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Laptop displays performance: Compliance assessment with visual ergonomics requirements☆

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A R T I C L E I N F O

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A B S T R A C T

The use of display devices such as smartphones, tablets, laptops is now massive and continuous in everyday life. It, therefore, becomes increasingly important to be aware of the performance of these devices, not only in terms of the tasks to be performed but also in terms of interaction with humans and therefore knows any possible effect on the ergonomics of vision. Following previous research activities conducted by the authors on the assessment of the visual ergonomics at video display terminal workstations, the aim of this study is to evaluate the ergonomics of human-system interaction of laptop displays. In details, a sample of 57 laptop displays is analyzed in accordance with the requirements of the EN ISO 9241-3xx series of international standards related to the display luminance, luminance ratio, contrast non-uniformity. An extensive luminance measurement campaign was carried out using a special pattern that allowed to measure the luminance in 13 different areas of the displays. The results obtained with this activity showed a great luminance variability between different displays. Almost all the displays are able to emit high levels of display luminance, and almost all the displays meet the requirement of contrast non-uniformity. However, several devices did not meet the recommended values of luminance ratio. Furthermore, the authors created a simplified graph to allow a rapid evaluation of the performance of the displays. This method could be periodically used in practice in order to evaluate the residual performance level.

1. Introduction

Over the last few decades, electronical devices have become inherent elements of people in many aspects of everyday life, such as working, communication, entertainment, e-shop and education [1–3]. Smartphones, tablets and small personal computers are today part of our everyday environment [4]. Following the increase in the use of these devices, the effects on users' well-being have started to be investigated; several researches have been conducted on the ergonomics [5,6], lighting [7,8], possible visual health effects [9] and circadian rhythms [4,10,11] in terms of their use. It is, therefore, a current trend to simultaneously consider multiple aspects, as occurs in the assessment of the lighting quality of the rooms [12], in order to obtain the holistic vision of the device users' exposure conditions [13]. To date, it is no longer sufficient to evaluate the ergonomics and lighting levels achieved on the main surfaces, but it is also necessary to evaluate the performance of the display, which in combination with the ambient lighting, must guarantee adequate performance and appropriate luminance contrasts so that the reading of the images is correct and comfortable. The performance of the displays is the main factor to represent the object of vision. The display can be considered as a light source placed close to the observer's eyes (40 - 80 cm) and it may affect the quality of the visual performance and any effects on health and well-being [14–17].

Concerning the computer, the video display terminal is a term used to define the primary medium through which humans and computers interact [18]. Display technology has undergone revolutionary changes in recent years which result in significant breakthroughs in display types and their specifications. Among video display terminals, cathode ray tube (CRT) was the leading technology until the late 1990s prior to the development of liquid crystal display (LCD) technology [19]. Advances

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in display technology have been followed by several emerging display technologies, such as LED displays, OLED displays, quantum dot displays, offering wide range of specifications for luminance, contrast, resolution, refresh rate and pixel density.

Display performance, characteristics, and specifications are of particular importance given that both visual comfort and visual acuity rely heavily on luminance factors [20]. Up to now, a considerable amount of research has been conducted focusing in particular on contrast and luminance ratios. Much of the previous work concerning screen variables has compared different display luminance scenarios, some of which investigated the influence of different luminance levels on visual acuity. For example, Sturr et al. [21] found that visual acuity reduced when the luminance level was decreased from a high level (245.5 cd/m^2) to a low level (0.2 cd/m^2) for participants of different ages, whereas Lin [22] showed no significant influence on visual acuity in the case of narrow range of luminance patterns. The latter was confirmed by Tsang et al. [14], who reported no significant effect on visual lobe area and shape, and hence anticipated similar visual search performance when the luminance range was kept narrow. Moreover, Cardona et al. [23] compared the spontaneous eye blink rate of participants under three different screen luminance and text distortion scenarios while working at the video display terminal and achieved better blinking rate performance when the screen luminance was higher. In contrast, a considerable amount of research indicated that visual fatigue is triggered by higher screen luminance values [24–26], although better visual performance is achieved.

Several studies have also been conducted on contrast ratio. Lin [27] investigated visual performance under different contrast ratio and text color scenarios and found that subjects performed better at higher contrast ratios whereas text color did not significantly affect visual performance. Ayama et al. [28] studied the legibility of Japanese texts presented on video display terminal and found that the readability for all characters was improved as the contrast ratio increased. In a similar study, Hasegawa et al. [29] studied the effects of different display contrast ratios on mobile phone screens and showed that legibility deteriorates as the contrast of display decreases. Wang and Chen [30] compared two different contrast ratios and obtained better visual acuity with 8:1 rather than 7:5. Likewise, Chen and Lin [31] also found higher subjective preference and increased visual recognition with a higher contrast ratio. Moreover, Tsang et al. [32] suggested an acceptable contrast range of 26:1 to 41:1 for visual search tasks.

In the literature, the effects of a variable screen luminance on the visual performance, comfort and health issues have been strongly focused; however, it should be further investigated how displays are influenced by multiple screen specifications such as display type, size, manufacturer and hours of use. In addition, to the best of our knowledge, few studies have examined the display performance of new technology screen types rather than comparing conventional CRTs to advanced LCD-TFFs, few studies have been conducted in accordance with the visual ergonomics requirements mentioned in the standards. To this purpose, this study was undertaken to characterize the display devices commonly used for computer activities, with a measurements campaign of 57 laptops having different specifications such as manufacturers, sizes and hours of use. This characterization was carried out in accordance with the EN ISO 9241-3xx series of international standards on the requirements and methods for evaluating displays in the context of human-system interaction. The main aim of this study is to characterize the performance, in terms of ergonomics of human-system interaction, and of displays that are commonly used for computer activities. With this study the authors intend to contribute to fill some gaps currently present in the scientific literature. The novelties of the study are: the creation of a database of displays performances for a significant group of laptops, based on the lighting parameters able to condition the interaction between the device and the user's vision; the development of an original simplified tool, which allows a quick assessment of laptops according to the international standards. The database can be useful for all researchers studying the visual ergonomics of laptops, the proposed tool can be useful for researchers and experts in order to perform laptop evaluations in the early stage of workers' health and safety assessment. This study is part of a larger project on the evaluation of the visual ergonomics of displays. In the larger project, the workstations have been analyzed with different scales of detail and using different investigation methodologies from the measurements of specific lighting parameters [8,20] to the administration of questionnaires to investigate the habits and preferences of a sample of 150 university students [33].

2. Materials and method

At the international level, attention is currently focused on human-system interaction, with special interest to the ergonomic requirements for office work with the display terminals that have been collected in the EN ISO 9241 series of international standards. In detail, the ergonomics of human-system interaction in relation to the requirements of electronic visual displays are dealt with in the EN ISO 9241-3xx sub-series. In these sub-series, several important parameters for the evaluation of visual ergonomic performance are introduced. Among those, the followings will be discussed: the display luminance, the luminance ratio, the contrast ratio, and the contrast non-uniformity.

2.1. Display luminance

Displays are required to guarantee, for the entire operational lifespan and in consideration of the ambient lighting where they are installed, a minimum value of luminance, which is needed to allow sufficient recognition of displayed information. In this respect, in the EN ISO 9241–307 [34] according to the display's technology (e.g. CRT, LCD) and the type of information predominantly displayed, the minimum and recommended luminance values that the display are introduced (see Table 1). For handheld devices, instead, EN ISO 9241–307 [34] introduces a minimum value of luminance according to the level (high, medium or low) of the visual display task.

