Criteria for the Quality of Digitised Halftone Color Prints

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Abstract

A grading system for the quality of hardcopy color prints is suggested. It uses two index numbers: One of them describes the size of the available colorspace in terms of psychooptical discriminability. The other describes the size of the digitalisation error with respect to the detection threshold. Several examples illustrate the grading system developed at the Lehrstuhl Feingeratebau of the Technical University of Munich.

In the CIELAB color space the number of printable and distinguishable colors is determined. It can be approximately calculated from the gamut values and the contrast of black and white. The number can be used as a color quality number for comparisons between hardcopy devices. A typical color inkjet printer now available on the market and using the recommended paper reaches about half the size of the color solid available in offset-printing.

Digitalisation errors are brought in relation to the detection threshold. Contouring, texture and positioning errors are examined separately in the frequency domain. The overall print quality is determined by the largest error beyond the detection threshold. The psychooptical basics of assessing digitalization errors are summarized. The influences of the dither method and of the halftoning cell are described. The connections between halftoning method, print resolution and visibility of digitalisation errors are shown. Orthogonal halftoning cells are compared to hexagonal cells. Improvements by using different dot sizes and presentation modes are discussed.

1. Introduction

The quality of offset-printing has reached a very high level since many years. We are also used to the high quality of color photographs. Colored halftone images from hardcopy devices have to compete with these high standards. Therefore it is adequate to quantize and judge the deficits seen by the eye. This paper does not consider the effects of uniform glossy or dull surfaces or the paper deformation in form of cockle and curl but the reproduction of the image contents.

The range of colors that can be reproduced by hardcopy devices is limited. Even by using black ink additionally to cyan, magenta and yellow inks especially the color dynamics of dark tones is restricted.

Disturbing textures may be caused by the binarization process of a halftone image or by discontinuous transitions in halftones. The latter effect is known as contouring. During reproduction of images which are already binarized very often a long-waved pattern occurs. All three types of errors, namely textures, contouring and moiré, are summarized as digitalisation errors.

Additionally there exist some analogous errors which have an influence on print quality. Errors of this category are: periodical positioning errors of the printhead, nonuniformity of dot sizes and dot intensity, and registration errors. They result in stripes, shadows or color edges in the printed images.

2. The Color Dynamics

Figure 1 shows a typical color photograph. In the proceedings it will be reproduced in black and white. All areas of the photograph than can be reproduced in exactly the same color by a typical 4-color-inkjet-printer are marked grey. A large area remains white. Better results can be achieved if offset prints are reproduced instead of photographs. The color dynamics of offset printing compared to color photography is definitely limited.

For a comparison of color dynamics it is suitable to make calculations in units of a uniform color space, for example CIELAB. Figure 2 shows a cross-section of the CIELAB space. It includes the L*-axis as well as the a*-axis. The grey area includes the measured color space of a typical 4-color-inkjet-printer. The solid line marks the color space of offset-printing.[1] For the comparison a reflectance value of 90 % is assumed for unprinted paper and 1% for paper printed with black in offset printing. To compare the color dynamics the volume of each color solid is calculated. This volume is proportional to the number of distinguishable colors that can be printed using these color inks and an ideal halftoning method. The volume of the offset-printing color solid is about double the size of the measured printer color solid.

The reproduction of the full image contents of a photograph or an offset print with a hardcopy device requires a color gamut mismatch compensation. Figure 3 shows strategies and problems of color gamut mismatch compensation which is performed in a plane of constant hue in CIELAB-space. A recommended image independent technique is clipping with constant hue and lightness. Only chroma is reduced to the realizable output[2] (Fig. 3a). However, pure clipping leads to no solution if there are colors in the input color space which are brighter than the brightest point or darker than the darkest point of the output color space (Fig. 3b). In some cases (especially in case of yellow) the reproduced image may become very desaturated. Both problems can be overcome by using a modified clipping method (Fig. 3c): Two lightness values L1 and L2 are chosen. For an input lightness between L1 and L2 conventional clipping is applied. For an input lightness below L1 or above L2 a projection onto the output gamut surface is applied. Good values are L1 = 50 and L2 = 75 (empirically found).[3]

For a suitable color gamut mismatch compensation without color measurements by the end-user the printer manufacturers should provide at least the color data of white, cyan, magenta, yellow, red, green, blue and black. In addition a device-independent color interface should be used for color printers.[4,5]

3. Digitalisation and Other Errors

The most striking textures in most digital halftone pictures are easily detected in the bright areas of the picture. If uniform dots are used, the first step of the greyscale in most cases shows a very dominant texture. The transition from one step of the grayscale to another can often be clearly detected by the eye. For an example see Fig. 7.

