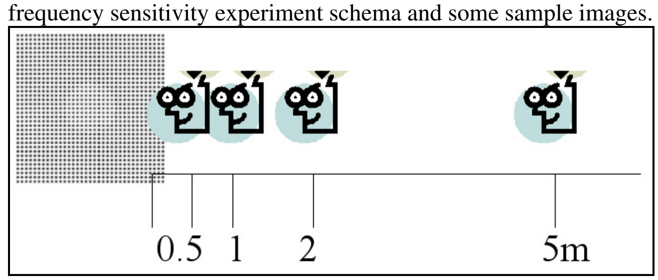

Figure 2(a). *Object recognition test*

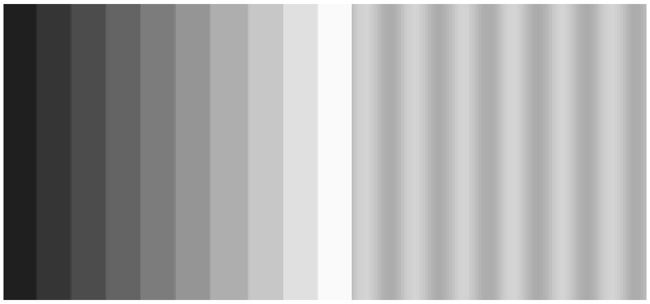

Figure 2(b). *A stepwise gradation (left) and a sine-wave grating (right).*

When we investigate object recognition mechanisms of human beings, it is important to study the sensitivity to contours in images. We know a characteristic of sensitivity to contours of a stepwise gradation image, which is related to both the step width, the number of pixels having the same brightness value, and the distance between the human eyes and the image. Fig. 2 shows an example of theoretical sensitivity curves at the distance of 0.5 m, 1.0 m, 2.0 m, and 5.0 m.

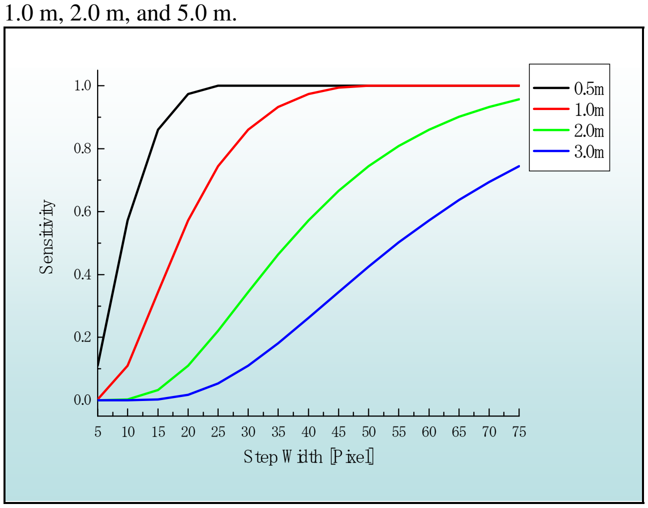

Figure 3. *Sensitivity to contours in several stepwise gradation images when we see from the distance of 0.5m (leftmost), 1.0m, 2.0m, and 3.0m (rightmost).*

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. When an original continuous-tone image is binarized, it is divided into cells and is compared generally to another cell that is called a halftone cell. If each cell is consist of vertical and horizontal pixels, the screen angle is 0°. A halftone cell is a kind of threshold matrix and each threshold value will be compared with repeatedly to generate an output binarized image.

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 x 4. However, when we need to reproduce 256 gray-levels by each output cell, we should use a halftone cell of 16 x 16 or higher. In Fig. 4, two binarized images of the sine-wave grating in Fig. 2(b). A 4 x 4 halftone cell was applied to the image on the left, while a 16 x 16 halftone cell was applied to the other image on the right.

