Lighting Research and Technology

http://lrt.sagepub.com

Inner contrast and perceptual quality in tasks with video display units

Beatriz M O'Donell Magister and Elisa M Colombo

Lighting Research and Technology 2001; 33; 145
DOI: 10.1177/136578280103300302

The online version of this article can be found at:
http://lrt.sagepub.com/cgi/content/abstract/33/3/145

Published by:
SAGE
http://www.sagepublications.com

On behalf of:

The Society of Light and Lighting

Additional services and information for *Lighting Research and Technology* can be found at:

Email Alerts: http://lrt.sagepub.com/cgi/alerts

Subscriptions: http://lrt.sagepub.com/subscriptions

Reprints: http://www.sagepub.com/journalsReprints.nav

Permissions: http://www.sagepub.co.uk/journalsPermissions.nav

Citations http://lrt.sagepub.com/cgi/content/refs/33/3/145

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Lighting Res. Technol. 33,3 (2001) pp. 145–161

Inner contrast and perceptual quality in tasks with video display units

Beatriz M O'Donell Magister MSc and **Elisa M Colombo** Dra PhD
Departamento de Luminotecnia, Luz y Visión 'Ing. Herberto C. Bühler', Tucumán, Argentina

Received 5 July 2000; in final form 10 March 2001

The purpose of this paper is to find the physical luminance contrast of an image that best relates to perceptual quality in VDU achromatic tasks. The studies were carried out by measurement of visual performance, comfort judgements and contrast adjustment, taking into account different resolutions, polarities, background luminances and illuminance values. The results add a new piece of evidence about inner contrast as an appropriate criterion to describe perceptual contrast. Inner contrast also provides a satisfactory criterion for the optimum relation of luminances in inner details of characters. This paper shows that when the relation between suprathreshold perceptual response and stimulus magnitude – inner contrast – is plotted, the power function relationship is a curve that is concave downward; there is a compression of the perceptual response. Illuminance on the horizontal plane, within the experimental range (480 and 930 lux) is not a significant parameter. Background luminance is significant for comfort judgements and contrast adjustment trials, but not for visual performance results. Grey background and characters brighter than background seem to be preferred by the observers. Mean luminance contrasts higher than 5 are sufficient to reach a visual performance of 90% and good visual comfort. The corresponding inner contrast is 1.4.

1. Background

The fast developments in display and image technology in general have caused a growing interest in the fundamental aspects of perceptual image quality. Perceptual quality of images can be defined in terms of its degree of excellence.[1] It can also be considered as a function on a multidimensional psychological space, where the main dimensions are perceptual attributes comprising brightness contrast, sharpness and colour appearance. These perceptual attributes are, in turn, determined by one or more parameters from physical space, such as luminance contrast, colour contrast, monitor resolution, spatial frequency distribution and spectral reflectance or transmittance of the stimulus.

The concept of image quality cannot be considered separately from the purpose the image was generated for, so it is useful to make a distinction between comfort oriented and performance oriented image quality evaluation. It is a common experience in performance research that people complain about the conditions in a situation which, it has been found, have no detrimental effect on task performance. Considerable effort has been devoted to developing general techniques for assessing the image quality, and then finding a psychophysical model that relates the salient physical features of the image to perceptual features.

It is possible to find ways to study perceptual quality (for a review, see Roufs and Boschman[1]) which are sufficiently sensitive under suprathreshold conditions; these methods are

Address for correspondence: Beatriz M O'Donell, Departamento de Luminotecnia, Luz y Visión 'Ing Herberto C Buhler', (4000) Av. Independencia 1800, Tucumán, Argentina. E-mail: bodonell@herrera.unt.edu.ar

© The Chartered Institution of Building Services Engineers 2001 1365–7828(01)LI010OA

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

based on measurements of objective and subjective variables. The former are related to visual performance in tasks such as numerical verification, search rate, fixation duration, saccade length for eye movements and reaction time for word identification. On the other hand, subjective variables are reflected by visual comfort measures such as numerical category scaling.

For most VDUs, the characters of the display are constructed from a matrix of dots – pixels. By turning on different pixels in the luminous array, different characters can be generated. The number of pixels in the matrix determines the resolution of the display.

The luminance of a display consists of an emitted component and a reflected one. These components are different in their spectral distributions and in their time modulations. In this paper we did not consider colour effects.

There are two VDU display modes or polarities: the positive, where bright characters are displayed on a dark background, and the negative, where dark characters are displayed on a bright background.[3]

There is no doubt that one of the most significant variables influencing perceptual quality is the contrast of the stimulus forming the task. Nevertheless, various definitions[2] of luminance contrast exist for the stimuli of VDU (Video Display Units) and the choice depends upon the kind of problems at hand. This diversity of definitions of contrast is explained by the complex relationship between luminance and brightness, that is, between physical and perceptual variables.

The mean contrast (K) is defined as the mean luminance ratio between the whole character (L_c) and its background (L_b). For positive polarity – character brighter than background – the equation is:

$$\text{Mean contrast } K = \frac{L_c}{L_b} \qquad (1)$$

For negative polarity – character darker than background – the contrast definition is the reciprocal of Equation (1).

The VDU character is a non-homogeneous luminance distribution. Because of this non-homogeneous distribution, it is not clear how to define character luminance. In terms of mean contrast, the luminance of the character is assumed to be expressed in terms of a mean luminance, which can be determined either by numerical integration of the luminance profile or very easily with the aid of a full matrix character using a conventional luminance meter.[3,4] The difficulty of using this definition lies in the fact that there is no accepted specification of the location and spatial extent of the area where the character luminance should be measured.[2,4] Moreover, the mean contrast can characterize the visual task difficulty only as a first approximation. It does not represent the actual character visibility, as it gives no information about the character details either.