2.2. Luminance Ratio

The Luminance Ratio (LR) is defined in the EN ISO 9241–303 [35] as follows:

$$LR = L_{Wmax}/L_{Wmin} \tag{1}$$

where L_{Wmax} and L_{Wmin} are respectively the maximum and minimum luminance values emitted by the display and measured in a predefined matrix (target white). Clearly, with $L_{Wmax} \geq L_{Wmin}$ it follows that $LR \geq 1$.

2.3. Contrast Non-Uniformity

Firstly, it is necessary to define the Contrast Ratio (CR) introduced in [35] as:

$$CR = L_W/L_B \tag{2}$$

where L_W is the higher luminance (luminance of the white element, for example, in the case of textual information, this element is generally the

Table 1
Requirements for LCD displays with predominant reproduction of artificial images [34].

Parameter	*Equation*	*Value*	
Display Luminance (L, cd/m^2)	-	*Minimum*	≥ 20
		Recommended	≥ 150
Luminance Ratio (LR)	(1)	*Maximum*	≤ 1.7
		Recommended	≤ 1.4
Contrast Non-Uniformity (C_{NU})	(3)	$C_{NU} \leq 50\%$	

background) and L_B is the lower luminance (luminance of the black elements, in the case of textual information these are generally the characters). It should be noted that on the surface of most of the displays available commercially, L_B is nearly constant while L_W varies considerably. Consequently, it is possible to determine several values for the contrast ratio and in particular to identify the maximum (CR_{max}) and minimum (CR_{min}) values needed in order to calculate contrast non-uniformity. Contrast must be as uniform as possible and commensurate with the visual task to be carried out.

The Contrast Non-Uniformity (C_{NU}) is defined as the unintended variations in contrast in the active area of the screen. C_{NU} values may be calculated using the following relation [35]:

$$C_{NU} = 1 - (CR_{min}/CR_{max}) = 1 - (L_{Wmin}/L_{Wmax}) \quad (3)$$

where $CR_{min} = L_{Wmin}/L_B$ and $CR_{max} = L_{Wmax}/L_B$, and where L_{Wmin} and L_{Wmax} are respectively the minimum and maximum luminance values of white targets. Targets are square or rectangular shaped areas on the display that identify the position in which the measurement is carried out. C_{NU} values are generally expressed as percentages.

In relation to the parameters indicated above, the requirements introduced for the LCD display and for intended use with the predominant reproduction of artificial images are indicated in Table 1. It should be noted that for the values of display luminance and Luminance Ratio there are two limit values, one value to be understood as a limit value that cannot be overtaken and the other as a recommended limit value that cannot be overtaken to obtain a better level of ergonomics of the vision. On the contrary, for the Contrast Non-Uniformity a unique limit value is indicated. Furthermore, the limit values of the display luminance should be understood as lower limit values, while the limit values of Luminance Ratio and Contrast Non-Uniformity has to be considered as upper limit values.

In this study, in order to characterize the display devices that are commonly used for computer activities, the results of an extensive luminance measurement campaign that was carried out on 57 laptops of different manufacturers and hours of usage are presented and discussed. This characterization was carried out in accordance with EN ISO 9241-3xx sub-series, which establishes the requirements and methods for evaluating the human-system interaction. [34,35].

2.4. Experimental set-up and procedure

The measurements were carried out inside a black test chamber in order to minimize any errors due to imperfect contact between the surface of the laptop display with the luminance probe. The measurements were repeated in two configurations: 100% Brightness (named B100) and 50% Brightness (named B50), because they represent the most frequent configurations according to previous research on a sample of 150 university students of the School of Engineering of Pisa [33]. It should also be specified that unlike the previous research on monitors for desktop PCs [20] in which the analyzed configurations were obtained by a combination of contrast and brightness, in this study the two configurations are obtained only by brightness settings. This difference is because in laptops the adjustment of brightness is very rapid (often adjustable through quick commands obtained from keyboard key combinations), while contrast adjustment is much less frequent and less rapid as it requires the use of specific applications.

The luminance measurements on the display surface must be carried out by measuring the luminance in predefined positions (target) both with a model having white targets on a black background and with a model having black targets on a white background (see Fig. 1). The measurements must be carried out by placing the luminance probe perpendicularly to the display surface and ensuring that the target area should be at least 100% larger than the measurement area of the luminance meter. Prior to conducting the measurements, in accordance with the recommendations of EN ISO 9241–307 [34], the artificial lighting system inside the test chamber was turned off and the windows were completely screened. Furthermore, in accordance with the recommendations of EN ISO 9241–306 [36], the display surfaces were cleaned and the display luminance was allowed to stabilize by waiting at least 20 min after power on. For both configurations (B100 and B50), the measurements of luminance were carried out by displaying a measurement pattern on the display (see Fig. 2).

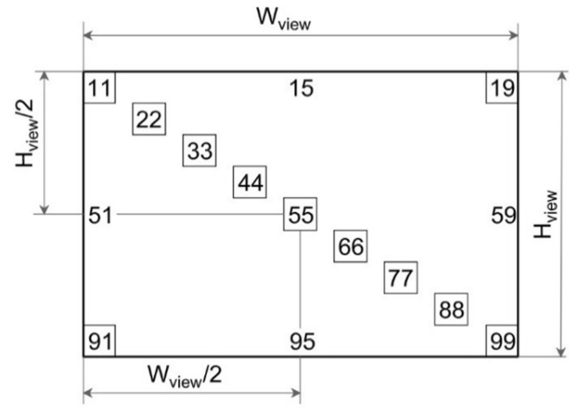


Fig. 1. Pattern used for luminance measurements [36]

The used measurement pattern shown in Fig. 2 is composed by 11 white targets and 2 black targets because the luminance on white areas (high luminance) generally present relevant variations, on the contrary the luminance on black target (low luminance) does not present significant variations. It is necessary to observe that the human eye adapts to the average luminance value in the visual field, and that the minimum perceptible percentage deviation is 1–2% of the average value [37]. Therefore, the variations in luminance in black targets, below 2 cd/m^2, can be considered as not perceptible by the human eye, when in the visual field there are white targets with high luminance values (even higher than 300 cd/m^2).

2.5. Sample of analyzed laptops

The measurements were carried out on a sample of 57 laptops of three different types (i.e.: LCD, LED and Retina) from different manufacturers, with different usage times. The laptops used for the investigations were made available by the students of the Master Degree in 'Building Engineering' at University of Pisa, who attended lectures of 'Lighting and Applied Acoustics' in the academic year 2018–2019. In the selection of laptops, the purpose was made to have a large number of

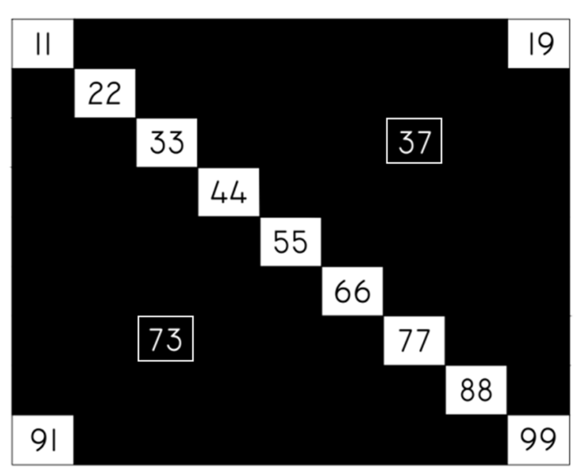


Fig. 2. Pattern used for luminance measurements with indicated the various target points [20].

displays with different characteristics and hours of use in order to verify the results of the survey on different displays (i.e.: manufacturers, technologies and hours of use). In this regard, it should be considered that the main aim of this study is not to establish which types of displays best meet the regulatory requirements but to collect performance data, that can be useful to the scientific community, and to test the simplified tool, proposed and described in Section 5 for an early assessment of the display requirements.

