TECHNICAL REPORT

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Ergonomics of human-system interaction —

Part 310: **Visibility, aesthetics and ergonomics of pixel defects**

Ergonomie de l'interaction homme-système —

Partie 310: Visibilité, esthétique et ergonomie des défauts de pixel

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Contents

Page

Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 9241-310 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 4, *Ergonomics of human-system interaction*.

ISO 9241 consists of the following parts, under the general title *Ergonomic requirements for office work with visual display terminals (VDTs)*:

— *Part 1: General introduction*

— *Part 2: Guidance on task requirements*

— *Part 4: Keyboard requirements*

— *Part 5: Workstation layout and postural requirements*

— *Part 6: Guidance on the work environment*

— *Part 9: Requirements for non-keyboard input devices*

— *Part 11: Guidance on usability*

— *Part 12: Presentation of information*

— *Part 13: User guidance*

— *Part 14: Menu dialogues*

— *Part 15: Command dialogues*

— *Part 16: Direct manipulation dialogues*

— *Part 17: Form filling dialogues*

ISO 9241 also consists of the following parts, under the general title *Ergonomics of human–system interaction:*

- *Part 20: Accessibility guidelines for information/communication technology (ICT) equipment and services*
- *Part 100: Introduction to standards related to software ergonomics [Technical Report]*
- *Part 110: Dialogue principles*
- *Part 129: Guidance on software individualization*
- *Part 151: Guidance on World Wide Web user interfaces*
- *Part 171: Guidance on software accessibility*
- *Part 210: Human-centred design for interactive systems*
- *Part 300: Introduction to electronic visual display requirements*
- *Part 302: Terminology for electronic visual displays*
- *Part 303: Requirements for electronic visual displays*
- *Part 304: User performance test methods for electronic visual displays*
- *Part 305: Optical laboratory test methods for electronic visual displays*
- *Part 306: Field assessment methods for electronic visual displays*
- *Part 307: Analysis and compliance test methods for electronic visual displays*
- *Part 308: Surface-conduction electron-emitter displays (SED) [Technical Report]*
- *Part 309: Organic light-emitting diode (OLED) displays [Technical Report]*
- *Part 310: Visibility, aesthetics and ergonomics of pixel defects [Technical Report]*
- *Part 400: Principles and requirements for physical input devices*
- *Part 410: Design criteria for physical input devices*
- *Part 420: Selection of physical input devices*
- *Part 910: Framework for tactile and haptic interaction*
- *Part 920: Guidance on tactile and haptic interactions*

The following parts are under preparation:

- *Part 143: Form-based dialogues*
- *Part 154: Design guidance for interactive voice response (IVR) applications*

Requirements, analysis and compliance test methods for the reduction of photosensitive seizures and evaluation methods for the design of physical input devices are to form the subject of a future part 411.

Introduction

This part of ISO 9241 summarises information that ISO/TC 159/SC 4/WG 2, *Visual display requirements*, collected on pixel defects and their impact on aesthetics and ergonomics during preparation of ISO 13406 and other parts in the ISO 9241 “300” subseries. It uses terms and definitions from ISO 9241-302 and VESA FDPM[20].

It is based on research and reports that were available at the end of year 2005. The annexes contain information upon which the Working Group could not reach consensus, as well as some additional information, collected during the year 2006, that did not undergo the same review and analysis process as the earlier material.

Ergonomics of human-system interaction —

Part 310:
Visibility, aesthetics and ergonomics of pixel defects

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This part of ISO 9241 provides a summary of existing knowledge on ergonomics requirements for pixel defects in electronic displays at the time of its publication. It also gives guidance on the specification of pixel defects, visibility thresholds and aesthetic requirements for pixel defects. It does not itself give requirements related to pixel defects, but it is envisaged that its information could be used in the revision of other parts in the ISO 9241 series.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
pixel
smallest addressable spatial unit of a display that can show all the colours of the display

NOTE 1 Typical pixel heights for single-user displays range from 0,05 mm to 0,40 mm. Multi-user displays viewed from a distance use bigger pixel sizes.

NOTE 2 Adapted from ISO 9241-302:2008, definition 3.4.29.

2.2
subpixel
independently addressable unit of a pixel, the smallest addressable unit of a display, used for spatial dithering to change colour or luminance

2.3
pixel fault
defective pixel or subpixel that is visible under the intended context of use

[ISO 9241-302:2008]

2.4
pixel defect
pixels that operate improperly when addressed with video information

EXAMPLE A pixel addressed to turn black could remain white. If it never changes state, it is said to be a stuck pixel. If it changes state without the proper addressing signal, it could be intermittent.

[VESA FPDM 303-6]

2.5
stuck on pixel
bright pixel on a black background

NOTE A stuck on pixel can be observed using a black screen.

[VESA FPDM 303-6]

2.6
stuck off pixel
dark pixel on a white screen

NOTE A stuck off pixel can be observed using a white screen.

[VESA FPDM 303-6]

2.7
stuck dim pixel
grey pixel independent of a white or black background

NOTE A stuck dim pixel can be observed using a white and then a black screen.

[VESA FPDM 303-6]

2.8
defective column/row
complete column or row of pixel defects

[VESA FPDM 303-6]

2.9
partial
pixels or subpixels that have defective sub area of defects

EXAMPLE Part of the pixel is stuck on or off but the rest of the pixel works properly.

[VESA FPDM 303-6]

2.10
temporal and intermittent defect
(sub)pixel defect that exhibits temporal variations not related to any steady-state video input

NOTE Temporal defects can be intermittent, exhibit a sudden change of state, or be flickering. They can be observed using a white and/or a black screen.

[VESA FPDM 303-6]

2.11
defect cluster
more than one defect present in a cluster of pixels of a defined size, e.g. 5×5 pixels

[VESA FPDM 303-6]

2.12
fill factor
amount of the area producing useful luminance compared to the amount of the area allocated to the (sub)pixel

[VESA FPDM 303-3]

2.13
mura
Japanese word meaning blemish that has been adopted in English to provide a name for imperfections of a display pixel matrix surface that are visible when the display screen is driven to a constant grey level

NOTE Mura defects appear as low contrast, non-uniform brightness regions, typically larger than single pixels. They are caused by a variety of physical factors. For example, in LCD displays, the causes of mura defects include non-uniformly distributed liquid crystal material and foreign particles within the liquid crystal. Mura-like blemishes occur in CRT, FED and other display devices.

[VESA FPDM 303-8]

3 Review of research

3.1 Detection of spots

3.1.1 General

Detection of spots is somewhat different to detection of spatially periodic targets. The vision research on spatially periodic targets is more extensive than the research on spots. The main factors affecting the visibility of small spots are spot size, spot duration, interaction of size and duration, the oblique effect, light adaptation, location in the visual field and spatial uncertainty.

Reading research [25] showed that the human being has three contrast channels suitable for reading; luminance contrast, Red-Green contrast and Yellow-Blue contrast. In normal reading, the signal from the contrast channel with the strongest signal is used and the two other channels are ignored. Since reading is dependent on detection of character features, it can be assumed that the same mechanism is valid for spot detection.

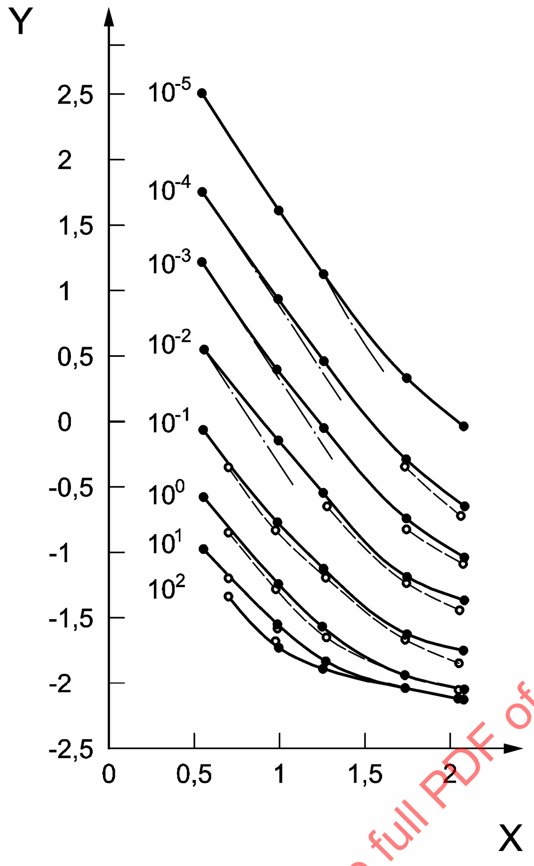
Effects of defect colour on spot detection can thus be analyzed for the three contrast channels separately and the spot will be visible if one or more of the three contrast channels produces a signal that exceeds contrast threshold.

3.1.2 Spot size

3.1.2.1 General

For small spots the visibility threshold decreases as the target area increases (spatial summation). There are five different types of spatial summation to consider in the study of pixel defects: Piper's Law, Ricco's Law, S-cones and M- and L-cones.

Spatial summation explains why stuck on defects on a black background are more visible than stuck off defects on a white background. On a black background the bright spot is summed with its black background and the contrast between the summed area and its background remains high enough to be visible. On a white background the black spot and its bright surround are summed and the contrast between the summed area and its background rapidly becomes less than threshold, when the size of the summed area increases.



Key

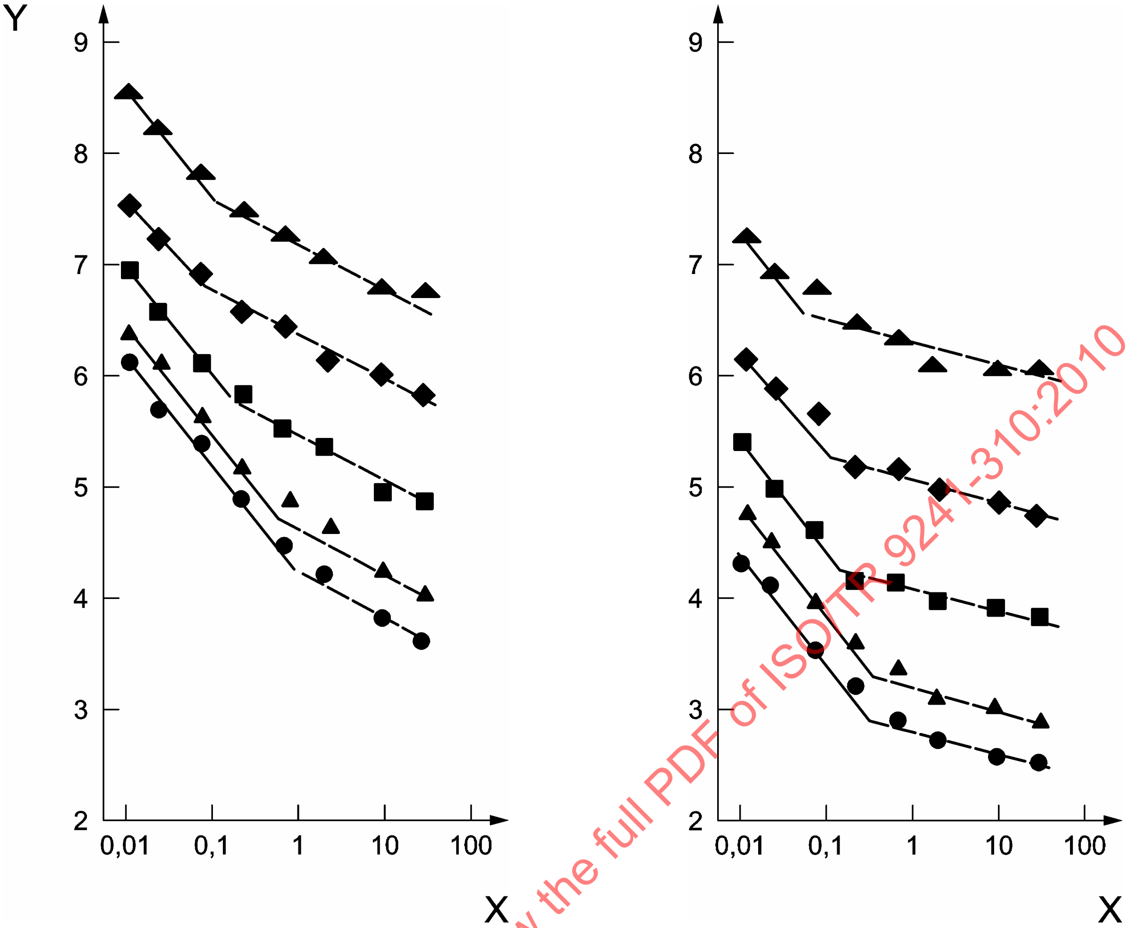
X log$_{10}$ stimulus diameter in min of visual angle

Y log$_{10}$ in $\Delta L / L_0$

NOTE Figure from Blackwell (1986) [29].

