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TECHNICAL REPORT

Electronic paper displays –
Part 5-1: Legibility of EPD in spatial frequency

colour inside

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CONTENTS

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ELECTRONIC PAPER DISPLAYS –

Part 5-1: Legibility of EPD in spatial frequency

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 62679-5-1, which is a technical report, has been prepared by IEC technical committee 110: Electronic display devices.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
110/836/DTR	110/864A/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62679 series, published under the general title *Electronic paper displays*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

A small device for an electronic paper display (EPD)[1] [1] was invented in 1997, and its first product as an electronic book was brought to the market in 2004. This product was the first electronic display which made human beings serious about reading letters and figures as well as those printed on a paper with ink. A definition of “electronic paper” was first given by N. K. Sheridon et al of PARC in 1998, as follows: Plane paper scatters light diffusely and efficiently, allowing for high contrast, high resolution images that can be viewed from broad angles without glare caused by specular reflection, in contrast, electronic display media can provide the extra benefits of reusability and easy integration into digital electronic systems. Electronic display media used in such a fashion can be called “electronic paper” [2]. For these reasons, the benchmark for estimation of EPD has always been printed paper.

The human action of reading is basically analysed through two subjective attributes, that is, legibility and readability. The legibility, as defined at 3.1.2, can be rated and analyzed by means of measuring optophysical or radiometric property of a certain pattern. This pattern is recognised by the retina as an aggregation of spatial frequencies. Legibility can be understood by analysing those kinds of spatial frequency. In 1967, the contrast sensitivity of the human eye for sinusoidal illuminance changes was measured as a function of spatial frequency [3]. As for readability, defined in 3.1.3, lot of human ergonomics tests and sophisticated statistical works are recommended with around a hundred human participants, to compare with printed paper, EPDs, and emissive displays; which will also require economical costs and expenditure of time. The readability of EPDs will be reported elsewhere.

IEC 62679 (all parts) specifies optical measuring methods for electronic paper displays (EPDs), but does not mention legibility and readability for EPDs, because there are no guidelines for measuring and estimating these elements in a practical fashion, especially under variation of optical environments.

This document offers permanent formulae to decide on the legibility level of EPD compared with paper, which will lead to specification of EPD with regard to the human action of reading. Legibility is one of the human actions of reading, which falls in the category of subjective assessments; on the other hand, the properties of EPDs fall in that of physical specifications, that is, objective assessments. The legibility in this document described by using a five-level rating system is revealed to show as a function of physical parameters.

In this document, legibility is suggested as having two essential parameters, that is, the spatial frequency, which can represent the complexity or size of a letter, font, or symbol, and the contrast, which shows brightness between a character and its background.

1 Numbers in square brackets refer to the Bibliography.

ELECTRONIC PAPER DISPLAYS –

Part 5-1: Legibility of EPD in spatial frequency

1 Scope

This part of IEC 62679, which is a technical report, specifies the legibility in terms of contrast, spatial frequency, and reflection of the screen as a function of the physical parameters of an EPD. This legibility evaluation model is introduced through both subjective and objective assessments. The scope of this document is restricted to EPDs using segment, passive, and active matrixes with monochromatic type displays.

2 References

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply [16].

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/ [4]
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
contrast sensitivity test chart [5,6]
CSC
chart for measuring and quantifying visual sensitivity in terms of contrast sensitivity and spatial frequency response, which contains a multiplicity of grating patches whose contrast, in term of luminance, varies sinusoidally for differing spatial frequencies

Note 1 to entry CSC is sometimes used for diagnosis in ophthalmology clinics.

3.1.2
legibility
ability for unambiguous identification of single characters or symbols that may be presented in a non-contextual format

[SOURCE: ISO 9241-302:2008, 3.3.35] [7]

3.1.3
readability
characteristics of a text presentation on a display that affect performance when groups of characters are to be easily discriminated, recognized and interpreted

[SOURCE: ISO 9241-302:2008, 3.3.38] [7]

3.1.4
multiple regression analysis [8]
analysis technique for composing a prediction formula which is easily and precisely calculated by making multiple selections for variables

3.1.5
spatial frequency
component of an image transferred by Fourier transform

[SOURCE: ISO 9241-302: 2008, 3.5.48, modified – the note has been removed.] [7]

3.2 Abbreviated terms

CCD charge-coupled device

CSC contrast sensitivity test chart

CSF contrast sensitivity function

EPD electronic paper display

IR infrared

SEP standard error of prediction

4 Contrast sensitivity test chart (CSC)

CSC is mostly used in ophthalmologic diagnoses, to evaluate the progression of cataract or glaucoma [9 to 11]. There was a US patent to define generalized visual sensitivity, but this idea has been already in the public domain [5, 6].