All the analyzed displays were liquid crystal displays, but showed some manufacturing differences. The commonly called LCD displays are illuminated with small fluorescent sources generally located on the perimeter of the panel, the LED displays are also liquid crystal displays but backlit by LED sources, while the Retina displays are also liquid crystal displays IPS ("In Plane Switching") backlit by miniature LED sources that allow a higher screen resolution. In particular, 4 Retina displays, 12 LCD displays and 41 LED displays were evaluated; the latter today represent the most commonly used technology both in the displays of laptops and in monitors for stationary computers. The analyzed displays belonged to 11 different manufacturers, display diagonal size ranged from 13″ to 17″, and the hours of use were between 50 h and 42,000 h. The hours of use of the laptops were determined using freeware software *Cristaldiskinfo* [38] capable of reading the number of hours of use of the computer's hard disk. Considering that in laptops the display is integrated into the computer, it was possible to assume, with a good approximation, that the number of hours of operation of the hard disk was equal to the number of hours of operation of the display. In this regard, those laptops in which the display or hard disk had been replaced have been excluded from the sample. For these laptops, obviously, the number of hours of use of the hard disk did not correspond with the number of use of the display and the actual hours of operation of the display was unknown.

The distributions of the sample in the different types and in hours use ranges are reported in Fig. 3.

The measurements were carried out by using the photo-radiometer Delta Ohm HD2102.1. The HD2102.1 is a portable instrument, composed of a data logger with a large LCD display that can be connected with different probes in order to perform illuminance and luminance measurements across VIS-NIR, UVA, UVB and UVC spectral regions. For the display luminance measurements a LP471Lum2 probe was used having the following operating characteristics: suitable for contact measurements; measurement range from 0.1 to 1999.9 (cd/m^2); resolution 0.1 (cd/m^2); optical angle 2°; calibration uncertainty $< 5\%$; agreement with photopic response V(λ) $< 8\%$; instrument reading error $< 0.5\%$; temperature coefficient $\alpha < 0.05\%$ per K.

3. Results

The results of the luminance measurements carried out according to the procedure described above (for each target point identified in Fig. 2) are shown in Table 2 and Table 3. Furthermore, in Table 2 and Table 3, the maximum and minimum values recorded on the 11 white targets (11,22,33,44,55,66,77,88,99,19,91) are highlighted in bold black and red bold, respectively. Finally, in the last two columns the values measured on the black portions corresponding to targets 37 and 73 are shown. From these results, it can be observed that, especially in the B100 configuration, the display luminance varies significantly. In the B50 configuration, these variations are mitigated but still evident. From the luminance values recorded on the white targets in B100 configuration, it can be seen how frequently the maximum luminance values (bold black values) were mainly detected in the central area of the displays (target 33.44.55, 66.77) while the minimum luminance values (bold red values) were recorded in the perimeter targets (target 11.99.19.19). These considerations can also be considered valid for the B50 configuration (Table 3) despite being less evident.

4. Discussion

4.1. Display luminance

From the measurements of the luminance on the 57 displays, the values recorded on the white targets were initially analyzed. Two box plot charts were created: one for the B100 configuration (Fig. 4a), and one for B50 configuration (Fig. 4b). In these graphs for each display, a box plot was presented in accordance with the recorded luminance values and a black dot corresponding to the average value of the luminance detected on the white targets. In Fig. 4a and Fig. 4b, the minimum required and the recommended minimum values indicated in [34], are shown with a thick continuous line and a dotted line, respectively.

From the measurements of the average values shown in Fig. 4a, it was found that in the B100 configuration, all the displays met the minimum required value of 20 cd/m^2, and only 11 displays had an average value lower than the recommended 150 cd/m^2. If each single box plot is considered, it is possible to observe that luminance variations (difference between maximum and minimum luminance values) overcome very often 50 cd/m^2 and in few cases they overcome 100 cd/m^2, highlighting a poor uniformity of the luminance emitted on the display surfaces.

From the measurements of the average values shown in Fig. 4b, it was found that all the displays in the B50 configuration, with the exception of the first, met the minimum required value of 20 cd/m^2, while only one display had an average luminance value higher than the minimum recommended value of 150 cd/m^2. If each single box plot is considered, it is possible to observe that luminance variations have a more contained values, generally lower than 60 cd/m^2. Although characterized by more contained values of luminance variations, also the results obtained with the B50 configuration show a poor uniformity of the luminance emitted on the display surfaces. This is evident considering the percentage difference (Δ) defined as:

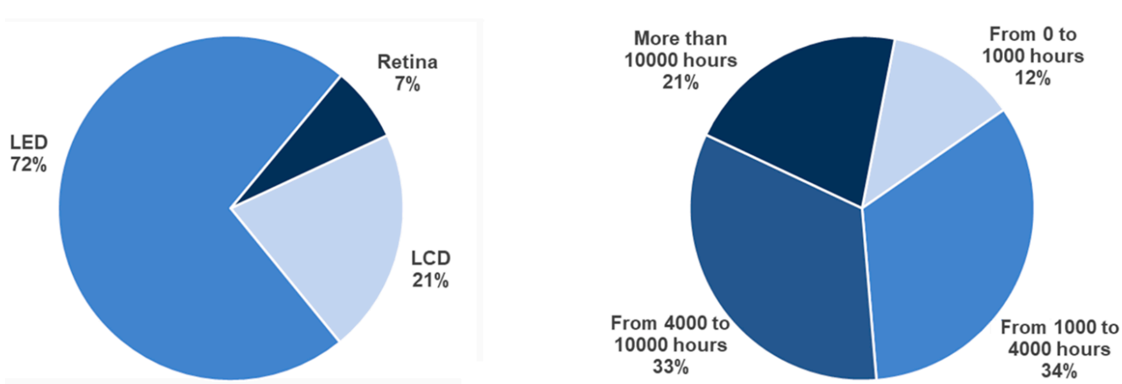


Fig. 3. Laptop distribution according to: type of display (left), and hours of usage (right).

Table 2
B100 configuration, measured values of luminance (cd/m^2), measurement positions according to Fig. 2.

