The Quantitative Evaluation of Image Quality and Definition of an Image

IVO CHUDÁČEK

Faculty of Mathematics and Physics, Charles University, Prague*)

Received 10 January, 1987

In the presented paper we introduce the definition of the entity "image" as some organization of signals in the space. We consider under the image quality the number of active pixels which take part in the understanding by the detector of this organization. We can calculate the image quality Q if you know the values of the surface of the image, the imaging efficiency of the image content and composition, the vision pixel and the signal to noise ratio in the form of the ratio of length borders, understandable to noisy. These Q values are proportional to the subjective quality determined by psychometric scalling in a serie of photographs.

1. Introduction

The questions arising today in connection with the image quality problems are very actual [1, 2]. This is given by the necessity to compare the quality of images produced by classic photography, TV screen, electrophotography, thermography, ink-jet printers and other new methods. These processes are the result of "electronization" or "digitalization" of the imaging, which occurs today in a higher and higher scale. We ask of course, if the new recording media will give higher image quality than the old ones.

The meaning of the term image quality has some philosophical aspect. It is given not only by the quality of recording media and other elements of the imaging chain [3]. In our concept it is also based on the possibility to understand the image content by the detector of the image. For example, to analyse spatial photographs of the Earth we utilize now robots, which themselves study imaged parts of the Earth surface. The "quality" of this work is given by the quality of the image input into the robot and is also a function of the education time of the robot [4]. Therefore, it seems that the image quality is an objective value given not only by the properties of the imaging chain but also by some properties of the imaged original and of recording detector where the perception of the image occurs.

The aim of the presented new approach for the determination of the image quality is the utilization of some results obtained in information transfer. In a short historical

*) V Holešovičkách 2, 189 00 Praha 8, Czechoslovakia

survey we sumarize the principal concepts and results. To introduce the notion of an universal vision detector we examine briefly the human vision. After this, we define, what is an image and we introduce an equation for the determination of the image quality. At the end we give some concrete calculations and results of psychometric scaling. We take in account the influence of the image content on the image quality by the introduction of a new value, called image efficiency.

2. A short historical survey

At each time the image quality in photograph practice [5] is given by:

- the maximum of clearly detected details
- the isolation of the detected object from the background
- the minimum of artefacts
- the good composition of the image
- the geometric and tone fidelity

After Biberman [3] two types of factors control the performances of an universal detector:

Physical factors	– photosensitive material – optics – light – photoelectronic device (eyes)
Psychophysical factors	– vision – time available – task of the observer

The spatial frequency utilized in image processing, as we know, is the reciprocal distance between recording or printing elements, which are obviously called pixels. The printing elements are in general in the form of dots.

For each element of an imaging chain at each spatial frequency v the possibility to transfer different light (information) modulation is not equal. This value is given by the modulation transfer function (MTF) of the element $T(v)$ [6]. As definition of the image quality a different types of integration of $T(v)$ were proposed for all spatial frequencies (integral criteria) [7, 8, 9, 10]. For example

$$Q \sim \iint_{-\infty}^{+\infty} |T(v_x, v_y)|^2 \, . \, \mathrm{d}v_x \, . \, \mathrm{d}v_y \tag{1}$$

where v_x and v_y are the spatial frequencies in the x and y direction. The integral criterium (1) shows, that a good quality image requires a deep modulation (large halftone scale) for a large spatial frequencies interval.

The radiation from the surface of the objects carries a full message concerning the configuration of the surface but only a small fraction of the total message is intercepted by the optical system. If D is the diameter of the receiving optics and λ the wavelength of the transmited light, then the received message obtains information about the spatial frequencies approaching $2D/\lambda$. In real system their difraction limits are overheaded by the imperfection limiting frequency. In a search for physical measure of image quality Scott and Hafnagel [in 3] utilize a serie of prints, which were degraded in image quality by a successive decreasing quality of the corresponding MTF. They have calculated the quality by the equation

$$Q = \frac{\iint T(v) \,.\, \mathrm{d}v_x \,.\, \mathrm{d}v_y}{1 + \iint |N(v)| \,.\, |T(v)|^2 \,.\, \mathrm{d}v_x \,.\, \mathrm{d}v_y} \tag{2}$$

and have compared with the subjective evaluation of the quality, $N(v)$ is the noise Wiener spectral density. The results show a linear dependence between Q and subjective jugement.

In general the research in image quality is connected with the desirable requirements of the recording material to obtain the "best" images. For negative photographic materials based on silver halides, it is now realized by the increase of the apparent sharpness and low granularity of the image [11]. The noise power spectrum of colour negative films with incorporated couplers is dependent of the dyecloud morphology, which appears to be Gaussian. Diameters of the clouds are 3 – 7 microns.

The sharpness of an electronic image is substantially lower. In fact in the field of solid state detectors the different working groups obtain detectors which have about 1 Megapixels where the diameter of the pixel is about 10 microns.