For instance, we can consider the luminance profile shown in Figure 1. We can see that simple details such as line elements can be characterized by different values of local luminance such as the peak luminance (L_m) and the background luminance (L_b). But critical character details such as

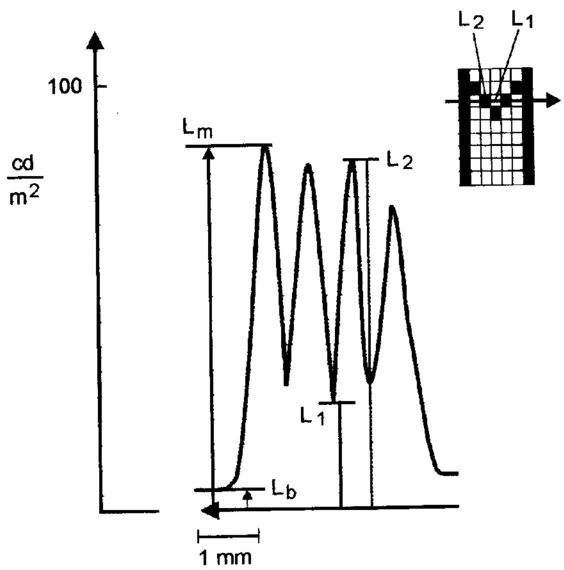

Figure 1 Typical luminance profile of the complex details of the character M, horizontal scanning. The scanned profile shows a typical configuration 'pixel on' – gap – 'pixel on'.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

the edges or inner parts of characters can be specified in terms of at least three luminances: the background luminance L_b and two others luminances, L_1 and L_2, the luminances which define the critical details. The inner part of the character **M**, which consists of alternating *on* and *off* dots, has been shown to characterize critical VDU details.[4]

The luminance modulation of the raster is theoretically and experimentally analysed by Kokoschka,[4] resulting in the definitions of local inner and local outer contrasts. For positive polarity – character brighter than background – they are:

$$\text{Local Outer Contrast } K_o = \frac{L_m}{L_b} \qquad (2)$$

$$\text{Local Inner Contrast } K_i = \frac{L_2}{L_1} \qquad (3)$$

For negative polarity – character darker than background – the contrast definitions are the reciprocal of Equations (2) and (3).

Kokoschka[4] showed that it is possible to predict the perceptual contrast of VDU characters using the concept of inner contrast of critical character details, based upon detection, identification and search tasks using a VDU with normal resolution.

The data analysed by Roufs *et al.*,[1] from objective and subjective measurements, using search tasks and a numerical category of scaling of visual comfort, on normal and high resolution display units, showed that these responses initially rise rapidly with the luminance contrast ratio, then level off and decrease again at high contrasts. However, he associates the responses with outer contrast as the parameter which represents the best perceptual contrast.

Finally, in the case of displays with higher resolution, it is not clear if preferred contrast values lie outside the CIE recommended range,[2,4] or if inner contrast will be a good criterion for perceptual quality.

All these arguments show the complexities of the problem at hand and the need to study it more systematically. The purpose of this paper is to add one more piece of evidence about inner contrast as an appropriate criterion for describing the perceptual contrast of VDUs by considering different resolutions, illuminances, polarities and background luminances. The experiments involve visual comfort, visual performance measurements and trials where the observers had to adjust the contrast of characters. This will be explained later.

2. Methods and procedures

2.1 Experimental room

All measurements were taken in a simulated, windowless 7 m × 3 m office, with a wall reflectance of 0.5.

The VDU was placed in the centre of a 760 mm high table, with a reflectance of 0.5. The line of sight met the top of the screen and the viewing distance was kept constant at 0.60 m throughout the experiment. The test stimuli was displayed on a high-resolution colour monitor.

In order to provide the illumination within the experimental room, the luminaires used were faceted aluminium batwing reflectors with transverse blades. The lamps used were 36 W warm-white fluorescent lamps. The luminaires were mounted 2 m above the desk and parallel to the line of sight but displaced to either side. This geometry provided high uniformity of illuminance with minimal ceiling reflections and body shadow on the VDU screen.

A switching system was used to obtain the two illuminances used in the experiment: 480 lux and 930 lux, measured on the horizontal plane at the centre of the desk.

2.2 Task and stimuli

The numerical verification task, used in this experiment, was developed by Smith and Rea[5,6] to assess the impact of task luminance and target contrast on speed and accuracy of processing visual information for a controlled, simulated realistic task. Every stimulus had two columns or lists (called *reference* and *response* lists) of 20

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

five-digit numbers, as shown in Figure 2. During the experiment both lists were placed side by side at the centre on the VDU screen.

The subject's task was to compare the two lists, as quickly and accurately as possible, looking for discrepancies.

The reference list, on the subject's left, acted as a standard with which the numbers on the response list were compared. The reference lists were random numbers. The numbers in the response list, located on the right hand side of the screen, were the same as those in the reference list except for interspersed discrepancies (errors). The errors are similar to those produced when numbers are written using a PC, for instance 67, instead of 76 or 34 instead of 45. The substituted digit and its location in the list were determined by randomized procedures. The frequency of errors in all response lists varied from 0 to 7. We prepared as many lists as necessary so that a

30456	30456
11563	11536
81178	81178
23477	23477
19034	19034
34880	34880
19625	19626
59643	59643
29811	29811
56771	56761
81430	81430
21613	21613
12367	13367
56332	56332
75664	75664
44890	44890
67330	67430
37661	37661
60432	60432
19625	19655

Figure 2 Sample list of numerals

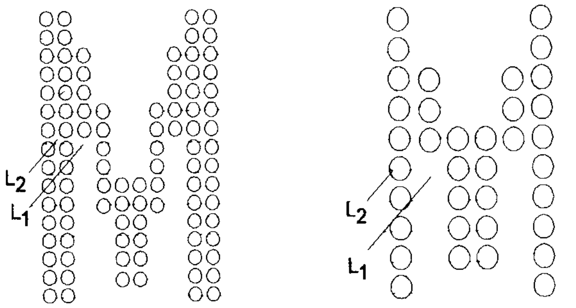

Figure 3 Simulations of 10 × 16 high resolution and 6 × 10 normal character resolution character, both used in this experiment

different one could be used for each experimental determination.

The stimulus was presented using:

- Two resolutions of pixels: one resolution with 768 × 1024 pixels and the other with 480 × 640 pixels. Even though the size of the characters was the same, the thickness of both characters was different, the latter being slimmer than the former, as shown in Figure 3. These resolutions will be referred to as H and N, respectively.
- Three background luminances: 91 cd/m^2, 41 cd/m^2 and 5 cd/m^2. These three values will be referred to as bright, grey and dark background, respectively.

The contrast values depend on illuminance, resolution, polarity and background luminance.

Character and background luminance levels were accomplished by varying grey levels (0–63) by software written in C++ programming language. The resolution was also changed by software.