Figure 1 — Spatial summation as a function of target size and adaptation level

Log-increment (solid lines) and log-decrement (dashed lines) thresholds $\Delta L / L_0$ plotted as a function of log stimulus diameter for several adaptation levels. Complete summation (Ricco's Law) is given by a slope of -2. The area of complete summation decreases as mean luminance level increases. The test stimulus was a variable diameter circle (3,6 min to 121,0 min) presented for 6 s on a 10° background. Adaptation level, L_0, ranged from 10^{-5} to 10^2 cd/m^2. Observers were 19 women, 19 to 26 years old with normal vision. Each freely scanned the background from a distance of 18,2 m, so that viewing was probably parafoveal for the three lowest adaptation levels. The test spot could appear at one of eight positions projected on the circumferences of an imaginary 3° radius circle, and a spatial forced-choice detection task was used to estimate threshold. Threshold was taken to be the point at which the probability of a correct detection was 0,5, corrected for chance.



0,5 ms

930 ms

Key

X area of increment in deg^2

Y threshold in log quanta per second and deg^2

▲ background luminance (log quanta/s deg^2) 7,83

◆ background luminance (log quanta/s deg^2) 5,94

■ background luminance (log quanta/s deg^2) 4,96

▲ background luminance (log quanta/s deg^2) 3,65

● absolute thresholds

Figure 2 — Summation at cone level or Ricco's law is represented by the solid line with a gradient of −1

Log luminance (quanta/sec.deg^2 is a another method of expressing illuminance, similar to troland) as a function of area for two different stimulus duration. Spatial Barlow's data from Lamming D., Spatial Frequency Channels. Chapter 8. In: Cronly-Dillon, J., Vision and Visual Dysfunction, Vol 5. London: Macmillan Press, 1991. [http://webvision.med.utah.edu/]

3.1.2.2 Piper's Law (probability spatial summation)

Piper's law applies to large-sized spots which are close to visibility threshold: It can hold for up to 24° in size in the peripheral vision. The mechanism behind the summation is probability summation. It has been mathematically shown that the probability of detection increases with the square root of the number of retinal ganglion cells involved.

$$I\sqrt{A}=k_{\mathrm{p}} \quad (1)$$

where

I is the intensity of the spot;

A is the area of the spot;

k_{P} is a constant.

When contrast and brightness are high, Piper's law has no impact on pixel visibility analysis.

3.1.2.3 Ricco's Law (neural spatial summation)

Ricco's law describes effects of neural-level spatial summation. If, close to detection threshold a spot is creating an image on the retina that covers several photoreceptors (cone cells), ganglion cells can be connected so that they receive stimuli from several photoreceptors and spatially integrate the signal from several photoreceptors.

In the fovea, the amount of spatial summation is small and neural spatial summation occurs mainly in the peripheral vision field. In the fovea, spatial neural summation can occur only up to 2' to 3'. In the parafovea, the summation can be up to 30'. For rod vision in the peripheral visual field, the summation can be up to 2°. The amount of spatial neural summation is dependent on the intensity of the stimuli.

$$I\times A=k_{\mathrm{R}} \quad (2)$$

where

I is the intensity of the spot;

A is the area of the spot;

k_{R} is a constant.

When contrast and brightness are high Ricco's law has no impact on pixel visibility analysis, which is demonstrated by the fact that humans can, in good conditions, detect spots subtending as little as 0,5'.

3.1.2.4 Spatial summation in S-cones (PSF and spacing summation)

The S-cone is critical to the blue-yellow contrast signal. It has (for small spots) only a minor contribution to luminance contrast and no contribution to red-green contrast.

The human resolution to spots with short-wavelength light contrast is determined by the spatial spacing of the S-cones and the limitations of the optical system of the human eye (light scattering, chromatic aberration etc). The characteristics of the optical system can be quantified as the PSF (point spread function) of the eye. The spacing of S-cones in fovea is well aligned to the PSF for short wavelengths. The highest density of S-cones occurs not in the centre of the visual field, but at an excentrity of 0,35° to 1°. The peak density is slightly higher than 10 cones/°, which is equivalent to a spacing slightly denser than one cone per 6'. In the central visual field there is a zone with no S-cones at all. The diameter of this zone subtends about 0,35°.

If the spot is smaller than the S-cones spacing, then spatial summation will occur within the photoreceptor. When evaluating if the blue-yellow contrast of a spot exceeds visibility threshold, any spots or features smaller than this spacing shall thus be spatially summed for an area of subtending approximately 6'.

3.1.2.5 Spatial summation in M- and L-cones (PSF and spacing summation)

The M- and L cones contribute to all three contrast channels. These cones have the highest spatial resolution in the fovea of all photoreceptors and set the absolute limit for human visual acuity.

The maximum M- and L- cone density is about 120 cones/°, which is equivalent to a spacing of one cone per 0,5’. When evaluating if the luminance contrast or red-green contrast of a spot exceeds visibility threshold any spots or features smaller than this spacing shall thus be spatially summed for an area of subtending approximately 0,5'.

3.1.2.6 Ricco's area

Ricco's area is the area (in the spatial frequency domain) where only partial summation occurs. The broader between full and partial summation, as well as between partial and no summation depends on the wavelength, luminance and duration of the stimuli. For practical applications, Ricco's' area can thus be considered an approximative definition that adds uncertainty to any analysis of spot detection. See Figure 2.

The uncertainty of Ricco's area also explains some of the differences between reported research findings.

3.1.2.7 Spatial summation: Summary

When analysing spot visibility, the effect of spatial summation needs to be considered. For fovea vision, the spatial width of the summation will be at least 0,5’ and at the most 2’ to 3’ for luminance contrast and red-green contrast and 6’ for blue-yellow contrast.

3.1.3 Spot duration

The highest detectable temporal frequency is slightly above 100 Hz, but for practical applications about 80 Hz. With lower average luminance, the maximum detectable frequency decreases towards about 40 Hz.

For frequencies higher than 10 Hz Bloch’s law is valid, according to which the luminance times the duration is constant:

$$I \times t = k_S \tag{3}$$

where

I is the intensity of the spot;

t is the duration of the spot;

k_S is a constant.

For frequencies less than 10 Hz, the detection threshold is unaffected by the frequency.

3.1.4 Interaction of size and duration

Within Bloch’s law and spatial summation according to Ricco’s law and cone level spatial summation, the summation effects are additive. At lower spatial and temporal frequencies no simple relationship exists.

3.1.5 The oblique effect

At horizontal and vertical orientations, elongated targets have lower thresholds than round or square targets.

3.1.6 Light adaptation

The literature and popular literature about contrast dynamics state contradictory ratios for maximum contrast dynamics, e.g. 2,5:100, 1:100 and 1:1000. These are not in conflict with each other but refer to different reference situations.

For the purpose of this Technical Report, a normal luminance dynamics range of 3 log units in total is assumed, extending from 1,5 log units below adaptation luminance to 1,5 log units above adaptation luminance.

Threshold for light spots is dependent on the adaptation luminance. For adaptation luminances less than 0,1 cd/m², the adaptation luminance has no impact on visibility threshold. For adaptation luminances between 0,1 cd/m² and 10 cd/m², there is an increasing dependency on the adaptation luminance. For adaptation luminances above 10 cd/m², Weber's law is valid:

$$\frac{\Delta I}{I} = k_{\mathrm{A}} \tag{4}$$

where

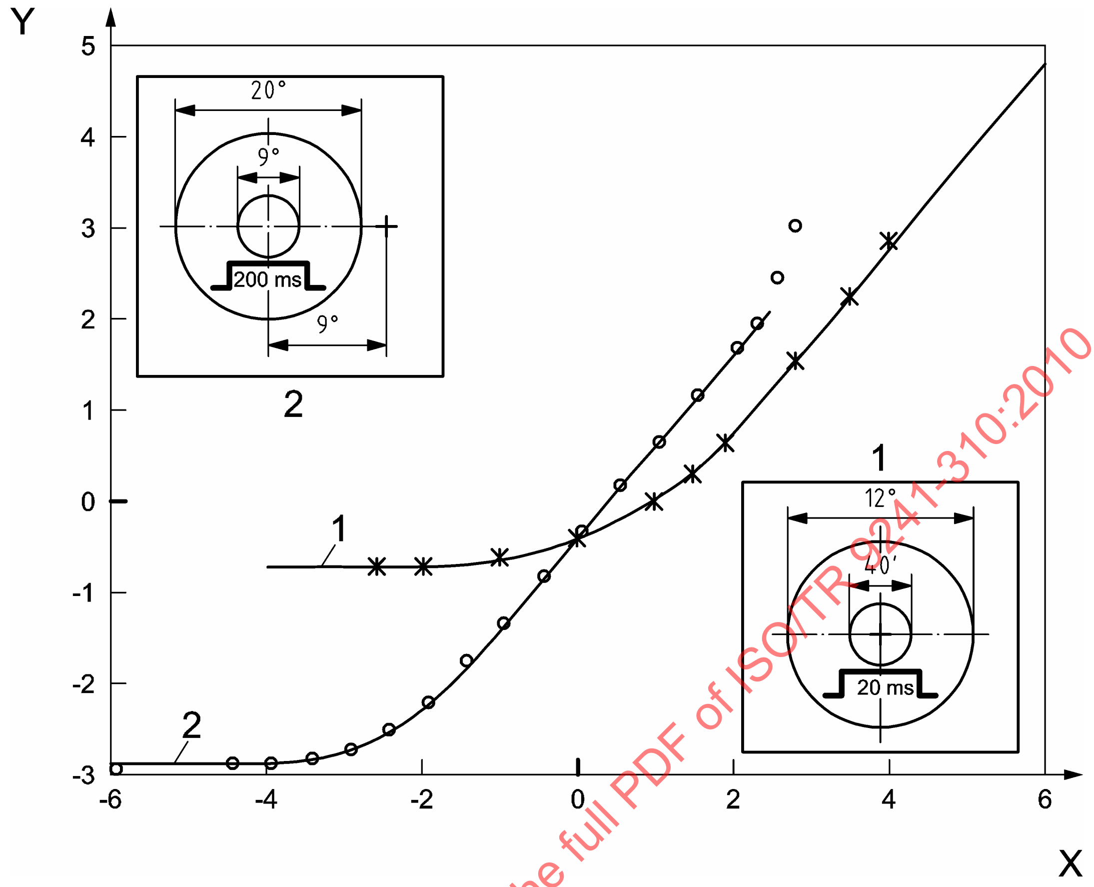
I is the intensity of the spot;

ΔI is the intensity difference threshold for detection;

k_{A} is a constant.

For normal usage situations $k \approx 100$

The size of the area determining the luminance adaptation is not covered in this report. Local luminance adaptation occurs concurrently and continuously for different areas of the field of view and could partially explain why a certain spot luminance can be clearly visible against a background, dimly visible in the neighbourhood of other patterns and not at all visible within the other luminance pattern.



Key

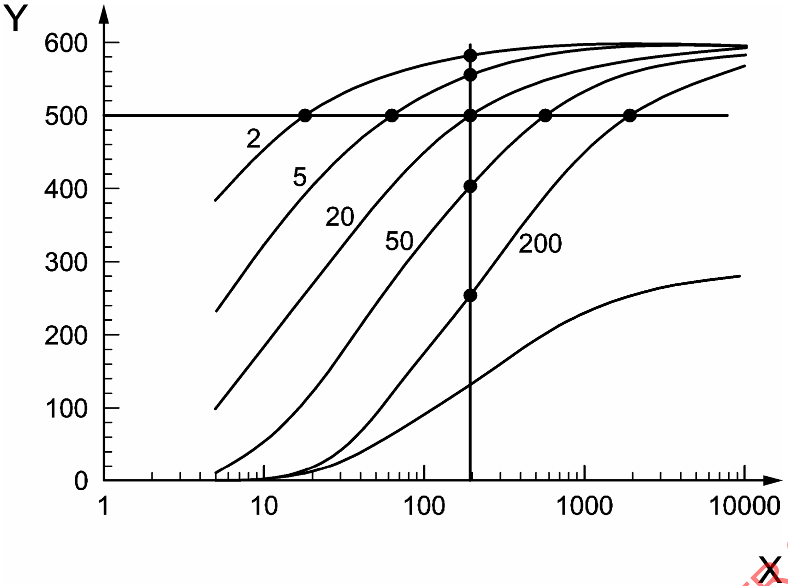
1 cones

2 rods

X log background luminance in cd/m^2

Y log threshold luminance in cd/m^2

Figure 3 — A psychophysical model of detection thresholds over the full range of vision; source: [26]



Key

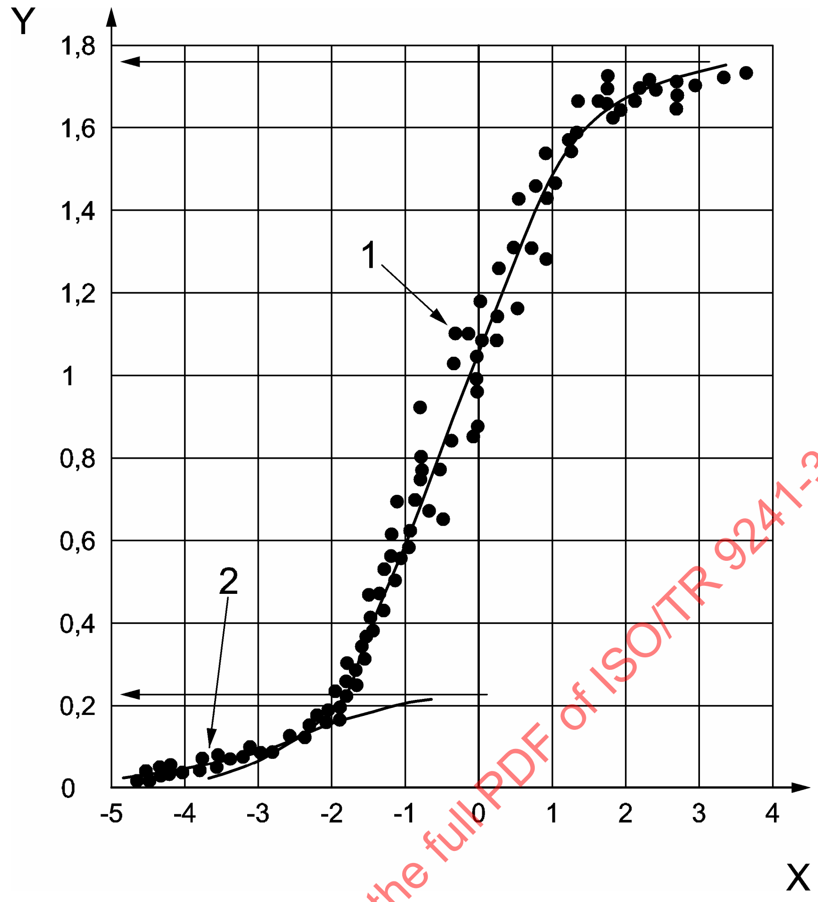
a rod response showing compression

X stimulus intensity

Y cone response in µ

Figure 4 — Cone responses vs. Stimulus at various background intensities; source: [30]

A second effect of light adaptation is the impact on visual acuity. The visual acuity improves with higher adaptation luminance up to about 300 cd/m² (for young adults, the level increases with age).



