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TECHNICAL REPORT

colour inside

Electronic displays –
Part 5-2: Visual assessment – Colour discrimination according to viewing direction

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The text of this Technical Report is based on the following documents:

Draft	Report on voting
110/1227/DTR	110/1251A/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62977 series, published under the general title *Electronic displays*, can be found on the IEC website.

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- withdrawn,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

This publication contains attached files in the form of compressed Zip files (“Pattern generator” program in Annex C). These files are intended to be used as a complement and do not form an integral part of the publication.

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INTRODUCTION

Current display measurement standards use mainly simple patterns for physical measurement methods to characterize display performance. Recent studies have introduced multiple colour test patterns to simulate real images based on physical measurements. Such types of physical measurements are commonly used and are an essential method of the industry. Often, humans can perceive a structural similarity [1][1] as much as physical factors (colour, luminance, etc.). This document describes a method of structural sensitivity assessment dependent on the viewing direction, interpretation of assessment results, and correlation between assessment results and physical measurements. This correlation value can be used as the basis for determining one aspect of the viewing direction range of a display, which has relevance from a visual quality point of view. However, it should be noted that several characteristics (e.g. contrast ratio, resolution, and colour shift) are simultaneously changing in the assessment of the viewing direction.

This visual assessment approach has the benefit of obtaining direct human response to variations for any given task. However, it can be challenging with this approach to get reproducible experimental results due to different colour matching functions (CMFs), differences in observer experience, observer fatigue, attitudes toward experiments, human adaptation to different experimental environments (including illumination conditions, surround, or other environmental factors), content-dependent differences, and other variables. Therefore, the uncertainty for these visual assessment methods can be higher compared to instrumentation-based evaluation methods. Accordingly, this document should be seen as a limited constrained model to help understand some of the various human responses to the experiment. It can be used as an indicator of such response and to provide a framework to guide the acquisition of performance data by way of reliable instrumentation-based measurement methods.

1 Numbers in square brackets refer to the Bibliography.

ELECTRONIC DISPLAYS –

Part 5-2: Visual assessment – Colour discrimination according to viewing direction

1 Scope

This part of IEC 62977, which is a Technical Report, describes the visual assessment method of the viewing direction characteristics of display devices. This document reviews the visual assessment of viewing direction by using special test patterns to estimate colour changes, image structure, and image luminance.

Experimental results are shown to reveal the effectiveness of this kind of visual assessment.

This method is a valuable tool for identifying image quality issues, but physical measurements will be used to confirm display performance specifications.

NOTE The visual assessment results will depend on the test pattern parameters and display setup conditions. As the viewing direction changes, characteristics such as contrast ratio, resolution, and device colour-shift simultaneously change in the perceived image.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

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

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

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

3.1 Terms and definitions

3.1.1
pixel
smallest encoded picture element in the input image

Note 1 to entry: Pixel is used as the unit of resolution of image sensor, image signal and display, respectively.

3.1.2
structural similarity
SS
measurement of the similarity between two images by comparison of the luminance, contrast and structure

Note 1 to entry: Refer to [1].

3.1.3
viewing direction
direction from which the display is viewed as measured from the normal using spherical-polar coordinates

3.2 Abbreviated terms

APL	Average picture level
CCT	Correlated colour temperature
CIE	Commission Internationale de L'Eclairage (International Commission on Ilumination)
CIELAB	CIE 1976 ($L^*a^*b^*$) colour space [2]
CMF	Colour matching function
CSF	Contrast sensitivity function
DFT	Discrete Fourier transform
DUT	Device under test
FF	Fill factor (of a dot)
HVS	Human visual system
JND	Just noticeable difference
LMD	Light measuring device
MSE	Mean squared error
PSNR	Peak-signal-to-noise ratio
SS	Structural similarity
TV	Television set
ZF	Zooming factor
$\Delta E^*_{\mathrm{ab},76}$	CIE 1976 ($L^*a^*b^*$) colour difference
ΔE^*_{00}	CIE 2000 colour difference [3]

4 Introduction to visual assessment

Traditional physical measurements to describe the properties of displays have been used on a regular basis. Sometimes, visual assessment methods have been introduced due to cost concerns, limitations of physical measurements, or to verify the effectiveness of physical methods with regard to HVS.

As typical examples, IEC has published a number of visual assessment methods (IEC 62629-13-1 [32], IEC 61747-20-3 [33], IEC 62341-6-2 [34] and IEC 61988-2-4 [35]). These documents focus on the qualities of images (perceptual screen resolution, cross-talk, colour gradation, half-luminance viewing angle, 2D-artefacts, and 3D-ghosts), and defects (subpixel-, mura- and line-defects) of displays. Such methods and the colour- and greyscale inversions under varying viewing directions were also the focus of IDMS:2012 [4], Chapter 4.

In broadcasting technology, for example, visual image quality assessments for video clips are popularly used. Many technical parameters, test environments, test methods and datasets used in image quality assessments are described in standards and recommendations issued by the International Telecommunication Union (ITU) [5] and the European Broadcasting Union (EBU) [6].

Usually the image quality of a display depends on the viewing direction. To describe the dependence in the viewing direction, the conventional physical measuring method [7] is well-established in industry. It is stable, robust and can uniquely determine the viewing direction range using the colour difference metric. But the viewing direction range is a complex feature and determined by multiple factors that vary simultaneously, for example luminance, tone rendering, and colour shift. It is a challenge to weigh these factors into a single viewing direction range metric. Another challenge is that measurements use aperture colours (colours in a small portion of the viewing field) which do not take into account spatial filtering in the HVS. To include the CSF of the HVS, the S-CIELAB method has been used [8].

The advantage of physical measurements is that CIELAB with ΔE^*_{00} takes chromatic, luminance adaptation and the uniform JND metric into account for the representative CIE-CMF. However, human colour perception is a very complex process. It depends on many factors, such as chromatic and luminance adaptation, lateral inhibition of ganglion cells, contrast sensitivity, simultaneous contrast, adaptation on local image features and subjectivity of colour perception (human colour experiences) [9].

An imaging LMD with ΔE^*_{00} metric can provide a stable and objective measurement result for the representative CIE-CMF. However, it cannot represent the entire colour perception of observers and observer variabilities. To achieve more precise perception an imaging LMD can be combined with a vision model, but it is not easy to describe complex processes of human colour perception with a few mathematical functions. As a concern, the physical measurement does not fully reflect the HVS sensations and abilities. A colour difference between two colours with physically constant colour differences can be perceived differently by humans, affected according to changes in various conditions (e.g. object size, shape, ambient brightness, etc.) [9]. In particular, colour discrimination between two coloured objects within the same viewing direction is not included in the physical measurement. Colour discrimination is the ability of human perception to distinguish two different coloured objects. It can also be expressed in terms of a colour difference between two coloured objects within the same viewing direction such as ΔE^*_{00}. In conventional physical measurement, there are only the measurement methods of colour and luminance differences between the normal-axis (as reference) and the other viewing direction (see Figure 1).

Recently, it was verified that the SS [1] is a meaningful criterion of image quality. SS was developed to improve on conventional methods such as peak signal-to-noise ratio (PSNR) and mean squared error (MSE). SS is a perception-based model that considers image degradation as perceived change in structural information. It is the reproduction ability of the image detail and shape. Thus, SS can be an additional important feature beyond the conventional measurement of the colour and luminance characteristic. Changing the viewing direction can diminish the shape of the object and the image details. One of the functional components of the SS is that two neighbouring colours could be discernible to each other.

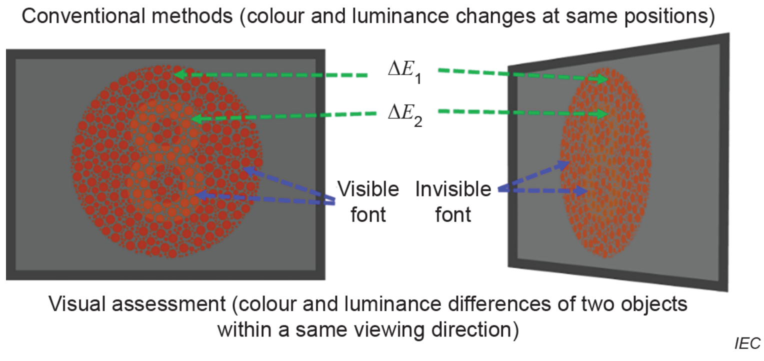


Figure 1 – Comparison between the proposed visual assessment and the conventional physical measurement

The conceptual Figure 1 shows the differences between the conventional physical measurement and the new visual assessment for the colour discrimination under varying viewing directions. The conventional method describes well the viewing direction-dependent characteristic in relation to the normal axis (IEC TS 62977-3-1 [7]). It checks the colour constancy between two viewing directions. With respect to the viewer, it is also important to get visual information within a same viewing direction.

Another meaning of the visual assessment method in comparison to the physical measurement is with respect to observers. The colourimetric value of the measuring instrument is evaluated by the 1931 CIE-CMF, which is approximately derived from the average sensitivities of a number of observers. The effectiveness of this CMF has been extensively studied and there has been a lot of demand for improvements to this CMF. Although 1931 CIE-CMF had to be supplemented, continuous use of this CMF was considered more efficient than revision [10], [11]. Recently, CIE published the observer's LMS-cone sensitivities by age and angle of view [11]. At a constant viewing angle, the cone sensitivities slowly shift towards the long wavelength. The shift is about 5 nm between 10 years and 60 years of age. This shift is accelerated from the age of 70 with 10 nm and more. Thus, it is preferred to supplement the physical measurement method with the visual assessment method because there is a limit to represent the change of the spectral sensitivity of different observers by the mean value derived CMF. Such observer variation would be roughly treated as a statistical plot of observer ratings by the visual assessment method.