If the picture contains smooth transitions in the bright areas, the change from step zero (unprinted paper) to step one can often be seen as a distinct line.

3.1 Psychooptic Approach

The best approach for the evaluation of the digitalisation errors is the Modulation Transfer Function MTF. It is the inverse of the Contrast Sensitivity Function CSF. MTF = 1/CSF. Fig. 4 shows the MTF following the equations of Barten.[6] But it is not so easy to compare digitalisation errors spread everywhere in a picture to the MTF. So we have to make some simplifications and we have to prove whether they can be used or not.

Now the difference between a perfect halftone picture, which is however reduced to the colorspace of the printer, and a digitised printer output will be considered.

First we will try to omit all effects of chromatism and look only at the luminance. Since the greyscale between black and white has the highest contrast, the modulation errors will not get lost.

We still have a mixture of many frequencies, directions and intensities. So we have to find out how this mixture can be compared to the simple one-dimensional sine-wave patterns used to determine the MTF.

Even if we take much simpler periodic patterns, a lot of questions arise:

- What about two-dimensional frequencies?
- What about the phase relation between harmonic components?
- How can the contrast of a harmonic be described if the surroundings have not got the average luminance?
- How linear is the relation between illumination and perceived luminance and what about the lateral interactions?

Figure 5 shows three periodic patterns that contain the same frequencies, but spreading in different directions.[7]

If we see them from a distance, so that the contrast of the texture does not reach the threshold, all three fields produce the same step of a grayscale in our eye. When we come closer, the texture can be seen. It is at exactly the same distance that the texture in all three fields can be detected by the eye. The two-dimensional fourier transform of the three patterns shows us that the predominat first harmonic exists in the first field only in one direction, in the second field in two and in the third field in three directions. They don't interact. We can use the central slice theorem and compare the harmonic contents of every direction separately to the MTF.

If we compare a square-wave grating that contains only unshifted sine-components to a grating with the same harmonic components but unshifted cosine-components, the detectability does not change, whereas the second grating shows significantly greater differences between dark an light partitions. Thus the single harmonics can be compared separately to the MTF while we neglect differences in phase.

Much more difficult is the question how much of the surroundings has to be taken into account for the calculation of the contrast. Fig. 6 shows a pattern in which the density increases from the left to the right. The overlying grid is designed to have the same modulation, not the same difference between dark and light. Parts of this grating were used for experiments in different surroundings. There was nearly no difference in the detectability of a texture whether it was limited to a small area, spread over a wide field or surrounded by black or white regions. It was always in quite good agreement with the predictions derived from the MTF, if the average value of the pattern was used to select the illumination.

Thus we can calculate the texture as if it were periodic to infinity in all directions, convert it into the frequency plane and compare the single harmonic components to the threshold. The first harmonic is predominant and it should be chosen as high in frequency as possible and as weak in amplitude as possible.

3.2 Texture and Contouring

Texture and contouring strongly depend on the dithering strategy. The ordered dither scheme of Bayer[8] tries to avoid large wavelengths, however it shows a strong contouring caused by regularly changing wavelengths. The tone response curve of real printers is very non-linear because the dot coverage increases over-proportionally in the first steps of a grey ramp. The digital halftone scheme of Judice[9] or Stucki[10] produces a striking texture because of the strong long-wave components which result from the clustered dot structure. On the other hand the linearity of the tone response curve is better. Error diffusion algorithms also produce long-wave-shaped patterns which look like worms. These effects can be reduced by a special adaptation.[11]

Much better results can be achieved by applying a sort of error diffusion within the halftoning cell by creating sub-cells. The sub-cells are filled alternately. Within each sub-cell a digital halftone scheme is used. As shown by Koch[7] and Wild,[12] halftoning cells using this principle can be well adapted to the threshold curve. Thus the advantages in processing speed of non-adaptive dithering can be combined with balancing the errors within the halftoning cell.