At the experimental viewing distance, the average angle for each character was equal to 20 minutes of arc with a ratio of height to width of 0.75. The shape of the character used emulated 10-point Arial font.

2.3 Photometric contrast measurements

The mean character luminance was measured with an LMT (model L1009) luminance meter with V(λ) correction with an angular field of 1°

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

over a matrix with all pixels activated. The background luminance was an average over the background near the character. Then the mean contrast was obtained using Equation (1).

The inner part of the character 'M' (Figure 3) was used as the characteristic critical detail for VDU characters.[2,4] The local inner contrast was obtained by Equation (3) by substituting the luminance of the non-activated *off* dots in L_1 and, the luminance in the centre of the activated *on* dot in L_2. The reference character was displayed at the centre of the screen. The luminances L_1 and L_2 were measured with the same luminance meter but with an angular field of 6′.

The local outer contrast was obtained by Equation (2).

The mean character luminance versus the grey level character for three background experimental conditions was adjusted by an ϒ calibration curve for use during the experimental trials.

The inner contrast plotted against mean contrast is shown in Figures 4, 5 and 6, for dark, bright and grey background luminances, respectively. In these curves illuminance and resolution are considered as parameters.

For characters brighter than background (Figure 4 and right side of Figure 6), the inner contrast first increases and after a maximum is reached, it decreases, while the mean contrast increases smoothly. The behaviour of the positive inner contrast in the figures above can be explained by a broadening effect of the dot size,[4] that is, the luminance of a non-activated *off* dot is increased by the activated adjacent *on* dots. This produces an increasing overlapping effect between *on* and *off* dots. This means that the inner detail contrast will be restricted to a relative maximum. When more dots are used to define a character, as in the high-resolution mode compared with normal-resolution, then, the overlapping effect is smaller. The inner contrast is

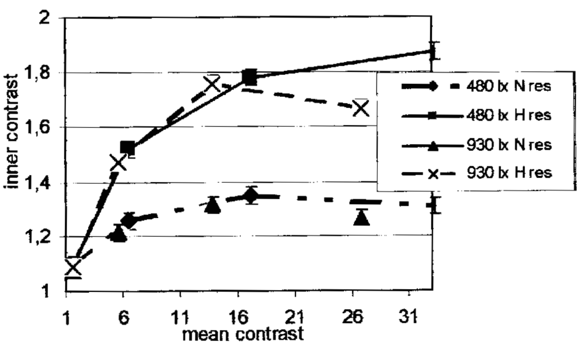

Figure 4 Inner contrast as a function of mean contrast at background luminance 5 cd/m^2. The measurements were carried out with character 'M' brighter than background, displayed at the centre of the display. N res means 480 × 640 resolution pixels and H res means 768 × 1024 resolution pixels.

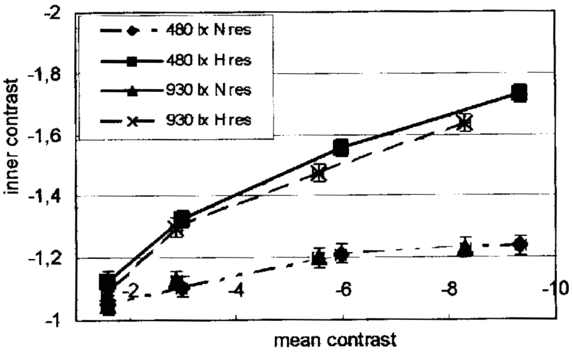

Figure 5 Inner contrast as a function of mean contrast at background luminance 91 cd/m^2. The measurements were carried out with character 'M' darker than background, displayed at the centre of the display.

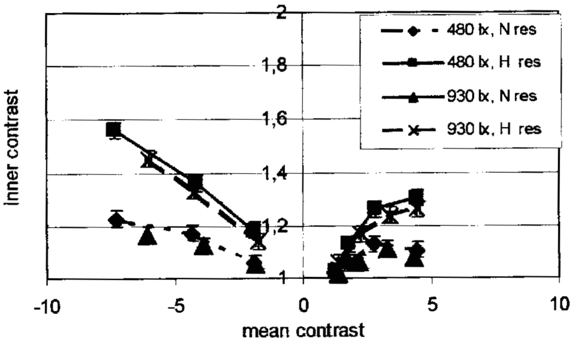

Figure 6 Inner contrast as a function of mean contrast at background luminance 41 cd/m^2. The measurements were carried out with character 'M' brighter and darker than background, depending on the polarities, displayed at the centre of the display.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

higher with a low background luminance and high resolution. This effect can only be noticed for the case of dark background and lower resolution (Figure 4). In the other cases, the maximum would be reached for further levels of mean luminances.

For characters darker than background (Figure 5 and left side of Figure 6) the absolute values of inner contrast increase with the mean character contrast up to a limit; they appear to tend to a constant maximum within each experimental range. The inner contrast increases more rapidly for a higher resolution and a higher background luminance. The behaviour is quite different for positive contrast, probably because an inversion of contrast is not simply the reverse behaviour. A single white pixel on a dark field is not the reverse of a single dark pixel on a white background.[8]

Tables 1–3 show the analysis of the variance summary table for mean, outer and inner contrast with character luminance as a co-variable.

While statistical significance is important, the practical significance of the variables examined is even more important. This importance can be quantified in terms of the percentage of variance explained by the variable. To take both statistical and practical significance into account when assessing the result of an analysis of variance, two criteria have been adopted in this study. Both criteria have to be met for a variable to be considered further. The criteria are: a) probability of occurrence by chance of less than 0.05; and, b) the variance explained by the variable has to be greater than 5%. We consider this value adequate to interpret the results.

Using these criteria and analysing the mean contrast and outer contrast photometry results for each polarity indicates that only background luminance is significant, while resolution and

Table 1 Analysis of variance summary table for mean contrast with illuminance, resolution and background luminance as effects for both polarities. Character luminance as a co-variable.

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
Mean positive contrast					
1	0.92	1	22756.	0.00	0.4
2	0.12	1	2956.	0.00	0.05
3	**229**	**1**	**5652793.**	**0.00**	**99**
Mean negative contrast					
1	0.0055	1	173.	0.00	0.04
2	0.041	1	1290.	0.00	0.3
3	**14.8**	**1**	**467465.**	**0.00**	**99**

1-Illuminance, 2-resolution, 3-background luminance.