CSC consists of a multiplicity of grating patches whose contrast, in terms of luminance, varies sinusoidally for differing spatial frequencies. These patches, in this document, were printed by offset printing with a black ink on several kinds of papers. The CSC consists of thirty types of sinusoidal grating, based on six levels of spatial frequency (1, 2, 4, 8, 16, 32) cycles per degree and five levels of contrast (3,8, 7,5, 15, 30, 60) % defined in Formula (1). These contrasts are Michelson contrast. The spatial frequency is defined as the number of cycles per unit viewing angle. The measure of contrast in this document follows Formula (1).

These combinations of patches are shown schematically in Figure 1. The dimensions of the patches are a square 76 mm on a side. These kinds of patches are printed simultaneously in the order given in Table 1, on a paper with dimensions of 610 mm x 920 mm.

The properties of the papers for printing are shown in Table 1 [12, 13]. These kinds of paper are widely used for books, paperbacks, magazines, and calendars (or posters) which will satisfy adequately any case of the human action of reading. This means there has been no standardized paper before for both legibility and readability testing. In Table 1, the specular gloss is given by ISO 8254-1 [19], and the ISO brightness is described in ISO 2470-1 [20] for paper.

Contrast m (also known as the Michelson contrast, which relates to visual stimuli) is defined in Formula (1) and shown in Figure 2:

$$\mathrm{m}(\%) = \frac{Lmax - Lmin}{Lmax + Lmin} \times 100 \quad m(\%) = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \times 100 \qquad (1)$$

where $L_{\max}$ and $L_{\min}$ are the maximum luminance and minimum luminance of a sinusoidal pattern on a patch, respectively.