The linearity of the tone response curves can be considerably improved by using hexagonal grids with hexagons as base elements instead of orthogonal grids with squares as base elements. A hexagon can be completely covered by a circle whose size is only 20 percent larger than the size of the hexagon. In case of a square the size of the circle is 57 percent larger than the size of the square.[13] Even on an hexagonal grid the raster-cells should be choosen rectangular, because hexagonal cells lead to lager wavelengths.

3.3 The Ideal Printer Resoution

Starting with the MTF, three characteristic points can be found for a halftoning cell: The minimum of the MTF, the threshold value of the wavelength of the halftoning cell and the wavelength corresponding to maximum modulation (see points 1, 2 and 3 marked in Fig. 4). To make contouring disappear the contrast increments in the whole grey ramp must be so small that all harmonic components are always below the threshold.

The difference between a continuous grey ramp and a grey ramp with quantized grey levels looks like the teeth of a saw blade. The contrast of the first harmonic of this periodic function must also be smaller than the minimum of the MTF. To meet both conditions, a minimum of about 256 grey levels is needed for orthogonal base grids. If hexagonal base grids are used, only about 190 grey levels are required.

Invisibility of texture at a viewing distance of 12 inches and full illumination while using a printer device with a single dot size and optimal halftoning cells requires a printer resolution of at least 1800 dpi. At this resolution the first grey level using a 16×16 pixel halftoning cell in an orthogonal base grid touches the MTF. If two strongly different dot sizes are used, the required printer resolution can be halved. If printers with lower resolution are used, the distance from which the texture becomes invisible increases accordingly. In the middle of a gray ramp the modulation approaches the value one. This leads to the recommendable base length of a sub-cell. To meet the demand for invisibility of this kind of texture at a viewing distance of 12 inches and full illumination, the sub-cells must have a size of no more than 1/300 inch.

In case of using a hexagonal base grid a 15×13 pixel halftoning cell is sufficient. At the same time the sensitivity to variations of the print dot size is greatly reduced, especially in dark areas.

If low-resolution printers (for example 300 dpi or 600 dpi) have to be used, the viewing distance should be increased and the number of grey levels should be decreased. A 52-stage halftoning cell with four sub-cells[14] yields a considerable print quality on a 300 dpi printer. Fig. 7 shows the first steps of grey-scales for different dither methods. Fig. 8 shows an enlarged view of Fig. 10 (left side).

3.4 Moiré

The scanning and reprinting of bilevel images causes aliasing effects between the screen angles. The effect, which is commonly known as moiré, can be seen especially in areas of constant grey level. It can be studied by taking two identical patterns, superimposing them and rotating one of them by some degrees. In Fig. 9 the three patterns of Fig. 5 have been superimposed and rotated by approximately 5 degrees. The results are enlarged negative images of the base patterns. They have a rectangular orientation with respect to the base patterns.

Ostromoukhov[15] suggests pseudo-random halftone screening to reduce moiré. In this way the texture of the image is made cruder.

Since an image is available as a file previously to printing, the filtering of the screen frequencies should be part of the preprocessing.

3.5 Analogous Errors

The influences of tolerances in the mechanical movements of the printer increase with higher print resolutions. In printers with paper feeding systems consisting of drums and rollers the paper thickness has an effect on the print quality if printing and paper movement are applied to the two different sides of the paper. Unwanted stripes occur if the printhead does not match the exact print position after a paper line-feed. On inkjet printers, a similar effect can be observed when the speed and direction of the droplets varies.

Inkjet printers should print neighbouring drops which will overlap on the paper with a delay allowing the first drop to penetrate the paper before the next drop arrives. In case of printheads with all nozzles arranged in one line this can be achieved by implementing a mode for staggered printing, commonly known as 'presentation mode' or 'shingling' (Hewlett Packard). For an example see Fig. 10.

