The Effects of Picture Size and Definition on Perceived Image Quality

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***Abstract*—The so-called square root integral (SQRI), which describes the effect of resolution on perceived image quality, is further evaluated to describe the effect of picture size on subjective image quality as well. This is possible by taking the effect of display size into account in the modulation threshold function of the eye, appearing in the integrand of the SQRI. In this way an excellent correlation is found between subjective image quality and calculated SQRI value for recent measurements by Westerink and Roufs. From the data it appears that there is an optimum display size or an optimum viewing distance for a given number of displayed pixels. The optimum conditions can be calculated with the aid of the SQRI.**

I. Introduction

It is well known that the resolution of a display has an important effect on perceived image quality. In the past, several attempts have been made to express this effect in a quantitative way [1]–[6]. In a previous investigation [7], we found that the visible resolution quality of a display can best be expressed by the following equation:

$$J = \frac{1}{\ln 2} \int_0^{u_{\max}} \sqrt{\frac{M(u)}{M_t(u)}} \frac{du}{u} \tag{1}$$

where u is the angular spatial frequency at the eye of the observer, expressed in cycles per degree (cpd), $u_{\max}$ the maximum angular spatial frequency displayed, $M(u)$ is the modulation transfer function (MTF) of the display, and $M_t(u)$ is the modulation threshold function of the eye. The development of this formula was largely based on an analysis of measurements of Carlson and Cohen [8] of projected slides and verified by our own measurements with CRT's. The integral expression is called the square root integral (SQRI). It expresses the resolution quality of a display in units of just noticeable differences (jnd's), where 1 jnd is defined as giving a 75-percent correct response in a two-alternative forced choice experiment. A well-defined jnd unit for picture quality has the advantage that the user has a good understanding of the practical value of calculated results and that these results can be verified and compared by experiments. For a correct interpretation, it should be noted that, according to Carlson and Cohen [5], an increase of 1 jnd must be considered as practically insignificant, an increase of 3 jnd's to be significant, and an increase of 10 jnd's to be substantial.

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The inverse of the modulation threshold function of the eye, appearing in the SQRI formula, is usually called the (threshold) contrast sensitivity function (CSF). For this function, we used the following equation that we derived from measurements carried out by van Meeteren [9]:

$$1/M_t(u) = au \exp(-bu) \sqrt{1 + c \exp(bu)} \tag{2}$$

where

$$a = 440 (1 + 0.7/L)^{-0.2}$$
$$b = 0.3 (1 + 100/L)^{0.15}$$
$$c = 0.06$$

and L is the display luminance in candelas per square meter.

The constant a describes the low-frequency behavior and b and c the high-frequency behavior of the contrast sensitivity function. If required, the constant b can be adapted to the visual acuity of the subject. The presence of the display luminance in these formulas means that the calculated picture quality also depends on display luminance. This is in agreement with general experience and will be treated in a later study [14].

In a second investigation [10], we studied the effect of contrast loss caused by stray light or reflected ambient light on perceived image quality and found that this effect is also well described by the SQRI. The contrast loss can simply be taken into account by replacing the display MTF M by

$$M' = \eta M \tag{3}$$

where η is the factor by which the modulation depth in the picture is reduced by the contrast loss.

Both investigations were based on measurements of just noticeable differences. Granger and Cupery [1] found in their investigation of the optical quality of photographic pictures that there is a linear relationship between just noticeable differences and subjective image quality. To test this relation we compared measurements of Knox [11], concerning the subjective image quality of line drawings and text images on a CRT monitor, with jnd values calculated with the SQRI method [10]. The comparison indeed showed a linear correlation, where 3 jnd's corresponded to 1 unit on an 8-point image quality scale.

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II. Effect of Display Size

Most metrics of image quality do not account for the size of the display. In the aforementioned analysis of subjective image quality data of Knox, we corrected for the effect of (accidental) differences in display size by replacing the value zero in the lower integration limit of the SQRI by the inverse of the angular display size. This corresponds to a minimum spatial frequency, equal to one cycle per display width. In this way a numerically satisfactory correction was obtained. Though this method is very simple, it is not very satisfactory from a theoretical point of view because it is not very likely that the reproduction capability of spatial frequencies that are subharmonics of the display size would not matter at all for the perceived image quality of the display.