Table 2 Analysis of variance summary table for outer contrast with illuminance, resolution and background luminance as effects for both polarities. Character luminance as a co-variable.

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
Outer positive contrast					
1	0.45	1	96.	0.00	0.5
2	0.20	1	44.	0.00	0.2
3	**86.**	**1**	**18600.**	**0.00**	**99**
Outer negative contrast					
1	0.10	1	20.	0.00002	2
2	0.0033	1	6418.	0.4	0.06
3	**3.77**	**1**	**743.**	**0.00**	**74**

1-Illuminance, 2-resolution, 3-background luminance.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Table 3 Analysis of variance summary table for inner contrast with illuminance, resolution and background luminance as effects for both polarities. Character luminance as a co-variable.

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
Inner positive contrast					
1	0.044	1	4.8	0.03	1
2	**0.67**	1	**73.**	**0.00**	**21**
3	**1.14**	**1**	**124.**	**0.00**	**36**
Inner negative contrast					
1	0.00046	1	0.12	0.7	0.03
2	**0.77**	**1**	**197.**	**0.00**	**58**
3	**0.10**	**1**	**27.**	**0.00**	**12**

1-Illuminance, 2-resolution, 3-background luminance.

illuminance have no statistical significance within the experimental range. These results were expected because the spatial extent of the area, where the target luminance L_c was measured, was the whole area occupied by the character, that is, the measurement field is higher than that considered for inner contrast.

For inner contrast results resolution and background luminance considered in this experiment are statistically significant, while illuminance is not, within the experimental range. Finally, the contrast results also show the typical non-linearity associated with CRT displays: a global, spatial non-linearity is exhibited as a dependence of the luminance at any part of the screen on the illuminated proportion of the screen, that is, the range of possible luminances is much lower when all the pixels on the screen are *on* than when they are *off*. This explains why the range and the behaviour under different background luminances are so different for the same range of grey level (0–63), that is, between a dark background and a bright background. Nevertheless, with inner contrast, the ranges for all background luminances are similar.

2.4 Observers

Ten paid volunteers (three female and seven male) participated in the experiment. All were undergraduate students of computer science between 18 and 22 years old, with normal vision, checked by tests of visual acuity. They all had had experience with VDU work.

2.5 Protocol

The experimental trials involved visual performance, visual comfort and character contrast adjustment measurements. The three experiments involved the same stimuli.

In the contrast adjustment experiments, the observers were allowed to modify, by software, the character grey level for different resolutions, background luminance and illuminance. The observer could adjust the character luminance up to what they considered to be an optimum contrast value, taking as starting point a value in the middle of the range. The software showed the adjusted character grey level, allowing the character luminances to be obtained by the γ calibration curve. Mean contrast was obtained by Equation (1), and inner contrast was obtained by a polynomial adjustment from inner contrast data plotted against the mean luminance character (Figures 4–6).

To estimate the *subjective assessments of visual comfort (VC)*, each observer was asked to rate comfort on a five-point numerical scale ranging from 1 (very low comfort) to 5 (excellent comfort) i.e.,

1: very low comfort	2	3	4	5: excellent comfort

Visual performance (VP) can be defined as:

$$VP = \frac{(20 - n)}{t} \qquad (4)$$

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

where

t = time taken for the task or total time (s)
20 = number of comparison numbers
n = number of incorrect or undetected differences

Relative Visual Performance (RVP) is then calculated as a ratio of the Visual Performance for this task and a reference value VP_{max} computed under highly visible conditions.[6]

$$RVP = \frac{VP}{VP_{max}} \qquad (5)$$

Before data were collected for analysis, the subjects read the instructions and were given practice trials. During the practice runs, the observers saw all of the conditions they would see in the subsequent experiment.

The Visual Comfort scale is not a well-known scale, and the observers cannot be expected to reliably rate a particular stimulus as poor or good. To overcome this, observers were first shown a stimulus representing the 'very low comfort' end of the scale and then a stimulus representing 'excellent comfort', top of the scale; thus giving polar benchmarks for their subsequent ratings.

Each subject completed the following steps:

A) Adaptation period to the illuminance, randomly chosen.
B) The observer randomly chose a trial. In each trial subjects were instructed to 'quickly and accurately' compare a response list with a reference list. The computer registered the total time (t) taken for the comparison of the lists, and the differences detected between columns.
C) After the numerical task comparison, the observer was asked to rate visual comfort.
D) This procedure was repeated until all 30 possible combinations of the variables under study were completed.
E) The observer was asked to adjust the contrast to a preferred level using the software for each experimental condition, chosen at random order.
F) Steps (A) to (E) were repeated for other illuminance levels.
G) Steps (A) to (F) were repeated three times.

3. Results and discussion

3.1 Contrast adjustment

Table 4 shows averages of the luminances after adjustment by the observers in this experiment.

Table 4 Contrast adjustment task: character luminance, mean contrast and inner contrast results

Background luminance (cd/m^2)	Illuminance (lux)	Resolution	Character luminance (cd/m^2)	Mean contrast	Inner contrast
5	480	N	107 ± 5	24.5 ± 1	1.35 ± 0.02
		H			1.86 ± 0.03
	930	N		17.5 ± 1	1.31 ± 0.01
		H			1.75 ± 0.03
91	480	N	13.2 ± 0.5	–7.7 ± 0.2	–1.23 ± 0.01
		H			–1.60 ± 0.02
	930	N			–1.23 ± 0.01
		H			–1.53 ± 0.03
41	480	N	149 ± 5	3.6 ± 0.1	1.13 ± 0.02
		H			1.29 ± 0.08
	930	N			1.10 ± 0.03
		H			1.25 ± 0.05
	480	N	7.6 ± 0.3	–5.6 ± 0.1	–1.19 ± 0.01
		H			–1.61 ± 0.02
	930	N			–1.17 ± 0.01
		H			–1.57 ± 0.01

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Table 5 Analysis of variance summary table for adjusted positive inner contrast

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	0.020	8	1.3	0.2	0.2
2	0.072	1	4.7	0.03	0.8
3	**4.76**	**1**	**313.**	**0.00**	**56**
4	0.0051	2	0.34	0.7	0.06
5	**1.59**	**1**	**105.**	**0.00**	**19**

1-Observer, 2-illuminance, 3-resolution, 4-trial repetition, 5-background luminance.