Usually the colour perception of humans is also influenced by geometric changes of object shapes and spatial frequency content which happen with a change of the viewing direction [9]. It would be helpful for visual assessment, if the proposed method would be added.

Therefore, the visual assessment method of this document is a supplemental method for the conventional method.

5 Standard measuring equipment and coordinate system

5.1 Light measuring devices

Light measuring devices (LMDs) for the initial setup of the visual assessment considered in IEC 62977-2-1:2021, 5.3, are used [13]. An LMD or imaging LMD can be used in order to measure the colour differences of the test pattern, the correlated colour temperature and peak luminance of a display white.

NOTE A vision model of an imaging LMD depends on products. Here, imaging LMDs are calibrated by *XYZ* values.

5.2 Viewing direction coordinate system

The viewing direction coordinate system for LMDs specified in IEC 62977-2-1:2021, 5.6 is used, and is represented in Figure 2.

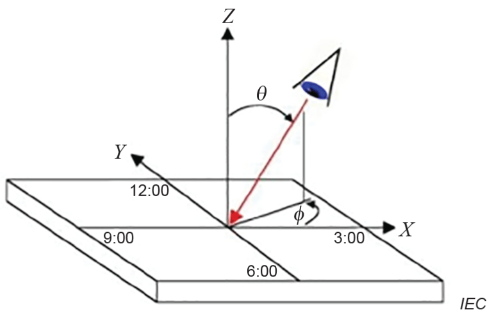


Figure 2 – Definition of viewing directions by the spherical angles of θ and φ

For visual assessment in the horizontal direction, the observer can be positioned as shown in Figure 3. The observing layout for the vertical viewing direction can also be used for the horizontal layout with a rotating the screen at 90° to construct a simple test equipment with only horizontal tilt, or by tilting the screen vertically at the normal viewing direction.

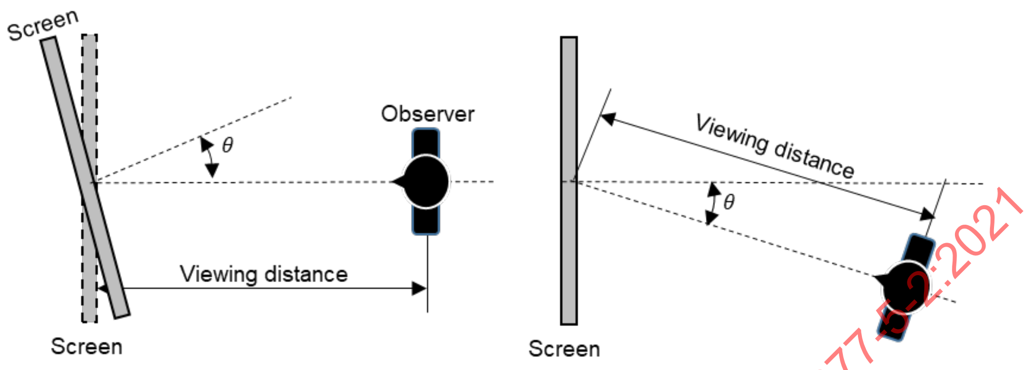


Figure 3 – Layout for horizontal viewing direction

The suggested ranges of the direction (θ and φ) are shown in Table 1 for DUTs in living rooms [7].

Table 1 – Measurement directions for DUTs in living rooms

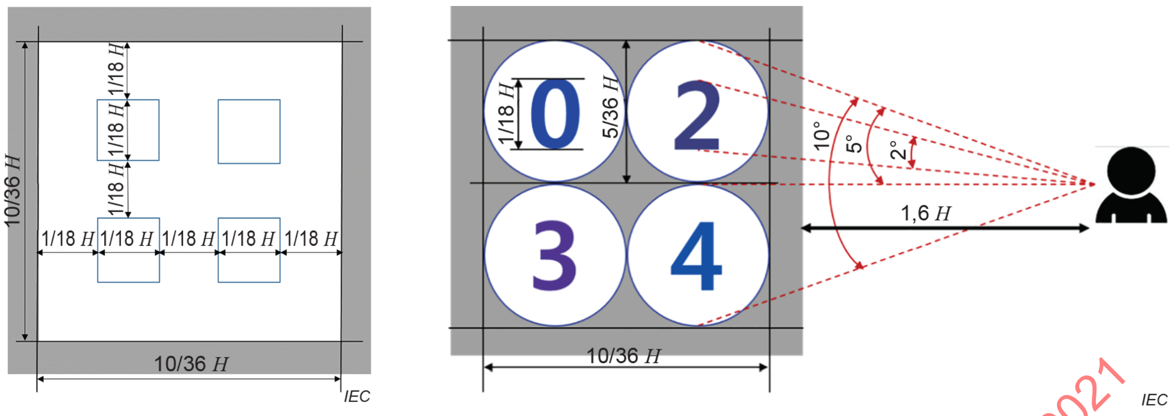
	θ (degree)	φ (degree)
Horizontal	0, ±15, ±30, ±45, ±60	0
Vertical	0, ±15, ±30	90
Diagonal	45	45, 90, 135, 225, 270 and 315

NOTE Table 1 is consistent with IEC TS 62977-3-1:2019, Table 1 [7]. If needed, it can be adjusted by test organizations for their purposes.

6 Test patterns

6.1 Geometrical construction

The geometrical structures and dimensions of the test patterns are shown in Figure 4. The first rectangular colour patch type (Figure 4a)) is designed for the optical measurement by the LMD. The second inside font (number or alphabet) type (Figure 4b)) is used for the visual assessment. All sizes are specified by factors of the display screen height (H), and the size of the inside stimuli is 1/18 × H (font height). Therefore, the font width is defined by the notation of the used font format. The inside font has a 2° viewing angle as the default for the observer. The viewing angle is kept at 2°.



a) Type 1   b) Type 2   c) viewing angle

Figure 4 – Pattern structures

The viewing angles of the number, intermediate circle and outer grey rectangle are designed for the stimulus (2°), proximal field (5°) and background (10°) according to the recommendation of Hunt [9], [14].

NOTE 1 The viewing angles of the test pattern in the visual assessment results in this document were as follows: 2°, 4°, and 8° for stimulus, proximal and background regions, which are slightly different from Figure 4.

NOTE 2 The test pattern used for this document can be modified, produced and used according to the purpose of each party.

6.2 Colour assignment

For the assigning of colours in the test pattern, a Macbeth colour chart was used (Table 2) [15], [16], [17]. It consists of six achromatic- and eighteen chromatic colours. These twenty-four colours were named as reference colours, and the proximal fields (outer rectangle of Type 1 and circle of Type 2 in Figure 4) were filled with these reference colours.

The inside stimuli (small rectangle of Type 1 and numbers of Type 2 in Figure 4) were filled with one of the variated colours in the lightness, hue and chroma direction in the CIE-$L^*C^*H^*$ colour space (Figure 5a)). For example, the hue (H^*) of the first row numbers in Figure 5b) was increased (+ marked number "1") or decreased (- marked number "2") from the hue values of the reference colours. The second row numbers “3” and “4” in Figure 5b) were changed by the chroma values (C^*) in the same way. Figure 5d) is the example for the chromatic and achromatic patterns for 5 ΔE^*_{00} difference.

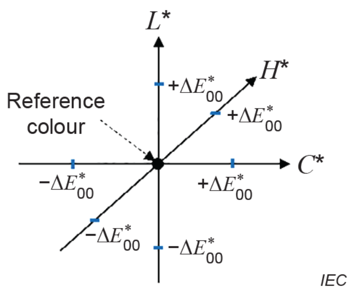
Table 2 – Reference colours of test pattern