Variations in the drop mass of inkjet printers or in toner density of electographic printers also result in unwanted stripes or shadows. Some hardcopy printers print complete pages in one color after another. These printers may have problems with misregistration, which shows in color displacements and reduced sharpness of edges in the picture.

3.6 Quality Number for Hardcopy Prints

The decisive error is the one which first strikes the observer who approaches a printed picture. Therefore the distance from which the first error becomes visible is a suitable quality criterion for hardcopy prints. It is at this distance that the observer realizes that he is not looking at an offset print. So, next to the criterion of color dynamics, the above-mentioned distance is the most important quality criterion.

4. Future Aspects

If offset printing quality is aimed at, the color space must be enlarged in the region of dark colors. At the same time the technology of scanners must be improved so that dark colors can be scanned correctly.[16] Resolution should be further increased, and improved dither methods should be used. Besides, it is advisable to use different raster grids for text on the one hand and halftone printing on the other hand. The dot-size should be adjustable for the user.

The adaptation of software to the different hardcopy technologies should be simplified. Postscript (TM) for example, generally is designed to drive a printer which has a very high resolution, and it uses rastering techniques for halftoning. For printers with lower resolutions (for example 600 dpi) however, dithering with sub-cells is much more suitable. The Postscript Interpreter Ghostscript[17] allows such a user-defined halftoning implementation.

Improvements like standardized interfaces for color interchange, color gamut mismatch compensation and the possibility of customized solutions for halftoning methods will make work much easier for the user. Printing colored halftone pictures will become more acceptable and more attractive.

5. References

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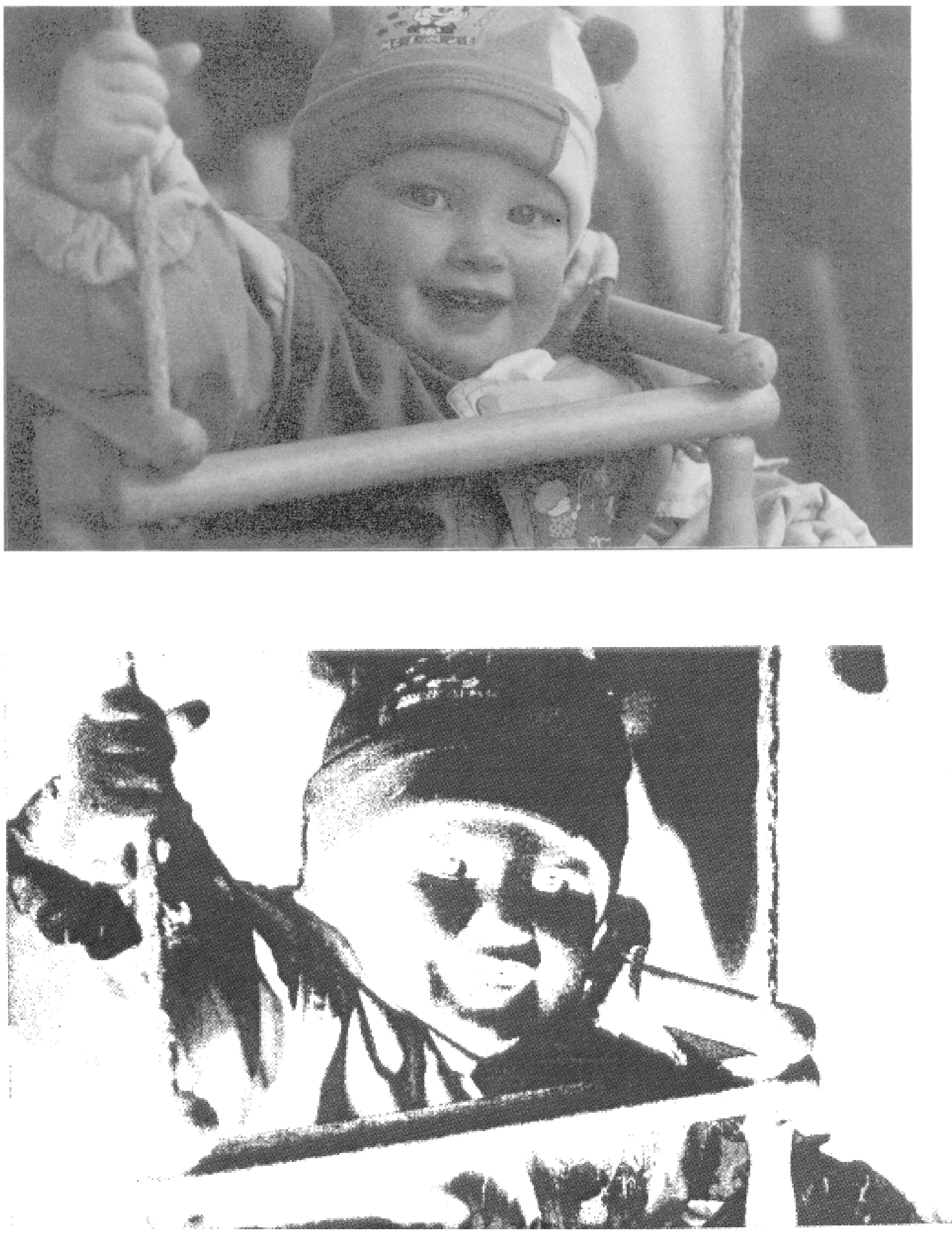