Table 6 Analysis of variance summary table for adjusted negative inner contrast

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	0.014	8	0.93	0.5	0.2
2	0.033	1	2.16	0.1	0.6
3	**3.38**	**1**	**223.**	**0.00**	**59.**
4	0.013	2	0.89	0.4	0.2
5	**0.44**	**1**	**28.**	**0.00**	**8**

1-Observer, 2-illuminance, 3-resolution, 4-trial repetition, 5-background luminance.

The adjusted mean character luminance is not so different from those recommended by CIE[3] (30–125 cd/m^2). For a character brighter than the background, the range obtained was from 107 cd/m^2 to 149 cd/m^2, the same order of magnitude as the highest from CIE, but with the other polarity we obtained about 10 cd/m^2, somewhat lower than the least value recommended by CIE. The range of mean contrast adjusted (from about 3–8) for grey and bright backgrounds is in agreement with CIE recommendations[3] (5–10), but with a dark background (15–25), the range is higher than the recommended CIE values. The inner contrast adjustment depends on resolution and background luminance; however, illuminance is not a significant parameter, one might expect, because the range considered agrees with the recommended one.

The statistical results shown in Tables 5 and 6 confirm these conclusions and, moreover, the observer effect and trial repetition are not statistically significant. The inner contrast adjusted for 480 × 640 pixels is slightly lower than for 768 × 1024 pixels resolution; the subjects notice that for a slimmer character type, the contrast is greater. It can also be seen that screens with a low background luminance require somewhat higher character contrasts, in agreement with the findings of other authors.[10]

Figure 7 shows the adjusted inner contrast plotted against maximum inner contrast. The correlation coefficient for these two variables is 0.99. This result could be interpreted as indicating that the observers were using the inner contrast criterion for all experimental variables.

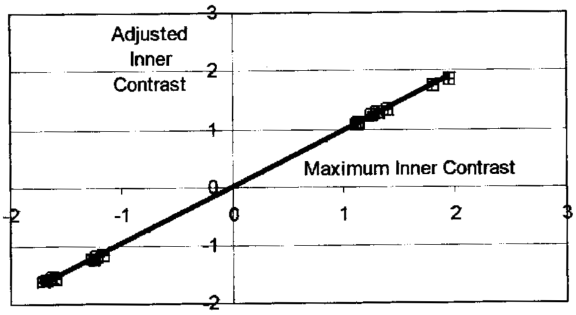

Figure 7 Mean inner contrast adjusted by 10 observers as a function of maximum inner contrast

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

3.2 Visual Comfort Judgements

The judgements of Visual Comfort (VC) results are shown in Figures 8–10, each one corresponding to different background luminances.

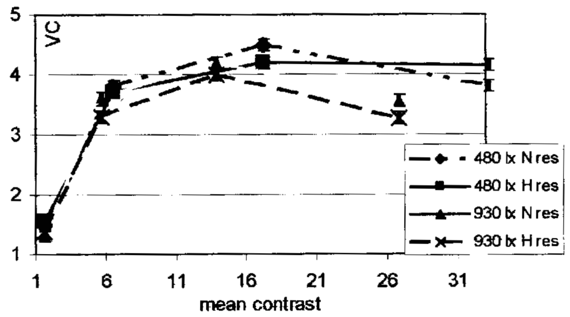

Figure 8 Judgements of Visual Comfort (VC) as a function of mean contrast at background luminance 5 cd/m^2. The measurements were carried out with 10 observers.

These show that the comfort judgement ratings increase with mean contrast and show similar behaviour as inner contrast plotted against mean contrast. As a consequence, we would expect a better correlation between comfort judgement and inner contrast than mean or outer contrast. In fact, the correlation coefficient is greater than 0.7 with inner contrast, 0.4 with mean contrast and 0.5 with outer contrast.

Analysis of variance results show that the resolution and background luminances considered in this experiment are statistically significant using inner contrast as a co-variable, as mentioned earlier (Tables 7 and 8). The analysis of variance of inner contrast as a co-variable (within cell regression) shows that inner contrast is statistically significant ($P < 0.00$).

Once again the inner contrast criterion seems to be adequate for subjective assessment of the characters, a finding in agreement with other authors.[2]

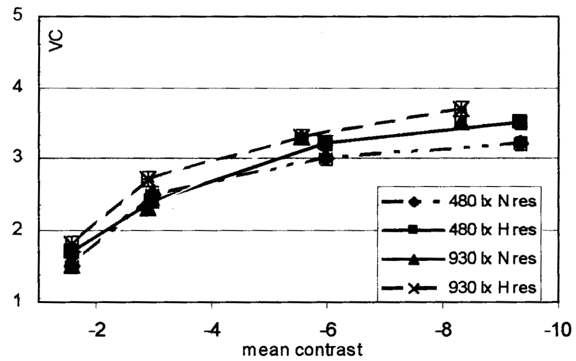

Figure 9 Judgements of Visual Comfort (VC) as a function of mean contrast at background luminance 91 cd/m^2. The measurements were carried out with 10 observers.

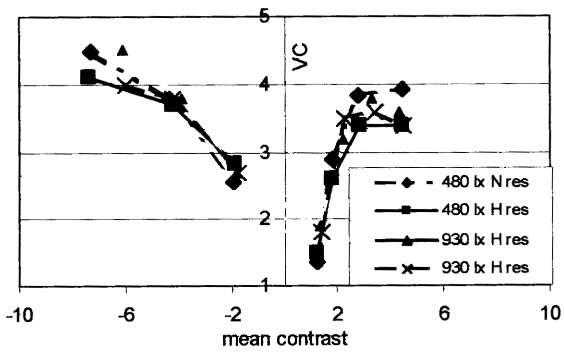

Figure 10 Judgements of Visual Comfort (VC) as a function of mean contrast at background luminance 41 cd/m^2. The measurements were carried out with 10 observers.