Laptop ID	Measurement positions											
	11	**22**	**33**	**44**	**55**	**66**	**77**	**88**	**99**	**19**	**91**	**37**	**73**
1	95	103	**109**	104	101	99	96	99	**90**	108	104	0.8	0.7
2	255	279	292	**300**	297	274	259	246	256	261	**245**	0.7	0.7
3	273	317	329	333	**357**	347	350	325	297	**270**	278	0.9	0.8
4	283	307	326	326	**345**	331	302	286	**258**	288	259	0.9	0.9
5	227	237	220	223	215	226	231	233	226	**214**	**252**	1.3	1.4
6	115	**182**	172	170	171	170	169	158	116	**99**	108	1.0	0.8
7	218	222	**245**	221	240	235	233	237	232	172	**170**	1.5	2.4
8	**145**	164	146	**178**	170	165	165	146	167	147	155	0.8	0.9
9	121	130	149	155	**159**	154	147	121	**110**	118	126	1.0	0.9
10	86	91	97	94	**100**	94	89	**75**	80	83	90	0.5	0.8
11	**185**	170	170	160	160	156	158	169	**145**	160	180	1.5	2.0
12	173	216	226	229	220	**234**	229	201	177	**154**	202	1.3	1.3
13	**153**	207	214	209	187	181	192	197	**219**	155	207	1.1	1.1
14	**178**	274	301	311	**321**	306	296	260	231	264	222	0.8	0.8
15	**150**	185	202	194	**199**	180	189	182	168	163	177	1.3	1.2
16	192	215	233	235	**243**	234	242	218	218	157	**188**	1.2	1.2
17	224	**287**	270	282	283	270	272	273	285	**231**	237	1.3	1.7
18	**111**	185	193	204	**218**	205	196	160	115	116	118	0.7	0.2
19	130	160	185	191	**197**	**197**	186	182	156	**126**	157	0.7	0.6
20	180	190	200	204	**205**	195	190	**170**	172	184	193	1.5	1.1
21	110	110	115	114	**116**	104	112	112	106	107	**101**	2.2	3.2
22	242	249	**252**	242	**252**	235	230	206	**173**	186	246	1.2	1.3
23	196	195	208	211	210	**232**	222	198	**175**	193	180	1.1	1.1
24	220	226	**240**	211	227	216	222	213	220	188	**176**	1.4	1.8
25	315	355	372	385	**398**	380	359	325	303	**302**	326	1.3	1.2
26	**113**	128	146	**149**	142	130	127	124	118	114	117	0.7	0.7
27	**137**	186	201	213	**218**	213	205	190	165	141	177	1.4	1.3
28	**102**	111	130	**140**	134	130	129	118	111	107	111	1.3	1.5
29	187	180	197	206	169	**226**	216	209	187	192	**142**	1.4	1.3
30	**146**	228	248	**250**	241	216	240	226	167	222	181	1.6	1.8
31	**123**	141	205	206	222	**227**	226	224	181	162	173	0.8	1.1
32	264	265	269	299	**317**	293	267	252	246	250	**234**	0.8	0.7
33	78	92	**99**	**99**	95	86	78	78	87	**64**	86	1	1
34	**123**	143	155	**167**	160	158	150	146	140	126	147	0.9	1
35	**77**	110	113	**116**	**116**	110	106	111	80	83	80	0.7	0.7
36	226	238	235	253	**263**	**263**	239	240	216	211	**200**	1.1	1.1
37	**121**	133	132	147	162	173	183	192	**199**	164	125	1.1	1.7
38	194	210	227	204	**228**	216	220	217	**176**	180	178	1.7	1.3
39	190	222	245	253	**257**	253	248	227	156	**145**	148	1.2	1.2
40	181	205	226	228	**229**	220	219	208	195	178	**173**	0.9	0.8
41	194	234	249	**229**	228	213	218	207	199	**185**	194	1	0.9
42	**115**	142	148	137	138	**160**	155	159	138	117	138	0.9	1.2
43	213	262	266	216	**255**	249	246	233	192	**152**	182	1.3	1.2
44	298	356	366	358	**365**	352	343	319	268	306	**264**	1	1
45	250	541	256	**274**	273	258	236	220	208	246	**233**	0.9	0.8
46	284	314	340	**350**	347	326	323	310	279	**253**	263	0.3	0.3
47	**225**	200	197	187	181	180	182	189	195	**163**	253	1.2	1.2
48	168	185	**186**	181	165	168	170	162	161	**149**	154	0.8	0.5
49	226	250	258	268	**270**	263	248	220	179	227	**176**	2.1	1.7
50	246	292	300	309	349	**350**	343	307	243	**240**	268	1	1.1
51	250	231	253	240	**270**	250	245	230	260	**190**	240	0.7	1
52	275	304	350	**359**	348	337	315	280	255	**250**	300	0.7	1
53	**224**	196	186	195	204	199	186	183	186	**183**	198	1	1
54	240	231	248	245	245	247	**250**	247	215	201	**200**	1.6	1.6
55	**107**	165	179	190	204	207	**212**	206	168	117	175	1.2	1.3
56	196	**201**	185	184	186	194	184	163	**128**	129	200	1.3	1.3
57	**122**	130	134	134	**140**	138	135	131	130	**122**	124	1	0.9

$$\Delta = (L_{Wmax} - L_{Wmin})/L_{Waverage} \quad (4)$$

where $L_{Waverage}$ is the average value of the luminance measured on all the white targets. From the values of Δ, it is possible to observe that there aren't relevant differences between the results obtained using B100 and B50 configurations. The average values of Δ on all 57 display laptops is about 35% in both configurations and the maximum values of Δ are 65% and 72% for B100 and B50 configurations, respectively.

Fig. 5 shows the box plot graphs of each type of display of the average luminance measurements on the white targets obtained on each display in the two configurations. From the graph in Fig. 5a (B100 configuration) it can be observed that the Retina displays had average luminance values higher than the LCD displays and, in any case, greater than 75% of the measurements (3rd quartile) of the LED displays. The LED displays showed both the higher and lower values of the average luminance measurements of the whole sample, indicating a strong variability in the results. Similarly, the graph in Fig. 5b (B50 configuration) confirms the greater variability in the results obtained on the LED displays.

The average values of the luminance measured on the white targets of the 57 laptops together with the minimum value required and the minimum value recommended in [34], were collected in Fig. 6 according to the types of displays and hours of use. From these results, no strong difference was found between the display luminance and the hours of use.

Table 3
B50 configuration, measured values of luminance (cd/m^2), measurement positions according to Fig. 2.