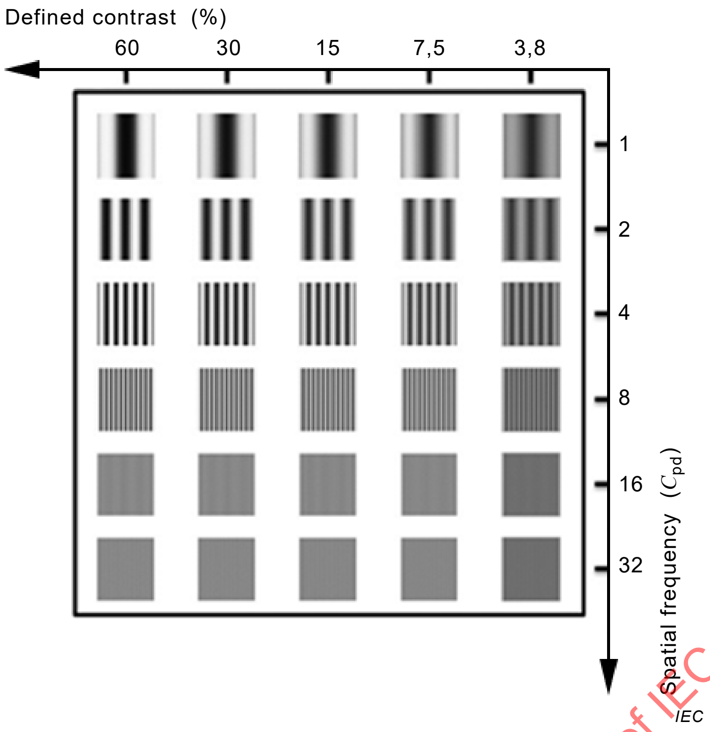


Figure 1 – Layout of patches

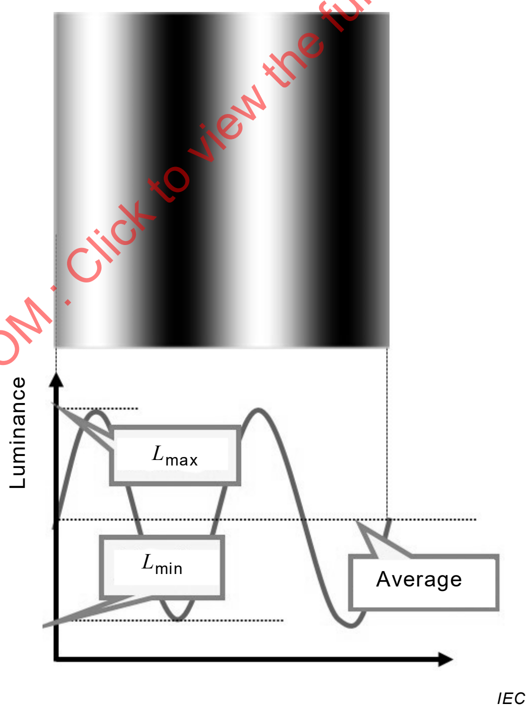


Figure 2 – Example of patch of CSC

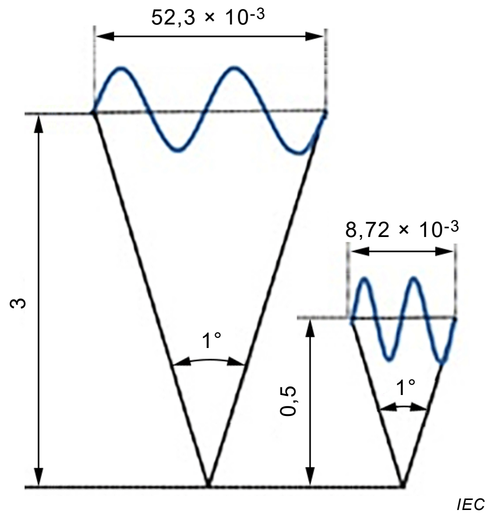


Figure 3 – Spatial frequency per unit viewing angle

Spatial frequency is defined as the number of cycles per unit viewing angle. Even though the spatial frequency is the same, the wavelength varies with the viewing distance (as shown in Figure 3). The expression of the relation is represented by Formula (8).

Table 1 – Properties of five kinds of paper

samples	Sample A	Sample B	Sample C	Sample D	Sample E
Typical application	Book	Book	Book	Magazine	Calendar
Specular gloss (%)	7	19	19	59	70
ISO brightness (%)	67,3	77,3	83,5	83,2	83,8

5 Objective assessment

5.1 General

A photometric measurement system is described below. Microscopic goniophotometry assumes an important role for quantifying a visual sense [14 to 17] by scanning the printed sinusoidal gratings. The goniophometric system was constructed to measure the distribution of the reflective intensity as shown in Figure 4.

This experimental apparatus consists of three movable parts:

a) The size of a sample holder is 76 mm × 76 mm. Each sample was fixated using two magnetic plates that were fixed to the sample holder.

b) The light source was connected to a diffused light source where the light was guided by optical fibres to the flat panel, scattered in the flat panel, and emitted diversely from the surface. The incident angle was defined as the angle formed by the light source's optical axis and the direction perpendicular to the sample holder.

c) The photometric unit consists of a focus lens and a charge-coupled device (CCD) camera that is equipped with a sensor array and a personal computer. The CCD camera (monochrome, with and image size of 35 mm × 20 mm) was calibrated using the grey-scale chart. An optical filter which can cut IR is necessary. Images were acquired using a personal computer that had a built-in image capture board, and they were quantized to an 8-bit grey scale (256 grey levels). The photometric angle was defined as the angle formed between the CCD camera's optical axis and the direction perpendicular to the sample holder.

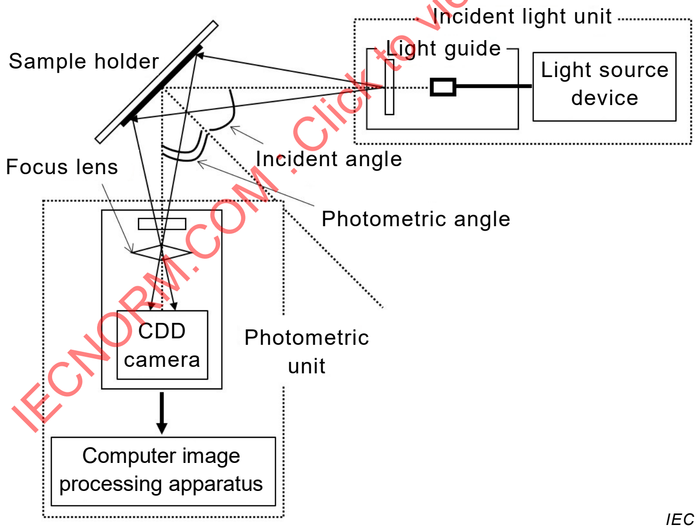
The recommended specifications on the apparatus are as follows:

1) Light source: according to a standard light source such as D65 [18].
2) Reflected region: to be illuminated more widely than 76 mm × 76 mm. Less than 3 % variation of the illuminance (non-uniformity) is necessary.
3) Spatial resolution: more than 640 pixels x 480 pixels.
4) Gradation resolution: more than 8-bit grey scale (256 grey levels).
5) Correlation coefficient among the datasets of the grey level and that of luminance (linearity): over 0,99 with more than 11 different datasets.

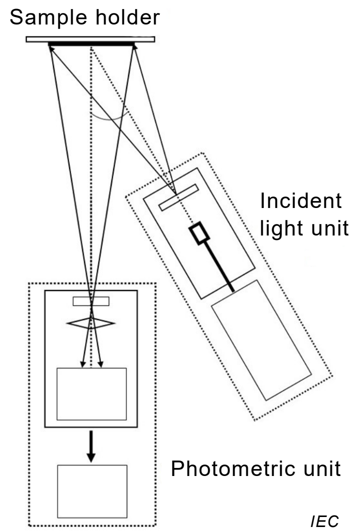
5.2 Conditions of objective assessment

The measuring conditions are as follows:

– measurement objects:	30 patches of a 76-mm square, measured separately
– number of repeated measurements	5
– camera image size:	35 mm x 20 mm (640 pixels x 480 pixels)
– vertical illuminance:	300 lx (see Figure 4b); the illuminance is measured in the normal direction to the surface of objects.)
– incident angle:	30°
– photometric angle:	0°



a) Schematic structure



b) Actual geometric structure

Figure 4 – Measuring apparatus geometry

5.3 Photometric characteristics for CSC

Ten photometric parameters representing the morphological characteristics of the luminance distribution component were obtained, as defined below (see Figure 5) [19].

1) Peak luminance (L_{max})

L_{max} is defined in Formula (2), where $L(y)$ represents the luminance of the pixel with local coordinates y, y_{max} represents the local coordinates of the pixel with the largest luminance, M represents the total number of pixels used to sample one period of the luminance distribution component, i represents the number of pixels and N_{max} represents the number of maxima.

$$L_{max} = \frac{\sum_{i=1}^{M} L(y_{max})}{N_{max}} \text{ (cd/m}^2\text{)} \tag{2}$$

2) Trough luminance (L_{min})

L_{min} is defined in Formula (3), where $L(y)$ represents the luminance of the pixel with local coordinates y, y_{min} represents the local coordinates of the pixel with the smallest luminance, M represents the total number of pixels in the luminance distribution component, i represents the number of pixels and N_{min} represents the number of minima.

$$L_{min} = \frac{\sum_{i-1}^{M} L(y_{min})}{N_{min}} \text{ (cd/m}^2\text{)} \tag{3}$$

3) Average luminance (L_{ave})

L_{ave} is defined in Formula (4) by means of L_{max} and L_{min}.

$$L_{ave} = \frac{L_{max} + L_{min}}{2} \text{ (cd/m}^2\text{)} \tag{4}$$

4) Michelson contrast (L_{con})

L_{con} is defined in Formula (5) by means of L_{max} and L_{min}.