Key

1 cone

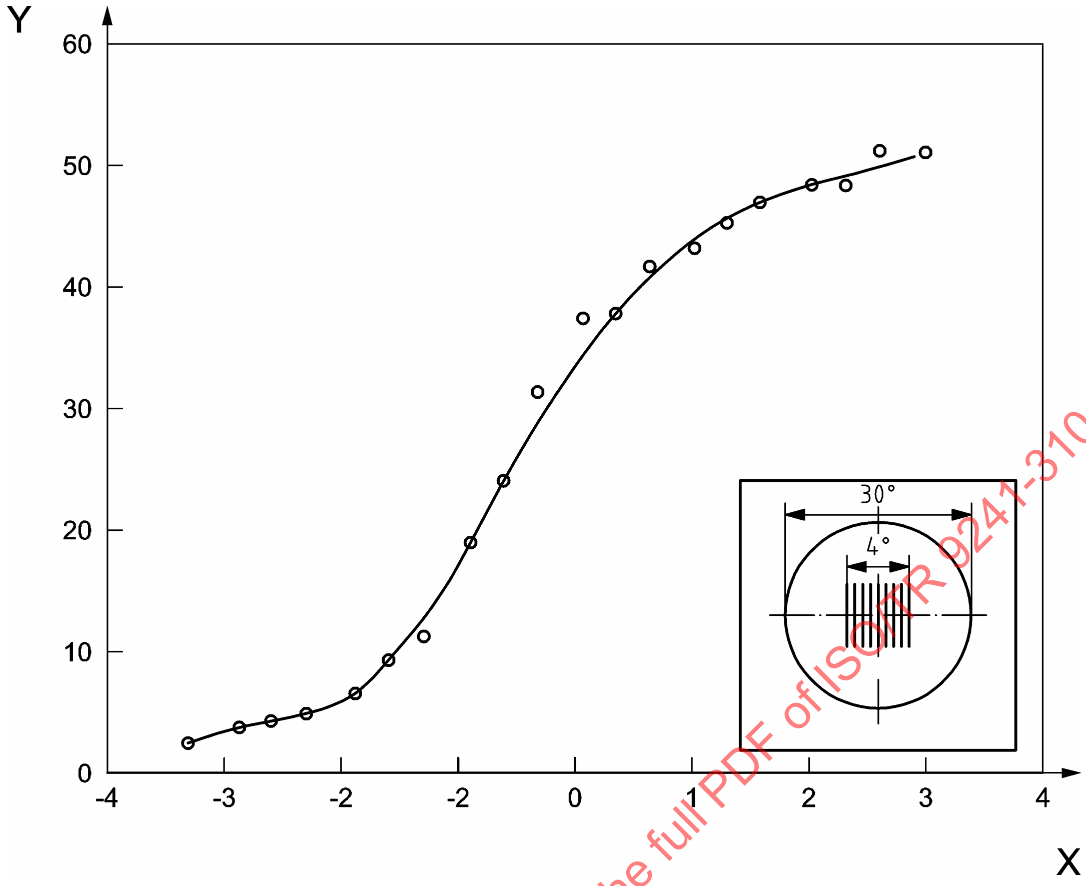
2 rod

X log *L*, in millilamberts

Y visual acuity

Figure 5 — For recognition tasks, visual acuity is greatly affected by the level of background luminance

Two branches are evident, the lower belongs to the rod (scotopic) function and the upper to the cone (photopic) function. Note the asymptote for both indicating the maximum visual acuity (arrows). The cone branch has a long "linear" range of about 3 log units which asymptote at the photopic level of about 300 cd/m². The shallow curve at low luminances is due to the rod response and the large sigmoidal curve is due to the cone response. The horizontal arrow identifies the maximum resolution of rod and cone systems. Konig's data from Riggs L. A., Visual acuity. Chapter 11. In: Graham, C. H. (ed), Vision and Visual Perception. New York: John Wiley and Sons, Inc., 1965. [http://webvision.med.utah.edu/]

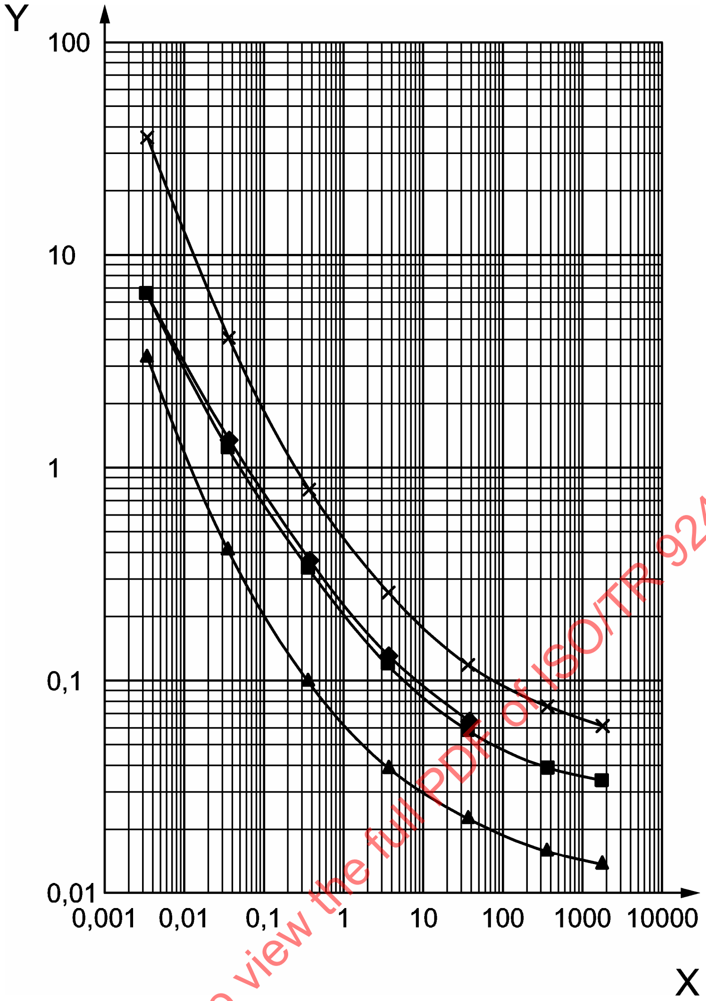


Key

X log luminance, in cd/m^2

Y highest resolvable spatial frequency, in cycles/deg

Figure 6 — Shaler, S. (1937) The relation between visual acuity and illumination; source: [31]

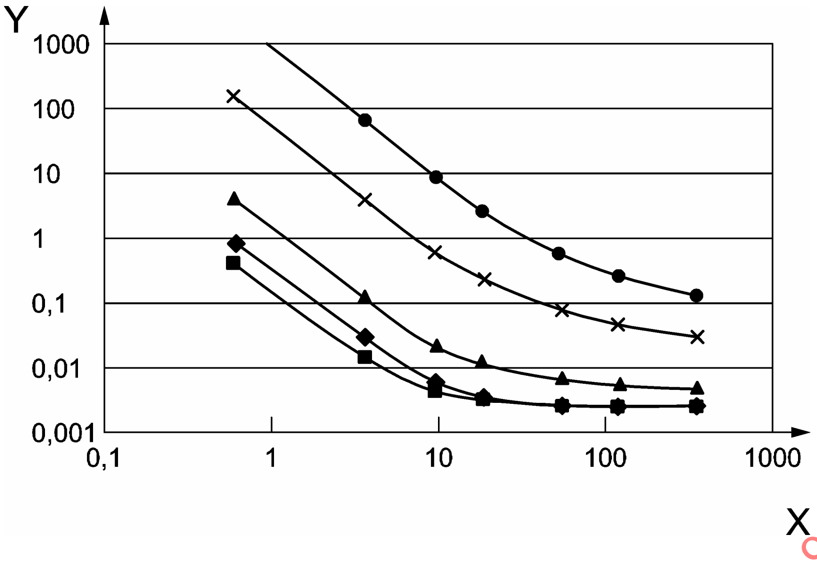


Note that positive contrast represents a bright spot on a dark background.

Key

- ■ Blackwell 1946 (1) Part I positive contrast t = 6 s
- ◆ Blackwell 1946 (1) Part II negative contrast t = 6 s
- ▲ Blackwell 1946 (1) Part III positive contrast t = unlimited
- × Blackwell 1946 (2) positive contrast t = 0,2 s

Figure 7 —The relation between threshold contrast and background luminance (adaptation luminance); Blackwell (1946, 1971) from http://arrow.win.ecn.uiowa.edu/



Key

X visual angle of target in minutes

Y threshold contrast, in

—■— Lb in cd/m^2 · 2 = 3426,2591

—◆— Lb in cd/m^2 · 2 = 34,262591

—▲— Lb in cd/m^2 · 2 = 0,34262891

—×— Lb in cd/m^2 · 2 = 0,003426259

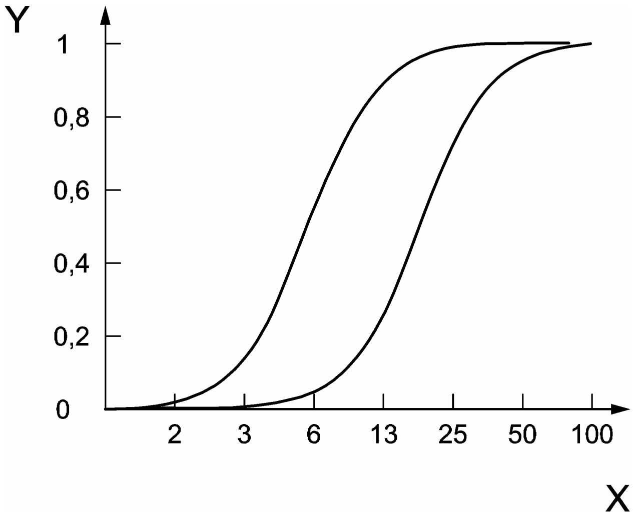
—●— Lb in cd/m^2 · 2 = 3,42626 · 10^{-5}

Figure 8 —The relation between threshold contrast, background luminance and visual angle of target, Exposure time unlimited; Blackwell (1946), part III. from http://arrow.win.ecn.uiowa.edu/

3.1.7 Contrast adaptation

Contrast adaptation is a not so well-known effect which might impact spot detection. It could partially explain why pixel defects are easier to detect when contrast of the pixel defect is not too far from the average contrast of the visual field. The visual system appears to have a fairly limited contrast response function and an ability to compensate by adjusting the gain so that it is optimal for detecting differences in contrast around the average level of contrast.

This contradicts the popular extrapolation of Weber's law. Although luminance differences as small as 1/100th of the adaptation luminance can be perceived, human beings do not have that resolution available in the whole luminance range at the same time, but only in a small window, around the adaptation contrast.



Note that the low contrast response function on the left is ideally suited to detect differences in contrast between 2 % and about 25 %. But for contrasts above 25 % the neuron can only respond at its maximum level.

Key

X contrast in %

Y response

Figure 9 — Example contrast response functions with low (left curve) and high (right curve) contrast adaptation levels; source: [27]

3.1.8 Spatial uncertainty

For spots that are close to detection threshold, the detection threshold decreases if the user knows the spatial location of the spot. (Uncertainty about the intensity or contrast does not decrease detection threshold.)