Figure 1. A paperprint of a color photograph, using nearly the full range of colors and the regions of the photograph that can be produced by an ink jet printer with its colorands on the recommended paper

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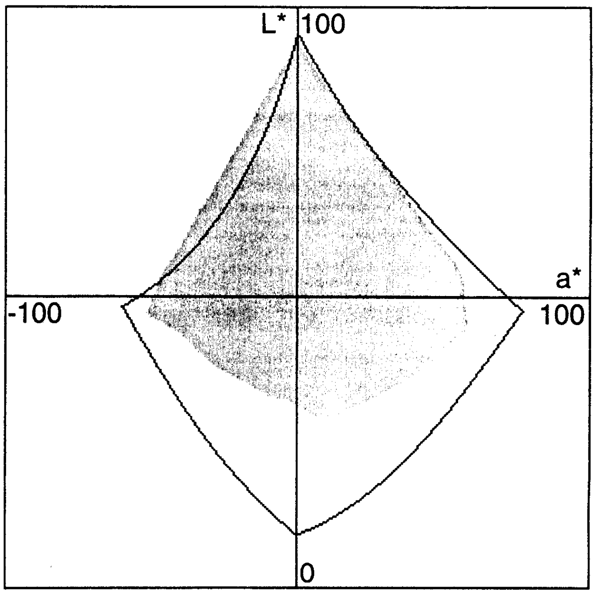

Figure 2. A cross-section through CIELAB colorspace comparing the color dynamics of an ink jet printer with the abilities of offset-printing

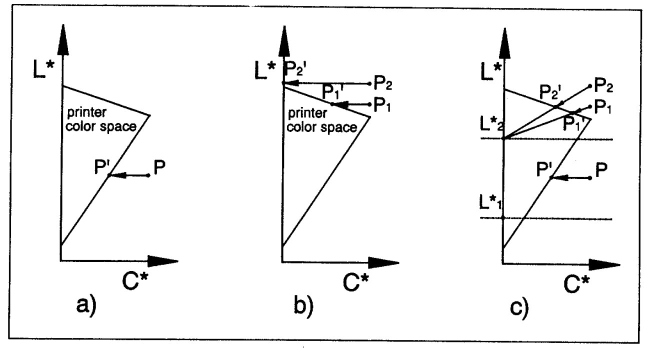

Figure 3. Different strategies of color gamut mismatch compensation: a) clipping, b) problems with clipping, c) modified c