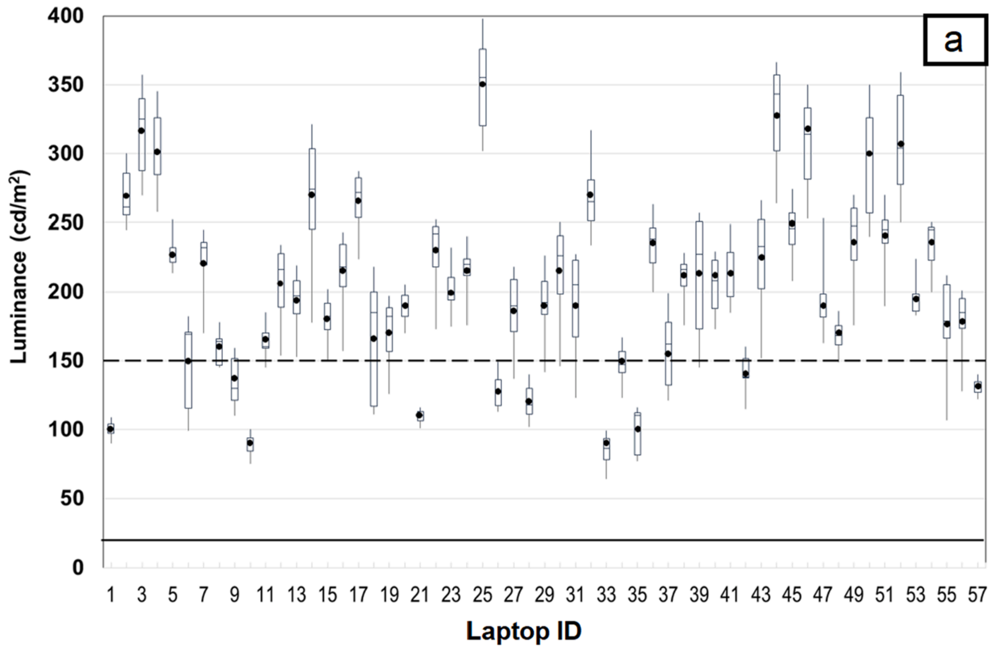
Laptop ID	Measurement positions												
	11	**22**	**33**	**44**	**55**	**66**	**77**	**88**	**99**	**19**	**91**	**37**	**73**
1	12	13	13	12	12	12	11	11	11	13	13	0.2	0.5
2	63	67	71	**73**	72	63	62	61	62	63	**60**	0.5	0.4
3	**72**	83	87	88	**94**	82	93	85	80	**72**	**72**	0.9	0.8
4	55	61	65	**67**	**67**	64	61	58	54	**53**	56	0.7	0.6
5	121	**130**	120	123	124	124	126	125	122	**117**	120	1.0	1.0
6	44	**66**	65	61	**66**	65	65	61	44	**39**	41	0.8	0.7
7	**83**	106	100	106	107	**110**	**110**	100	105	90	102	1.2	1.2
8	**48**	78	76	**85**	80	82	74	68	66	69	68	0.8	0.8
9	52	55	64	66	**69**	65	60	55	46	49	**43**	0.7	0.7
10	81	66	85	76	83	**87**	73	61	**56**	70	78	1.2	0.3
11	80	89	80	78	81	**78**	83	83	**78**	80	**96**	1.7	1.5
12	66	72	75	77	76	**78**	77	68	58	**57**	65	0.8	0.7
13	73	81	**85**	82	75	76	73	75	86	**61**	81	0.6	0.8
14	108	135	148	151	**155**	151	146	129	113	126	**105**	0.6	0.6
15	89	96	99	98	**103**	**84**	93	87	85	85	92	0.7	0.7
16	**75**	82	90	92	**94**	90	94	85	78	80	81	0.7	0.9
17	135	144	146	141	144	138	136	139	146	**118**	**170**	0.9	0.9
18	62	97	99	102	**113**	109	96	88	58	**52**	59	0.7	0.2
19	77	96	100	**101**	100	100	97	90	64	**55**	85	0.7	0.7
20	70	72	78	**79**	78	76	73	**67**	71	72	73	0.8	0.9
21	54	53	55	57	56	56	56	**59**	53	**43**	46	1.2	1.5
22	**66**	**66**	65	65	**66**	63	58	54	**43**	46	64	0.6	0.5
23	**70**	96	102	105	108	**113**	100	96	82	90	90	1.2	1.0
24	108	121	**117**	114	113	103	104	98	108	**90**	93	0.7	0.8
25	64	71	74	**79**	78	76	72	63	56	**53**	68	0.5	0.6
26	**51**	65	74	**76**	74	71	69	58	53	62	54	0.7	0.8
27	86	98	104	111	112	**109**	105	102	90	**64**	90	1.0	1.0
28	59	68	80	**84**	81	80	80	74	71	65	66	1.1	1.2
29	67	74	84	90	92	**93**	87	81	73	**66**	**66**	0.8	0.9
30	**72**	113	**131**	**131**	**131**	117	114	110	83	113	92	1.6	1.2
31	**48**	80	83	**95**	76	93	94	85	71	56	63	0.7	0.7
32	38	40	43	46	**49**	45	41	39	32	40	**33**	0.6	0.7
33	**29**	45	48	**49**	45	43	41	41	43	32	40	0.7	0.7
34	70	72	80	**85**	80	80	77	75	71	**66**	74	0.6	0.8
35	**33**	47	48	**49**	**49**	46	45	47	34	35	34	0.4	0.5
36	98	101	98	98	102	101	97	94	83	**106**	**72**	0.7	0.7
37	74	79	85	89	98	108	**109**	108	112	95	**63**	1.2	1.3
38	79	87	93	91	**98**	92	**98**	86	**67**	69	74	0.8	1.2
39	**42**	48	63	66	**67**	64	60	59	51	54	50	0.8	1.1
40	**78**	95	103	**106**	105	101	101	95	90	84	80	0.6	0.6
41	**95**	115	**118**	**118**	117	108	110	106	100	99	99	0.8	0.9
42	38	34	43	43	46	**47**	**47**	40	40	**34**	40	1	0.7
43	**62**	74	**62**	**78**	75	75	73	72	68	**62**	63	0.7	0.7
44	59	72	75	73	**76**	71	70	64	53	**52**	53	0.7	0.7
45	129	126	136	141	**146**	141	125	**112**	113	127	121	0.7	0.7
46	148	160	177	**182**	180	161	170	**182**	148	154	**140**	0.1	0.1
47	116	102	100	96	95	89	93	97	93	**83**	**127**	0.6	0.5
48	**75**	72	70	74	66	70	**63**	70	64	**63**	**63**	0.5	0.5
49	54	62	68	72	**74**	71	65	60	54	58	**48**	0.5	0.5
50	**47**	57	62	66	**70**	**70**	69	62	49	**47**	54	0.7	0.7
51	57	55	62	65	**71**	66	60	55	64	**53**	**53**	0.7	0.5
52	56	60	64	**69**	67	64	61	56	46	**55**	58	0.7	0.5
53	**113**	101	**85**	92	101	93	97	94	107	93	108	0.8	0.8
54	90	90	**96**	93	94	95	94	92	**80**	83	81	0.7	0.7
55	**63**	98	105	111	116	122	123	**124**	96	70	102	0.8	0.8
56	54	69	**70**	**70**	60	68	62	56	**53**	60	68	0.8	0.8
57	**27**	28	29	30	31	30	29	29	28	31	**33**	0.6	0.6

The luminance values recorded, especially for the B100 configuration were particularly high for most devices. Therefore, these devices can also be used in conditions of high levels of illuminance and luminance, however, it is very important that the Brightness levels are set appropriately according to the lighting conditions of the workplace (using the laptop) in order to avoid large differences between the luminance of the display with that of the surrounding environment.

The difference between the luminance values obtained for the three types of displays was also analyzed through the two-tailed *t*-test for independent samples (see Table 4). A *t*-test of each pairwise comparison was carried out between the three types of average luminance displays in the two configurations (B100 and B50). For each comparison, the Levene's Test for Equality of Variance was preliminarily carried out and from which it was always found that the equal variance cannot be assumed. As shown in the last column of Table 4, comparisons between Retina displays and LED displays and between Retina displays and LCD displays in the B100 configuration showed significant differences with p-value ≤ 0.01.

4.2. Luminance Ratio

The second analyzed parameter is the Luminance Ratio; therefore, equation (1) was applied to the luminance measurements recorded in the two tested configurations (Tables 2 and 3). The results obtained were



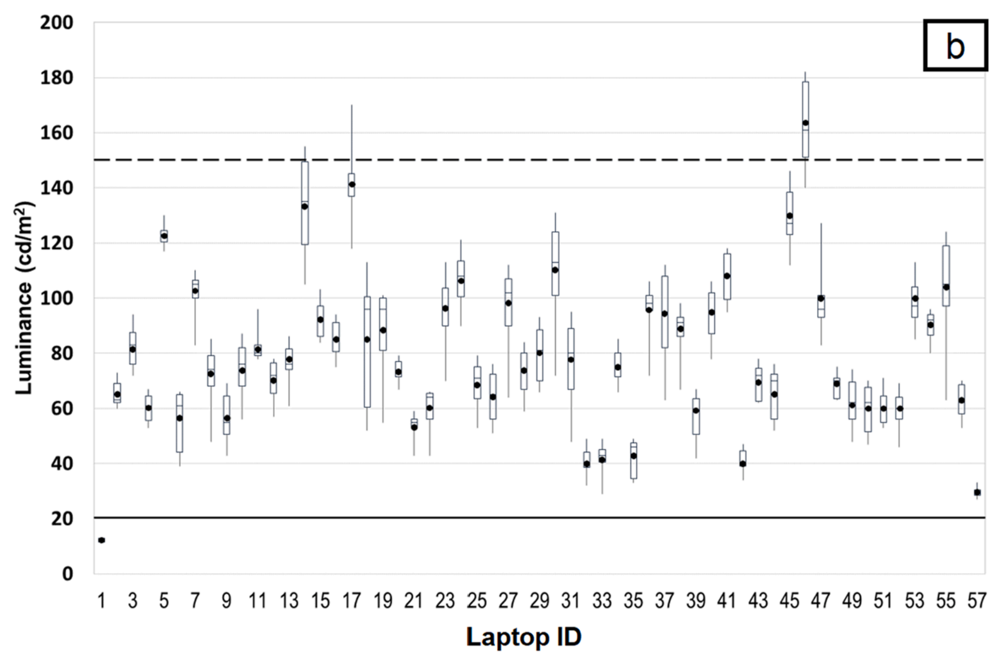


Fig. 4. Box plot of luminance values measured on white targets in (a) B100 configuration and (b) B50 configuration, the minimum required and recommended values indicated in [34] are shown with horizontal lines, a continuous and dotted respectively.

represented in relation to the type of display in the Box plots of Fig. 7 and then in relation to the hours of use in Fig. 8.