No.	CIE/ SMPTE-303M(D65)								ITU-R. BT.709			ITU-R.BT.2020		
	X	*Y*	*Z*	*L**	*a**	*b**	*C**	*H**	*R'*	*G'*	*B'*	*R'*	*G'*	*B'*
1	0,109 7	0,097	0,060 6	37,3	13,71	15,54	20,72	0,85	0,404 1	0,25	0,187 4	0,352 4	0,262 7	0,198 7
2	0,381 2	0,355 8	0,259 2	66,2	14,43	17,78	22,9	0,89	0,747 1	0,548 6	0,46	0,677 5	0,563 8	0,474 5
3	0,178 6	0,190 8	0,345 2	50,78	-1,46	-21,23	21,28	4,64	0,313 6	0,432 7	0,573 6	0,370 8	0,427 4	0,559 3
4	0,101	0,129 8	0,066 9	42,73	-16,33	22,35	27,68	2,2	0,281	0,366 7	0,186 1	0,308 5	0,359 8	0,209 1
5	0,258 3	0,243 8	0,453 2	56,47	11,51	-24,38	26,96	5,15	0,475 3	0,463 6	0,663 4	0,481 2	0,467 2	0,645 7
6	0,312 7	0,427 3	0,446 9	71,37	-31,43	2,02	31,49	3,08	0,345 4	0,717 8	0,630 8	0,512 3	0,697 7	0,635 4
7	0,364 6	0,293 2	0,058 9	61,06	31,13	57,23	65,15	1,07	0,838	0,432 6	0,101 2	0,710 3	0,470 3	0,184 9
8	0,134 2	0,117 6	0,372 3	40,83	15,4	-41,86	44,6	5,06	0,229 9	0,301 3	0,609 5	0,280 6	0,302 1	0,584 5
9	0,284 5	0,192 2	0,137 5	50,94	45,92	15,09	48,33	0,32	0,746 3	0,273 9	0,327 4	0,616 4	0,329 3	0,334 2
10	0,086 8	0,065 2	0,146 9	30,69	23,92	-22,07	32,55	5,54	0,304 4	0,171 3	0,364 5	0,270 3	0,186	0,350 5
11	0,332	0,436 6	0,111 9	72,00	-27,18	58,05	64,1	2,01	0,585 3	0,706 9	0,180 4	0,617 3	0,695 4	0,277 7
12	0,461 7	0,431 2	0,084	71,64	15,31	65,96	67,71	1,34	0,890 3	0,599 2	0,115 6	0,786	0,620 9	0,230 6
13	0,084	0,062 2	0,3	29,96	24,61	-50,89	56,53	5,16	0,117 4	0,180 6	0,548 9	0,176 1	0,184 6	0,522 2
14	0,145	0,235 8	0,095 1	55,66	-41,73	34,83	54,36	2,45	0,210 9	0,545 8	0,212	0,356 1	0,526 7	0,257 8
15	0,201 7	0,118 2	0,052	40,93	52,85	25,6	58,73	0,45	0,665 2	0,122 3	0,165 1	0,531 6	0,204 8	0,179 9
16	0,560 5	0,596 4	0,095 6	81,64	-1,58	79,46	79,48	1,59	0,923 6	0,760 8	0,047 6	0,852 4	0,769	0,242 4
17	0,294 2	0,192 7	0,302 9	51.00	49,43	-15,03	51,66	5,99	0,71	0,270 9	0,537 6	0,594 7	0,324 5	0,523
18	0,144 7	0,198 7	0,395 2	51,69	-24,78	-25,95	35,88	3,95	0,139 6	0,488 8	0,616 4	0,248 9	0,469 3	0,600 5
19	0,839 8	0,887 6	0,923 5	95,48	-0,73	2,9	2,99	1,82	0,947 4	0,943 6	0,918	0,944 9	0,943 6	0,920 8
20	0,558 8	0,588 7	0,628 7	81,22	-0,18	1,09	1,11	1,74	0,769 4	0,767	0,758 1	0,768 1	0,767 1	0,759 1
21	0,336 7	0,355 1	0,381 1	66,14	-0,28	0,69	0,75	1,96	0,590 9	0,591 2	0,585 4	0,590 7	0,591 1	0,586
22	0,183	0,193	0,208 3	51,04	-0,23	0,35	0,42	2,16	0,424 6	0,425 6	0,422 7	0,424 9	0,425 5	0,423
23	0,079 6	0,084	0,090 6	34,8	-0,22	0,28	0,36	2,23	0,260 9	0,261 9	0,259 7	0,261 2	0,261 8	0,259 9
24	0,028 3	0,029 5	0,032 2	19,84	0,48	-0,05	0,48	6,19	0,128 9	0,125 3	0,126 4	0,127 6	0,125 5	0,126 4

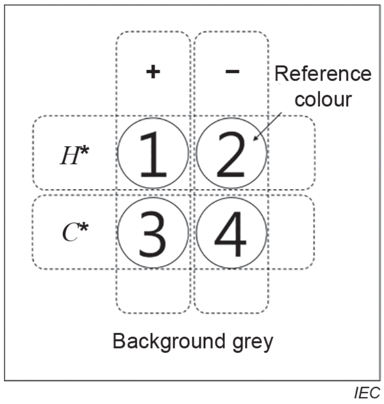
NOTE The values of *R'G'B'* are the normalized nonlinear values. The hue values (H^*) are presented here in radian.

Luminance and size of the background grey can be freely assigned by test organizations. However, it is preferable to assign the 18 % (L^* = 56 for dim-surround) luminance of the display white and full screen size. Therefore, 18 % grey luminance represents the average luminance of scenes when watching natural scene videos according to the grey-world theory [18]. Hence, the human visual system might be adapted to a white with five times the average luminance of this scene approximately [19], [20]. This grey background might contribute to the stabilization of the light adaptation of the HVS.

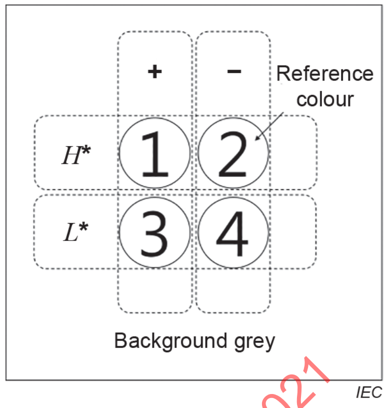
Figure 5d) shows an example of the achromatic and chromatic test patterns. Twenty-four test patterns, each with four fonts, can be shown to observers for the visual assessment.



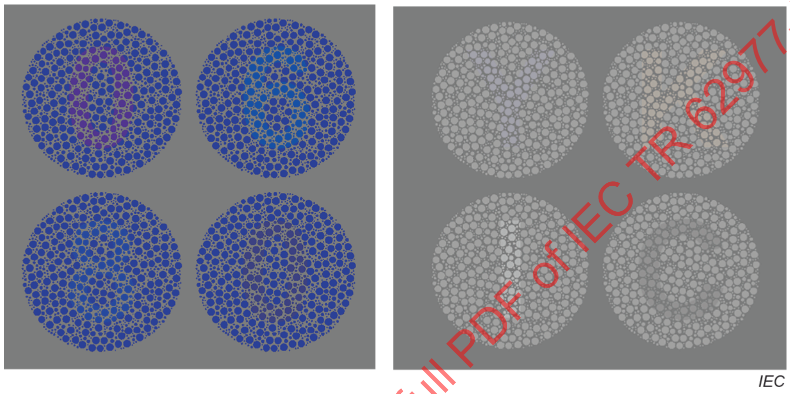
a) **Colour variation**



b) **Chromatic pattern**



c) **Achromatic pattern**



d) **Example for** $\Delta E^*_{00} = 5$

Figure 5 – Colour assignment of test pattern

6.3 Dots fill factor

Most image contents are usually structured. This image complexity can be represented as a fill factor (FF) in the test pattern as shown in Figure 5d). Formula (1) defines the fill factor FF as a ratio of the area of dots (A_D) to the area of circles (A_C). This type of construction is similar to the Ishihara pattern for colour deficiency check [21].

$$FF[\%] = 100 \times \frac{A_D}{A_C} \qquad (1)$$

For the visual assessment, an FF of 70 % was utilized by default. The dots with multiple dot sizes and locations in the circle of the test pattern were randomly generated by a program. The diameters of the dots have a viewing angle between 0,178° and 0,028°. For all observers the same dot patterns shown in the same order would be viewed in order to get the same sensation within a same visual assessment session.

More details related to this topic are described in Annex A.

7 Visual assessment method

7.1 General description of the assessment

This visual assessment method was constructed based on the single stimulus method (SSM) of ITU-R BT.500-13 [5]. A sequence of a single test pattern was presented and the observers provided their responses for the entire presentation. All responses were gathered by an operator and the statistical results of all responses were evaluated.

Figure 6 shows the test room environment. The DUT was connected via an HDMI interface with an operating PC, in which the test pattern sequence was generated by an operator manually or semi-automatically. These test patterns on the DUT were sequentially exposed to the observer, who was asked about the visible fonts in each test pattern. The operator recorded the observer's responses as 'True' or 'False' on a form or in a "pattern generator" program for example. The program could also generate all observer responses as a spreadsheet file after the test session. The pattern generator will be provided and more details about this program can be found in Annex C.

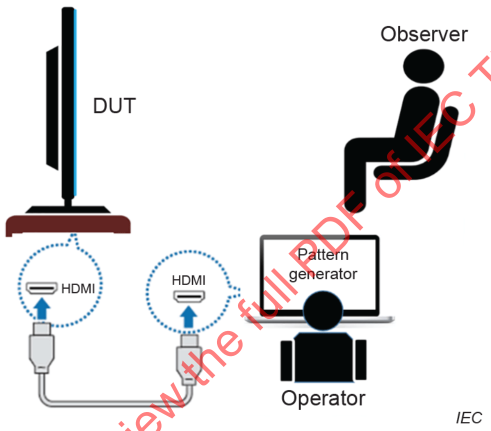


Figure 6 – Test environment

7.2 Test room conditions

The observers' viewing conditions were arranged as follows (Table 3). The room was set to dark to prevent any reflection on the screen. The surrounding area of the DUT screen was equipped with a grey curtain with a neutral reflectance of about 20 %, allowing for a neutral visual adaptation. Before starting the visual assessment, the observers had at least a 15 min adaptation time to the test room environment including the screen with the 18 % grey pattern. The viewing distance for a given pattern size satisfied the described viewing angle condition in Figure 4c). Here, the zooming factor (Z_F) is an integer scale factor (for example, from 1 to 4) of the dotted test pattern to obtain a sufficient visual resolution during the visual judgment with a low resolution and a small screen size DUT. For example, applying Z_F = 2 doubles the horizontal and vertical size of the test pattern. When using Z_F, the aspect ratio of the test pattern remains unchanged.

Table 3 – Test room condition

Surround	Dark < 1 lux on the screen (measured perpendicularly to the screen)
Viewing distance	1,6 × H × Z_F Z_F: zoom factor of pattern

7.3 DUT parameters

Table 4 shows the experimental setup parameters of the DUT. The correlated colour temperature (CCT) of the DUT was set at D65 white. However, another CCT is also possible. In this case, the CCT with chromaticity coordinates can be reported in the results document. The luminance of the display white varies from display to display, so the luminance of white can be freely adjusted by the test organization, otherwise it is possible to use the factory setup. To check the quality between two different DUTs, it was necessary to keep the setup parameters of the display the same. However, it was preferred to set over 100 cd/m^2 because the visual assessment result was slightly affected by the luminance of the pattern images. This luminance dependency is discussed in Annex B. All physical values were measured from the normal direction of the DUT screen.

NOTE 1 The minimum white luminance of some displays does not guarantee sufficient colour luminance. In this case, the display would be additive or the total luminance of all primary colours would be greater than 100 cd/m^2.