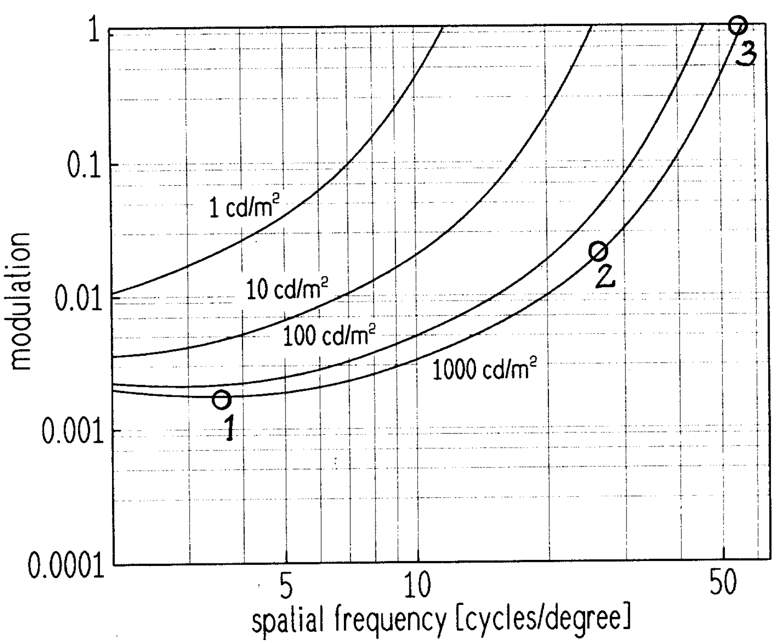

Figure 4. The modulation transfer function

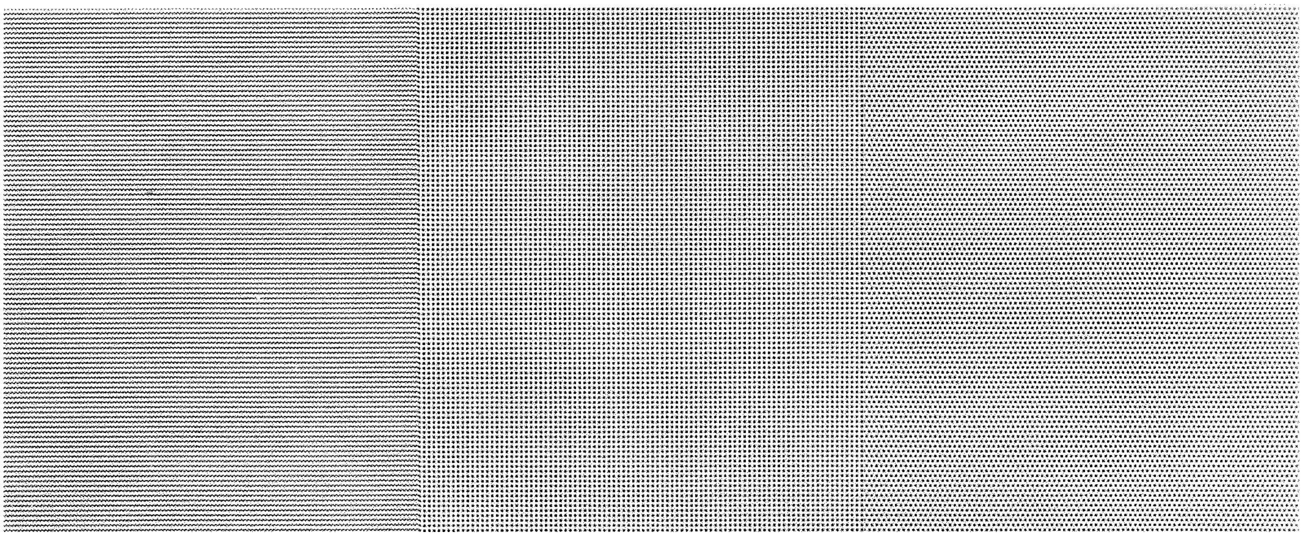

Figure 5. Three different patterns that produce the same greylevel with frequencies in one, two or three directions