Table 7 Analysis of variance summary table for visual comfort with positive inner contrast as a co-variable

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	7.33	9	6.45	0.00	0.6
2	14.6	1	12.85	0.00	1
3	**221**	**1**	**194.**	**0.00**	**18**
4	**157**	**1**	**138.**	**0.00**	**12**
5	0.24	2	0.21	0.8	0.02

1-Observer, 2-illuminance, 3-resolution, 4-background luminance, 5-trial repetition.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Table 8 Analysis of variance summary table for visual comfort with negative inner contrast as a co-variable

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	13.6	9	21.9	0.00	2
2	12.9	1	20.9	0.00	2
3	**95.**	**1**	**154.**	**0.00**	**13**
4	**209.**	**1**	**337.**	**0.00**	**29**
5	2.7	2	4.3	0.01	0.4

1-Observer, 2-illuminance, 3-resolution, 4-background luminance, 5-trial repetition.

Comfort judgements are higher for N resolution than for H resolution, probably because, for the former, the character is perceptually slimmer. Probably, the sharpness perception of the character is involved in this case.[1,10,11] This result is in agreement with the contrast adjustment experiment, because to obtain equal levels of visual comfort, a high contrast for a high resolution is necessary.

Comparing Visual Comfort values at the same level of contrast, we can see that a grey background gives the best visual comfort.

3.3 Visual Performance

The relative Visual Performance (RVP) results are shown in Figures 11–13. Relative visual performance increases with mean contrast showing similar behaviour to that obtained with inner contrast. As a consequence, we would expect a better correlation between relative visual performance and inner contrast (correlation coefficient 0.4) than mean contrast (correlation coefficient < 0.1) or outer contrast (correlation coefficient < 0.2).

The background luminance seems to have no effect upon Visual Performance, a finding in agreement with other authors.[9] However, an improvement of visual conditions would be expected from a dark character on light screens

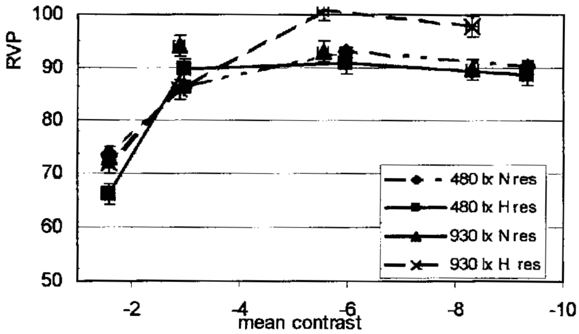

Figure 12 Relative Visual Performance (RVP) as a function of mean contrast at background luminance 91 cd/m^2. The measurements were carried out with 10 observers.

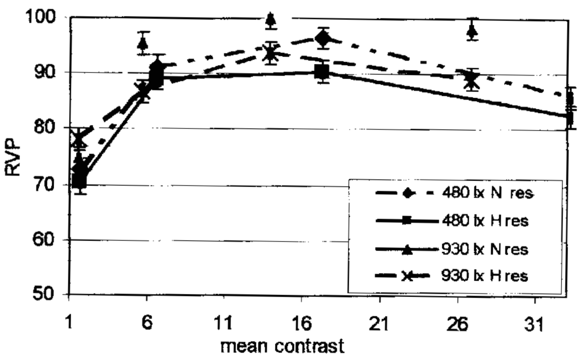

Figure 11 Relative Visual Performance (RVP) as a function of mean contrast at background luminance 5 cd/m^2. The measurements were carried out with 10 observers.

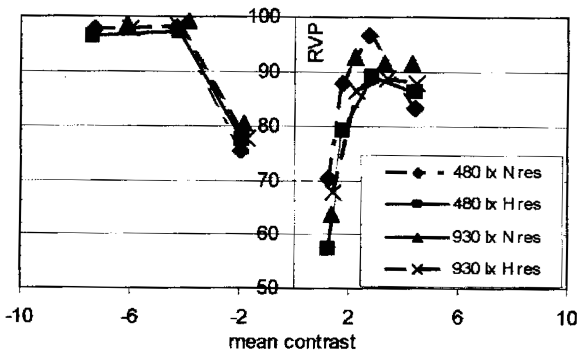

Figure 13 Relative Visual Performance (RVP) as a function of mean contrast at background luminance 41 cd/m^2. The measurements were carried out with 10 observers.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

(negative contrast). This could be attributed to the increased background luminance of about 90 cd/m^2, which results in an enhanced contrast sensitivity and a better balance of luminance distribution between the working media. In addition, it means reduced annoyance due to reflections in the screen. However, increased background luminance is associated with increased sensitivity to luminance fluctuations, which means that an increased refresh rate is necessary for flicker-free representation. Commercially available units are not always flicker-free, and also elements of the characters, such as their line thickness, are not matched to this negative contrast representation. If only the contrast polarity is inverted without optimizing the form of representation as a whole, no significant difference in visual performance between contrast directions can be determined.

The analysis of variance shows that the resolution considered in this experiment is slightly significant at only 5%, using inner contrast as a co-variable, as mentioned before (Tables 9 and 10). The analysis of variance of inner contrast as a co-variable (within cell regression) shows that inner contrast is statistically significant ($P < 0.009$).

Again the inner contrast criterion seems to be adequate for visual performance, a finding in agreement with other authors.[4]

4. A model of visual compression

Additional important supporting evidence of the robustness of these results is that experimental data can be represented by an empirical equation that models the psychophysical response of visual performance and visual comfort satisfactorily. The experimental data closely fit the expression developed by Naka and Rushton.[13,14]

$$\frac{R}{R_{max}} = \frac{I^n}{I^n + k^n} \tag{6}$$

where R is the response produced by the observer, R_{max} is the maximum response, I the stimulus intensity, and n and k are free parameters. The values of n, k and R_{max} vary with the experimental conditions.

Hood and his co-workers[15] and Rea and his co-workers[6] also used the same response function to model psychophysical responses.

In this way, visual comfort judgements were substituted in Equation (6):

Table 9 Analysis of variance summary table for visual performance with positive inner contrast as a co-variable

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	**1.08**	**9**	**410.**	**0.00**	**43**
2	0.0006	1	0.22	0.6	0.02
3	**0.14**	**1**	**51.**	**0.00**	**6**
4	0.001	1	0.43	0.5	0.04
5	0.0007	1	0.26	0.6	0.03

1-Observer, 2-illuminance, 3-resolution, 4-background luminance, 5-trial repetition.