Table 4 – Experimental setup of the DUT

Correlated colour temperature	Test organization specific Recommended: D65 CIE – (x, y) = (0,312 7, 0,329 0)
White luminance	Factory default or test organization specific
Dark room contrast ratio (ratio of the luminance of the peak luminance to the inactive screen)	Factory default, test organization specific or DUT specific maximum value
Display brightness and contrast	Factory default or test organization specific
Display resolution	≥ 30 pixels per degree

NOTE 2 Current TVs can reach over 500 cd/m^2, where the R colour can be saturated. In such a case, such a high level of brightness would be avoided for the test.

To display the test pattern, the required resolution of the DUT would be greater than 30 pixels per degree (240 pixels × 240 pixels for the test pattern). Any type of DUT with a resolution over this minimum resolution can be tested.

All setting parameters and all other measurements are retained throughout the whole visual assessment.

7.4 Observers

The following criteria on observers are reproduced from ITU-R BT.500-13 [5].

Usually, observers can be experts or non-experts depending on the objectives of the assessment. An expert observer is an observer that has expertise in image artefacts. A non-expert observer is an observer that has no expertise in image artefacts. In any case, observers would not be, or have been, directly involved in related research and development. Prior to a session, the observers could be screened for normal visual acuity on the Snellen or Landolt chart, and for normal colour vision using specially selected charts (Ishihara, for instance). At least 15 observers would participate [5], [22]. For studies with limited scope, for example of an exploratory nature, fewer than 15 observers may be used. In this case, the study would be identified as "informal". Fifteen observers with a limited age range (e.g., 20 years old to 60 years old) and a regular sample can be sufficient to reproduce average results. However, 15 observers would be insufficient to reproduce observer variability in perceived colour differences (or colour discrimination) for the test pattern [23]. In this case, the test organization can manage to increase the number of observers.

A study of consistency between results at different testing laboratories has been carried out. A possible explanation for the differences between laboratories is that there can be different skill levels amongst different groups of observers. However, in the interim, experimenters would include as many details as possible on the characteristics of their assessment panels to facilitate further investigation of this factor. Suggested data to be provided could include: occupation (e.g., broadcast organization employee, university student, or office worker), gender, and age.

The 1931 CIE-CMF is derived from average values of the spectral responses of a number of colour-normal observers [10]. The CMF is usually dependent on age, viewing field size, density of eye-lens and macula, and optical densities of LMS-cones rather than on ethnic origin and gender, according to Asano [23]. These characteristic values depend on individual observers.

The average CMF of 151 observers of Asano's database (122 Europeans, 9 North Americans, 17 Asians and 3 Africans) according to the ethnic origin are reproduced in Figure 7.

NOTE More relevant factors on CMF are the above-mentioned characteristics of individual observers rather than ethnic origin.

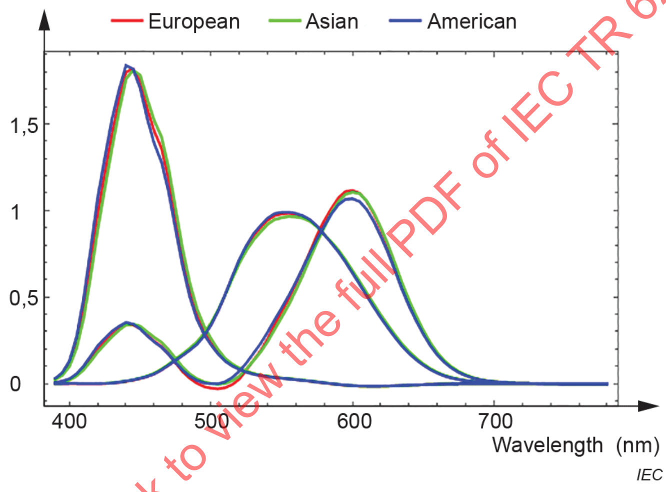


Figure 7 – Average CMF according to ethnic origin

7.5 Instructions for visual assessment method

A session would not be exceeding 30 min to prevent any response affected by tiredness or adaptation.

The method of assessment would be carefully introduced to the observers and sufficient training sequences would demonstrate the range and the type of the test pattern to be assessed (Figure 8). During this training session, all of the observers' doubts would be cleared. The training sessions would be conducted for the same duration (e.g., 5 min) for all observers.

The DUT would be set to the desired viewing direction before starting the test session. At the beginning of the first session, about three to five "dummy sessions" would be introduced to stabilize the observers' answers. The results of these tests would not be included. If several sessions are necessary, about three dummy presentations would be necessary at the beginning of the following session.

As in Figure 8, each test pattern (Type 2) would be presented for T1 seconds (5 s to 7 s) to the observer who provides answers to the recognized fonts (number or character). The operator records the correctness of the answers during the next grey pattern within T2 seconds (8 s to 10 s) (see NOTE 2). This procedure would be repeated until the end of the test patterns.

To set a desired viewing direction, a break time (1 min to 3 min) would also be inserted. To test all directions, 24 sessions (Table 1) are held.

A typical session for establishing average results using this method will take approximately 24 h of observation time for 15 observers with 9 viewing directions (15 min for one observer and one viewing direction).

NOTE 1 If the DUT has a symmetrical characteristic to the viewing direction, total sessions can be reduced to 9 sessions; normal: (θ, φ) = (0, 0), horizontal (φ = 0): θ = {15, 30, 45, 60}, vertical (φ = 90): θ = {15, 30} and diagonal (φ = 45): θ = {0, 45}.

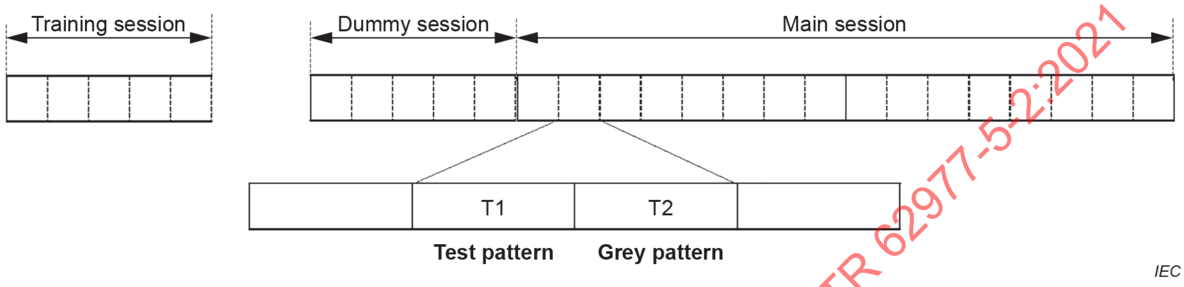


Figure 8 – Assessment procedure

NOTE 2 Grey pattern with 18% luminance of display white helps to neutralize the visual adaptation of HVS for the following T1 test.

7.6 Repeatability

To ensure the repeatability of an assessment result, all of the stated conditions (described in 7.1 to 7.5) regarding the test room environment, setting parameters of the DUT, screening of the observers and instructions for the visual assessment help to keep the whole evaluation process constant.

Depending on viewing distance, a few centimetres' variation in the head position leads to a few degrees change in viewing angle, which can bias the results significantly especially at a shallow angle (e.g., H_45° versus H_60°). As a solution, a headrest could be used to fixate the viewing angle as in ISO 20462 [31].

The main factors influencing the test results regarding the observer can be observer fatigue and adaptation to the DUT and test room environment. Therefore, the test organization is encouraged to conduct preliminary experiments with a small number of observers to determine the appropriate session and break times of the visual assessment. The determined result is applied to all observers. However, if an observer feels tired during the test session, the observer may request a break at any time.

In addition, a sufficient training phase for each observer is also preferred before starting the main test. Training experiments include, for example, viewing directions of 0° and 60°, designed to allow observers to experience easy and difficult decisions within a limited time.

7.7 Presentation and interpretation of the experimental assessment results

The result of the visual assessment can be presented as the statistical plot of the recognition rate of all observers' ratings for the test patterns in relation to the viewing direction as shown in Figure 9. In most cases the plot of the mean ("-" marked) values of the recognition rates is sufficient to characterize the viewing direction dependency where the recognition rate (R) is defined as the ratio of the number of correctly answered fonts (N_f) to the total number of fonts (N_t = 24 colours × 4 fonts) in the test patterns as given in Formula (2).

$$R[\%] = 100 \times \frac{N_f}{N_t} \quad (2)$$

This example was carried out for a 55 inch LCD type UHDTV DUT at a viewing distance 1,6 × H, 24 test patterns with 4 patches and 16 observers (seven females) in an age range of 22 years to 55 years from Asia.

As the spherical angle of the viewing direction gradually increased (from 0° to 60°), the recognition rate decreased correspondingly.