3.1.9 Spot colour

In some reports a dependency on spot colour has been reported. This dependency can more or less be attributed to the differences in luminance or luminance contrast.

Gordon Legge et al [28] showed that the human being has three contrast channels suitable for reading; luminance contrast, Red-Green contrast and Yellow-Blue contrast. In normal reading, the signal from the contrast channel with the strongest signal is used and the two other channels are ignored. Since reading is dependent on detection of character features, it can be assumed that the same mechanism is valid for spot detection.

Adapting Legge et al, the following can be assumed: Spot detection origins from the perceived contrast. Contrast is perceived through three channels: achromatic (luminance), Red-Green and Blue-Yellow. In spot detection, the detection is based on the channel with the highest contrast and the channels which have less contrast do not impact the detection speed. Furthermore, the spatial resolution of the blue-yellow contrast channel is not as good as the luminance channel, and will not be as efficient in detecting pixel defects appearing as small spots.

Summarizing, for practical application, it can safely be assumed that the colour will influence pixel defect detection only through the luminance contrast created by the colours.

3.1.10 Conclusions

Spot detection depends on several factors described above. For the context of electronic visual displays (currently available technology) the following factors seem to be the most important:

- size of the spot;
- contrast of the spot;
- adaptation luminance.

Differences between positive polarity and negative polarity pixel defects are fully explained by the difference in light adaptation level and contrast (see Figure 1).

Thus there seems to be no need to define different requirements for positive and negative polarity, if the requirements are defined as a function of both contrast and adaptation luminance.

3.2 Visibility of pixel defects

Yoshitake [9] reported a study on the spatial summation related to pixel defect visibility threshold. He verified the hypothesis that for stuck on pixel defects on a black background the luminance times the area is constant. This is the effect occurring from both Ricco's law and from photoreceptor-level spatial summation. He also identified several factors that influence the experimental conditions; i.e. factors that need to be included in a model for pixel defect visibility threshold:

a) display factors:
   - colours (wavelength);
   - viewing angle characteristics;
   - background luminance;
   - reflectance;
   - fill factor.

b) test subject factors:
   - visual characteristics such as visual acuity.

c) environment factors:
   - screen illuminance;
   - viewing distance;
   - viewing angle.

Strik [10] reported a study on the perception of subpixel defects in displays. The display was a typical advanced mobile phone display. This means a smaller display size and a smaller pixel size compared to earlier studies. Also the impact of ambient reflections on the display is different from fixed-position larger displays.

NOTE 1 At the time, high-end mobile displays had a pixel size of 0,15 mm to 0,30 mm. The report should not be interpreted outside of that context.

Strik and his colleagues draw the following conclusions, which are valid only for the display characteristics that the test display had:

a) experts have a significantly lower pixel defect detection threshold than non-experts;

b) defects covering two or more neighbouring pixels will always be noticed by users. (The stroke width of the test display was one pixel);

c) green subpixels will be noticed by end users;

d) stuck-off blue subpixels are not visible for most viewers;

e) red subpixels are almost invisible for non-experts;

f) a better controlled study is needed to find a numeric acceptance threshold. At least luminance, pixel size and ambient illumination need to be controlled.

Swinkels et al [11] conducted a well-controlled visual perception study, as a continuation of the research reported by Strik, with the aim of establishing a numeric visual detection threshold. The results they obtained were compared with existing models of vision and they were able to establish a numeric model for bright pixel defect detection on black background, based on numeric addition of the effects from spatial summation, adaptation luminance and Weber's law.

$$L_{\text{th}} = \frac{10^{-7}\sqrt{L_{\text{bk}}}}{\tan^{2}\alpha} + L_{\text{bk}} + \frac{1}{100}\cdot L_{\text{bk}} \tag{5}$$

where

L_{th} is the threshold luminance for pixel defect detection;

L_{bk} is the luminance of the background of the pixel defect;

α is a the visual angle subtended by the pixel defect, in degrees.

NOTE 2 In the experimental condition the adaptation luminance was equal to the background luminance. In real-life situations the adaptation luminance is the local average luminance around and including the pixel defect. Thus the third term in the equation should probably be $L_{\text{adaptation}}$.

The model has the following known limitations:

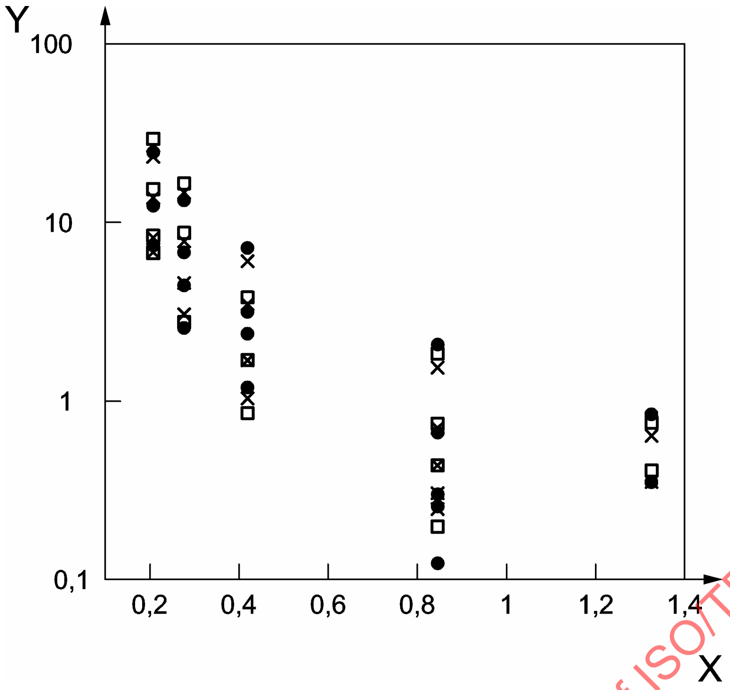
— The model has been validated with data from only one experiment and that experiment was carried out only with bright pixels on a black background.

— The model is valid for healthy, young adults with normal vision. For older people and for people with visual disorders the threshold luminance will be higher.

— The model predicts only the worst case pixel defect visibility, i.e. a single pixel defect in a known location on a spatially uniform background. In real-world situations the background is usually spatially non-uniform and there are usually ambient reflections on the screen and some amount of glare in the visual field of the user. All of which increase the threshold for pixel defect detection.

— The model does not include the change in visual acuity as a function of adaptation luminance.

The data by Swinkels et al has been correlated both to the model proposed by Swinkels et al and to the contrast thresholds predicted by the simplified contrast sensitivity function by Barten [7], see 3.1.1. The plot and the correlation indicate that both models predict pixel defect detectability equally well.



Pearson's r correlation coefficient is 0,996 for both equations. The contrast is defined as the luminance difference (spot – background) divided by the background (adaptation) luminance.

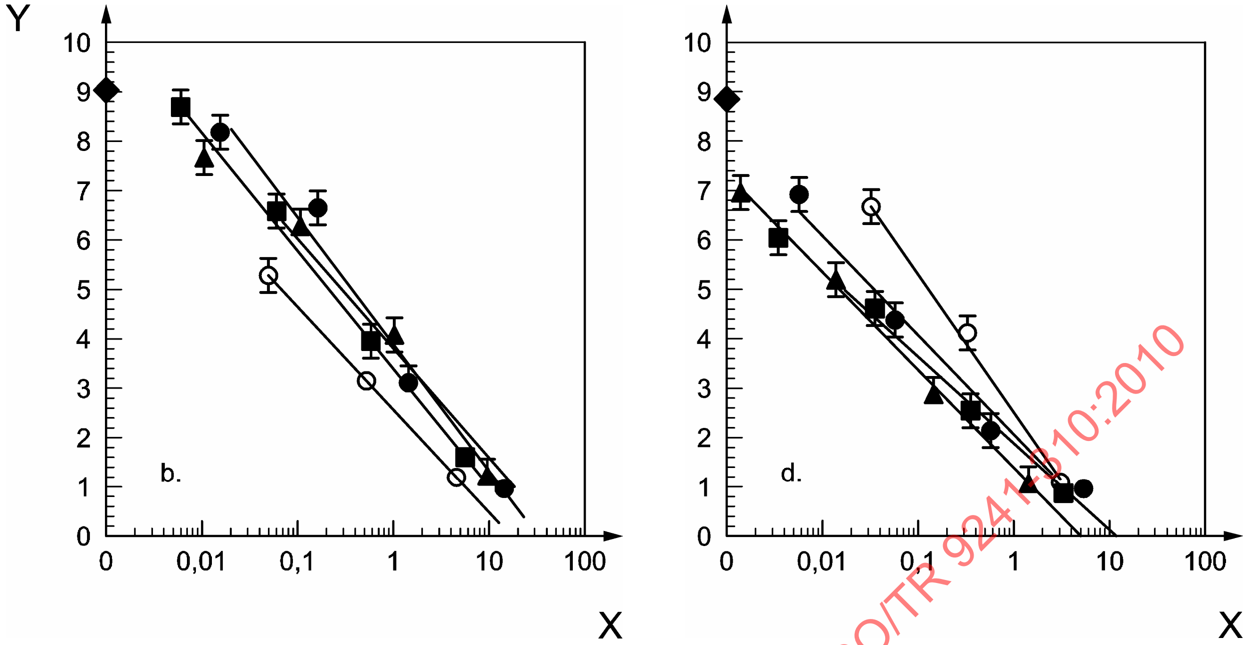
Key

- ● Swinkel's data
- □ Swinkel's equation
- × Barten's equation

Figure 10 — The correlation of the Swinkels and Barten equations to the Swinkels et al empirical data

It is expected that the Barten model can be more widely applied to different pixel defect cases, such as stuckoff pixel defects. No explicit validation has however been made. The larger number of parameters in the Barten model allows for larger adaptability but increases the risk of error from applying the wrong parameters.

[Mustonen & Lindfors 2005] [12] asked their test persons to rate pixel defects on a 9-point scale. For the display used, all types of pixel and subpixel defects were visible in negative polarity, whereas in positive polarity stuck off low contrast subpixel defects were very close to imperceptible; and all types of pixel defects were close to imperceptible at the lowest tested amount of pixel defects (covering 0,02 % or less of the total display area).



Positive polarity

Negative polarity

Rating results are plotted as a function of the display area (%) that the defects cover. Visibility of pixel defects was assessed with 9 point scale labelled as follows: 1 = very annoying, 3 = annoying, 5 = slightly annoying, 7 = perceptible, but not annoying, 9 = imperceptible. Each data point represents the average over five test subjects and error bars are standard errors of the mean. Logarithmic trendlines are added.

Key

X percent of display area that the faults cover

Y visibility of pixel defects

◆ reference

■ stuck off low contrast subpixel

▲ stuck off high contrast subpixel

● stuck off pixel

○ stuck off pixel (2 × 2)

Figure 11 — Subjective evaluation of stuck off defects on white background and stuck on defects on black background

For techniques used in medical displays to make visible pixel defects non-visible, see 3.4.2.

3.3 Aesthetical acceptability of pixel defects

3.3.1 Japan-Korea study 2004

Hisatake et al [13] studied the user patience limit for pixel defects with 4 typical contents on a 15 inch display, 4 typical contents on an 8 inch display, 4 typical contents on a 4 inch display and 5 typical contents on a 2,2 inch display. The contents were non-identical over display resolution. The visual angle subtended by one pixel was non-identical over display resolution. The luminances were not recorded. Thus the results cannot be used for establishing a model for pixel defect visibility, if the criteria for a model established by Yoshitake [10] are used, but the results can be used to understand the variations in acceptability.

It was found that the subtended visual angle of the display, the display resolution and the content affects the patience limit and it was found that one general patience limit for all types of displays and tasks is not possible to establish, but the patience limit will vary with display size, pixel size and type of content typically shown on the display.

A concept of R-values was introduced by Hisatake et al. The patience limit (how many defects can be accepted in a display) is defined as a numerical value times the coefficient R. R is a function of at least panel size, viewing distance, display resolution and application area. Some tables of R-values have been published. Since the model includes only some of the parameters affecting aesthetical acceptability, then R-value has not been accepted as a general model for aesthetical acceptability.

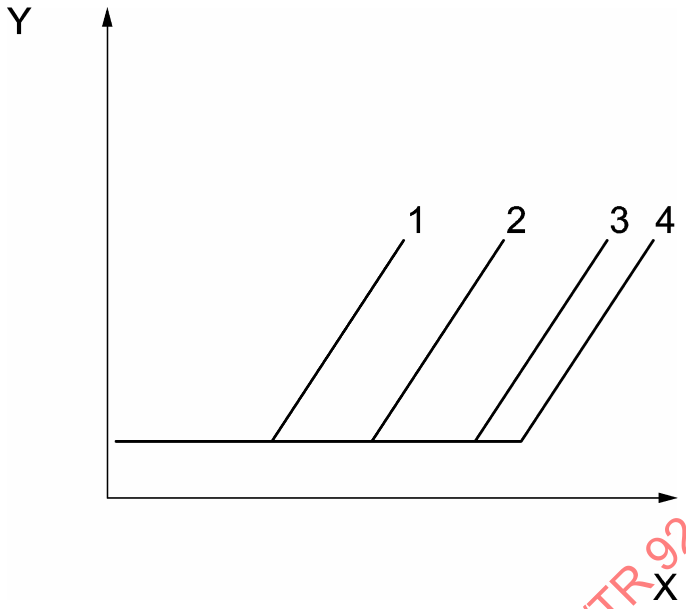
In [Mustonen & Lindfors 2005] [12] or [17] the test subjects were asked to rate the subjective comfort related to the visible pixel defects. The questions were asked after the test subjects had performed a visual performance test with random-character pseudo-text in positive and negative polarity using the procedure in ISO 9241-3. The threshold for reduced subjective comfort was 0,01 % for black background and 0,6 % for white background, where the percentages describe how large portion of the total display area is covered by pixel faults.