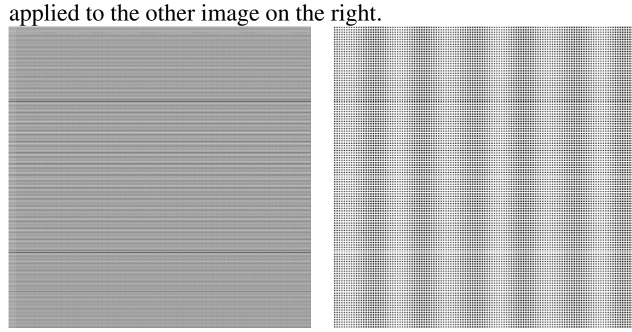

Figure 4. *Two binarized images of the sine-wave grating in Fig. 2(b). To the one on the left 4 x 4 halftone cell was applied, while to the other on the right 16 x 16 halftone cell was applied.*

Experiment

We firstly make 4 patterns of sample digital images CC(*f*, *b*, *c*), SS(*f*, *b*, *c*), CS(*f*, *b*, *c*), and SC(*f*, *b*, *c*). For example, CC(*f*, *b*, *c*) is an image which consists of circular shaped clustered dots having grayscale value *b*, and the circular shaped clustered dots within the circular area in the center of it have grayscale value *c*,.and its dot frequency is *f* dots/mm. We fix *f* is one of {0.2, 0.5, 1.0}, *b*=192 and *c* is an integer value in [182,191]. Thus, for each of these 4 patterns, we have 30 different images. We show the specification of these sample images in Table 1.

Table 1: Specification of sample images

	CC (*f*,192,*c*)	SS (*f*,192,*c*)	CS (*f*,192,*c*)	SC (*f*,192,*c*)
Shape of each cluster	Circle	Square	Circle	Square
Shape of the area in the center	Circle	Square	Square	Circle
Dot REQUENCY *f* (cycle/mm)	0.2, 0.5, 1.0	0.2, 0.5, 1.0	0.2, 0.5, 1.0	0.2, 0.5, 1.0
Image SIZE (cm)	16 x 16	16 x 16	16 x 16	16 x 16
Grayscale value *b* of background	192	192	192	192
Grayscale value *c* of the center area	182 to 191	182 to 191	182 to 191	182 to 191

Next we print these sample digital images on high quality papers by using an inkjet printer with maximum resolution 600 dpi which are widely used for personal usage. Two of the sample images CC(0.5, 192, 182) and CS(0.5, 192, 182) are shown in Fig. 5. After that we start the test for human recognition of a figure in each image. 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, and evaluate the clarity according as the following criteria;

0 : Nothing but dots can be seen,
1 : Something but not sure,
2 : Something with different tone,
3 : A circle, or a square, in the center,
4 : Clearly a circle, or a square, can be seen in the center.

Repeat these processes at a distance of 0.5 m, 1 m, 2 m, and 5 m, respectively.

Results

The results of experiments with CC(0.5, *b*, *c*), SS(0.5, *b*, *c*), CS(0.5, *b*, *c*), and SC(0.5, *b*, *c*) used as the sample images are shown in Table 2(a), (b), (c), and (d), respectively.

Table 2(a-1): Observation results (average) for CC(0.5,*b*,*c*)

Distance\c	182	183	184	185	186	187	188	189	190	191
0.5 m	4.5	5.0	5.0	5.0	4.0	3.0	1.5	0.0	0.0	0.0
1.0 m	5.0	5.0	5.0	5.0	5.0	4.5	4.5	3.0	1.5	0.0
2.0 m	5.0	5.0	5.0	5.0	5.0	4.5	4.0	3.5	1.5	0.0
5.0 m	5.0	5.0	5.0	5.0	3.5	3.0	3.0	1.5	0.0	0.0

Table 2(b-1): Observation results (average) for SS(0.5,*b*,*c*)

Distance\c	182	183	184	185	186	187	188	189	190	191
0.5 m	3.5	2.5	1.5	1.5	1.0	1.0	0.0	0.0	0.0	0.0
1.0 m	4.0	4.0	4.0	3.5	2.5	3.0	0.5	0.5	0.5	0.5
2.0 m	5.0	5.0	4.5	4.5	4.0	4.0	2.5	0.5	0.5	0.5
5.0 m	4.5	5.0	4.5	4.0	4.5	4.0	3.0	1.5	0.5	0.5