From the results of Fig. 7, it can be observed that most of the displays met the maximum required level (LR $<$ 1.7) and that in the transition from B100 configuration (Fig. 7a) to B50 configuration (Fig. 7b) there is a slight deterioration of the results. Analyzing the results of the individual types of displays, it can also be observed that all Retina displays met the maximum required level (LR $<$ 1.7) in both configurations. In addition, in the B100 configuration three quarters of the sample showed results lower than the maximum recommended value (LR $<$ 1.4). As far as LED displays are concerned, about half of the sample met the maximum recommended value in both configurations, however, in B50 configuration the largest LR value of the whole analyzed sample was recorded (LR $=$ 2.2). LCD displays perform worse than the other two types with less than half of the displays meeting the maximum recommended value. For this type, the results when switching from one configuration to another were almost unchanged. From the results of Fig. 8, it can be observed that there was no deterioration of the LR values with the increase in the hours of use. However, it is important to note that some devices, despite having very few hours of use, did not meet the maximum required values of LR, and several devices did not meet the recommended values of LR.

4.3. Contrast non-uniformity

The third analyzed parameter is the Contrast Non-Uniformity (C_{NU})

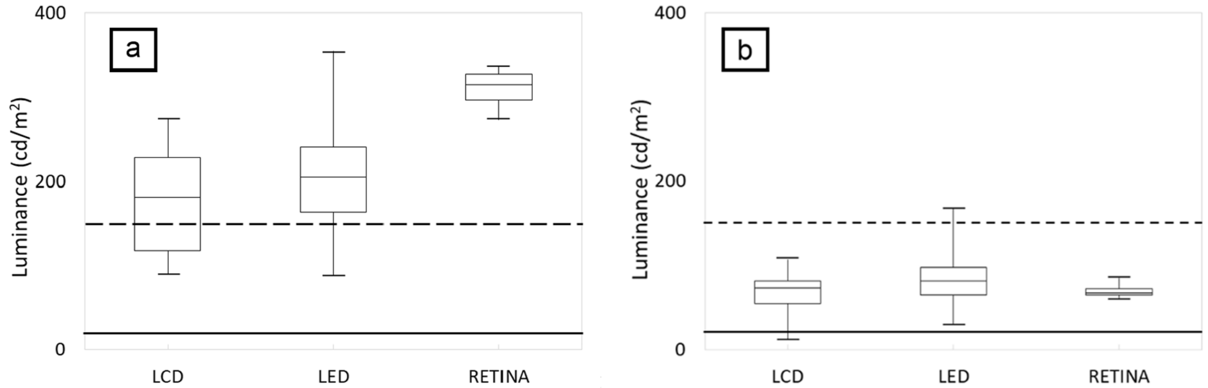


Fig. 5. Box plot of the average luminance values relating to the types of displays in (a) B100 configuration and (b) B50 configuration, the minimum required and recommended values indicated in [34] are shown with horizontal lines, a continuous and dotted respectively.

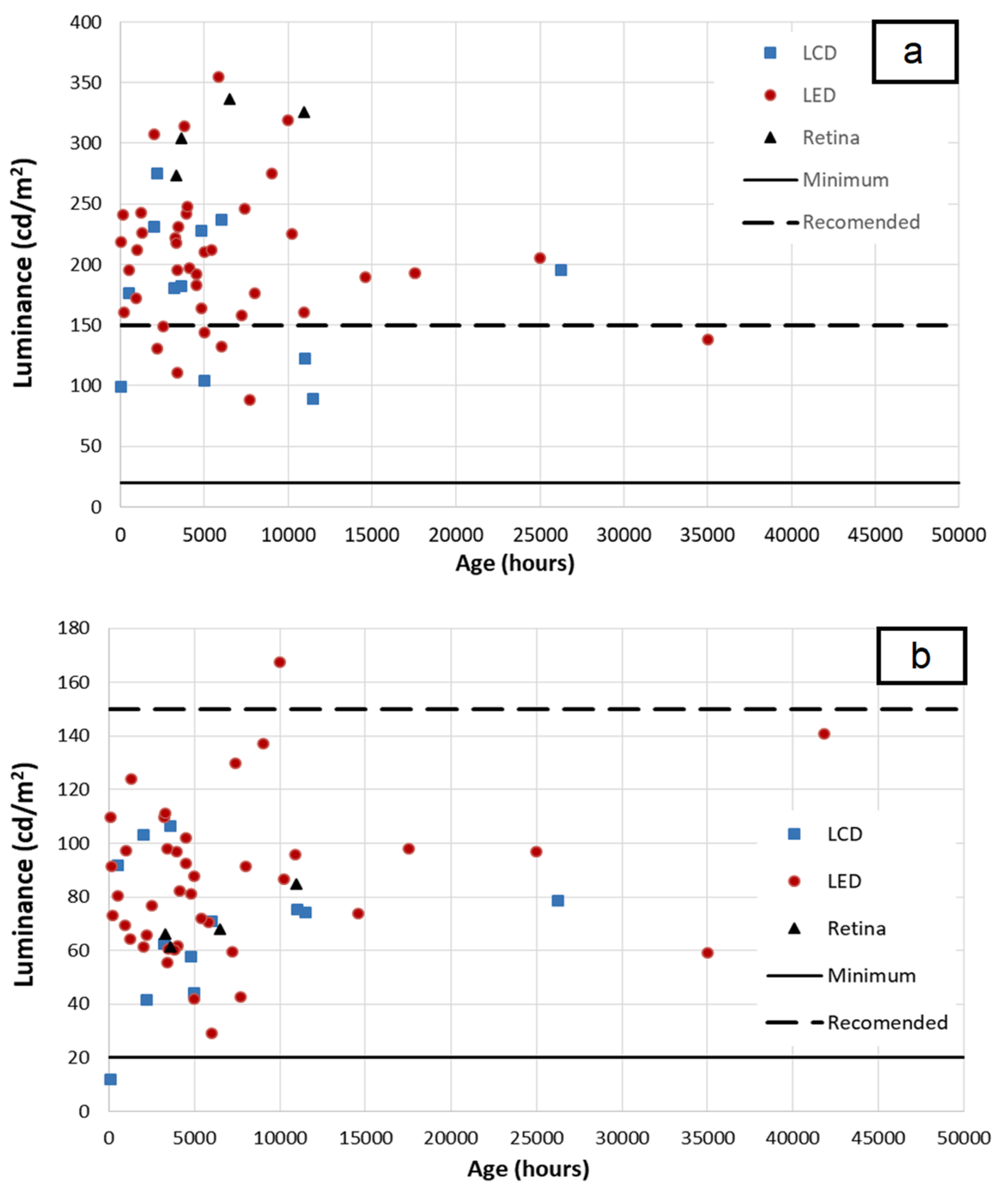


Fig. 6. Average luminance on the laptop displays in relation to the hours of use in in (a) B100 configuration and (b) B50 configuration, the minimum required and recommended values indicated in [34] are shown with horizontal lines, a continuous and dotted respectively.

Table 4
Results of two-tailed *t*-test for independent samples to analyzing the differences in luminance values.