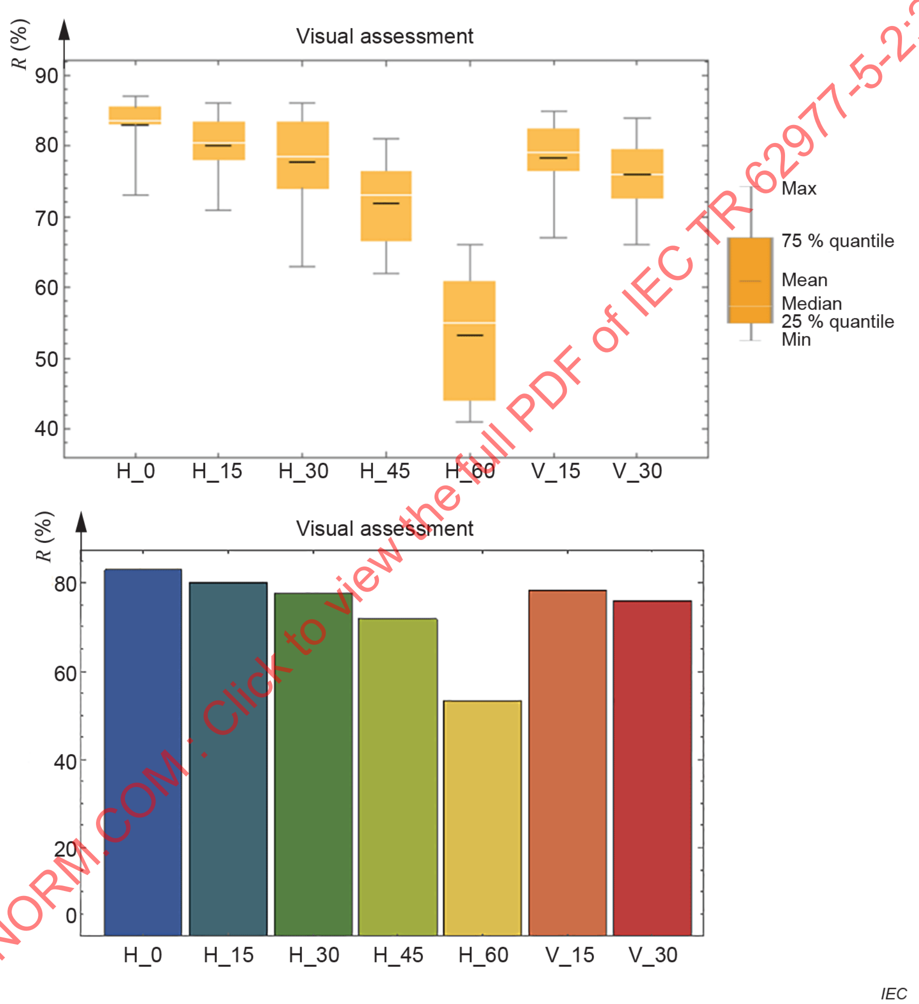


Figure 9 – Visual assessment results: statistical plot (upper figure) and mean recognition rates (lower figure)

A performance of the proposed visual assessment was described in relation to the physical measurements in CIELAB ΔE^*_{00} and a quality judgement based on S-CIELAB transformation [8], [24].

Figure 10 shows the statistical plot of the measured colour differences between the reference (background dots) and the font colours for all 24 colour patterns, which were generated for a given $\Delta E^*_{00} = 5$, in relation to the viewing directions. The viewing directions were varied horizontally (0°, 15°, 30°, 45°, 60°) and vertically (15°, 30°).

As the angle of view is increasingly off-axis (further away) from the normal viewing direction, the mean value of the colour difference was reduced due to the colour reproduction characteristics of a specific DUT. However, the variance was increased due to the viewing direction-dependent changes of the DUT colours and noise of the LMD.

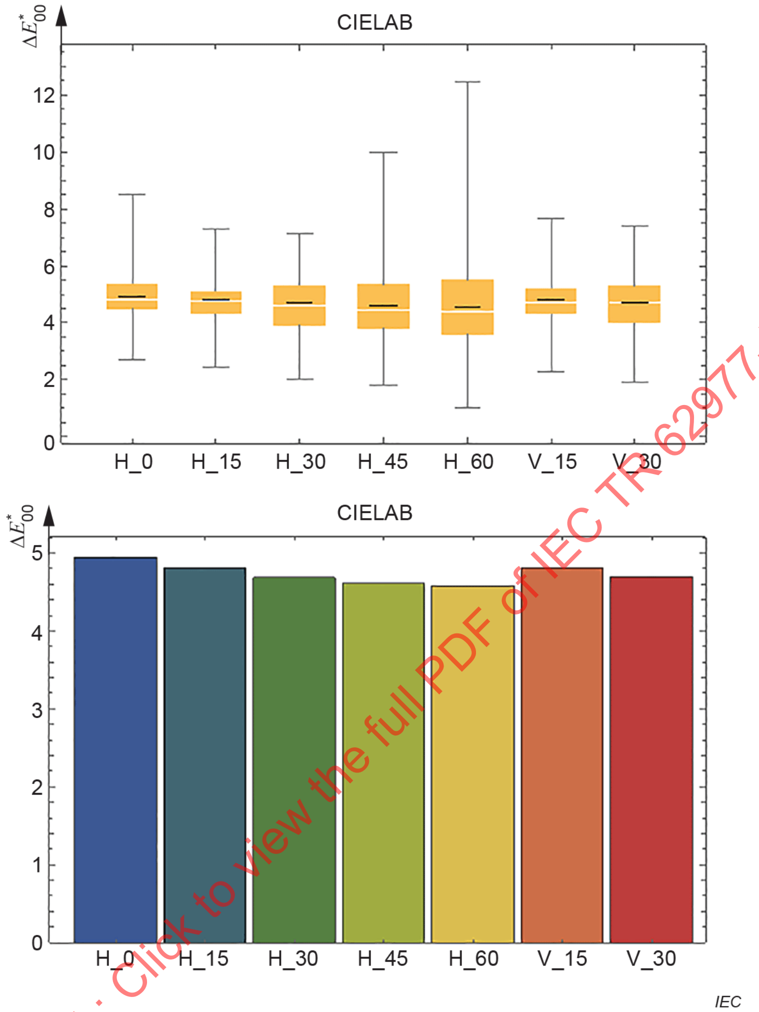


Figure 10 – Statistical plot (upper) and mean of colour differences (lower) of test patterns

The whole process of the quality judgement in S-CIELAB is shown in Figure 11. For the S-CIELAB transformation, the computer-generated colours (font and background colours) of all 24 test patterns were replaced by the measured values for the given viewing directions.

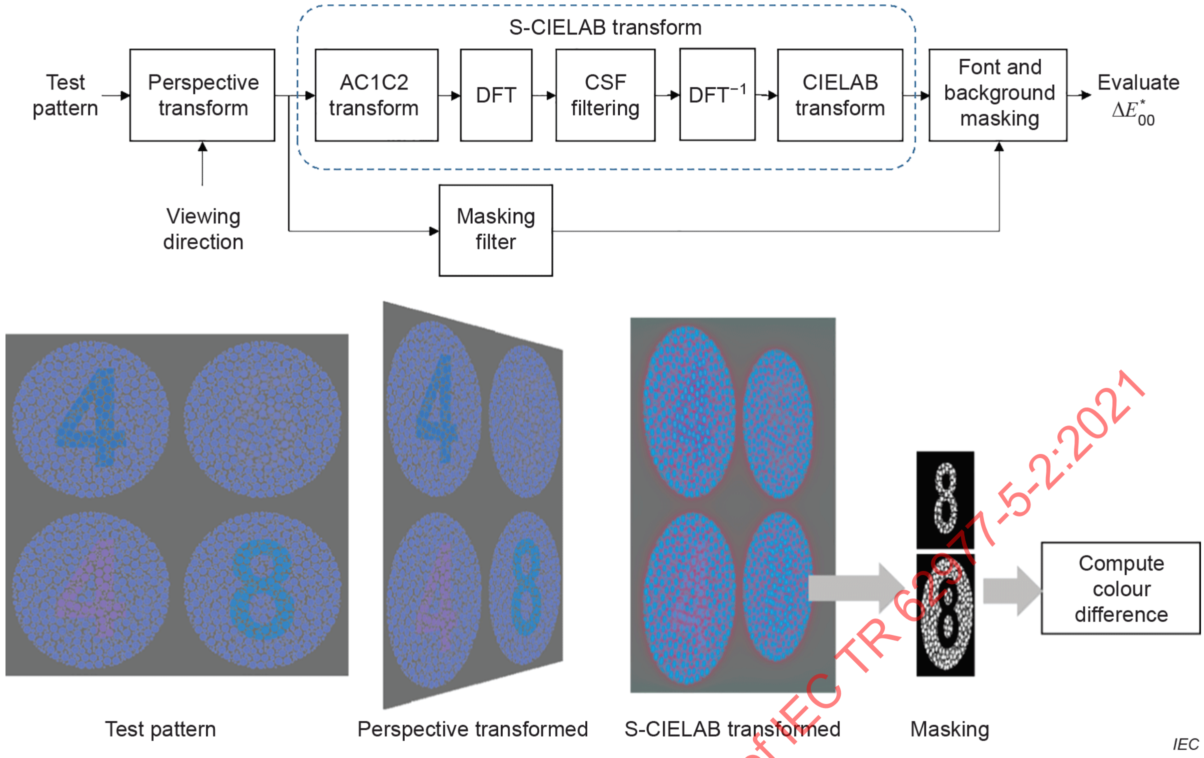
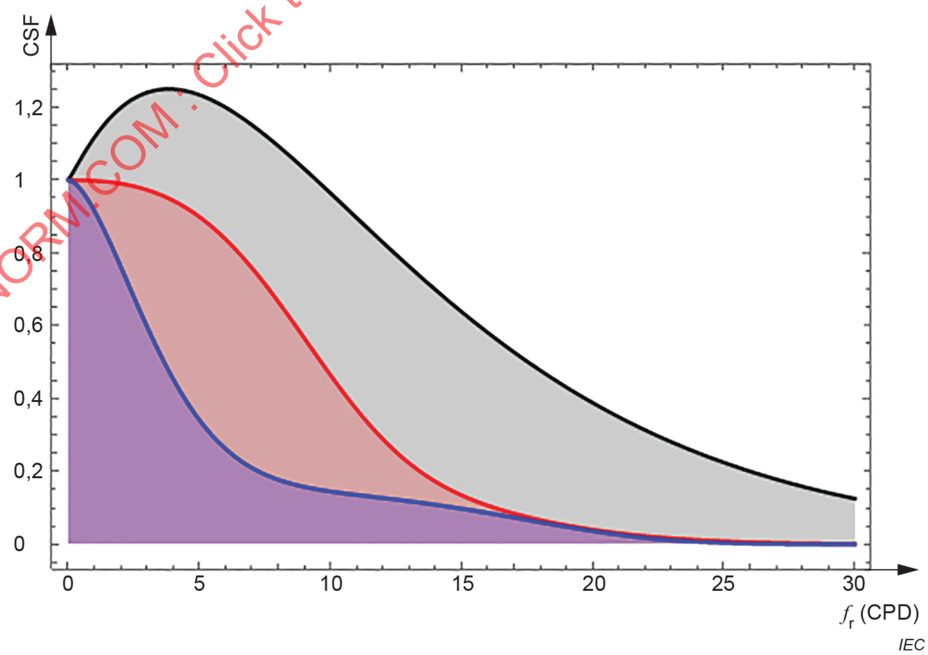


Figure 11 – Process of S-CIELAB transformation

As a first step, the perspective transformation for a given viewing direction was applied to the test pattern. This geometric transformed test pattern was then transformed to the opponent colour space (AC1C2) of the HVS, and transformed further into the frequency domain using DFT (discrete Fourier transform). In the frequency domain, the CSF in Figure 12 of the HVS was applied separately [24], [25], [26]. After that, the filtered images were inversely transformed to AC1C2 and CIELAB spatial domain.