3.4 Ergonomics limits related to pixel defect

3.4.1 General office use

[Mustonen & Lindfors 2005] tried to replicate the non-published research and understanding that lay behind the pixel defect limits of the original text for ISO 13406-2. They conducted a visual performance test with a high number of repetitions in controlled lighting and viewing distance conditions. The test users performed the ISO 9241-3 visual performance test in a reference condition free of pixel defects and with a logarithmically increasing number of pixel defects until significant performance decrement could be observed. The test was repeated in both positive and negative polarity. The test was repeated with different pixel defect sizes, average luminance levels and luminance contrasts.

The order of effects from pixel defects in normal reading tasks was identified:



Key

X number of faults

Y amount

1 number of detected faults

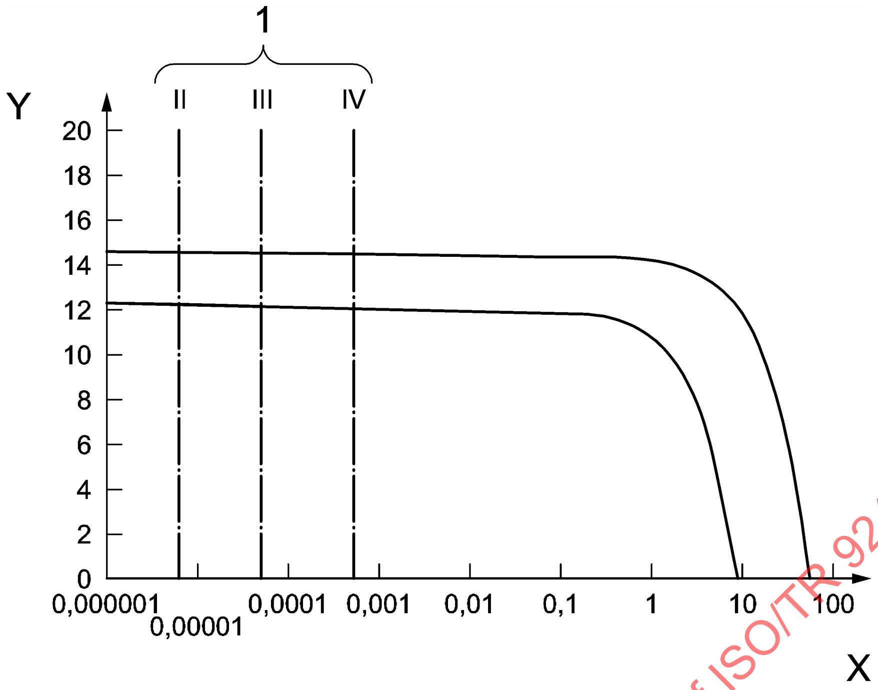
2 reduction of subjective reading comfort

3 reduction of reading speed

4 number of reading errors

Figure 12 — Relation between detection threshold, comfort, reading sped and reading errors [17]

A relation between reading speed and the amount of pixel defects was found. It was found that the dependent factor is the total area covered by pixel faults, not the number of pixel faults. This expression is valid for any size of pixel defects. The contrast of the pixel defects did not have a significant further impact on the reading speed once the contrast was clearly above the visibility threshold. The threshold for performance reduction was amazingly high.



Visual performance curves, positive and negative

Key

X screen area covered by faults, in percentage of area

Y search velocity, in characters/s

a visual performance curve, black on white background (positive polarity)

b visual performance curve, white text on black background (negative polarity)

1 ISO 13406-2 fault classes

Figure 13 — Reading speed as a function of total area of pixel defects [17]

3.4.2 Medical use

Den Boer et al [19] report that displays used for medical applications have a typical pixel defect density (in number of pixel defects) of 0,001 %. They report that for medical applications this pixel defect ratio can be eliminated in image processing by nearest neighbour interpolation without compromising the need to reach equal quality with traditional film-based X-ray images. This was reported for a display with 0,155 mm pixel-to-pixel distance.

Kimpe et al [18] report that displays for medical applications have a typical pixel defect rate of 1 defect per 2 million pixels. They established a solution to the problem of pixel defects in matrix displays for medical applications using the nearest neighbour interpolation approach. An algorithm was constructed based on the point-spread function of the human eye. They implemented the algorithm and successfully tested it at viewing distances of 300 mm and higher with both low and high resolution displays. They report that the visibility of the pixel defect was significantly reduced in all cases and in most cases the pixel defect became totally invisible. Based on their experience with medical displays the authors believe this is a sufficient solution even for the most demanding medical applications.

4 Review of standards

4.1 ISO 13406-2, Ergonomic requirements for work with visual displays based on flat panels - Part 2: Ergonomic requirements for flat panel displays

4.1.1 Origin and intent of the fault class table

The rationale behind the pixel defect classes of ISO 13406-2 has not been clearly documented. The following is an account of the creation of the fault classification.

In 1992 the Working Group ISO/TC 159/SC 4/WG 2 "Visual display requirements" totally redefined the pixel fault classification. The new classification established in 1992 is included in Table 1. The rationale for the four classes has been researched by reviewing ISO/TC 159/SC 4/WG 2 documents from 1992 and by interviewing members present at the meeting at that time. The rationale was the following:

a) the document was being prepared as an annex to ISO 9241-3, the scope of which was limited to alphanumeric text presentation;

b) ergonomics was considered strictly according to the definitions of ISO 6385 and the scope of ISO 9241-3. The then current state of the art was considered to meet all known ergonomics requirements with great margin, e.g. X-ray image analysis was not included in the scope;

c) in addition to ergonomics requirements, the Working Group knew about aesthetic requirements and commercial requirements, which were more stringent than ergonomic requirements. They were, however, considered to be outside the scope of this ergonomics standard;

d) current state of the art in display manufacturing was represented by class C;

e) class D was simply defined as 10 times more pixel faults than class C, the number 10 had no other background. It was included since class D was considered to still meet all ergonomics requirements and thus introduce some margins for manufacturers and because ISO is committed to avoid the introduction of unnecessary barriers to technical innovation;

f) class B was simply defined as 1/10 the amount of pixel faults as in class C, the number 1/10 had no other background;

g) in 1992 it was not considered to be realistic to mass-manufacture LCD displays with less faults than represented by class B;

h) class A was defined as "zero errors".

At that point in time, the pixel fault requirement was completely rewritten to reflect the state of the art. From industry, the following companies and organisations participated in the creation of the following table: NEC, Sharp, Toshiba, Hitachi, IBM and EIAJ.

Table 1 — Fault classes

Maximum number of faults per type per million pixels.

Class	Type I or II	Type III	Cluster
A	0	0	0
B	5	50	0
C	50	500	5
D	500	5 000	50

Flat panels should be in class A.

NOTE 1 Class C panels are considered state-of-the-art today. All classes are useful in most applications.

NOTE 2 The required fault level contains large margins for protection against usability issues. The probability that a faulty pixel is a foreground pixel is about 0,05. The probability that a foreground pixel is critical to usability (e.g. that it causes the incorrect identification of a character) is a number in the 10^{-4} range. The joint probability, $p_{fault} \times p_{foreground} \times p_{critical}$ is in the order of 10^{-9} even for class D.

Thus the original intent of the table in ISO 13406-2 was twofold: to reflect current state-of-the-art (class C) and to communicate that even a high number of pixel faults is not detrimental to usability or performance.

When analyzing this status it has to be kept in mind that class C was state-of-the art and the state-of-the art pixel size was big; 0,4 mm × 0,4 mm or larger. Pixels and subpixels were big enough to be visible.

4.1.2 Final version of ISO 13406-2

Table 2 — Fault classes in ISO 13406-2

Maximum number of faults per type per million pixels.

Class	Type 1	Type 2	Type 3	Cluster with more than one type 1 or type 2 faults	Cluster of type 3 faults
I	0	0	0	0	0
II	2	2	5	0	2
III	5	15	50	0	5
VI	50	150	500	5	50

Flat panels should be in class I. If not, the supplier shall specify the class of the display.

Table 3 — Fault types in ISO 13406-2

Fault type	Description
Type 1 fault	Pixel in stuck high state
Type 2 fault	Pixel in stuck low state
Type 3 fault	Pixel or subpixel abnormal, but not of type 1 or 2. For example, a stuck subpixel or intermittent fault.
Fault cluster	Two or more pixels or subpixels with faults within a 5 × 5 block of pixels.
NOTE This is an abbreviated version of the full table in ISO 13406-2.	

At time of finalization of ISO 13406-2 in 1998, state-of-the-art of displays had a few faults per million pixels. The pixel size studied was 0,3 mm × 0,3 mm and bigger.

4.1.3 Deployment of ISO 13406-2

4.1.3.1 Approval

In the authority approval industry ISO 13406-2 has been important. Most current display certification schemes require compliance to the ISO 13406-2 pixel defect requirement, to receive the approval.

NOTE The European CE label and the Swedish TCO label do not require compliance with the ISO 13406-2 pixel defect requirement, whereas for instance the German GS mark and the US AAPM label require compliance. For information on GS see www.zls-muenchen.de. For information on AAPM see www.aapm.org.

4.1.3.2 Quality control and quality assurance

In 100 % inspection ISO 13406-2 is generally not used. In random inspection both ISO 13406-2 and other methods are in use. Some factors affecting the choice of method are: Faults like mura are not covered ISO 13406-2, but still need to be controlled in display manufacturing. The ISO subdivision into fault classes does not fit well enough into vision based manual inspection tasks. In most existing inspection procedures it is not possible to differentiate between fault types within a reasonable time or with a reasonable amount of operator effort. A third factor is that the manufacturing industry had already adopted different quality assurance and technical specification methods, which the new ISO standard did not replace.

4.1.3.3 Sales and marketing

On the desktop display market ISO 13406-2 is the recognized requirement for pixel defects. Manufacturers may e.g. publish the pixel fault classification for each model.

4.1.3.4 Research and development

The pixel fault definitions in ISO 13406-2 did not become generally adopted in the industry as technical specifications for display components or display modules. ISO 13406-2 is a part of the requirement specification in the office computing industry. One reason is that faults like mura are not covered in ISO 13406-2. Another reason is that the subdivision into fault classes does not correlate well enough with either the technological reasons for the defects or with the methods used in research and development for visual inspection of display samples. A third reason is that industry had already adopted different quality assurance and technical specification methods.

4.2 ISO 9241 300-series

ISO 13406-2 was revised and partly replaced by ISO 9241-307. This International Standard follows the main lines of ISO 13406-2 and it is expected that it will have the same impact on industry, market and authority approvals as ISO 13406-2.

Table 4 — Table 183 "Number of faults" from ISO 9241-307

$Class_{Pixel}$	Type 1	Type 2	Type 3		Cluster with more than one type 1 or type 2 faults	Cluster of type 3 faults
			stuck high	stuck low		
0	0	0	0	0	0	0
I	1	1	2	1	0	0
(for Type 3 = 5 PSU)	1	1	1	3	0	0
	1	1	0	5	0	0
II	2	2	5	0	0	1
(for Type 3 = 10 PSU)	2	2	$5 – 1 \times n_{II}$	$2 \times n_{II}$	0	1
	2	2	0	10	0	1
III	5	15	50	0	0	5
(for Type 3 = 100 PSU)	5	15	$50 – 1 \times n_{III}$	$2 \times n_{III}$	0	5
	5	15	0	100	0	5
IV	50	150	500	0	5	50
(for Type 3 = 1000 PSU)	50	150	$500 – 1 \times n_{IV}$	$2 \times n_{IV}$	5	50
	50	150	0	1000	5	50

The following notes refer to table 4, column 4, Type 3.

NOTE 1 Faults that are below visibility threshold are not considered.

NOTE 2 For ergonomics performance the number, size and contrast of blemishes and pixel faults shall not exceed the threshold for performance decrease.

NOTE 3 For reading tasks a display in any of the pixel fault classification classes (0 - IV) will be well above the threshold.