Table 2(c-1): Observation results (average) for CS(0.5,*b*,*c*)

Distance\c	182	183	184	185	186	187	188	189	190	191
0.5 m	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0	0.0
1.0 m	1.0	1.5	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
2.0 m	2.5	3.0	2.5	3.0	0.5	0.5	0.5	0.5	0.0	0.5
5.0 m	5.0	4.0	3.5	3.0	3.0	2.0	0.5	0.5	1.0	0.5

Table 2(d-1): Observation results (average) for SC(0.5,*b*,*c*)

Distance\c	182	183	184	185	186	187	188	189	190	191
0.5 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0 m	1.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0
2.0 m	1.0	1.0	1.0	0.0	0.0	0.5	0.0	0.5	0.5	0.0
5.0 m	4.5	4.0	3.0	2.0	1.5	1.0	1.0	1.5	0.0	0.0

Discussion

From the result the recognition rate is highest in the cases of the distance 5.0 m. Here, let us consider human visual sensitivity for contrast. Fig. 1 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 5 cycles per degree. When we define the standard viewing distance as 50 cm, then the 1 degree at 50 cm translates to 500 * tan(1 degree)=8.7 mm. Thus the spatial frequency of maximum contrast sensitivity is around 5 cycles/8.7 mm = 0.57 cycles/mm at the viewing distance of 50 cm.

We make graphs of the results as shown in Fig. 6(a)-(d), where (a), (b), (c), and (d) shows the case of 4 different patterns with a distance of 0.5 m, 1.0 m, 2.0 m, and 5.0 m, respectively.

Now we calculate each viewing condition of our experiment as the number of cycles per degree and get Table 3. Let us explain one case of the values. When we look at an image which is printed at the resolution of 0.2 cycles/mm at the distance of 0.5 m, we can see it as an image with 1.74 cycles/degree because 0.2 x 8.7 = 1.74. In Table 3, the following three pairs of original resolution and viewing distance make most sensitive spatial frequency for our eyes; (1) 0.2 cycles/mm and the distance 2.0 m, (2) 0.5 cycles/mm and the distance 1.0 m, and (3) 1.0 cycles/mm at the distance 0.5 m.

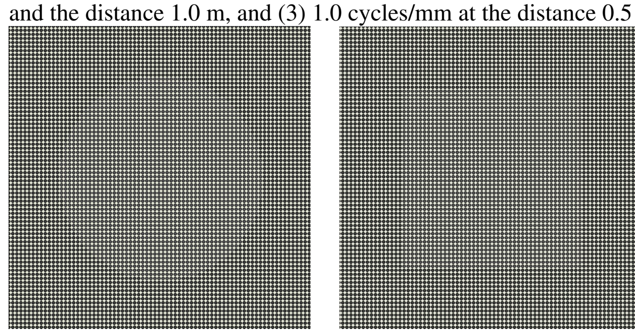

Figure 5. *CC(0.5,192,182); the center circle consists of the circular dots with brightness value 182, whereas the background consists of the circular dots with brightness value 192* ***(left) and*** *CS(0.5,192,182); the center square consists of the circular dots with brightness value 182, whereas the background consists of the circular dots with brightness value 192 (right).*

Table 3: Dot Frequency (cycle/degree): Exprimental Condition

Dot frequency of sample images (cycle/mm)	Distance from eyes			
	0.5m	1m	2m	5m
0.2	1.7	3.5	7.0	17.4
0.5	4.4	8.7	17.4	43.5
1.0	8.7	17.4	34.8	87.0

In the case of using the sample image printed with 0.5 cycles/mm, average point is the highest when we look at it at the distance of 5.0 m, and the distance of 2.0 m follows. We can explain these results as the following manner; our sensitivity for spatial frequency is lower at these viewing condition than the other cases.

As for the difference of brightness value between the figure's and background's, the 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.