At present time purely electronic systems, with an electronic camera, an electronic signal processing unit and with a nonconventional image technology seem not to be able to reach the high levels of image quality of today photographs [2]. But some research laboratories as Agfa-Gevaert [1] utilize a hybrid system, where the information is stored into a negative film and the image carrier is a conventional photographic paper.

In digital processing Powell [12] proposes the reduction of graininess and subsequent enhancement of the sharpness by the estimation and reconstruction of the average gradients in the neighbourhood of a picture element over areas of different sizes and orientations. Miyake and all [13] have evaluated the image quality of digital pictures obtained by drum scanner and photoprinter. A strong correlation was obtained between observer rating values in subjective jugements and information capacities.

It is possible to take the image process as a communication channel. According Shannon [6] the channel capacity C in bits . s^{-1} is equal

(3) $$C = \Delta f \,.\, \log_2 \left(\frac{P + N}{N} \right)$$

where P and N are the average signal and noise power in the channel, $P + N$ is the power limitation of the channel, Δf is the frequency bandwidth of the channel. Altman and Zweig [14] utilize eq. (3) for imaging systems based on a unit storage cell area A, which is a local property of the recording media. Each storage cell or pixel stores the information in the form of one or more M distinguishable density levels. They have obtained for the value C the relation

(4) $$C = \frac{1}{A} \,.\, \log_2 M$$

In the photographic process we don't have discrete signals but continuous signals and it is possible to calculate the pixel surface from the equation valid for the low frequency limit G of the Wiener spectrum

(5) $$G = A \,.\, \sigma_A$$

where σ_A is the main square image density fluctuation. In the Miyake and all study Wiener spectrum, autocorelation function, resolving power and granularity were determined. The relationships between these parameters and subjective judgement have not been cleared.

Zwick [15] has demonstrated from the psychometric scaling of image attributes that a 9-step category scale satisfies the criteria of being unidimensional of defining intervals and of being unambiguous. These steps are: extremely low, very low, moderately low, midly low, medium, midly high, moderately high, very high, extremely high.

3. The human vision and the vision processor

Now, our task is to find the principal parameters of the vision, which are connected with the image quality. For this purpose we utilize our knowledge of the human vision.

The visual processes accomplished by human eyes and brain shall be divided into three parts [16]:

(i) OPTICAL IMAGING: the photons scattered by objects are focused on the receptor cell of the retina.
(ii) PHOTOTRANSDUCTION: the absorbed photons generate electric signals
(iii) NEURONAL PROCESSING: the transport, coding and analysis of these electric signals by the brain.

ad (i):

The diameter of the retina pixel has the value of 5 microns. A retina rod cell has 90% effficiency for the absorption of light at wavelength 500 nm. The photoresponse is comparable to an "analogue transducer", where with increasing illumination of the eye the progressive change of the electrical polarization of the cellular membrane occurs. One to one connection between retina rods and nerve fibres is only on the center of the retina in the so called fovea. The angular resolution is therefore not constant over the whole visual field. But we orient the unconscious movements of the eyes towards the details we want to observe. These movements are important for the recognition of the imaged object.

ad (ii):

The phototransduction is accomplished by a collection of informations not of energy. The eye system has a high S/N ratio with high gain about 10^4 in the energy scale. The noise rejection is perfect and the capacity to adapt in a very larger intensity range is very great: a light contrast of 1% remains detectable over 5 log units of light intensity. The mechanism is analogous to the final stage of a power amplifier. It results from the cutting off of a large current.

ad (iii):

In the neuronal processing the brain analyse the signal contrast by the intensity of the signal stimuli, their colour and disposition. In the brain occurs the comparison of the perceived scene with previously stored scenes [17]. Analogous visual elements tend to combine spontaneously into groups with common perceptable properties such as shape, size, colour, brightness, spatial orientation etc. The visual identity of an object is most effectively converged by some structural skeleton of its main axes and proportions.

In our concept of image quality it is necessary to introduce the term of the uni-