NOTE Black (A), Red (C1: R-G) Blue (C2: B-Y), and f_r: radial frequency.

Figure 12 – Contrast sensitivity function of HVS

As a next step, the S-CIELAB transformed images were divided into four sub-images (4 fonts), and masked in the font region and background region for each colour pattern (see the bottom Figure 11, "masking 8"). The masking filters were obtained from the perspective transformed image. Using the masking images, the pixel values (CIELAB) of the font and background region were gathered and computed as the mean of the colour difference in ΔE^*_{00}. The S-CIELAB results are shown in Figure 13.

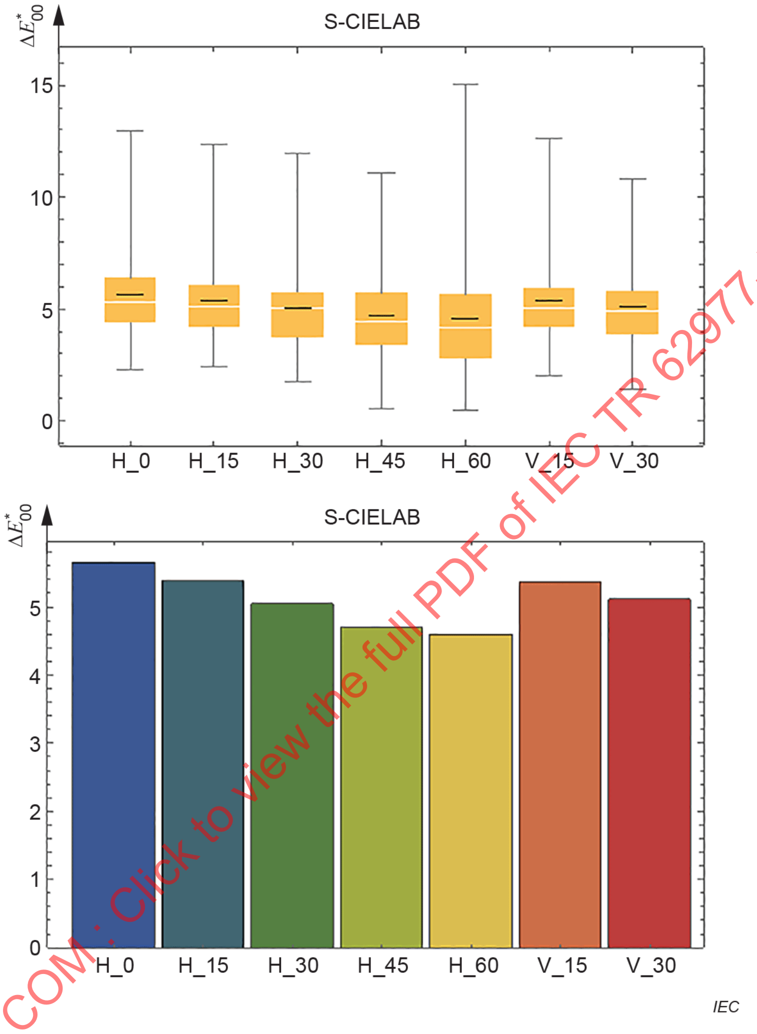


Figure 13 – S-CIELAB results: statistical plot (upper) and mean colour difference (lower)

The correlation between the two results is shown in Figure 14. The correlation coefficient using Pearson's correlation test resulted in a reasonable value of 0,958 in this experiment.

Hereafter, it will be shown how the visual experiment relates to the S-CIELAB method. The recognition rate of the visual assessment is usually decreasing with the increasing viewing direction, like the result of the physical measurements and the S-CIELAB. Specifically, at H_60 (horizontal viewing direction of 60°), this reduction rate was relatively more than the others because the HVS could perceive not only the colour changes but also the geometric changes (narrower fonts) of the patterns. Furthermore, at this viewing direction the perceived colour difference of the HVS was near the JND threshold.

The result of Pearson's correlation test in Figure 15 showed that the visual assessment was correlated with S-CIELAB. The correlation coefficients with S-CIELAB (Table 5) were reasonable values of 0,962 and 0,836, excluding and including the critical data of H_60.

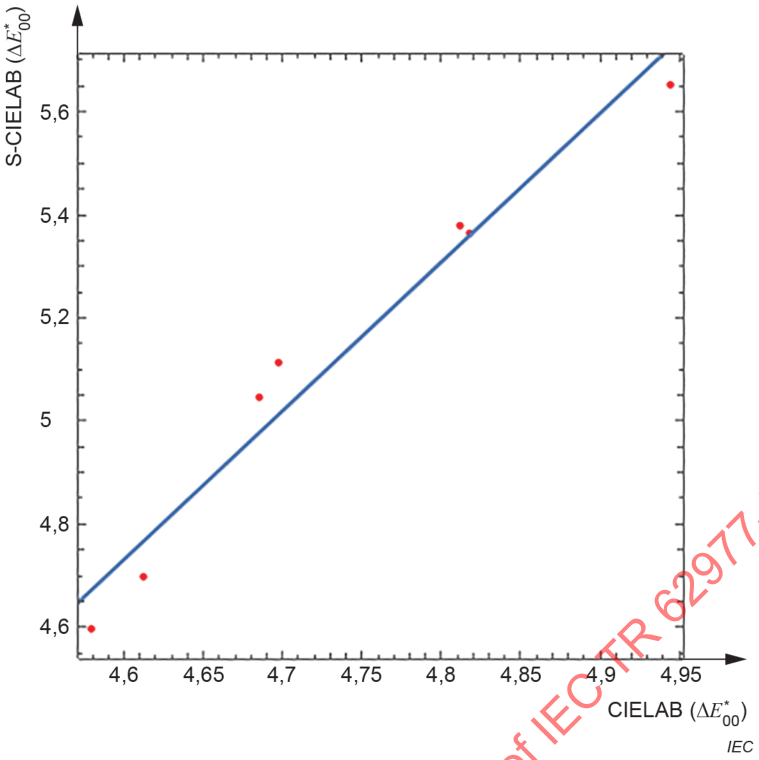


Figure 14 – Correlation between physical measures and S-CIELAB results

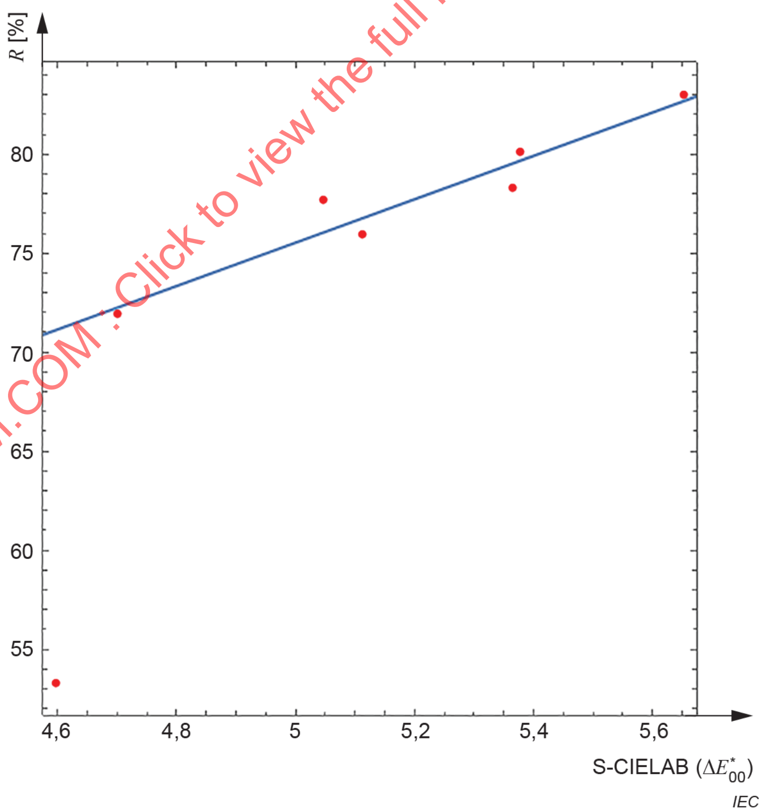


Figure 15 – Correlation between visual assessment and S-CIELAB method

Table 5 – Correlation coefficients

Correlation coefficient	S-CIELAB
Include H_60	0,836
Exclude H_60	0,962

If required, the test pattern dependency can be also presented as in Figure 16. Usually, the recognition rates depend on the test pattern because the colour difference metric ΔE^*_{00} is not perfectly uniform in the whole CIELAB colour space [12]. A few patterns (9, 13, and 21) were not well designed in this aspect.