NOTE It is distinguished from the design contrast in the contrast sensitivity chart.

$$L_{con} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \tag{5}$$

5) Depth (LD)

LD represents the luminance modulation and is defined in Formula (6) by means of L_{max} and L_{min}.

$$LD = L_{max} - L_{min} \text{ (cd/m}^2\text{)} \tag{6}$$

6) Width (Wid)

Wid is defined in Formula (7), where LT (length) represents the number of pixels between adjacent maxima, and P (pitch) represents the distance per unit pixel which is defined by the measurement distance.

$$Wid = LT \times P \text{ (mm)} \tag{7}$$

7) Spatial frequency (C_{pd})

C_{pd} is the number of cycles of the luminance distribution component per unit viewing angle (degree) and D is the distance. It is defined by Formula (8).

$$C_{pd} = \frac{D \times 2}{Wid} \tan(1/2) \text{ (cycles per unit viewing angle)} \quad (8)$$

8) Full width at half *LD* (*HW*)

HW is the distance between the adjacent L_{ave}. It is defined in Formula (9), where $y(L)$ represents the local coordinates' y pixel (however $y_2 > y_1$).

$$HW = \{y_2(L_{1/2LD}) - y_1(L_{1/2LD})\} \times P \text{ (mm)} \quad (9)$$

9) Slope (*S*)

S is the slope from the trough height to the peak height of the luminance. It is defined by Formula (10) (see Figure 5).

$$S = \frac{LD}{Wid/2 \times P} \text{ (cd/m}^2\text{/mm)} \quad (10)$$

10) Luminance coefficient (ρ)

ρ is defined in Formula (11), where L_p represents the luminance of displays (including printed paper) and E represents the illuminance on the sample vertical plane.

$$\rho = \frac{L_p}{E} \text{ (cd/lm)} \quad (11)$$

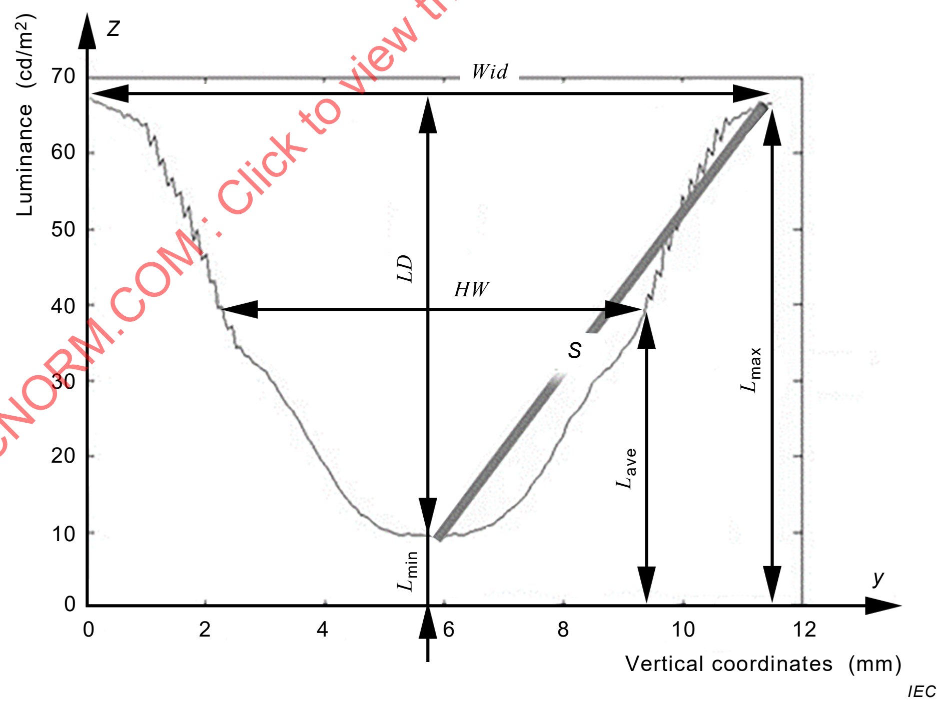


Figure 5 – Luminance distribution components

6 Subjective assessment

6.1 Conditions of subjective assessment

The subjective assessment for legibility is done under the following conditions:

a) Ambient lighting: 70 lx, uniform light source: D65

This lighting condition is identical to that of the ophthalmologic diagnosis using CSC.

b) Distance:

Different observation distances were observed for two different applications: book reading (model A) and signage (model B). These are defined as follows:

– Model A:

Distance between CSC and examinee: 500 mm

Size of patch: 76 mm x 76 mm

CSC includes 30 patches

– Model B:

Distance between CSC and examinee: 3 000 mm

Size of patch: 76 mm x 7 6mm

CSC includes 30 patches

c) Examinee classification:

1) number of examinees: 20
2) Demographic definition: students
3) Gender of the examinees: male

Visual acuity of the examinees was 0,6 to 1,4

d) Rating scales and points: invisible (1pt), almost invisible (2pt), somewhat visible (3pt), visible (4pt), and clearly visible (5pt)

An examination environment is shown schematically in Figure 6.