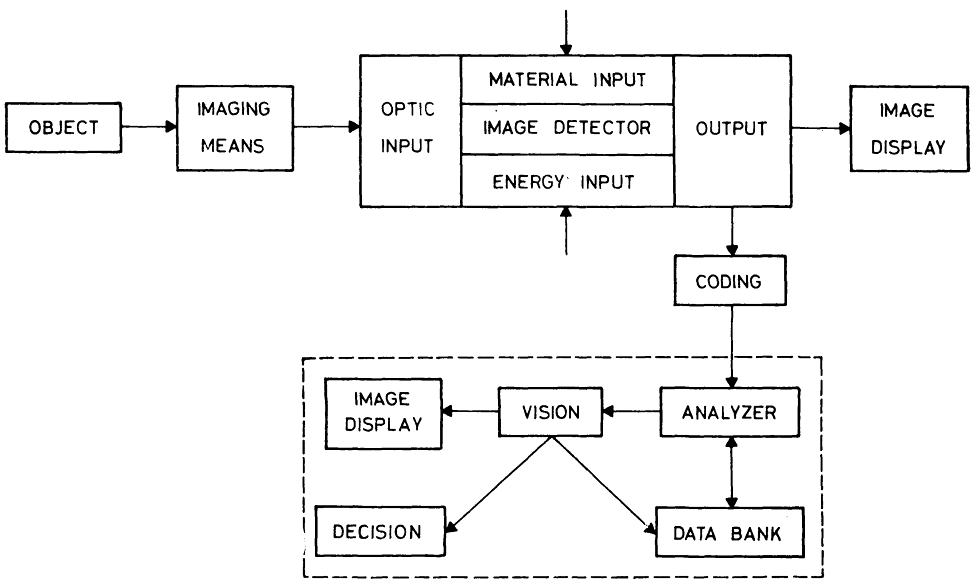

Fig. 1. The schematic chain of the vision processor.

versal observer or the term of the universal vision processor. Each analysis of perceived light giving image by brain, by organism or by robots is accomplished by different types of vision processors. But these processors have some common parts, which give the vision processor of the universal observer. Its schematic chain is in Fig. 1. The processing of the image in the visual processor is as follows: the pictural information about the OBJECT is going by the aid of IMAGING MEANS to the input of the IMAGE DETECTOR. This detector utilizes material and energetical input to create the IMAGE or the PHOTOTRANSDUCTION accompanied by the coding of the image in SIGNALS. The signals go to an ANALYSER, which compares them with standard PICTURE ELEMENTS in the same logic language. The result of the analysis is the VISION. Now the display of the coded or decoded image can occur. For new images the introduction of the image into the standarts is realized and at the end occurs the transmission of a part of the image for possible decision.

The vision processor "sees" the object by means of a lot of pixels at different levels of the vision process. The pixels realized in the vision processor are:

- the object pixel of diameter a_0 given by the time-spatial noise in the structure of the object.
- the transport pixel of diameter a_T given by the nature of the imaging means.
- the detection pixel with diameter a_D given by the construction and the mechanism of the detector.

The minimum $(a_i)^2$ of operating surfaces which are necessary to transmit an element of the image is different for object, for imaging means and for detector. When in the object change in time the position of its "anatomistic" curves around some mean position, we have object noise. For high object noise it is not necessary to utilize imaging means and recording material with very small pixels. The same occurs for large transport pixel (bad optic elements or bad imaging "light") or large detector pixel. In the vision process the sharpness and the detection of details is realized by the pixel of diameter a_V, which we shall call the vision pixel. The vision pixel diameter is the greater value of the triade a_D, a_T and a_0.

In the vision process we have also the understanding of the image pattern. Today it is accepted that in the recognition of objects the analyser utilizes two possible approaches: the symptomatics where elementary properties of the image are numerical values (symptoms) or the sindiotactic where the elementary properties are symbols (primitives) [17]. In the hybrid approach we have primitives with numerical space interactions. During the recognition of the image we compare the primitives of the image with similar ones before memorized and stored in the brain.

4. The analysis and definition of the image

It is clear that each image is an ensemble of specks of different colours and brightnesses. The observed specks are of two types:

(i) each pixel contained in the speck has the same colour and brightness. We shall call these specks tones.
(ii) It is possible to find in the speck an elementary cell, which is repeated with some repetition mechanism on the whole surface of the speck. We shall call these specks textures.

Now the question is, where is located the information present in the image and the corresponding quality. The experience shows that it is mainly in borders between tones and textures and borders in the textures. To make sure for us this conviction we show some examples.

FIRST EXAMPLE: The information role of the shape

One letter of the english alphabet transports with regard to its philologic content approximately 2 bits [6]. On the other hand one letter has a border equal around $L = 6$ mm. The value of a printing pixel (diameter) is for good books around $a_V =$ $= 50-100$ microns. To produce border of the letter it is necessary to utilize $L/a_V =$ $= 120-60$ pixels, which give us the information carried by one letter in bits. We assume that the thickness of the letter does not carry information. We see that the information present in the shape is about $60-30$ times greater that the information carried by the philologic content. This is in connection with the fact, that each letter can be printed in very different ways and for this reason the shape of the letter carries informations. For one page we have approximatelly 5 kbits for the content and 150 kbits for the shape. With smaller number of letters the total length of the borders between letters and white background and therefore the information falls. The same occurs when the diameter of the pixels grows. In this case the quality of the printing of course goes down.