Recent measurements of subjective image quality by Westerink and Roufs [12]—covering a large range of resolutions and picture sizes—offered a good opportunity to test the SQRI formula more extensively with respect to the effect of display size.

A first analysis showed that for these measurements a good correlation between subjective image quality and SQRI value is obtained by using the inverse of the angular display size as a lower limit of the integration. However, after further investigation it appeared that the correlation could be considerably improved by keeping the lower integration limit at zero and incorporating the effect of display size into the modulation threshold function of the eye, as is also done by Carlson and Cohen [5]. Therefore, and also for the previously mentioned theoretical reasons, we decided to use only this last method.

For this purpose we had to modify the equation for the modulation threshold function. In order to obtain the required modification, we analyzed data measured by Carlson [13] concerning the contrast sensitivity of the eye for different display sizes. See Fig. 1. As a result, we found that the effect of display size on the modulation threshold function can be described by modifying the formula for the low-frequency constant a of (2) in the following way:

$$a = \frac{540(1 + 0.7/L)^{-0.2}}{1 + \dfrac{12}{w(1 + u/3)^2}} \tag{4}$$

where w is the angular display size in degrees. In the case of a rectangular picture, w is the average display size, equal to the square root of the picture area. This modification has been chosen such that it not only describes the dependence on display size in good agreement with the measurements by Carlson (see Fig. 2) but also gives a good description of the measurements by van Meeteren, which were carried out at a fixed angular display size of 17° × 11° (see Fig. 3).

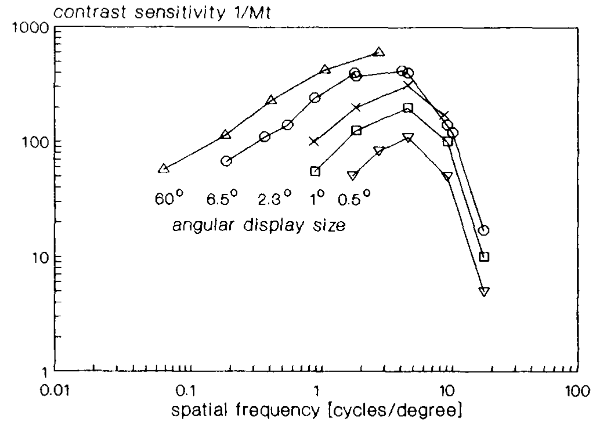

Fig. 1. Measured data of Carlson [13] of the contrast sensitivity $1/M_t$ as a function of angular spatial frequency at various display sizes. Viewing distance is 1.9 m. Display luminance is 34 mL = $340/\pi$ cd/m^2.

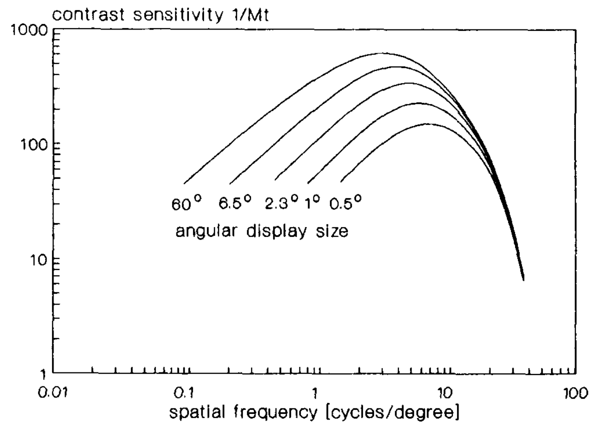

Fig. 2. Contrast sensitivity $1/M_t$ as a function of angular spatial frequency, calculated with (2) and (4) for the conditions of Fig. 1.