Table 10 Analysis of variance summary table for visual performance with negative inner contrast as a co-variable

Effect	Mean square	Degrees of freedom	F ratio	Significance level	% Variance explained
1	**0.95**	**9**	**363.**	**0.00**	**42.**
2	0.0006	1	0.24	0.6	0.03
3	**0.042**	**1**	**15.9**	**0.00**	**5**
4	0.0041	1	1.56	0.2	0.2
5	0.0001	1	0.04	0.8	0.005

1-Observer, 2-illuminance, 3-resolution, 4-background luminance, 5-trial repetition

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Table 11 Parameters adjusted by statistical software corresponding to the model of visual compression for visual comfort judgements results

Background grey level/polarity	Resolution	*n*	*b*	% Variance explained
0	N	15.42	1.13	97
0	H	5.71	1.23	95
63	N	15.46	1.07	94
63	H	6.67	1.13	93
29 positive	N	28.29	1.04	92
29 positive	H	9.16	1.09	87
29 negative	N	21.92	1.04	91
29 negative	H	7.01	1.08	97

$$\frac{VC}{VC_{max}} = \frac{K_i^n}{K_i^n + b^n} \quad (7)$$

The parameters are shown in Table 11. Comparing the obtained values, parameter *n* is higher for N resolution than for H resolution.

The visual performance values were adjusted by:

$$\frac{VP}{VP_{max}} = \frac{K_i^n}{K_i^n + b^n} \quad (8)$$

Values obtained for the parameters are shown in Table 12.

The solid line in Figures 14–19 represents the model for RVP and VC results. The experimental data correspond to average values from all the observers.

This compression visual model predicts that suprathreshold visual response will increase only slightly when inner contrast is high and more strongly when inner contrast is low.

If visual performance measurements and visual comfort judgements follow a compression law with inner contrast, there is strong support for the conclusion that inner contrast is a significant parameter for the visual stimuli, a finding in agreement with other authors.[4]

Table 12 Parameters adjusted by statistical software corresponding to the model of visual compression for visual performance results

Polarity	Resolution	*n*	*b*	% Variance explained
Positive	N	24.4	0.98	58
Positive	H	18.4	0.99	86
Negative	N	46.5	1.02	83
Negative	H	10.4	1.00	77

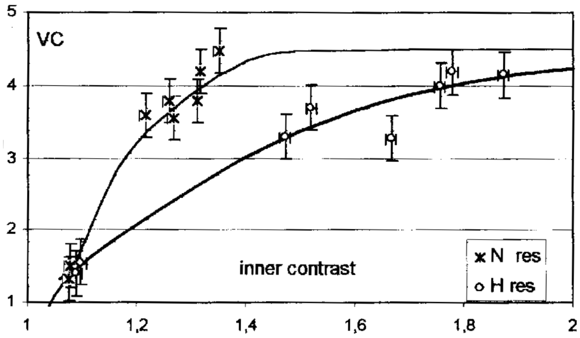

Figure 14 Judgements of Visual Comfort (VC) data as a function of inner contrast at background luminance 5 cd/m^2 compared with visual compression model

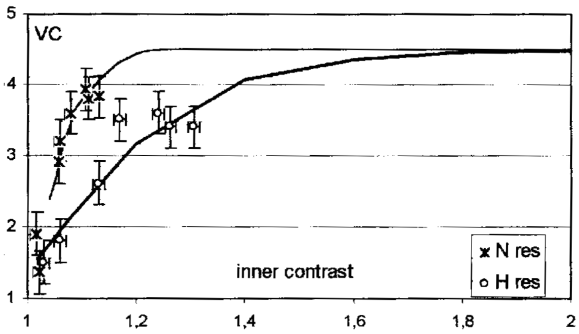

Figure 15 Judgements of Visual Comfort (VC) data as a function of positive inner contrast at background luminance 41 cd/m^2 compared with visual compression model

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

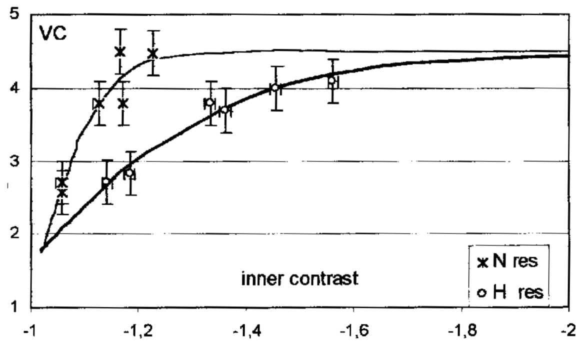

Figure 16 Judgements of Visual Comfort (VC) data as a function of negative inner contrast at background luminance 41 cd/m^2 compared with visual compression model

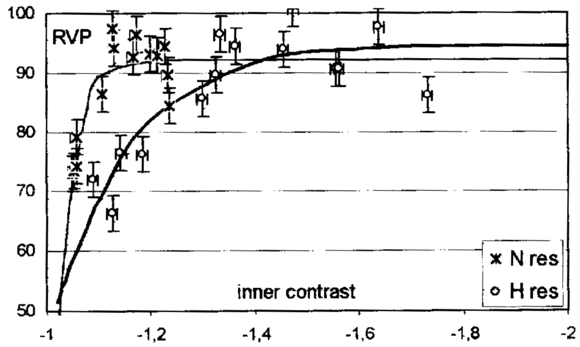

Figure 17 Judgements of Visual Comfort (VC) data as a function of negative inner contrast at background luminance 91 cd/m^2 compared with visual compression model

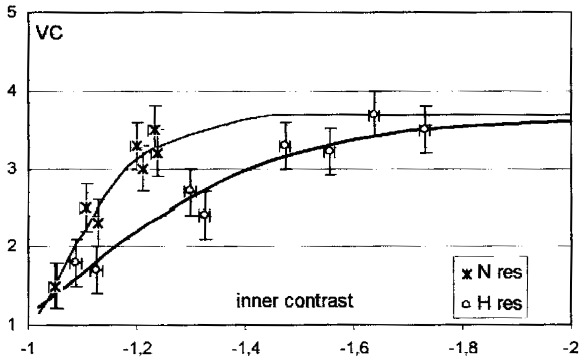

Figure 18 Relative Visual Performance (RVP) data as a function of positive inner contrast at background luminance 5 cd/m^2 and 41 cd/m^2 compared with visual compression model