SECOND EXAMPLE: The counting of dots localized or not on a full line

To prove that during vision the detection of the image is effectivelly sensitive to present border, black and white or between different colours, we do this experiment. We put accidentelly some number of black or colour dots on a conjoint but not visible curve as is shown in Fig. 2. This case is depicted in A. In the second case B we add on the invisible curve between the present dots other type of dots, for example of other colour. In the third case C we made visible the conjoin curve on which lie the dots of the two types. Now we measure the time necessary to count the same number of dots in the above mentioned three examples A, B and C. We do this for different persons and made mean values t_A, t_B and t_C. We obtain reproducible results for different types of dot shapes, dot colours and curve shapes. Typical values are

$$t_B/t_A = 1.2 \pm 0.04 \quad t_C/t_A = 1 \pm 0.03$$

which show that in the presence of the full line (the border), the detection of the image is faster.

THIRD EXAMPLE: The role of the primitive

In Fig 3 is shown a type of simple geometrical optical illusion. Without direct measurement we don't accept that the length of the abscissa *a* is the same in cases *A*, *B* or *C*. The illusion occurs only for case *B*. The existence of the optical illusion, which is a well known effect, is given on our opinion by the fact that vision utilize higher hierarchies, recognized in ensemble of primitives. One primitive is the border, which are organized in a simple understandable graphic symbol. In each primitive we have a essential number of typical borders (structural skeleton, recognoscation group) for its comprehension.

FOURTH EXAMPLE: The fish in an aquarium

Between primitives occur space relations, which lead to the observation of scenes. In Fig 4 we see in (a) the construction of the fish primitive. It is necessary five graphic elements: one lense, one triangle, one curve, one abscissa and one point. In (b) the

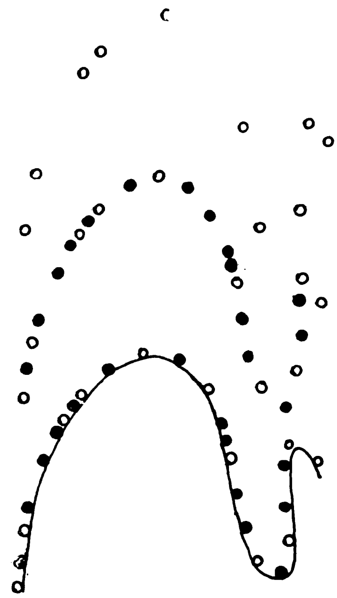

Fig. 2. The schema for the experiment of the second example.

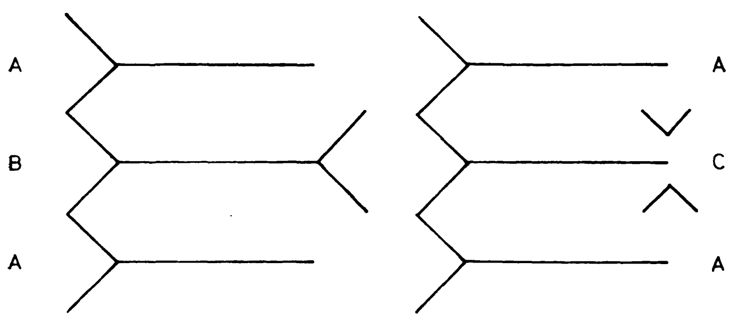

Fig. 3. One type of classical optical illusion.

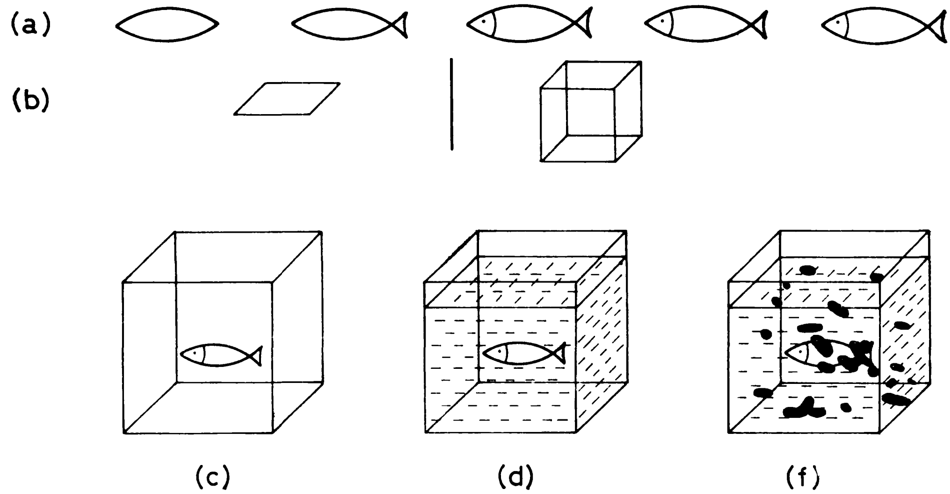

Fig. 4. The construction of the picture "The fish in an aquarium".

aquarium primitive contents two rhomboedra and four absissae. But when we put the fish in the aquarium, as is shown in (c), we observe an unrealistic scene. Of course, it is necessary to add water (d), which has a texture structure. In the case (f) we observe our fish in the aquarium with water but also with some not understandable ensemble of black specks. This is an information noise, which diminish the image quality of the picture.