Dimensions in millimetres

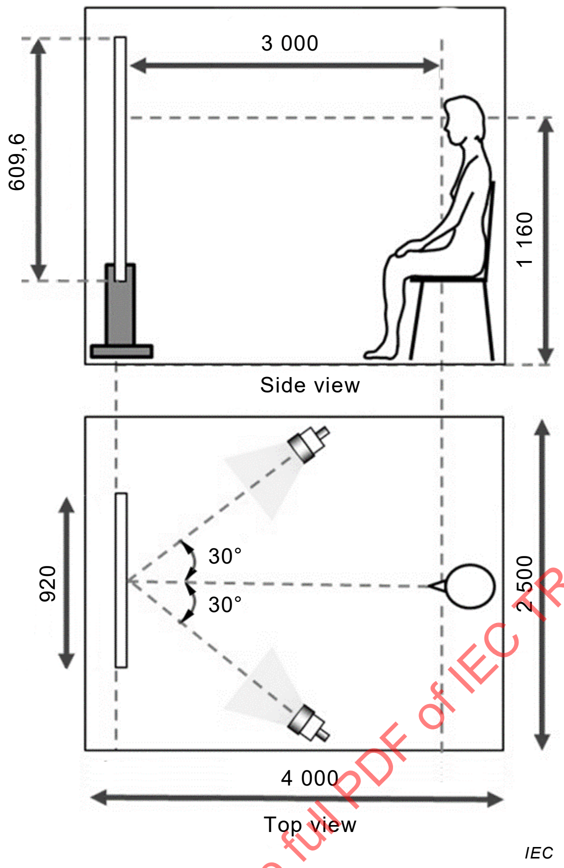


Figure 6 – Examination environment

The incident light angle of 30° was determined by limitation of the measuring chamber as shown in Figure 6.

6.2 Result of sensory evaluation

Figure 7 shows one of the results of a sensory evaluation session. The points shown in the matrix are the averages of twenty examinees whose visual acuity was in a range of 0,6 to 1,4.

The evaluators thus assessed five kinds of paper, which were each printed with thirty kinds of CSC, and categorized them as: 1pt: invisible; 2pt: almost invisible; 3pt: somewhat visible; 4pt: visible; 5pt: clearly visible.

Spatial frequency (C_{pd}) \ Defined contrast (%)	60	30	15	7,5	3,8
1	4,3	3,5	2,5	1,6	1,3
2	4,8	4,6	3,6	2,4	1,5
4	5,0	4,6	3,6	2,9	1,5
8	4,7	4,3	3,0	2,2	1,3
16	4,0	3,0	2,3	1,5	1,2
32	1,9	1,3	1,2	1,2	1,0

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Figure 7 – Result of sensory evaluation

7 Creating a legibility evaluation model

7.1 Multiple regression analysis

The main purpose of this study is to determine a formula that predicts performance. Hence the dependent variable was the mean rating score for the degree of legibility for all the samples. The independent variables were the ten photometric parameters. The variable selection was conducted with a stepwise forward regression consisting of a forward selection method with the possibility of excluding a previously selected variable.

7.2 Results of multiple regression analysis

1) Regression model A (viewing distance 500 mm)

The regression model A for the prediction of the degree of legibility is defined as shown by Formula (14), where VL is the mean rating score of the degree of legibility, L_{con} is the contrast, and C_{pd} is the spatial frequency.

$$VL = 1{,}51 \times \log (L_{con}) - 0{,}11 \times C_{pd} + 5{,}3 \quad (14)$$

The formula was statistically significant at the $p < 0{,}01$ level, and the coefficient of correlation R^2 was 0,94.

Formula (14), that is, model A, is useful for evaluating a tangible EPD.