B100 configuration					
	t	**df**	**Mean Difference**	**Std. Error Difference**	**Sig. (2-tailed)**
LED - LCD	−1,513	17,162	−29,90335	19,76855	**0,149**
LED - Retina	−6,237	5,969	−103,09415	16,53073	**0,001**
Retina - LCD	5,933	11,975	132,99750	22,41514	**0,00007**
B50 configuration					
	t	**df**	**Mean Difference**	**Std. Error Difference**	**Sig. (2-tailed)**
LED-LCD	1,955	19,139	17,11970	8,75639	**0,065**
LED -Retina	2,362	9,031	15,77220	6,67773	**0,042**
Retina - LCD	0,148	13,344	1,34750	9,07578	**0,884**

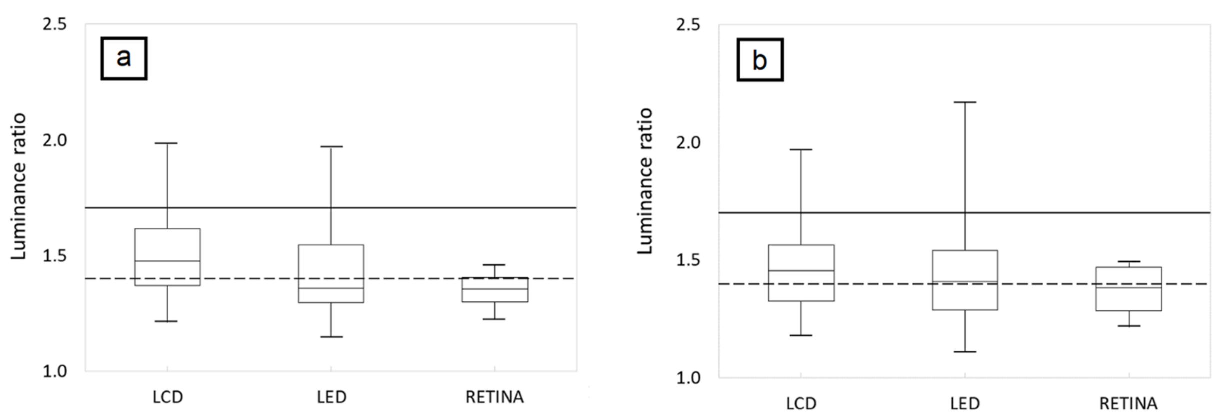


Fig. 7. Box plot of the Luminance Ratio obtained for the different type of displays in (a) B100 configuration and (b) B50 configuration, the minimum required and recommended values indicated in [34] are shown with horizontal lines, a continuous and dotted respectively.

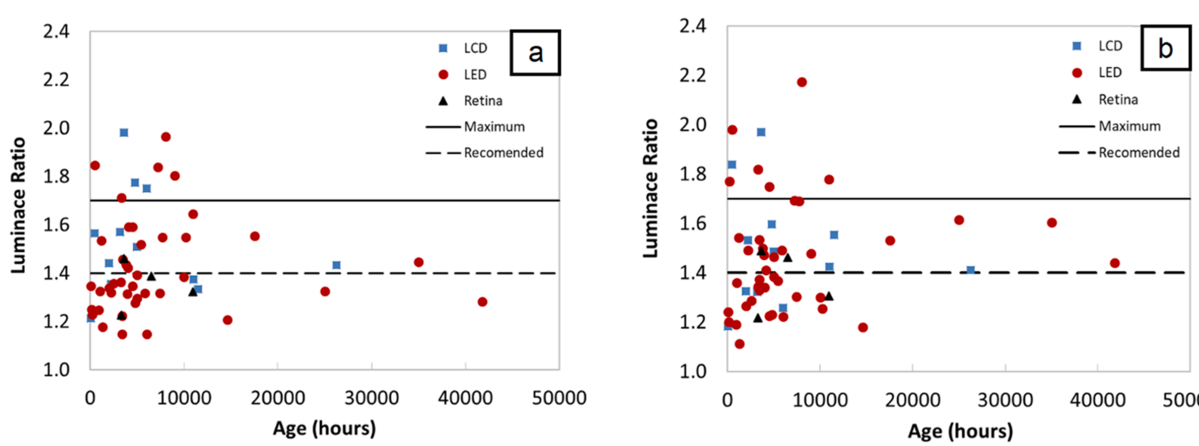


Fig. 8. Results Luminance Ratio and age of the displays in (a) B100 configuration and (b) B50 configuration, the minimum required and recommended values indicated in [34] are shown with horizontal lines, a continuous and dotted respectively.

in accordance with equation (3). Maximum and minimum Contrast Ratio were calculated for each display and then the C_{NU} value was determined. The results of these calculations are summarized in Fig. 9 and Fig. 10. From the results shown in Fig. 9 it can be observed that a single display in the B50 configuration does not satisfy the maximum C_{NU} limit ($C_{NU} \leq 50\%$), while all the other results satisfy this requirement.

On the other hand, Fig. 10 shows the results of C_{NU} in relation to the hours of use of the displays; similarly to what was observed for the Luminance Ratio, there is no significant reduction in the C_{NU} values with the increase in hours of use.

5. "Combined verification chart" of luminance Ratio and contrast Non-Uniformity

In order to facilitate the verification of Luminance Ratio (LR) and Contrast Non-Uniformity (C_{NU}) requirements, a simplified chart was created which contains both the limit values of LR and the limit values of C_{NU}, and which can be used to know the maximum and minimum luminance on the white targets (L_{Wmax}, L_{Wmin}). This chart was created starting from the definitions of LR and C_{NU}, and assuming that the L_B luminance of the black pixels is almost constant (acceptable simplification; the mean absolute difference between the luminance values of the black targets of each display is equal to 0.17 cd/m^2). It can be observed that, with this simplification, both parameters depend exclusively on the maximum and minimum luminance measured on the white

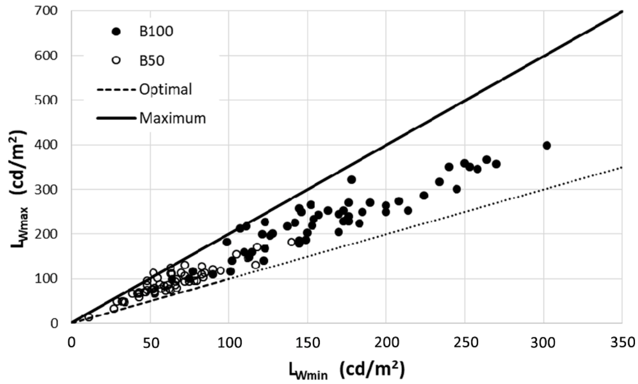


Fig. 9. Contrast Non-Uniformity of the whole sample of displays in both tested configurations.

patterns (L_{Wmax}, L_{Wmin}). It is therefore possible to represent the maximum and recommended values of LR and C_{NU} in a single graph (Fig. 11a).

In Fig. 11a are shown: the black line continues the trend of the limit line obtained by setting C_{NU} equal to 50% (maximum allowed value); the continuous grey line obtained by setting LR equal to 1.7 (maximum allowed value); the dashed grey line obtained by setting LR equal to 1.4 (maximum recommended value); the grey dotted line obtained by setting the best possible ratio or $L_{Wmax} = L_{Wmin}$ which represents the ideal condition in which the luminance is constant over the entire surface of the display.

From these four lines, it is possible to identify five zones: zone A represents the cases in which neither the requirement on the C_{NU} nor that on the LR (unacceptable operating zone) are met; zone B represents the cases in which the condition on the C_{NU} is satisfied but not that on the LR (No LR); zone C represents the cases in which the verification on the C_{NU} and on the maximum LR is satisfied, even if the values of LR are greater than the recommended value (intermediate zone); zone D represents all cases in which all the conditions relating to both the C_{NU} and the LR are met (optimum operating zone); finally zone E is a zone that is not possible since it would represent the conditions in which $L_{Wmax} < L_{Wmin}$ (error in data acquisition).