After our analysis of an arbitrary image it comes clear, that each image percepted by our brain has some internal organization, necessary for its perception. Now we give the DEFINITION OF THE IMAGE: "The image is an ensemble of signals organized in the space with an internal logic." This definition seems valid for all types of images, not only for those utilized in photography and different types of technical imaging processes. The existence of the image is closely related to the existence of the detector and the quality of an image is dependent of the qualification of the detector.

5. The equation of images quality

Now we are able to build up the equation for the evaluation of the image quality. We change the Shannon equation in the following form

$$(6) \qquad Q = \int_0^{t_{exp}} \Delta f \cdot \log_2\left(\frac{P+N}{N}\right) \cdot \mathrm{d}t = \overline{\Delta f} \cdot t_{exp} \cdot \log_2\left(\frac{\overline{P}+\overline{N}}{\overline{N}}\right)$$

where t_{exp} is the exposition time to obtain the given image, Δf is the mean frequency bandwidth and $\overline{P}$ and $\overline{N}$ the respective mean values during the exposition time for the given frequency spectrum. Fot the analysis of the image quality we obviously don't utilize $\overline{\Delta f}$ and t_{exp} but some interval of space frequencies Δv. The mean interval of spatial frequencies $\overline{\Delta v}$ must be connected with $\overline{\Delta f}$. At first, it is possible to express $\overline{\Delta v}$ as

(3) $$\overline{\Delta v} = \overline{\left(\frac{1}{r_{min}} - \frac{1}{r_{max}}\right)} \doteq \overline{\left(\frac{1}{r_{min}}\right)} \doteq \frac{1}{\bar{a}_V}$$

where r_{min} and r_{max} are the possible smallest and greatest distances between neighbouring pixels. But r_{min} is equal to the mean vision pixel of the image. Now we can write the equation

(8) $$\overline{\Delta f}(s^{-1}) \,.\, t_{exp}(s) = \overline{\Delta v}(m^{-1}) \,.\, L(m) = L/\bar{a}_V$$

Because on the left side of the eq. (8) we have the number of informations, which have travelled throught the information channel to realize the "image", we have on the right side the number of imaged informations in our record. Therefore if L is the greatest possible length of all borders in the photosensisive area S of our detector, then η is the imaging efficiency of the imaged content. We have

(9) $$L \,.\, r_{min} = L \,.\, \bar{a}_V = \eta S$$

The imaging efficiency η is a quantity which strongly depends on the nature of the image content and of the shape of this content. This value takes in account the necessity of some background surface S_B for the comprehension of the given image or of a given part of an image. If the background is itself understandable, has some sense, it don't take part into S_B. In printed text the relation of the white background to the whole information surface S is of the order of 0,95 (95% is the white background). On the other hand the surface occupied by artefacts or noise S_N must be also taken into account for the calculation of the imaging efficiency. Thus we have

(10) $$\eta = \frac{S - (S_B + S_N)}{S} = 1 - \frac{S_B + S_N}{S}$$

From (6), (7), (8) and (9) follows

(11) $$Q = \frac{\eta \,.\, S}{(\bar{a}_V)^2} \,.\, \log_2 \left(\frac{\bar{P} + \bar{N}}{\bar{N}}\right)$$

The signal P, as follows from the text above, is possible to express for one primitive by the equation

(12) $$P_i = \frac{L_i}{(\bar{a}_{Vi})^2} \,.\, \delta(E_i, E_{Si}) \,, \quad \delta(E_i, E_{Si}) \begin{smallmatrix} \nearrow 1 \\ \searrow 0 \end{smallmatrix}$$

where L_i is the length of all borders of the given primitive, $\bar{a}_{Vi}$ the corresponding pixel diameter and the delta function $\delta(E_i, E_{Si})$ assures that the given primitive is recognized. It means that all standart elements E_{Si} for the primitive (i) are present in the evaluated image. The signal from the whole image is

(13)
$$P_{image} = \sum_{i=1}^{n_P} P_i = \sum_{i=1}^{n_P} \frac{L_i}{(\bar{a}_{Vi})^2}\, \delta(E_i, E_{Si})$$

where n_P is the number of primitives in the image. For the mean value we have

(14)
$$\bar{P} \doteq \frac{1}{(\bar{a}_V)^2} \sum_{i=1}^{n_P} L_i \,.\, \delta(E_i, E_{Si}) = \frac{1}{(\bar{a}_V)^2} \,.\, L_S$$

where L_S is the total length of active (understandable) borders. Per analogy we obtain for the mean value of the noise $\bar{N}$

(15)
$$\bar{N} \doteq \frac{1}{(\bar{a}_V)^2} \,.\, L_N$$

where L_N is the total value of the noise (not understandable) borders. In the presence of some texture areas in the image values L_S and L_N include also borders originating from texture areas.