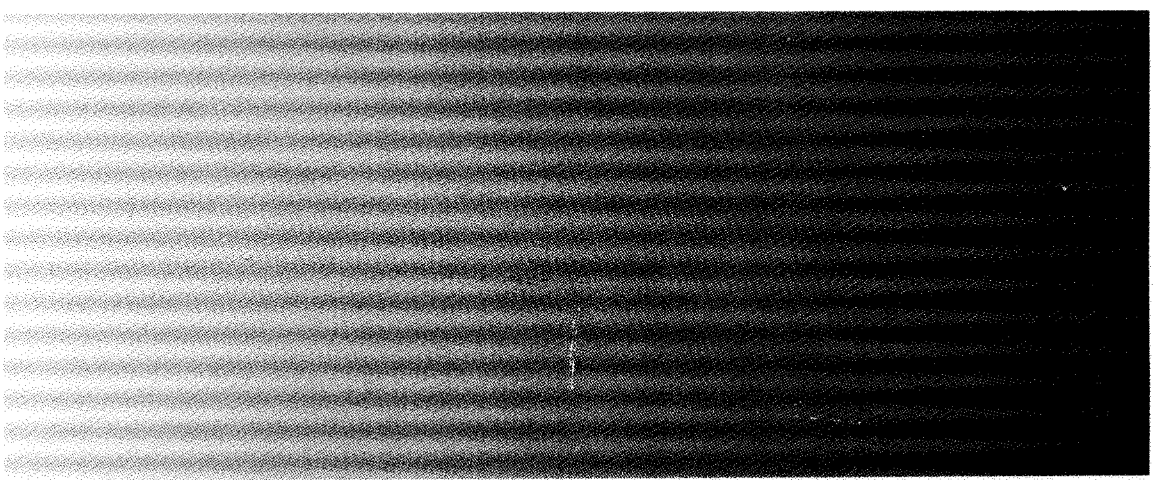

Figure 6. Pattern with increasing density and with constant modulation

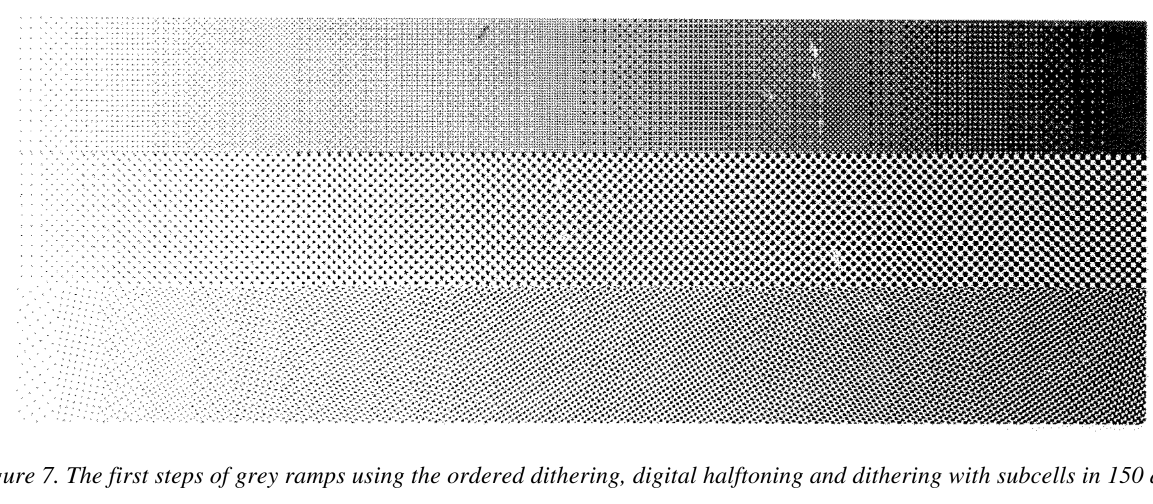

Figure 7. The first steps of grey ramps using the ordered dithering, digital halftoning and dithering with subcells in 150 dpi

Figure 8. Enlarged section of a dithered picture using a rectangular base grid, a 52- greylevel halftoning-cell with four subcells with 13 pixels each