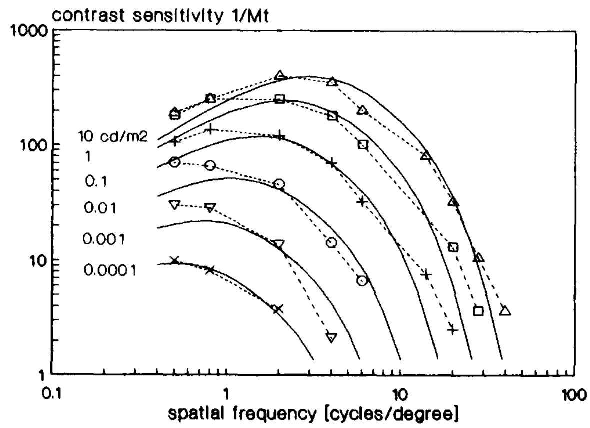

Fig. 3. Measured data of van Meeteren [9] of the contrast sensitivity $1/M_t$ as a function of angular spatial frequency at various luminance levels for a viewing distance of 4 m and an angular display size of 17° × 11°. The solid lines are calculated with (2) and (4).

III. Image Quality Measurements by Westerink and Roufs

The subjective image quality measurements by Westerink and Roufs [12] were performed with square slide pictures of five different complex scenes, projected on a screen with an average display luminance of 30 cd/m^2. The viewing distance was constant (2.9 m), and the viewing angle was varied by using copies of the same

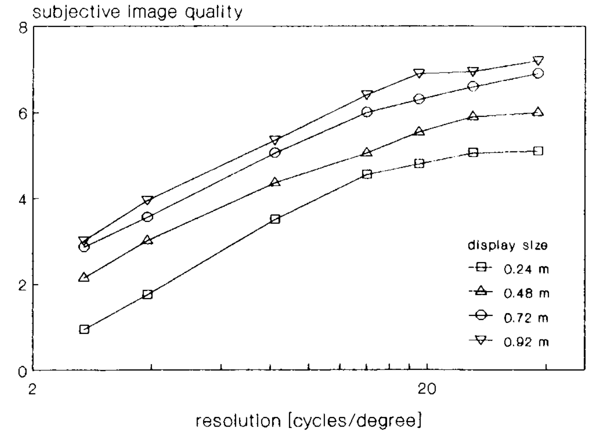

Fig. 4. Subjective image quality data of Westerink and Roufs [12] as a function of angular resolution, with display size as parameter. Viewing distance is 2.9 m. Average display luminance is 30 cd/m^2.

slides in four difference sizes. In this way the picture width was varied in four steps from 0.24 to 0.92 m, corresponding to a viewing angle ranging from 4.7° to 18°.

The resolution was varied in discrete steps by defocusing the projector lens with the aid of a stepper motor. For each focus condition the (Gaussian) line spread function was determined, and from this the 6-dB cutoff frequency $u_{0.5}$, where the MTF has decreased to 50 percent, was calculated. In this way the resolution was varied in seven steps from 2.7 to 38 cpd.

The pictures were shown in random order of scene, resolution, and size to 20 subjects, all with a visual acuity of at least 1.0. They rated the quality on a scale from 0 to 10.

The average results of the measurements are shown in Fig. 4 as a function of $u_{0.5}$, with the display size as a parameter. The parallel shift of the curves at different display sizes is striking.

IV. Comparison with SQRI Values

For each of the measurement conditions, the SQRI value was calculated using the modified expression for the modulation threshold function. However, for L twice the average display luminance was used, rather than the average display luminance. This was based on the idea, suggested by Westerink and Roufs [12], that the quality impression of a picture is largely determined by the high-luminance parts. For pictorial scenes we found that the most representative value in this respect is twice the average display luminance. This value we would also recommend to use for TV pictures.

The resulting SQRI values are plotted in Fig. 5 with the display size as a parameter. The curves show the same behavior as the measured curves of Fig. 4. For better comparison a plot of the subjective image quality as a function of the SQRI value is given in Fig. 6. In this graph the curves for the various display sizes approximately coincide.