The result of our considerations about image quality is then given by the equation

(16)
$$Q = \frac{\eta \,.\, S}{(\bar{a}_v)^2} \,.\, \log_2 \left(\frac{L_S + L_N}{L_N} \right)$$

This relatively simple equation shows, that for high quality image ($L_N \to 0$), the signal to noise ratio L_S/L_N plays a role in the evaluation of Q. In the case when the noise is very great ($L_N \to L_S$), the mean influence is given by the number of effective vision pixels.

6. Some evaluation of image quality

We utilize eq. (16) for the evaluation of the quality of very various pictures, obtained by different ways. In table 1 we summarize our calculations for image surface of 1 cm^2.

Table 1

Imaging process	Image content	a_V (micron)	η	L_S/L_N	Q (kbits . cm^{-2})
technical drawing	technical sketch	100	0,01	80	0,63
newspaper	text	50	0,03	10	4,2
TV screen	speaker	200	0,7	50	9,9
art drawing	portrait	100	0,5	10	17,3
book	text	20	0,05	100	83,0
colour print	country side	40	1	30	310,0
high quality photograph	country side	10	1	200	7.700,0

From the presented calculations follows that high quality images, from the subjective point of view, have quality density higher then 1000 kbits . cm^{-2}. Poor image quality is lower then 1 kbits . cm^{-2}. The acceptable image quality of 1 cm^2 is therefore into three orders of magnitude from 1 kbits . cm^{-2} to 1000 kbits . cm^{-2}.

For the calculation of the image quality according equation (16) it is necessary to determine the diameter of the vision pixel a_V, the image efficiency η and the ratio of understandable to noise borders L_S/L_N. In the case of human vision it may be a good possibility to found the value a_V by the comparison of irregularities of image borders with lines of different thicknesses as is depicted in Fig. 5. The value of the determined a_V is different for different eyes and for eyes armed with different optics. From this follows that the image quality is dependent on the resolution power of the vision detector input.

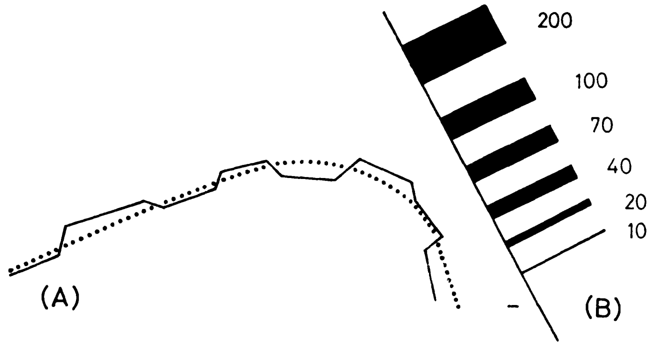

Fig. 5. The determination of the vision pixel. A) Understandable border of analysed image: ..... assumed and —— realistic course of the border. B) The measure with lines of different thickness in microns.

The determination of the image efficiency η depends on the understanding of the image composition. For example the grass in a countryside picture is not a background, but in the case of a photograph of a rabbit on the grass it is. In our determination of η we take the rule, that S_B is that surface, which is possible to change of brightness, colour or internal structure without the changing of the sense of the image.

In principle it is not difficult to determine the signal to noise ratio L_S/L_N, but in practice it take long if you don't utilize some pattern recognition methods with appropriate instrumentation. But in this case up today the vision pixel is very great because we utilize as detector input some optoelectronic device with high $\bar{a}_v$. In the present work we determine the length of border by the help of a vibrating pencil home made. The pencil has a constant vibration frequency in the interval of 2 – 4 Hz and at each contact with a transparencie, deposed on the image, produce black dot of a diameter approximately equal 0,3 – 0,4 mm. When we run with constant velocity with this pencil on the border, we produce a series of black dots which are separated with the neighbor dots by a practically constant distance. The border length is measured as the sum of these distancies, which is given by the number of needed vibrations multiplied by the mean distance between contact points. For