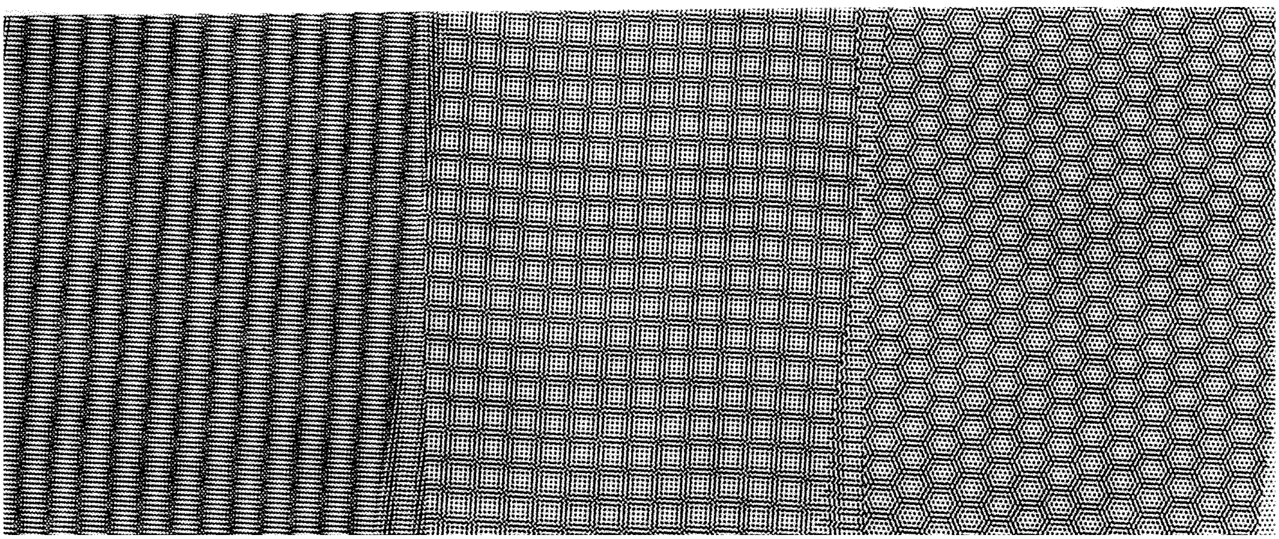

Figure 9. Moirés produced by superposition of the pattern of Fig. 5 with itself

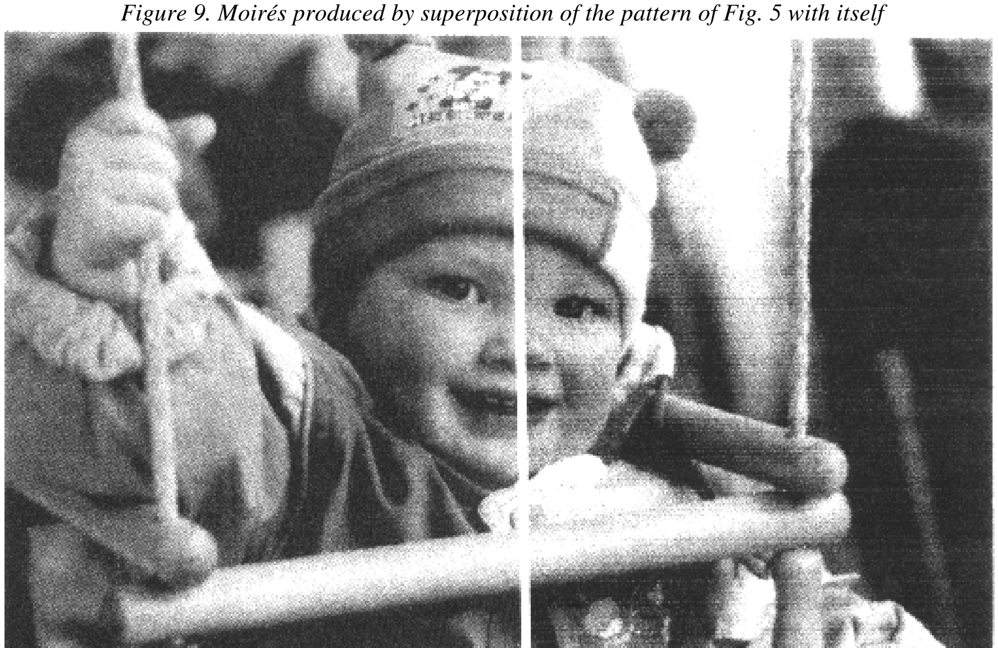

Figure 10. The effect of analogous errors: right side: presentation mode, left side: simple mode