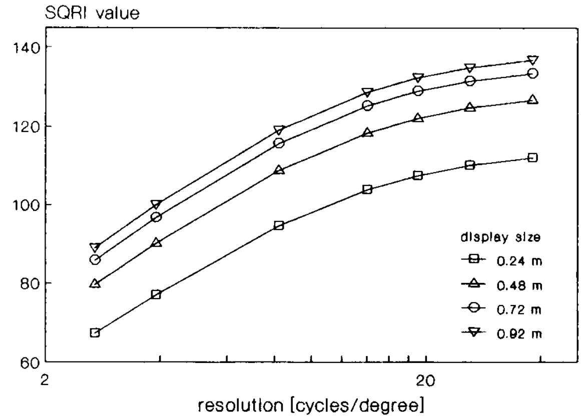

Fig. 5. SQRI values calculated for the measurements of Fig. 4.

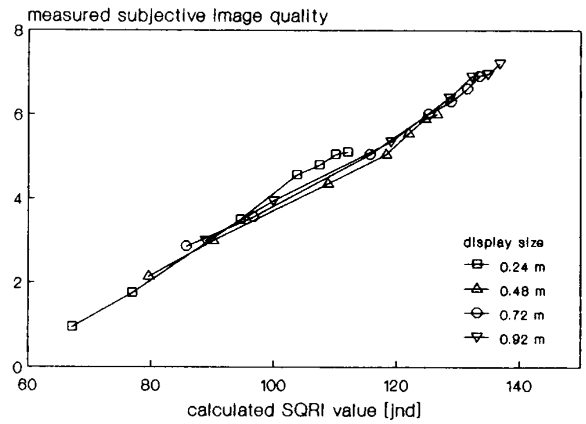

Fig. 6. Subjective image quality as a function of SQRI value for the measurements of Fig. 4. Points of equal display size are interconnected.

V. Discussion of the Results

The approximate coincidence of the curves in Fig. 6 means that the dependence of subjective image quality on angular display size as well as on angular resolution is very well described by the SQRI with the modified formula for the modulation threshold function. This is further illustrated in Fig. 7, where the regression line is given for the correlation between subjective image quality and the SQRI value. From the regression analysis it appears that the correlation coefficient R amounts to 0.994 and that the standard deviation of the data points from the regression line is 0.19 scale point or 2.2 jnd's.

As the SQRI value is expressed in just noticeable differences, the linear correlation between subjective image quality and SQRI value also indicates that there is a linear correlation between perceived image quality and just noticeable differences. This provides a further confirmation of previous observations.

From the regression it also appears that one unit on the subjective image quality scale coresponds to 11.6 jnd's on the SQRI scale. This figure differs considerably from the value of 3 jnd's we calculated for the measurements

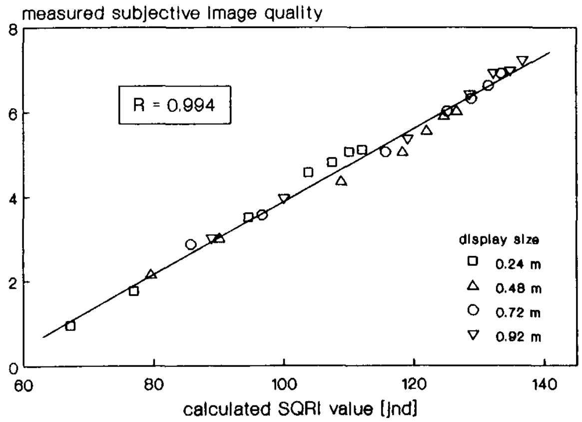

Fig. 7. Linear regression between measured subjective image quality and calculated SQRI value for the data of Fig. 6.

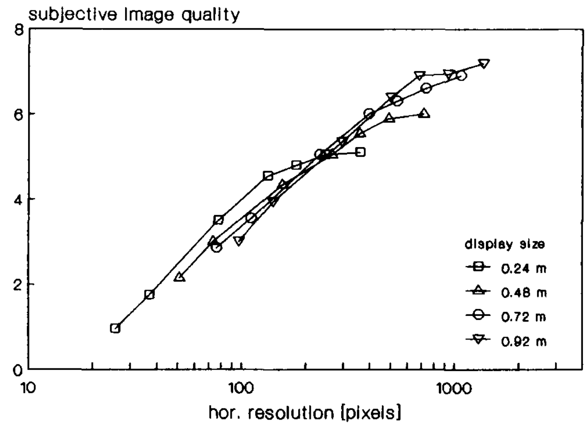

Fig. 8. Subjective image quality data of Fig. 4 as a function of the number of pixels per display width, resolved with an MTF value larger than 0.5.