NOTE 4 These fault classes consider

a) that bright sub pixel faults are perceived more sensitive than dark sub pixel faults. Therefore pixel faults are weighted in Perceived Sensitivity Units (PSU), where

— 1 Type 3 stuck high fault ≡ 2 PSU

— 1 Type 3 stuck low fault ≡ 1 PSU

Therefore different combinations of Type 3 faults in ClassPixel I, II, III and IV are possible:

b) that for smaller displays < 9,1“ (23,1 cm) in predominant the pixel density is higher and less sensitive as for bigger displays >9,1” (23,1 cm) with less pixel density,

c) a class definition, that addresses primary the acceptance levels of the users and their related tasks, were for example the classes can reflect the following contexts,

1) $\text{Class}_{\text{Pixel}}$ 0, for special video display unit tasks with a very high sensitivity and importance to minimize risks in the information perception, like inspection of critical information in processes or critical process indicators with a high risk of wrong decisions and process inherent errors;

2) $\text{Class}_{\text{Pixel}}$ I, for specific video display tasks with high sensitivity and special importance to pixel faults, like observation, surveillance, image quality inspection tasks with less risks to inherent faults in the case of reading and observation errors;

3) ClassPixel II, for general user display tasks with a sensitivity to pixel faults, like reading and process text information, perceive object and symbol information with a sufficient reading performance to operate the task;

4) ClassPixel III and ClassPixel IV, for display tasks with less sensitivity to pixel faults, like process public information and advertisement, text book reading, fast moving images, but with a sufficient performance to perceive the information without discomfort by the user.

NOTE 5 Related ergonomics performance criteria with the threshold values of defects for visibility and different tasks are under investigation. Please observe Technical Reports and annexes to this standard.

NOTE 6 Type 3 faults are including dim pixels of 25 % < Lx < 50 % (dark), 50 % ≤ Lx < 75 % (bright), where Lx is the average pixel response to a maximum luminance command (e.g. white). Intermittent pixels or blinking pixels are rated with 2 PSU's. The weighting of the PSU is indicated in front of the multiplier nClassPixel of Type 3 faults.

NOTE 7 Multiplier $n_{\text{ClassPixel}}$ can vary with the PSU and can take $n_{\text{II}} = 1$ to 4, $n_{\text{III}} = 1$ to 49, $n_{\text{IV}} = 1$ to 499. If not fault class, ClassPixel 0 or I the supplier shall specify the fault class, ClassPixel as well as the multiplier $n_{\text{ClassPixel}}$ depending on the specified distribution of PSUs.

NOTE 8 Maximum number of faults in addition is calculated as follows:

a) for displays ≤ 9,1“ (23,1 cm) with > 1 million pixels: maximum number of faults per type per million pixels;

b) for displays ≤ 9,1“ (23,1 cm) with ≤ 1 million pixels: number of faults per display;

c) for displays ≤ 9,1“ (23,1 cm) with ≤ 100 000 pixels: number of faults per type per 100 000 pixels;

d) for displays ≤ 9,1“ (23,1 cm) with ≤ 10 000 pixels: number of faults per type per 10 000 pixels.

Compared to ISO 13406-2, ISO 9241-307 introduces new finer distinction between fault types. Since quality assurance of manufacturing processes and end users were not able to efficiently do the fault type classification of ISO 13406-2, this new addition will only impact labs with advanced equipment for pixel defect analysis. The limit values of the classes have been changed and have become more strict, based on the ALARA principle (as low as reasonably achievable) based on the product maturity level of LCD displays in the office computer market. The new limits are not based on published and validated research results. The revision also introduces a new calculation parameter, called PSU. The changes from ISO 13406-2 to ISO 9241-307 are not based on the research reviewed in this technical report. This technical report was written after the finalization of the technical content of the pixel defect requirements of ISO 9241-303 and ISO 9241-307.

Between 1998 and 2005, the state-of-the-art of LCD technology improved considerably. The smallest pixels available in commercial consumer products have a pixel-to-pixel distance of 0,08 mm and a subpixel-to-subpixel distance of less than 0,03 mm. These pixels are so small, that single subpixel or single pixel defects might not be visible even in worst case conditions.

The error rate in high end LCD displays (medical field, year 2005) is 1 non-functional transistor per 3 Million pixels. In consumer products, error rates as high as one non-functional transistor per 5 000 pixels are common and fully accepted by users. Such displays would be in class IV if all the defects are visible. When promising new technologies for rollable and ultraportable displays reach the market in 1 to 5 years, it is expected that the number of pixel defects will rise even further. Some displays won't meet class IV if both visible and non-visible pixel- and sub-pixel defects are counted. The number of defects will grow because less-mature display technologies will initially have more faults, and because of the switch to flexible electronics. The flexible products will be more suspectible to errors and wear-out during operation.

4.3 International Electrotechnical Commission (IEC)

IEC has produced a standard series – IEC 61747 – covering LCDs. It has been intended to include pixel defect and mura error classification in this series but at the time of writing (2005) no such drafts had yet been published.

4.4 Video Electronics Standards Association (VESA) Flat Panel Display Measurements (FPDM)

The VESA FPDM document (2001) contains several sections related to pixel defects.

Section 303-6 of the VESA FPDM document (2001) is a measurement specification technically identical with but not covering all of ISO 13406-2. The details and concepts are described in an easy to read fashion.

Section 303-6B of the VESA FPDM document (2001) is an extension of the cluster concept of ISO 13406-2. It defines clustering to the extent to make it suitable for automated measurements.

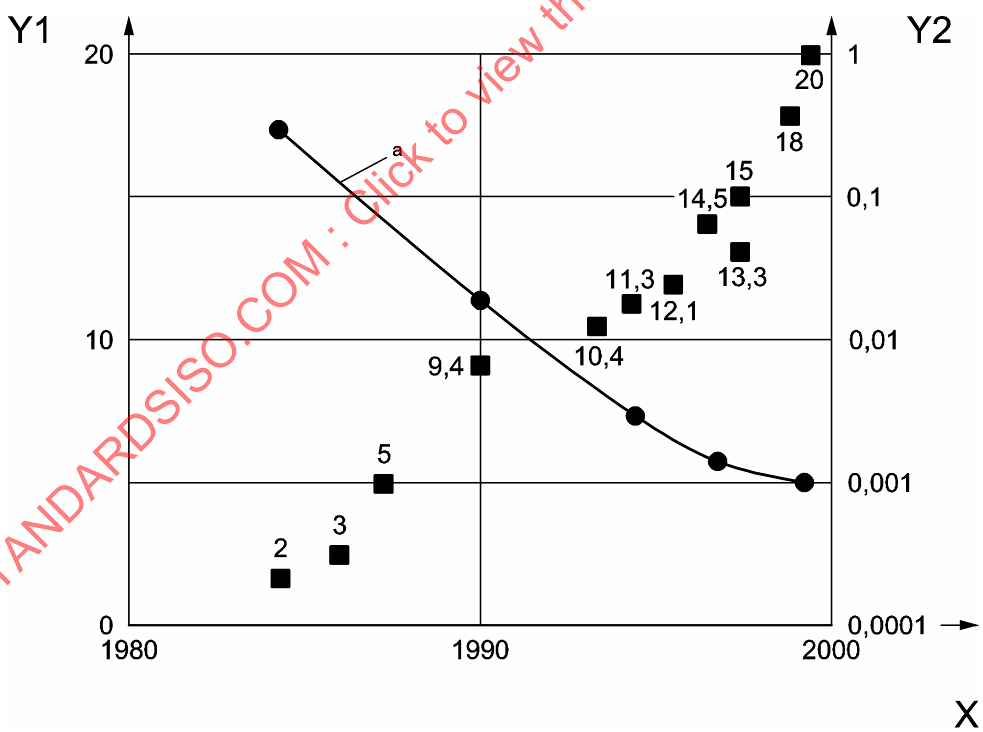
Section 303-6C of the VESA FPDM document (2001) Introduces a new concept about defect separation and defines the measurement and specification methods.

Section 303-8 of the VESA FPDM document (2001) is an extensive section on measurement and specification methods for Mura defects.

5 Review of industry practice

5.1 General

The maturity of LCD technology has developed considerably when it comes to pixel defects, as shown in Figure 14.



Key

X year

Y diagonal display size, in inch

Z defect density in defects per square meter

a defect density

Figure 14 — Display size and defect density in LCD displays in the years 1980 to 2000; source: [32]

In 2005, state of the art high end displays for medical use have one defect transistor per 3 million pixels. [Tom Kimpe, Stefaan Coulier and Etienne Dorval. Solving the Problem of Pixel Defects in Matrix Displays based on Characteristics of the Human Visual System. In Proceedings of EuroDisplay 2005, Edinburgh, Scotland, pp 822 – 84.] Consumer products might have as much as 1 defective pixel per 5000 pixels and still be accepted by users. Some future technology products are expected to have even more defects and still be acceptable on the market. This is possible for technologies (such as rollable displays) which do not compete in terms of cost or image quality, but in terms of unique end-user value-adding features that are not possible to create with conventional display technology.

5.2 Technical specification

In the display industry, the technical specification of pixel defects and mura is widely based on existing outgoing inspection methods and quality statistics from the outgoing inspection.

5.3 Specification for end customers

Specification for consumers used to be very limited or non-existent, but has improved recently and nowadays full pixel fault specifications are available for at least leading display brands. In the past it happened that the salesman gave the impression that the display was fault-free, even if somewhere in the user's manual there was a sentence or a reference that allows the manufacturer to have a small number of pixel defects. ISO 13406-2 was then wrongly used as an excuse to for claiming fault-freeness even with a few pixel defects.

In the high end professional market (medical displays) where a pixel defects can be critical it is common practice among some companies to screen every display before delivery to the customer and give a map of where the pixel defects are located. The intention is to make the radiologist aware of where the pixel defects are so that the doctor can take that into account when judging an electronic X-ray image.

5.4 Outgoing inspection

Outgoing inspection at manufacturing plants is widely based on manual, visual inspection by trained operators. The inspection sequence can, for example, proceed as follows:

— with the display in full black state, the number of bright defects and dim defects are counted;

— with the display in full white state, the number of dark defects and dim defects are counted;

— if any of the four sets of defects exceed the quality limit, the display is not accepted but sent to the quality department for further judgement.

In order to detect only defects that will be visible to end users, the inspection can be carried out in controlled lighting conditions and the display might be viewed through a neutral density filter to adjust the sensitivity of the detection.

In the year 2005, automated testing inspection is not used very widely. In the microdisplay industry and in displays with very small pixel number automated inspection is more widely used. (This is used in areas where visual inspection is not possible and areas where automated inspection is more efficient than visual inspection.) Since 2005, the availability of automated inspection systems has improved.

Summarizing; the limitations of what is practical and feasible in outgoing inspection is heavily affecting all industry activities and efforts in the area of pixel defects.

5.5 Incoming inspection

Incoming inspection is performed by large companies, such as system integrators or distributors, when receiving displays from display manufacturers. The industry trend is to do only final random inspection or no incoming inspection at all. When the total number of samples to inspect is small, then laboratory methods, like ISO 13406-2 are used, especially in the desktop display industry. Large-scale inspection is almost entirely based on manual, visual inspection. The inspection is sometimes further simplified compared to outgoing inspection. For higher grade displays, the criteria in the inspection can be that the display is set aside if any type of defect is detectable within, for example, 15 s. Those displays set aside are separately analyzed by a quality team.

For special markets, 100 % incoming inspection can be made and the customer can even receive a pixel defect map (medical X-ray imaging).

6 Illustrations and descriptions of pixel defects

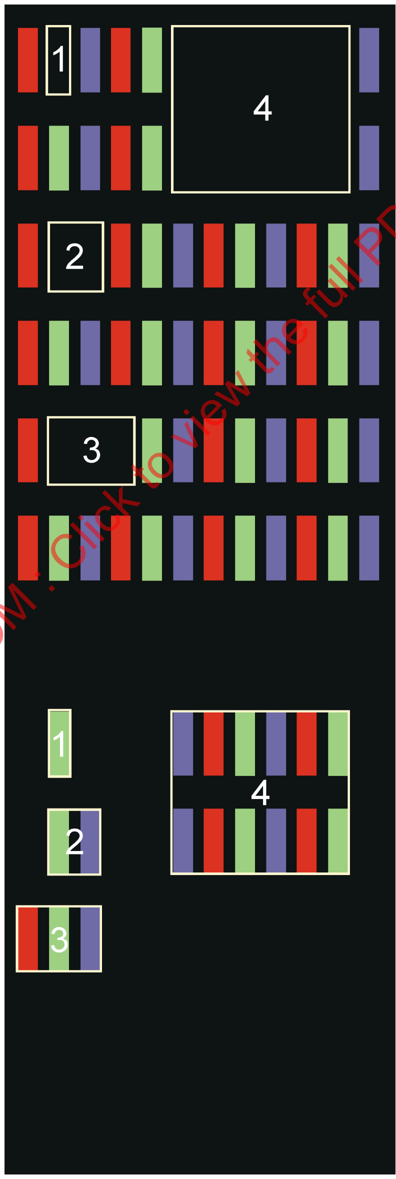


Figure 15 — Illustration of the difference in spatial dimensions of total pixel defect area in positive and negative polarity

The fill factor will impact the effective size. In negative polarity the effect will be cancelled by spatial summation. In positive polarity the effect can be significant for visibility threshold.

The size of a stuck on subpixel fault on a dark background is the “addressable size” of the subpixel times the “fill factor” of the subpixel. The size of a stuck off subpixel fault on a bright background is the “addressable size” of the subpixel divided by the “fill factor” of the subpixel.