In Fig. 11b, each dot is the combination of the maximum and minimum luminance measured on the white targets in the two combinations B100 (full dots) and B50 (empty dots). From this graph, it is possible to quickly observe how many measures have met the requirements of Luminance Ratio and Contrast Non-Uniformity in accordance with [34].

For a better understanding, the results showed in Fig. 10b were collected in Table 5 in order to quantify exactly how many measures fell in each of the four areas of the schedule and then to quantify how many measures met the different requirements. In total, 50% of the measurements provided satisfactory values for both the C_{NU} and the recommended LR value, 36% fell in zone C, 36% in zone B and only one device fell in Zone A in B50 configuration.

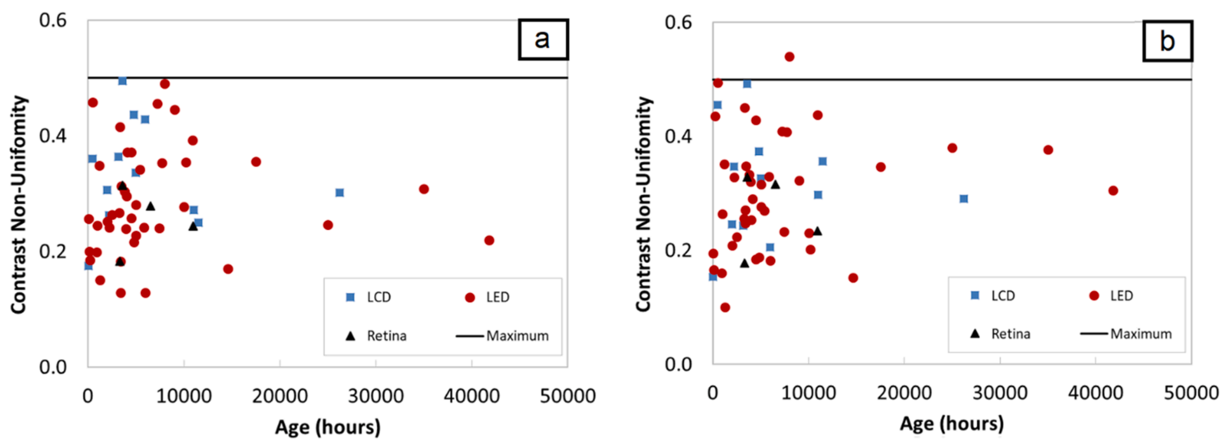


Fig. 10. Contrast Non-Uniformity and age of use in (a) B100 configuration and (b) B50 configuration, the maximum required value indicated in [34] is shown with horizontal continuous line.

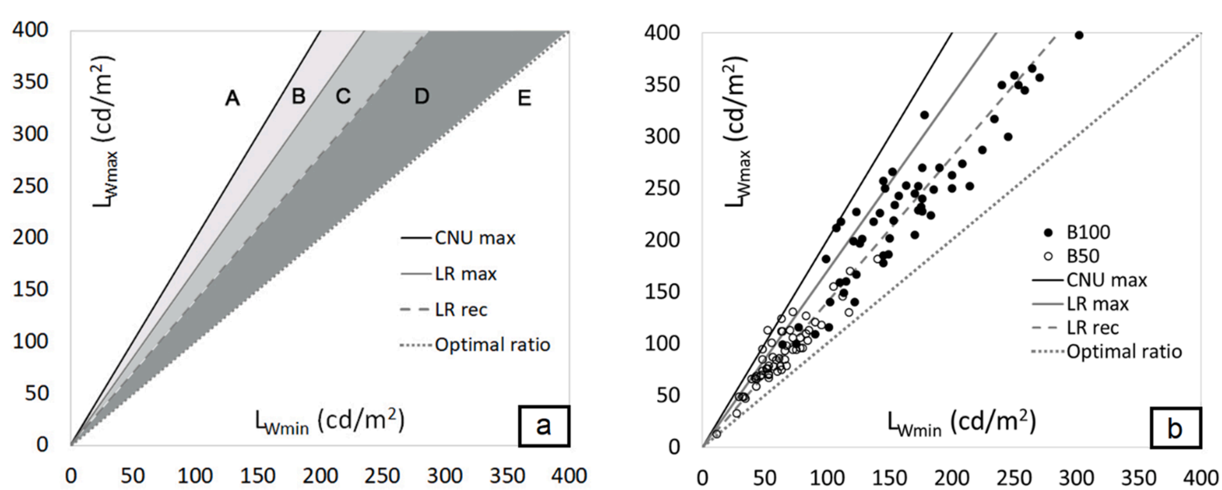


Fig. 11. Combined Verification chart: (a) scheme, and (b) with the results obtained with the whole sample of displays in both configurations.

Table 5
Laptop display distribution in the zones of the Combined Verification chart LR e C_{NU}.

Configuration \Area	A Nr. (%)	B Nr. (%)	C Nr. (%)	D Nr. (%)	Total Nr. (%)
ALL	1 (0.9%)	15 (13.1%)	41 (36.0%)	57 (50.0%)	114 (100%)
B100	0 (0.0%)	8 (14.0%)	18 (31.6%)	31 (54.4%)	57 (100%)
B50	1 (1.8%)	7 (12.3%)	23 (40.3%)	26 (45.6%)	57 (100%)

6. Conclusion

The results showed in this study are part of a larger project on the evaluation of the visual ergonomics of workstations with video display terminals, where these workstations have been analyzed using different scales of detail and using different investigation techniques. Specifically, this study examined the performance of a sample of 57 laptop displays in accordance with the requirements of the international standards. An extensive luminance measurement campaign was carried out using a special pattern that allowed us to measure the luminance in 13 different areas of the displays.

The results obtained in this study showed a great luminance variability between different displays. The high luminance values, especially in the configuration with the brightness set to 100%, demonstrated that most displays can also be used in such environments characterized by high levels of luminance and illuminance in which there is a considerable amount of natural lighting. However, it is extremely important that the brightness levels are appropriately adjusted (reduced) when the device is used in normally or dimly lit environments (medium or low illuminance levels) in order not to create luminance contrasts between the display and the surrounding and generate problems of visual fatigue. From a previous survey of a sample of 150 university students of the School of Engineering of Pisa, it can be seen that these aspects are generally underestimated by the laptop users, who should be particularly sensitized to pay attention the differences in lighting between the surfaces where the visual tasks take place and the surrounding environment.

Analyzing the discussed displays parameters, some devices, despite having very few hours of use, did not meet the maximum required values of Luminance Ratio, and several devices did not meet the recommended values of Luminance Ratio. On the contrary, almost all the displays meet the requirement of Contrast Non-Uniformity. Regarding the time of use, no significant changes in performance were found in terms of parameters evaluated with the increase hours of use. However, it should be noted that only 20% of the analyzed devices had more than 10,000 h of use, so further investigations with a larger display sample are needed.

Furthermore, given that in previous studies carried out by the authors "*the importance of realizing a simple and quick procedure to determine the performance level of the monitors*" had emerged, in this study a simplified tool, based on a chart, to allow a rapid assessment of the display performance is proposed. This kind of assessment could be periodically repeated in order to evaluate the residual performance level. If the laptops are used in the workplaces, this chart could be used as a simplified tool for staff assigned to assess the risks arising from video display terminal use in the workplace within the Occupational Health and Safety Assessment Procedure. Similarly, if the laptop is used for personal use, but still extensively (e.g. for study purposes), these evaluations could still be carried out in order to verify the performance of the device also given the greater variability of the typical conditions of use in which a mostly the variation of brightness configurations.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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