For number 9, even though the pattern had a measured colour difference of around 5 ΔE^*_{00} on the DUT, it could hardly be perceived by the observers, at least for the participating observers.

On the contrary, the pattern number 13 was perceived well by all observers, as a case of too well perceived colour difference. Such types of patterns were reflected as DC-offset in the recognition rates.

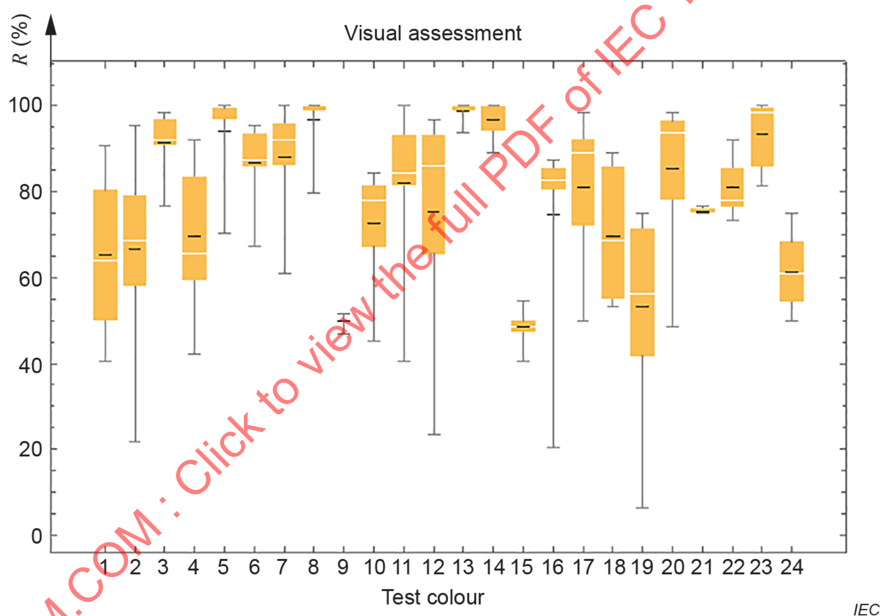


Figure 16 – Pattern dependency

Figure 17 shows the observer dependency. The last column "All" indicates the statistic plot of the recognition rates for all observers. A distinguished result in the recognition rate regarding mean and variance was achieved by observer number 7 who may have a high ability of visual acuity and colour discrimination, and was reliable on the experiment. A relative low performance was recorded by observer number 13. The screening of an extreme outlier observer in relation to the average data ("All") can be carefully eliminated according to ITU-R BT 500 [5] .

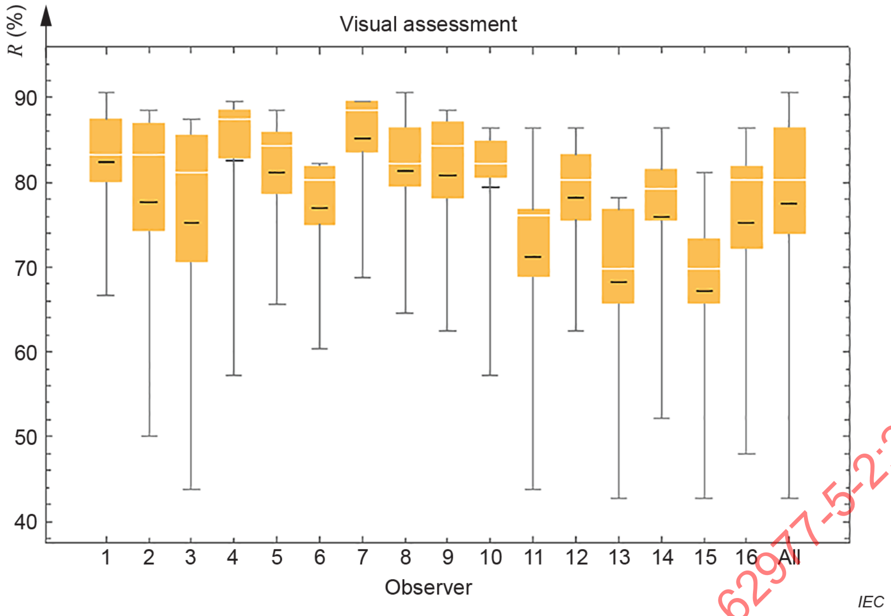


Figure 17 – Observer dependency

Annex A
(informative)

Fill factor dependency

The test pattern, like Ishihara's colour deficiency check pattern, was designed with multiple-sized dots, whose positions were randomly generated. The recognition rate of the fonts of the test pattern (Type 2) in the visual assessment depends on the fill factor of dots.

In prior research, Fairchild et al. have established that the JND of colours in a complex scene is about 2,3 $\Delta E^{*}_{\text{ab,76}}$ [27], [28]. In order to use a test pattern instead of a typical complex scene with the same JND performance of $\Delta E^{*}_{\text{ab,76}}$ = 2,3, the fill factor of the test pattern was adjusted (see Figure A.1). In Annex A, the experimental results of the recognition rate of the fill factor dependency were studied.

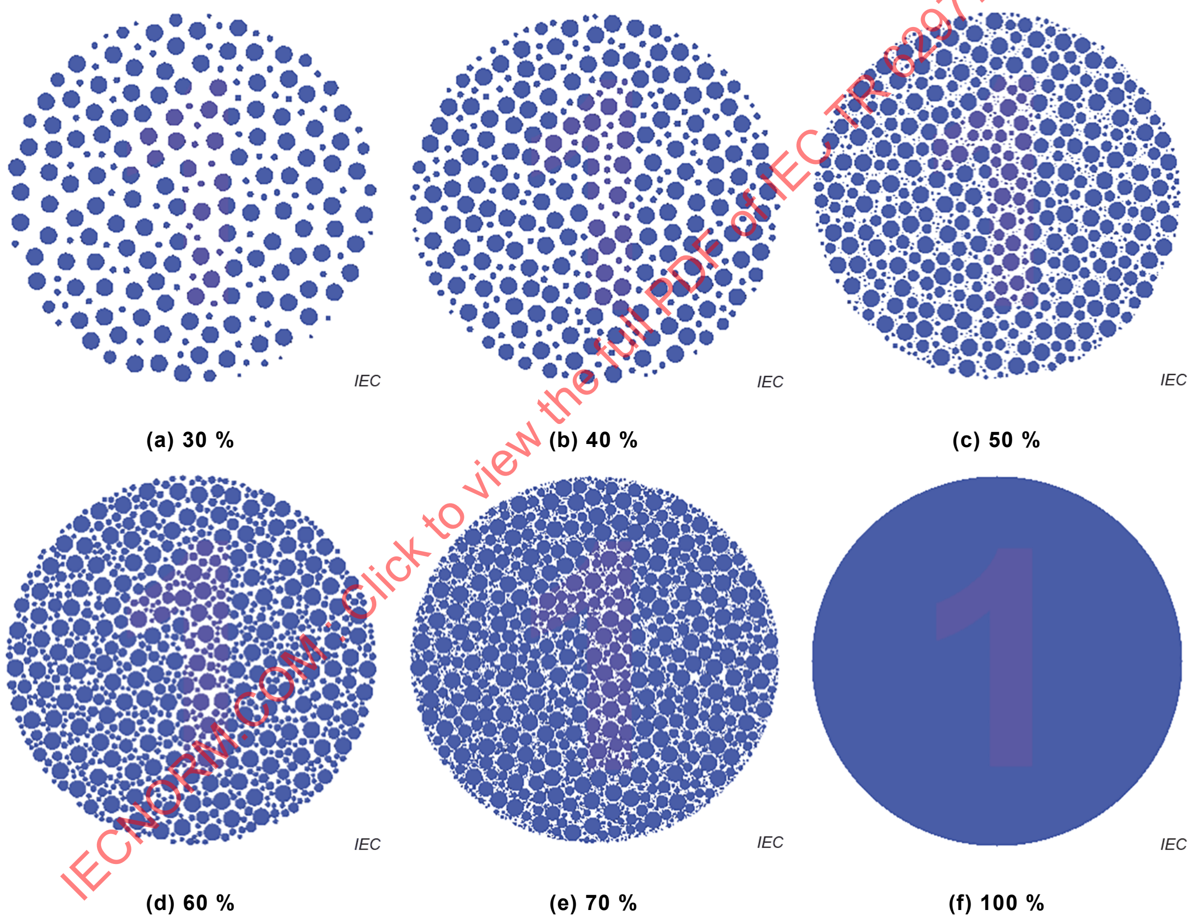


Figure A.1 – Fill factor variation

For this experiment the following test conditions were used:

– 15 observers (9 male) with an age range of 20 years to 30 years;
– test patterns for 18-chromatic reference colours with 4 inside numbers which were ΔE^{*}_{00} = 3 variated in hue and chroma;
– dots fill factors from 30 % to 70 % with 10 % incremental steps and 100 % (uniform pattern) were tested;
– dark surround;

– normal viewing direction (θ, φ) = (0, 0);
– viewing distance of 4,8H with a pattern zoom factor of 3;
– display: 55 inch LCD-UHDTV, Rec.709 colour space, D65 white, disable image enhancement function and HDMI-RGB signal connection with an operating notebook-PC;
– white luminance of display: 100 cd/m^2;
– background: 20 % grey (cd/m^2) of the display white luminance with full screen size.

The result of the assessment for 15 observers is shown in Figure A.2 as a box-whisker statistic plot of a recognition rate (Formula (A.1)) in the fill factor (FF) dependency.

As expected, the recognition rate was proportional to the increased FF. The deviation of R was decreased from low to high FF.