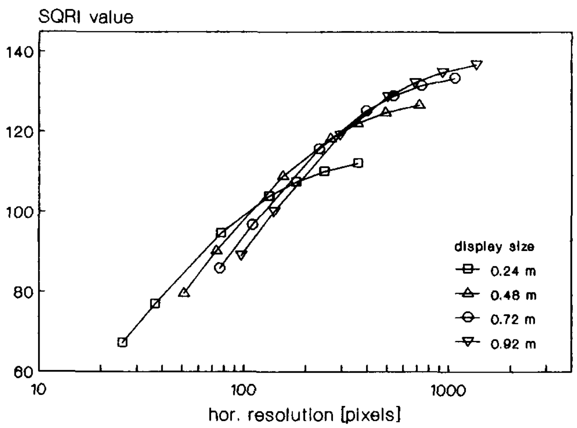

Fig. 9. SQRI values calculated for the measurements of Fig. 8.

of Knox. It should be remarked, however, that such a figure has no absolute meaning because the number of jnd's per scale point generally depends on the size of the rating scale and the size of the quality variation.

The improvement of image quality at increasing picture size, suggested by Figs. 4 and 5, is due to the fact that the data in these figures are plotted as a function of angular resolution. However, the total resolution of a picture is determined by the product of angular display size and angular resolution. The number of pixels per display width, resolved with an MTF value larger than 0.5 is

$$N = 2\, w u_{0.5} \tag{5}$$

taking into account that one cycle contains two pixels. For a better understanding of the effect of display size in practical cases where the resolution is determined by the number of resolved pixels, the data of Figs. 4 and 5 are plotted in Fig. 8 and Fig. 9, respectively, as a function of N. These graphs show that, for a given number of pixels, a larger picture size does not always mean a better quality. The curves also indicate that there is an optimum display size (or for a given display size, an optimum viewing distance) for each value of N. The SQRI can be used to calculate the optimum value.

Another presentation of Figs. 4 and 5 is obtained by using the "spot size" as an independent variable. Though the measurements are carried out with projected slides, an equivalent spot size can be defined with the aid of the line spread function of the projection lens. For reasons explained in a previous paper [7], we prefer the 5-percent width of the line spread function for the definition of spot size over the often used 50-percent width (for a Gaussian distribution, the 5-percent width is 2.08 times the 50-percent width). In view of a more generally applicability of the results, the spot size is further expressed in angular size at the eye. The resulting curves are shown in Figs. 10 and 11. Plots of this type are very useful for practical applications. A similar plot was made by Westerink and Roufs [12] using the standard deviation of the line spread function instead of the spot size. The quasi-linear shape of the curves obtained in one of these ways, however, does not justify to draw straight lines through the measuring points.

VI. Conclusions

An equation for the threshold modulation function of the eye is presented that descibes the effect of display size in good agreement with measurements of Carlson [13]. By introducing this expression in the square root integral, this integral can be used for the calculation of the effect of resolution as well as for the effect of display size on perceived image quality. Subjective image quality data measured by Westerink and Roufs [12] show an excellent linear correlation with SQRI values calculated in this way. As the SQRI values are expressed in just noticeable differences, this also means that there is a linear relation between subjective image quality and just noticeable differences. For a given number of pixels to be displayed, there is an optimum display size at a given viewing distance or an optimum viewing distance at a given display size. The optimum value of these parameters can easily be calculated with the aid of the square root integral.