As future works, the following items will be remained;

1) consider the influence of the angle of vision and light level using the contrast response function,

2) consider the eyesight of observers.

3) Define the function that explains the relation between (resolution, tone difference) and the object recognition rate.

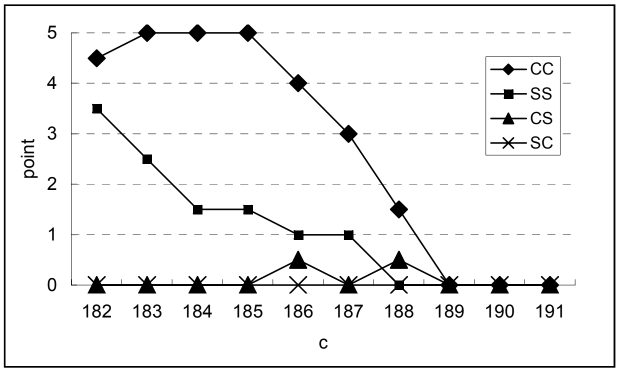

Figure 6(a). *Average point at the distance of 0.5 m.*

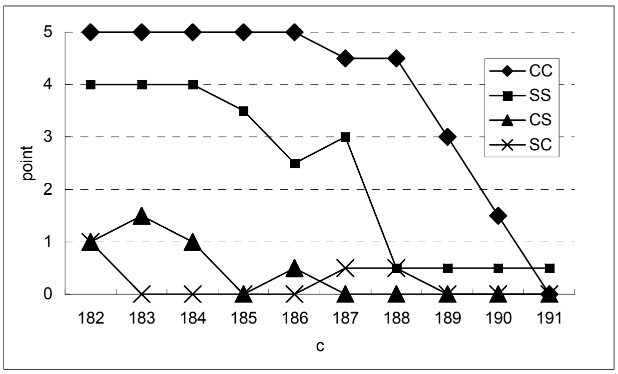

Figure 6(b). *Average point at the distance of 1.0 m.*

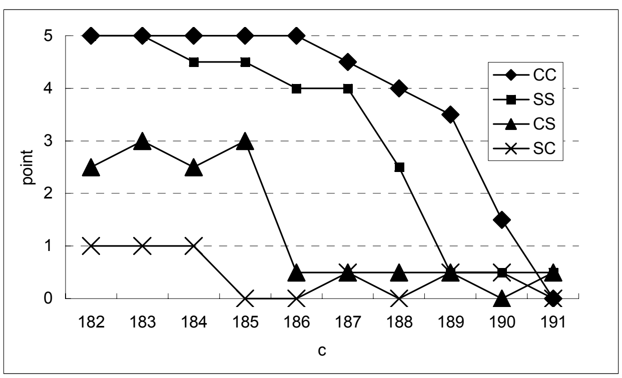

Figure 6(c). *Average point at the distance of 2.0 m.*

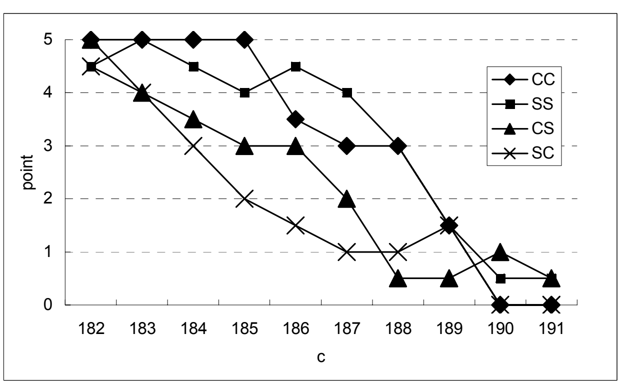

Figure 6(d). *Average point at the distance of 5.0 m.*

Conclusion

We made some grayscale images with two different shapes of clusters, circular and rectangular, of pixels and 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 see some difference of a certain extent between the two shapes with respect to contour recognition rate, and also explain the results by considering the spatial frequency sensitivity of human visual system.

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