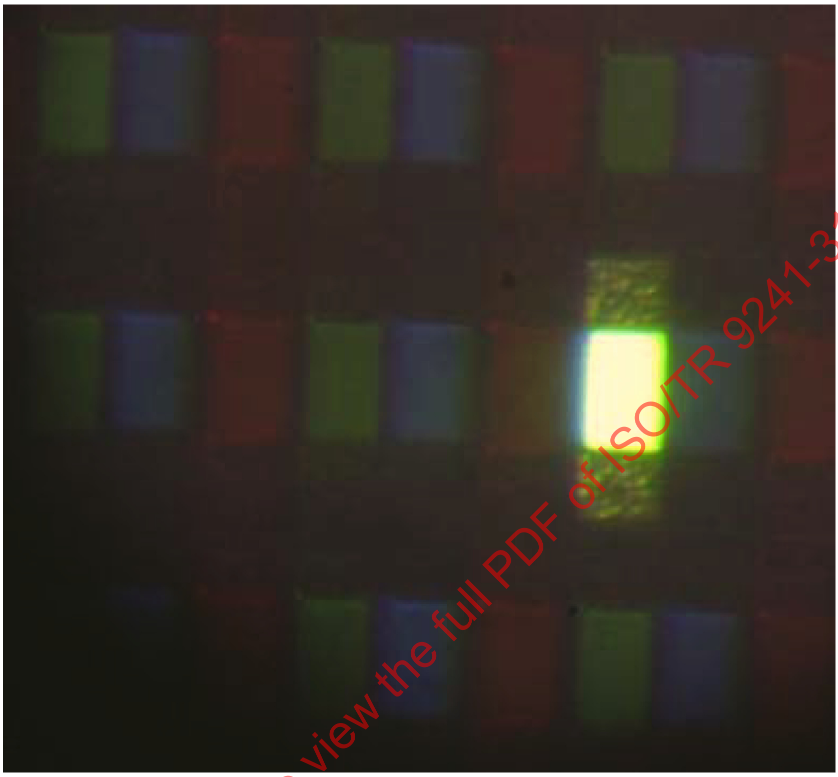


Figure 16 — Subpixel defect in a transflective LCD in dark

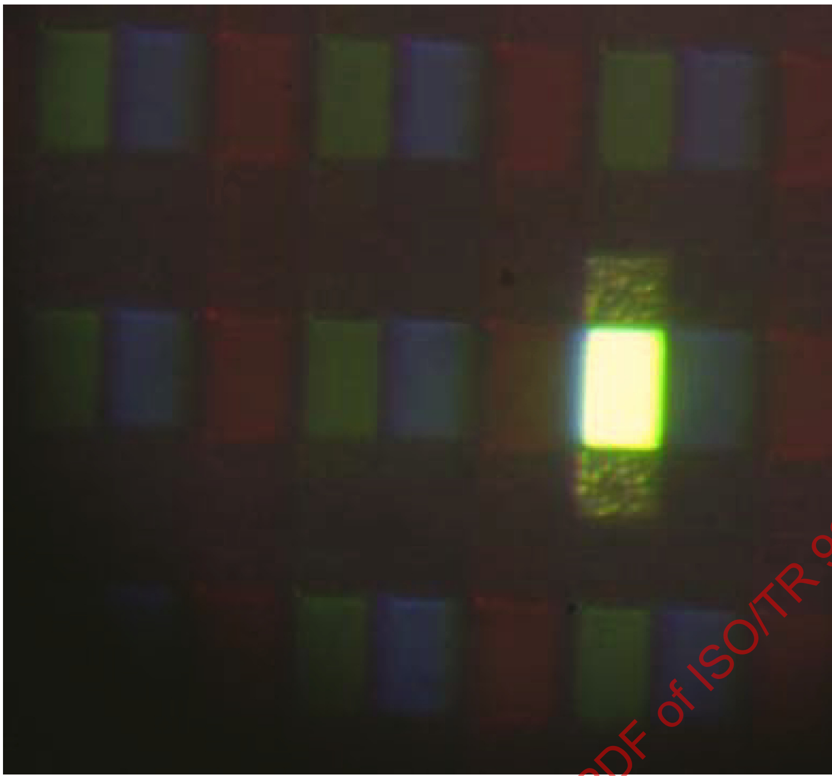


Figure 17 — Subpixel defect in a transflective LCD in ambient lighting

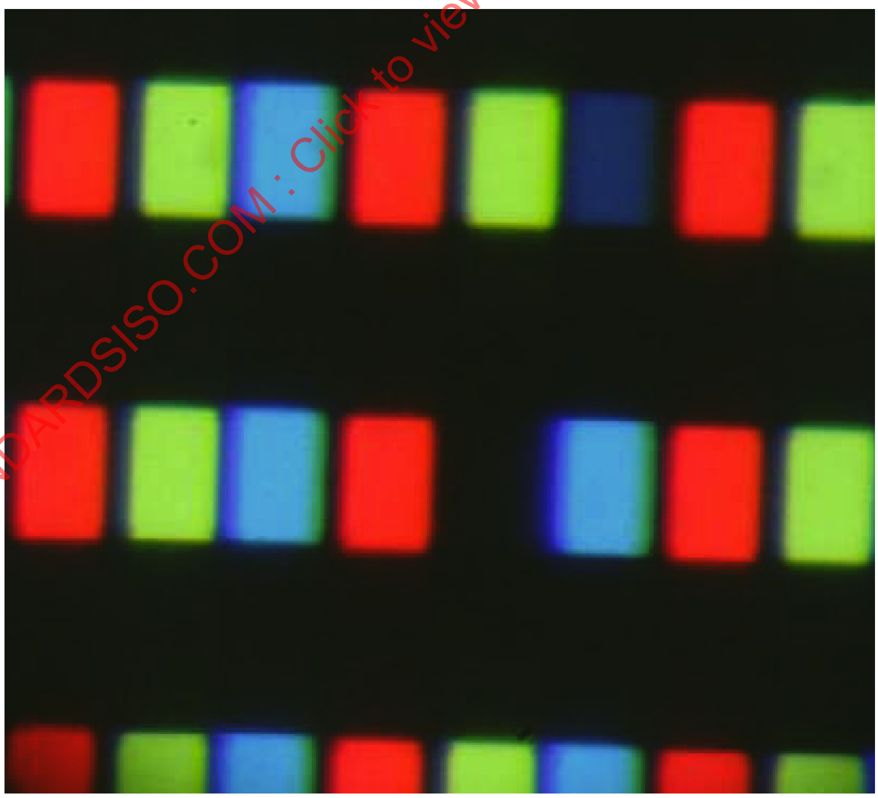


Figure 18 — Subpixel defect in a transflective LCD in dark

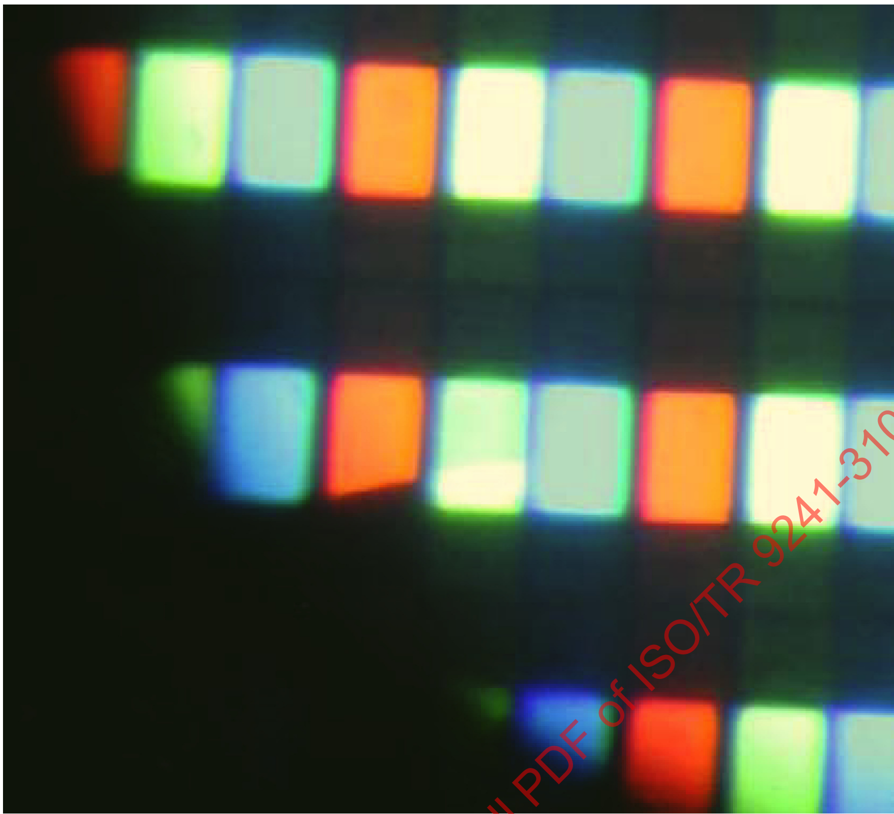


Figure 19 — Cluster of partial subpixel defects in a transflective LCD in dark, full white screen

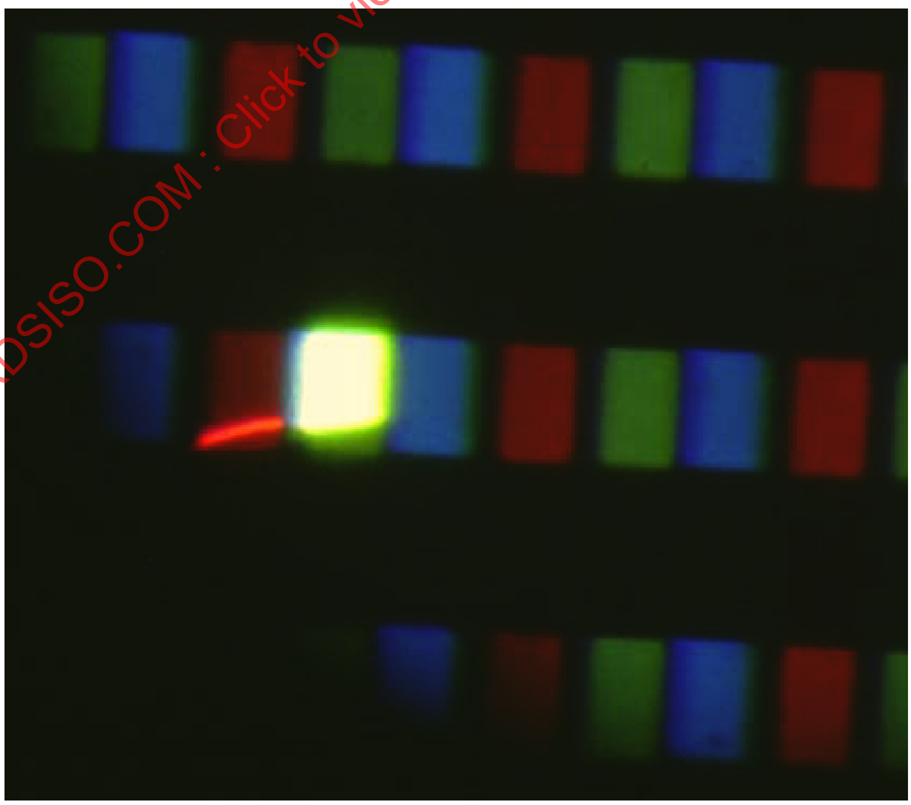


Figure 20 — Cluster of partial subpixel defects in a transflective LCD in dark, full black screen

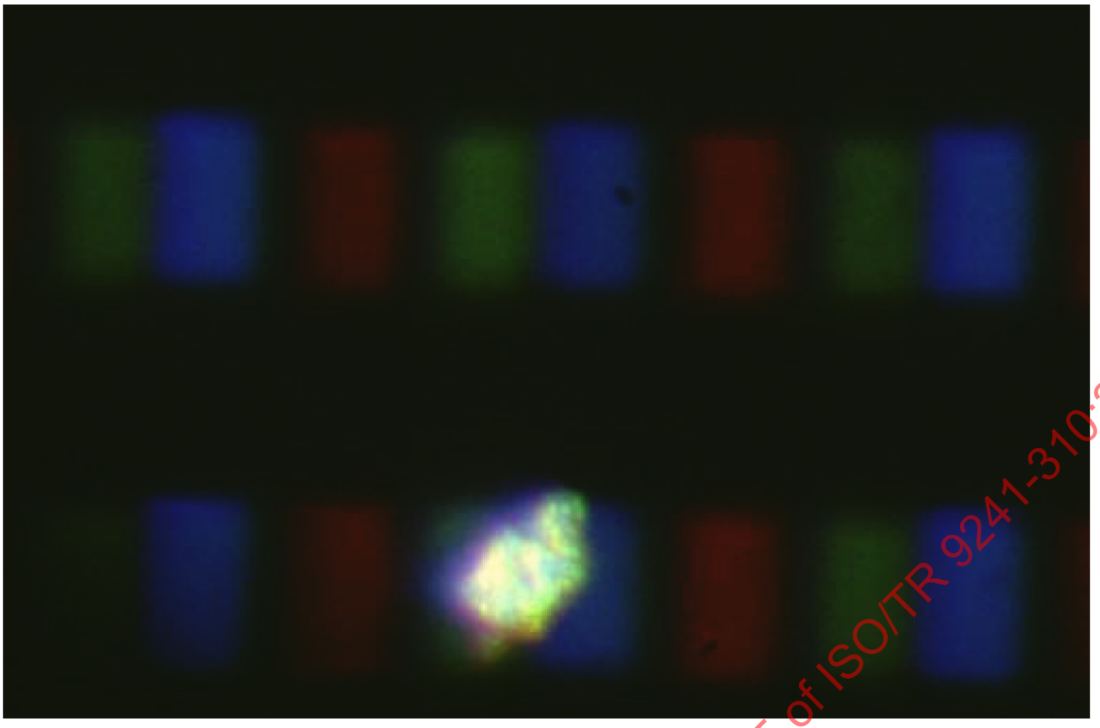


Figure 21 — Non-pixel-related defect in a transflective LCD

Annex A
(informative)

Overview of the ISO 9241 series

The annex presents an overview of the structure of ISO 9241. For an up-to-date overview of its structure, subject areas and the current status of both published and projected parts, please refer to:

ISO 9241 series

The structure reflects the numbering of the original ISO 9241 standard; for example, displays were originally Part 3 and are now the 300 series. In each section, the “hundred” is an introduction to the section; for example, Part 100 gives an introduction to the software-ergonomics parts.