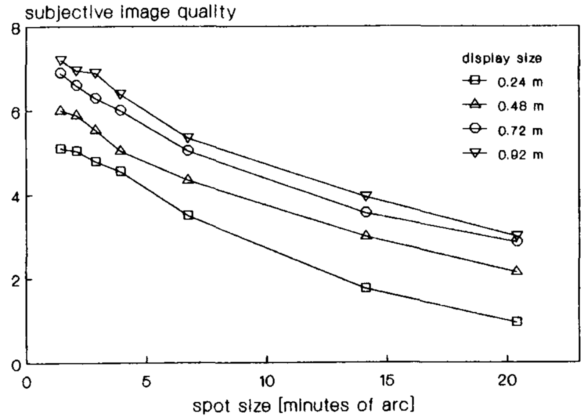

Fig. 10. Subjective image quality data of Fig. 4 as a function of spot size. The spot size here is an equivalent spot size, defined by the 5-percent width of the line spread function of the projection lens. For practical reasons the spot size is expressed in angular size at the eye.

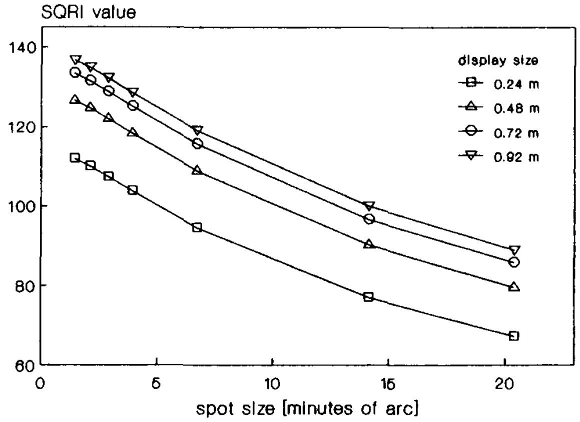

Fig. 11. SQRI value as a function of spot size for the measurements of Fig. 10.

References

[1] E. M. Granger and K. N. Cupery, "An optical merit function (SQF), which correlates with subjective image judgments," *Photographic Sci. Eng.*, vol. 16, pp. 221-230, May-June 1972.

[2] H. L. Snyder, "Modulation transfer function area as a measure of image quality," presented to the Visual Search Symp. Committee on Vision, National Academy of Sciences, Washington, DC, 1973.

[3] G. C. Higgins, "Image quality criteria," *J. Appl. Photographic Eng.*, vol. 3, no. 2, pp. 53-60, 1977.

[4] H. L. Task, A. R. Pinkus, and J. P. Hornseth, "A comparison of several television display image quality measures," *Proc. SID*, vol. 19, no. 3, pp. 113-119, 1978.

[5] C. R. Carlson and R. W. Cohen, "A simple psycho-physical model for predicting the visibility of displayed information," *Proc. SID*, vol. 21, no. 3, 1980.

[6] R. J. Beaton, "Quantitative models of image quality," in *Proc. Human Factors Soc. 27th Ann. Meeting*, 1983, pp. 41-45.

[7] P. G. J. Barten, "The SQRI method: A new method for the evaluation of visible resolution on a display," *Proc. SID*, vol. 28, no. 3, pp. 253-262, 1987.

[8] C. R. Carlson and R. W. Cohen, "Visibility of displayed information: Image descriptors for displays," Office of Naval Research, Arlington, VA, Rep. ONR-CR 213-120-4F, July 1978.

[9] A. van Meeteren, "Visual aspects of image intensification," Ph.D. dissertation, Univ. of Utrecht, The Netherlands, 1973.

[10] P. G. J. Barten, "Evaluation of CRT displays with the SQRI method," *Proc. SID*, vol. 30, no. 1, pp. 9-14, 1989.

[11] S. T. Knox, "Resolution and addressability requirements for digital CRT's," *SID Dig.*, vol. 18, pp. 26-29, May 1987.

[12] J. H. D. M. Westerink and J. A. J. Roufs, "A local basis for perceptually relevant resolution measures," *SID Dig.*, vol. 19, pp. 360-363, May 1988.

[13] C. R. Carlson, "Sine-wave threshold contrast-sensitivity function: Dependence on display size," *RCA Rev.*, vol. 43, pp. 675-683, Dec. 1982.

[14] P. G. J. Barten, "The square root integral (SQRI): A new metric to describe the effect of various display parameters on perceived image quality," *Proc. SPIE*, vol. 1077, 1989.

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