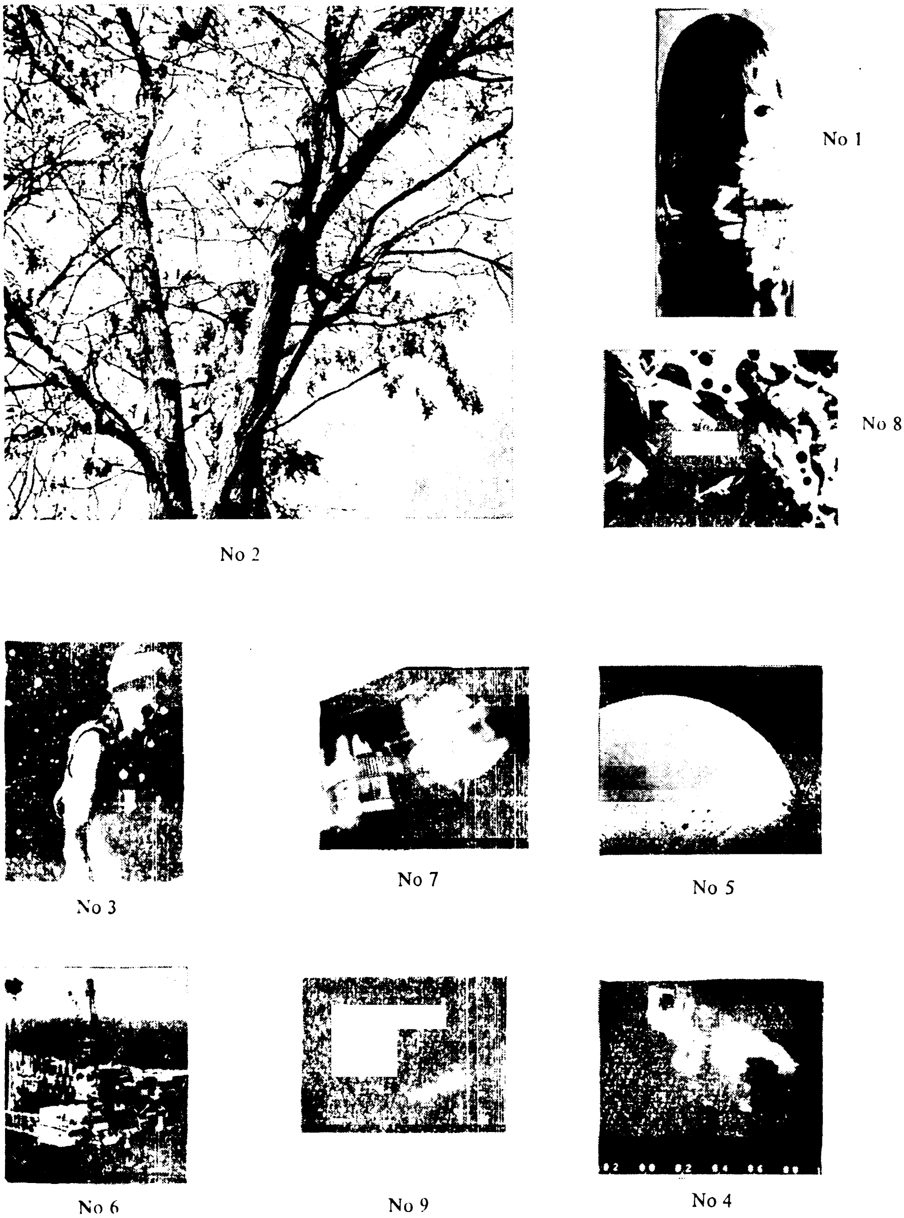

Fig. 6. Black and white representation of colour originals with size reduction.

very small border length is necessary a precise geometric analysis. From our experiment follows that the ratio L_S/L_N is a function of a resolution power of the vision detector input. For example somebody with a small resolution power of its eyes don't see the granularity of the given photographic record and the image seems him excellent.

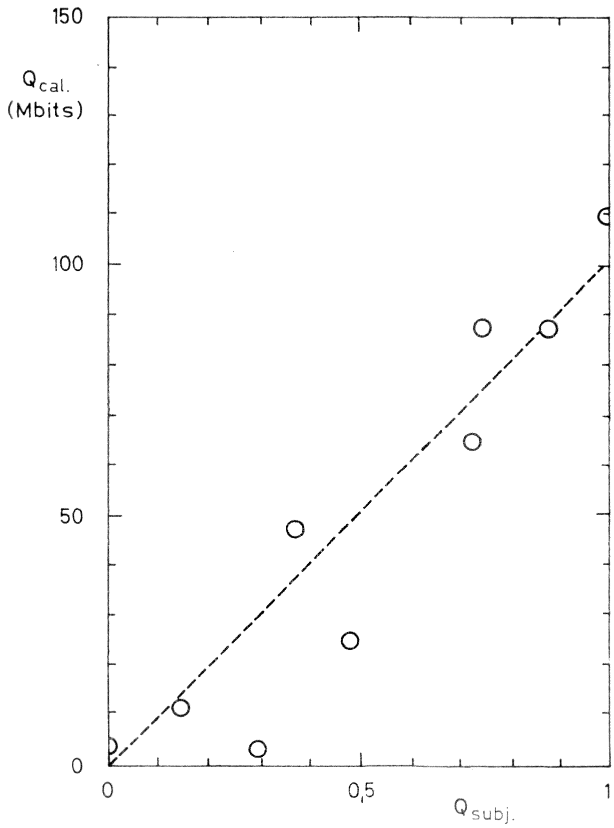

Fig. 7. The dependence of calculated image quality Q_c on subjective quality Q_s. Each point is for one image.