Table A.1 — Structure of ISO 9241 — Ergonomics of human–system interaction

Part	Title
1	Introduction
2	Job design
11	Hardware and software usability
20	Accessibility and human–system interaction
21-99	Reserved numbers
100	Software ergonomics
200	Human–system interaction processes
300	Displays and display-related hardware
400	Physical input devices — Ergonomics principles
500	Workplace ergonomics
600	Environment ergonomics
700	Control rooms
900	Tactile and haptic interactions

Annex B
(informative)

Pixel defect industry and market status 2005

The current quality level of pixel defects is dependent on market segment and technology. This annex briefly describes the currently available quality level expressed in the terms used in the ISO 9241-300 series of standards.

In the medical display market, the displays are mostly class 0, but also class I can be found. Class 0 displays are based on 100 % screening of manufacturing.

In the consumer TV market, class I is most common. Individual products can be class 0 too but manufacturers do not usually guarantee class 0.

In the computer display market, classes I and II are most common. The smaller the pixel size is, the more likely it is that the market accepts a less good class. This is natural since the ISO 9241 definition is not perfectly linked to pixel defect visibility. Individual products can be class 0 too but manufacturers do not guarantee class 0.

In the mobile device display market classes I and II are most common. Since the user interfaces are more static than in computer and consumer TV markets, there are areas of the screen where pixel defects are more acceptable than in other areas.

In the industrial markets, classes 0, I, II and III can be found, depending on the specific needs and requirements of the task.

For new technologies, all classes (0 to IV) can be found. For new technologies, that do not fit so well into the definitions of ISO 9241, a display might formally get a bad class rating but might appear better, and vice versa. In such cases, the class rating is not useful for quality judgement. In other cases the class rating can be bad, and appear bad, but the product might still be acceptable on the market, since the technology might enable a new type of task or device interaction, which is not possible with conventional display technologies. In such situations users tend to accept a less good pixel defect quality rating.

Annex C
(informative)

A draft of a model for acceptable pixel level

C.1 General

The relevant ISO working group has not reached full consensus about modelling the acceptable pixel level. The working group decided to include both proposed models as an annex.

There is insufficient proof for any of the proposed generic simple numeric correlations between number of acceptable pixel defects and size of display. On the contrary, the data shows that standard visual contrast models accurately predict how the number of average acceptable pixel defects changes as a function of contrast and defect size. There seems to be a strong relationship between average number of acceptable pixel defects and the ratio between defects contrast and threshold contrast for visibility.

Contrast is being defined as the percent contrast between the luminance of the defect and the local average luminance.

C.2 First model based on data by Hisatake et al

For the purpose of amending ISO 9241-307, the following model was developed and was proposed to replace note 7 of that standard. Maximum number of faults is calculated as follows:

a) For displays > 9,1" (23,1 cm): maximum number of faults per type per million pixels.

b) For displays ≤ 9,1" (23,1 cm) with > 250 000 pixels: maximum number of faults per type per 250 000 pixels.

c) For displays ≤ 9,1" (23,1 cm) with ≤ 250 000 pixels: maximum number of faults per display.

C.3 Second model based on data by Hisatake et al

C.3.1 General

The best available research data is the Hisatake et al results reported at SID 2005 [13]. The full data is stored by the secretariat of ISO/TC 159/SC 4/WG 2 Visual display requirements and is available for future research.

When these data are analyzed, the relationship is very strong and independent of the size of the display, the viewing distance etc. The contrast-to-threshold-contrast-ratio explains all variation, as long as the same test image is compared.

In the Hisatake et al [13] data, there is an additional variation between test images, a "shift leftwards in a log-log-plot of the data.

This left-right-shift seems to depend on the screen content and can either depend on the masking effect caused by the content or be caused by the fact that the actual local average luminance values were not recorded, but predicted.

The shift might also be caused by limitations of the Swinkels et al [11] equation.

Further study of the Hisatake et al data can possibly provide an explanation of this other correlation.

At this point, a general formula can be presented for the average acceptable number of pixel defects:

$$N = a \cdot R^{-b}$$

where

N is the average number of acceptable pixel defects

R is the ratio between pixel defect contrast and visibility threshold contrast (calculated with the Swinkels et al equation)

a is a constant with a value of approximately 2000 to 20 000 depending on the content or depending on the local average luminance (see above)

b is a constant with a value of approximately 2.4 to 2.8

At this stage, with the aid of the Hisatake data, the general equation is already useful for manufacturers, consumer organizations and test houses.

It is, however, important to compare the general equation with data from other research in order to validate the range of values for constants a and b.

C.3.2 Earlier data from Hisatake et al

Hisatake et al made a prestudy which was less rigorously controlled but had some test cases which were excluded from the final study. From the pre study, the extreme values (not only the average values) are also known.

The earlier data from Hisatake et at thus shows more variation, but supports the same type of correlation as found in the final study by Hisatake et al. This also illustrates the need for careful control of any experiment related to pixel defect acceptability.

C.3.3 Test images used by Hisatake and Lee

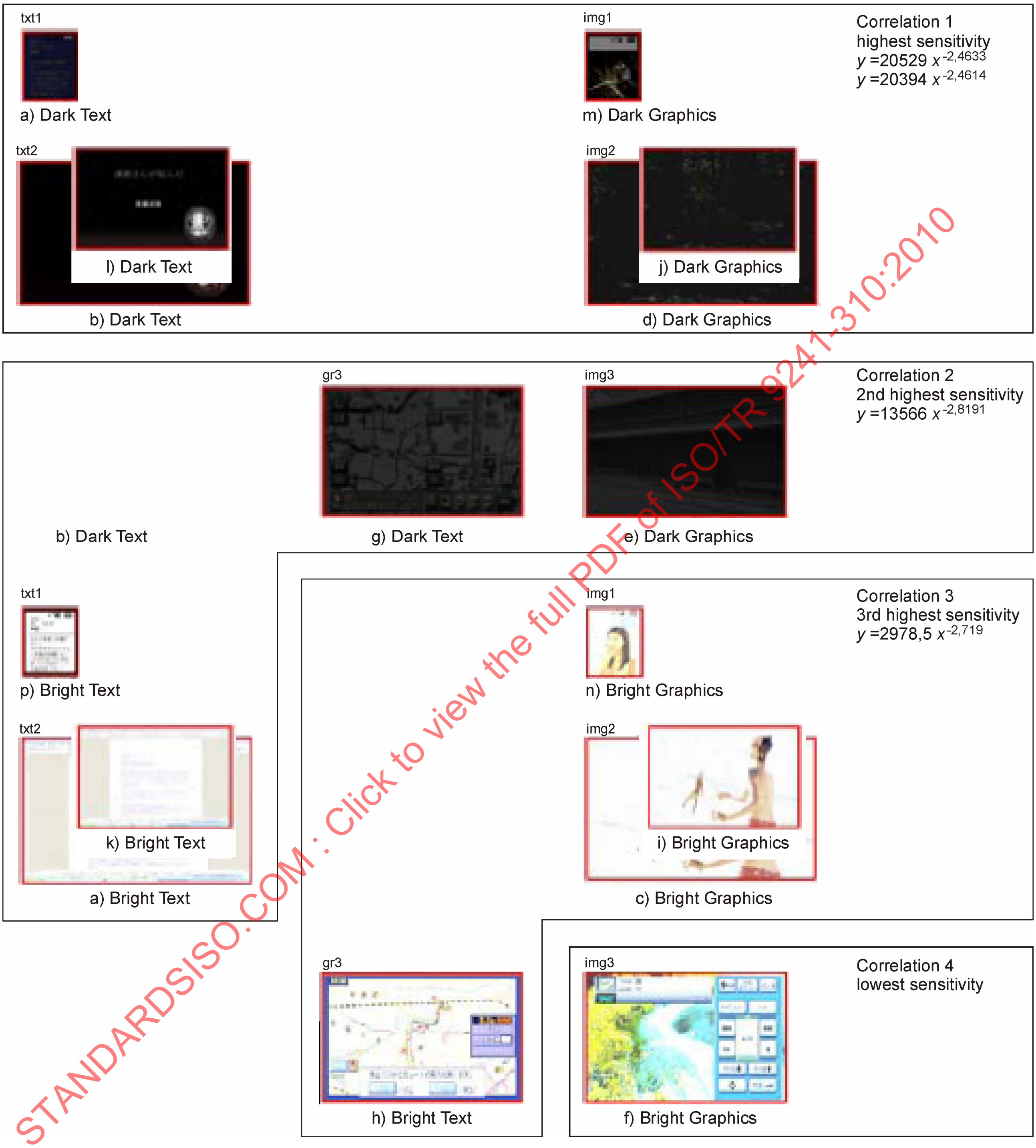
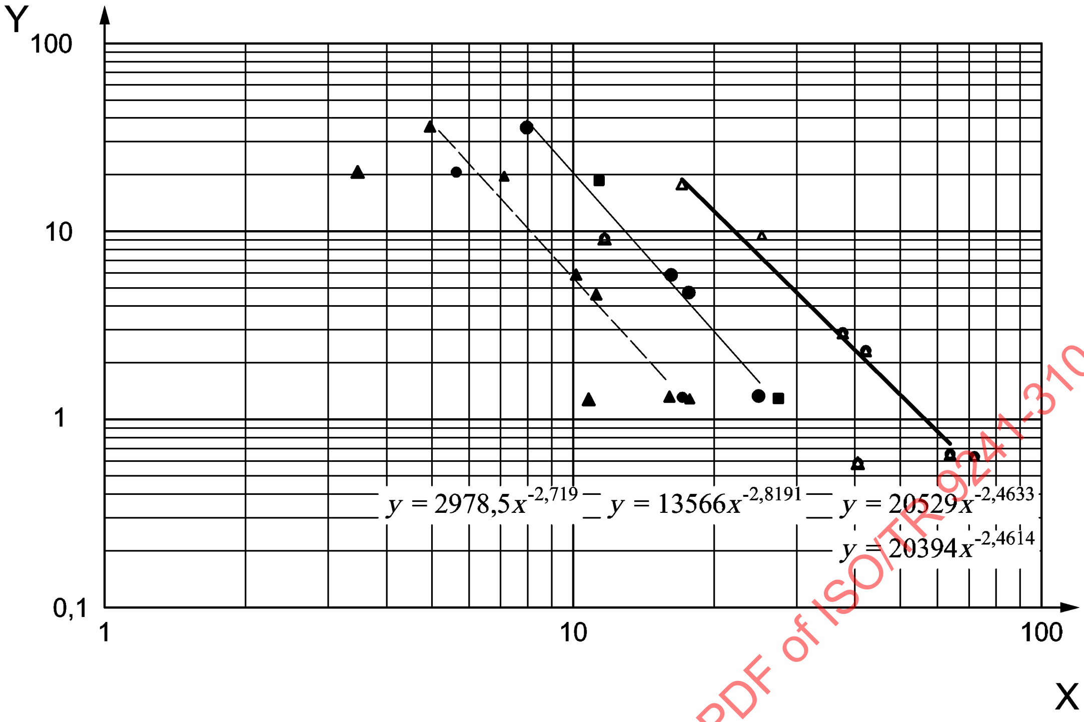


Figure C.1

C.3.4 Analysis of the Hisatake and Lee data



Key

X ratio contrast to threshold contrast

Y number of pixel defects

△ img3

△ img2

△ img1

□ gr1

○ txt2

○ txt1

▲ img3

▲ img2

▲ img1

■ gr1

● txt2

● txt1

—— Power (txt2)

– – Power (img2)

—— Power (txt2)

—— Power (img2)

Figure C.2 — Analysis of data from Hisatake et al (SID 2005)