2) Regression model B (viewing distance 3 000 mm)

The regression model B for the prediction of the degree of legibility was defined as shown by Formula (15), where VL is the mean rating score of the degree of legibility, L_{con} is the contrast, C_{pd} is the spatial frequency, and ρ represents the luminance coefficient of the paper. The relationship between the experimental scores for the degree of legibility and the scores predicted by Formula (15) are shown in Figure 7. The formula was statistically significant at the $p < 0{,}01$ level, and the coefficient of correlation R^2 was 0,84.

$$VL = 2{,}06 \times \log(L_{con}) - 0{,}073 \times C_{pd} + 13{,}6 \times \rho + 3{,}03 \quad (15)$$

7.3 Demonstration experiment

It should be experimentally verified how applicable the above two regression model for commercial electronic paper displays (EPDs) [20] are. Three types of EPD used for verification are shown in Table 2.

Sixteen types of CSC patches were selected for each EPD in the form of a portable document format [21]. Both objective assessment and subjective assessment were done by the same method described in Clauses 5 and 6. These experimental results are shown in Figure 8. A statistically significant result was a p < 0,01 level, a correlation coefficient of r^2 = 0,89, and SEP was less than the 1° of legibility.

Table 2 – EPDs for verification

Sample	EPD1	EPD2	EPD-HR
Vendor	A	B	B
Resolution (ppi)	167	167	212
NOTE ppi means pixels per inch.			

These results suggest that this kind of regression model for the prediction of the degree of legibility can be applicable to EPDs as well as paper.

NOTE Levels are not decided solely by the resolution of the EPD.

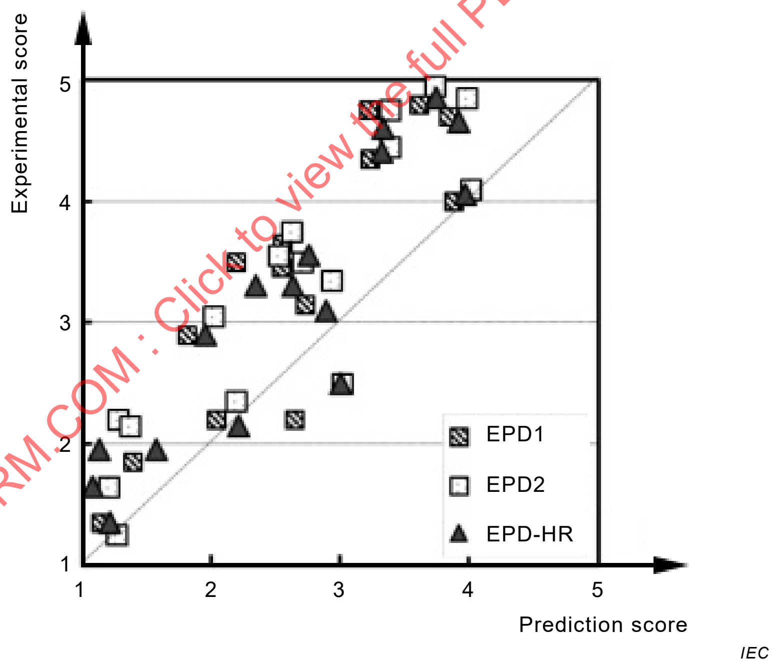

Figure 8 – Experimental score versus prediction score (VL) of EPD

The moire image of particular concern for the sinusoidal patterns displayed on the EPD screen was not observed because the sinusoidal patterns were inclined (or tilted) at an angle of 5° to 15° to the axis of the screen and constantly compared to the original sinusoidal pattern.

7.4 Conclusion

Both regression models A and B are expected to be practical. In the case of reading an EPD such as a book or magazine, the discriminant model A should be applied to estimate its legibility; on the other hand, in the case of viewing the EPD as a digital signage, the discriminant model B can be applied to its estimation.

All that is needed is to measure the optical properties, that is, L_{con}, C_{pd} and ρ of spatial frequencies on the screen of an EPD, to get a legibility level by using the grading system from invisible to clearly visible for a spatial frequency (that is, a sine wave pattern). In future work, the experimental methodology described in this document could be applied to character analysis with spatial frequency and its amplitude, and the character properties indicated by that kind of EPD could be derived.

These models show a close correlation between the legibility levels and the specifications of the EPD.

It is important to note that this technological potential should have a broad-based helpful impact for the engineers and scientists engaged in EPD development. This technological result that will help also the business leaders and policy-makers develop appropriate market strategies and responses, may bring them new customers or force them to redefine their existing bases or inspire them to invent new strategies in the field of EPD business.