At the end we mention and experiment in which we compare the calculated by equation (16) image quality Q_c of some series of images with a subjective judgements of the same images, obtained by psychometric scaling method [15]. We choose 9 different images with different contents but produced by the same technique. On Fig 6 we can see the black and white reproduction of our series where originals were colour network prints. The determined values $\bar{a}_V$, S, η, L_S/L_N and calculated Q_c are listed in Table 2. We do the psychometric scalling by the ensuing way: We choose

Table 2

No	a_V (micron)	S (cm^2)	η —	L_S/L_N —	Q_c (mbits)	Q_s (1 to 0)
1	100	225	1	11,9	8,3	0,83
2	50	225	0,4	17,0	14,8	1
3	80	225	0,95	3,0	6,7	0,57
4	300	225	0,05	0,08	0,0014	0
5	200	225	0,6	0,75	0,27	0,45
6	100	225	0,7	5,1	4,1	0,4
7	50	195	0,6	1,2	5,2	0,49
8	100	221	0,7	9,3	5,4	0,63
9	50	225	0,05	0,04	0,025	0,26

the best (No 2) and the poorest (No 4) photographs and we give them values 1 and 0 respectively. The quality of each records of our series is a point between these two final points of the abscissa $\overline{01}$. The judgements are obtained from a population of 25 students of physics. The subjective quality Q_s is the distance between 0 and the mean chosen point for each photograph. The determined values Q_s are showed in table 2 and in Fig 7, where is depicted the dependence of Q_c on Q_s. We see that nevertheless large fluctuations of the points (Q_s, Q_c) we observe a linear dependence between Q_c and Q_s.

7. Conclusions

We succeed in our new approach to the image quality to correlate the definition of the entity "image" with the image quality. We have defined the meaning of the term "image" as some organization of signals with an internal logic. We consider under the image quality the number of active pixels which take part in the understanding by the detector of this organization. The understanding is the comparison of some characteristic groups of symbols of the image with their analogues stored in the memory of the detector. Under signals we imagine in general arbitrary local fluctuations of the registration media. This approach is quantified in a relatively simple equation, where for the calculation of the quality it is necessary to know the surface of the image, the image efficiency of the image content and composition, the diameter of the vision pixel and the signal to noise ratio in the form of the ratio of the lengths of understanding to noisy borders. The image quality in our approach depends not only on the adequate physical properties of the object, the imaging means and the detector, but also on the informatics properties of the detector.

References

[1] Birgmeir, K.: Proceed. Symposium Photographic Electronic Image Quality (SPEIQ), Ed. H. M. Graves, RPS Cambridge 1984, p. 108 .

[2] Biederman, K.: in "Progress in Basic Principles of Imaging Systems" Eds F. Granzer and E. Moisar, F. Vieweg Braunschweig, 1987, pp. 41—48.

[3] Bieberman L. M.: Perception of displayed information. Plenum Press New York 1973.

[4] Nagao, M., Matsuyama, T., Moris H.: in Computer Graphics and Image processing Vol. 10 (1979) fl. 195.

[5] Corey, G. P., Clayton, M. J., Cupery K. N.: Phot. Sci. Eng. 27 (1983) p. 9.

[6] Dainty, J. and Shaw, R. Image Science. Academic Press, London 1974.

[7] Shade, E. M.: J. SMPTE, 73 (1964) p. 643.

[8] Crane, E. M.: J. SMPTE, 73 (1964) p. 81.

[9] Biederman, K.: Photogr. Korresp. 103 (1967) pp 5, 26, 42.

[10] Granger, E. M., Cupery, K. N.: Phot. Sci. Eng., 16 (1972) p. 221.

[11] Saunders, A. E.: J. Phot. Sci., 29 (1981) p. 51.

[12] Powell, P. G.: Brit. Pat. Appl. 8, 015, 710, 8, 015, 711

[13] Miyake, Y., Inoue, S., Takazawa, H., Kubo, S.: Proceed. ICO 84, Sapporo 1984, p. 270. Proceed. SPEIQ, Ed. H. M. Graves, RPS Cambridge 1984, p. 62.

[14] Altmann, J. H., Zweig, H. J.: Phot. Sci. Eng., 7 (1963) p. 7.

[15] Zwick, D. M.: Proceed. SPEIQ, Ed. H. M. Graves, RPS Cambridge 1984, p. 46.

[16] Chabre, M.: Europhysics News, 16 (1985) p. 1.

[17] Rosenfeld, A., Kak, A. C., Digital Picture Processing. Academic Press, New York 1976.