The blue line in Figure A.2 and Formula (A.1) is a sigmoidal approximation of the mean of the recognition rates (R) depending on FF. The fitting performance of R-squared value was 0,993.

$$R(FF) = \frac{100}{1+e^{(52,59-FF)/10,95}} \quad \text{(A.1)}$$

NOTE Due to the saturation characteristic of the R rate in the low and high FF regions the range of the R rate from 0 % to 100 %, i.e. the sigmoidal function, can well match the assessment result.

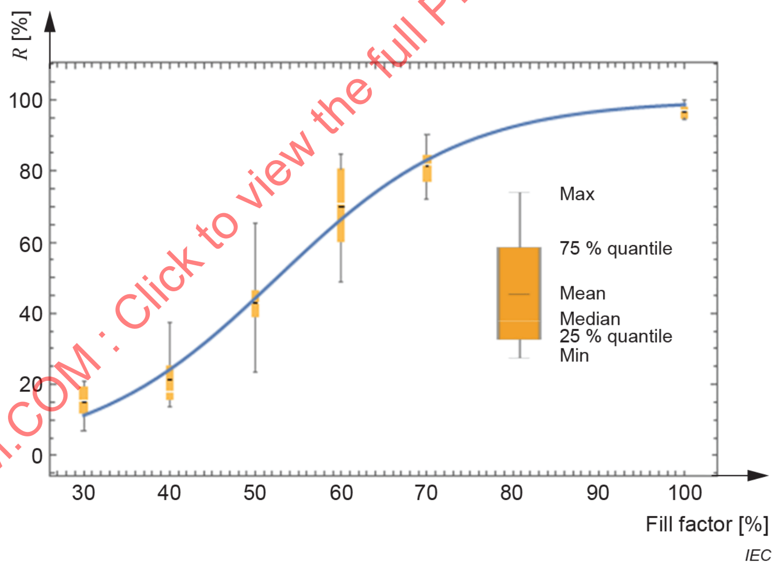


Figure A.2 – *FF* dependency

Figure A.3 shows the recognition rate comparison between the uniform pattern (100 % FF) and the various FF. The four red triangles are the mean recognition rates for a 100 % FF pattern with the variation of the font colours for ΔE^*_{00} = {0, 1, 2, 3} cases.

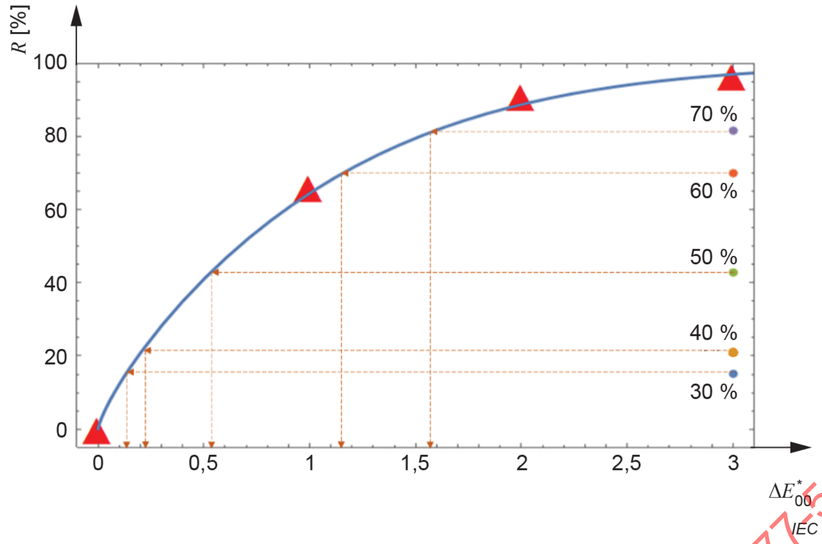


Figure A.3 – Colour difference relationship between pictorial image and test patterns with various *FF*

The blue line is a fitting function of the mean recognition rates for a 100 % fill factor in the dependency of colour difference ΔE^*_{00}. This fitting function was approximated by an error function since the R rate is at most 100 %, and its R-squared value was 0,999.

$$R[\%] = 100 \times Erf\left[\left(\frac{\Delta E^*_{00}}{1{,}72}\right)^{0{,}78}\right] \quad \text{(A.2)}$$

where $Erf[z] = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$ is the error function which is the integral of the Gaussian distribution.

For example, the recognition rate of the FF 70% pattern with ΔE^*_{00} = 3 was equivalent to the result of the 100 % FF with ΔE^*_{00} = 1,586 (see the dashed line of 70 % FF in Figure A.3).

The previously mentioned JND $\Delta E^*_{ab,76}$ = 2,3 of a complex scene is then replaced by the 70 % FF pattern with around 5 ΔE^*_{00} considering that the value of ΔE^*_{00} is generally less than $\Delta E^*_{ab,76}$. Therefore, the pattern with 5 ΔE^*_{00} and 70 % FF could be used instead of the complex scene.

Annex B
(informative)

Display white luminance dependency

To verify the effect of white adaptation of the HVS the following visual experiment has been carried out. Table B.1 shows the parameters of the visual assessment.

Table B.1 – Experimental setup and parameters

Display type	55 inch LCD UHDTV
Display setting	Colour temperature: D65 white White luminance: (38,83, 77,41, 115,6, 153, 190,3, 227,9, 265,7) cd/m^2 by adjusting the backlight Disabled APL and any image processing algorithm
Surround condition	Dark room
Viewing direction	Normal direction (θ, φ) = (0, 0)
Test pattern	18 chromatic patterns for Type 2 (FF = 100 %: Figure A.1f)) with $\Delta E^*_{00} = 2$, described in 6.1.
Visual assessment	Observers: 15 (9 males) Asians with an age range of 22 years to 55 years Test procedure: described in Clause 7.

Before starting the visual assessment, the colour reproduction performance of the display was verified. For this purpose, 18 uniform Type 1 patterns with 4 variations of hue and chroma were generated for $\Delta E^*_{00} = 2$. They were reproduced on the DUT and measured with an LMD. These measured values were compared with the computed theoretical values (Figure B.1). Some data fluctuation was caused by the noise of the LMD and quantization of the digitalized signals. The mean of the computed, measured and difference ΔE^*_{00} was 2,06, 2,0, and 0,3 respectively. The performance of the DUT was sufficient for purpose of this visual assessment.

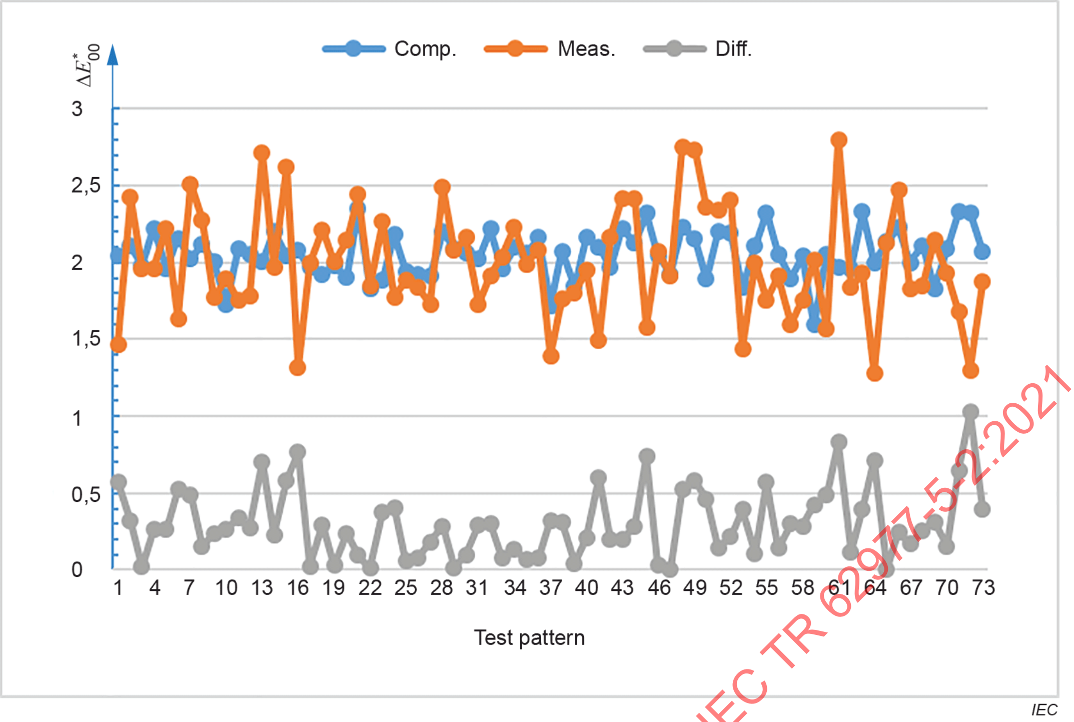


Figure B.1 – Colour reproduction performance of the DUT

The assessment result of 15 observers is shown in Figure B.2. At each luminance level the recognition rate produced approximately a 15 % deviation from observer to observer. The mean recognition rate was slightly increased from 83 % to 92 % with a tendency to gradual saturation. The following fitting function, as indicated in the blue line in Figure B.2, approximates the mean recognition rate with a good R-squared value of 0,957.

$$R[\%] = 100 \times Erf\left[Y^{0,125}\right], Y\text{: white luminance}\left[\text{cd/m}^2\right] \quad \text{(B.1)}$$

The white luminance dependency was much higher in the low luminance because of an incomplete white adaptation of the HVS for low luminance colours in a dark surround [29], [30]. At over 100 cd/m^2 of white luminance of the DUT, the white luminance dependency of the test patterns might be practically ignored. To have a stable visual assessment, it was preferred to set the white luminance of a DUT over 100 cd/m^2.