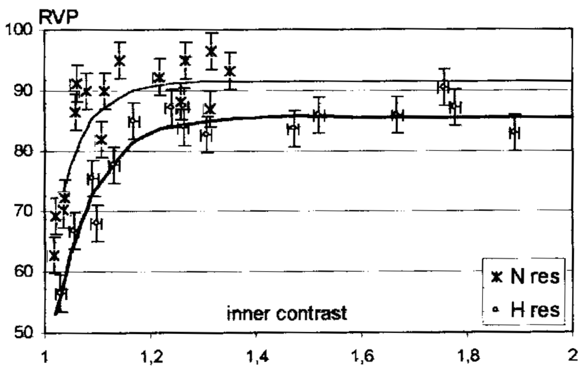

Figure 19 Relative Visual Performance (RVP) data as a function of negative inner contrast at background luminance 91 cd/m^2 and 41 cd/m^2 compared with visual compression model

5. Conclusion

The principal result of this paper is that inner contrast is a physical variable representing perceptual contrast. Mean contrast and outer contrast cannot characterize the distinct amount of detail recognition that the perceptual human visual system is able to perform.

This conclusion is supported by:

- The similarity found between the behaviour of the results for visual performance, visual comfort and inner contrast as a function of mean contrast.
- The observers' adjustment of the contrast using the inner contrast criterion. The subjects seem to prefer precisely the adjustment that leads to the maximum inner contrast.
- RVP and VC following a visual compression law with inner contrast.
- RVP and VC having higher correlation with inner contrast than with outer and mean contrast.
- Inner contrast being a statistically significant variable.

Some other conclusions are:

- Illuminance, within the experimental range (480–930 lux), is not a significant parameter.
- Background luminance is significant only for comfort judgements and contrast adjustment trials, but not for visual performance results.

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

- Grey background seems to be preferred by the observers.
- The inner contrast involves two characteristics of the visual stimuli: contrast and sharpness, so the influence of neighbouring pixels on each other affects both the sharpness and the contrast of the character.
- The fact that both the visual performance and the visual comfort were lower for the lower resolution would indicate that the thickness of character involved in the resolution is more important than the resolution itself.
- Mean contrasts higher than 5 are sufficient to reach a visual performance of 90% and a visual comfort rating of 3. The corresponding inner contrast is 1.4.

Acknowledgements

We thank Ing. José Barraza for his help with the software, and Mrs Elena B. Lavanda for the statistical processing results. This work had the support of CIUNT and CONICET from Argentina.

6. References

1 Roufs J, Boschman M. *Vision and visual dysfunction*. New York: MacMillan Press, 1992.
2 Commission Internationale de l'Eclairage. Contrast and visibility. CIE 95, 1992.
3 Commission Internationale de l'Eclairage. *Vision and the visual display unit work station*. CIE 60, 1984.
4 Kokoschka S. Visibility aspects of VDUs in terms of contrast and luminance. *Behaviour Inf. Technol.* 1986; 5: 309–33.
5 Rea MS. Toward a model of visual performance: a review of methodologies. *J. Illuminating Eng. Soc.* 1987; 16: 128–49.
6 Rea MS. Toward a model of visual performance: foundations and data. *J. Illuminating Eng. Soc.* 1986; 15: 41–57.
7 Rea M, Oullette M. Relative visual performance: a basis for application. *Lighting Res. Technol.* 1991; 23: 135–44.
8 Naiman A, Makous W. Spatial non-linearities of greyscale CRT pixels. SPIE vol. 1666. *Human Vision Visual Processing and Digital Display* 1992; III: 44–56.
9 Perry M. *Daylighting for display screen equipment*. BRE, 1993.
10 Haubner P, Kokoschka S. Visual Display Units, characteristics of performance. *CIE Reports* 2 B3/1–B3/8. Amsterdam, Holland, 1983.
11 Colombo E, Raitelli M, Kirschbaum C. Legibility of texts: the influence of blur. *Lighting Res. Technol.* 1987; 19: 61–79.
12 Colombo E, Kirschbaum C. Print quality and visual performance. *Lighting Res. Technol.* 1990; 22: 85–93.
13 Naka KI, Rushton W. S potentials from colour units in the retina of fish. *J. Physiol.* 1966; 185: 536–55.
14 Naka KI, Rushton W. An attempt to analyse colour reception by electrophysiology. *J. Physiol.* 1966; 185: 556–86.
15 Hood DC, Finkelstein MA, Bucckingham E. Psychophysical test of models of the response function. *Vision Res.* 1979; 19: 401–406.

Discussion

Comment 1 on 'Inner contrast and perceptual quality in tasks with video display units' by B O'Donell and E Colombo

Peter Boyce (Lighting Research Center, Rensselaer Polytechnic Institute)

This is an interesting paper based on the idea that saying contrast is what matters to visual comfort and visual performance is inadequate unless you also specify where the contrast is measured. The results are interesting but there are two aspects where more information is needed before the conclusions should be accepted. The first is the performance characteristics of the luminance meter used, specifically, the extent of light scatter in the optics of the luminance meter. Measurements of the minimum luminance for the inner contrast are taken with surrounding pixels activated. Light scatter in the optics of the luminance meter will tend to increase the measured minimum luminance and hence reduce the inner contrast from its true value. The second aspect requiring more information is the correlation between the various measures of contrast; mean contrast, inner contrast and outer contrast, over

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

Lighting Research and Technology

http://lrt.sagepub.com

Comment 1 on 'Inner contrast and perceptual quality in tasks with video display units' by B O'Donell and E Colombo

Peter Boyce

Lighting Research and Technology 2001; 33; 159
DOI: 10.1177/136578280103300303

The online version of this article can be found at:
http://lrt.sagepub.com

Published by:
SAGE
http://www.sagepublications.com

On behalf of:

The Society of Light and Lighting

Additional services and information for *Lighting Research and Technology* can be found at:

Email Alerts: http://lrt.sagepub.com/cgi/alerts

Subscriptions: http://lrt.sagepub.com/subscriptions

Reprints: http://www.sagepub.com/journalsReprints.nav

Permissions: http://www.sagepub.co.uk/journalsPermissions.nav

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

- Grey background seems to be preferred by the observers.
- The inner contrast involves two characteristics of the visual stimuli: contrast and sharpness, so the influence of neighbouring pixels on each other affects both the sharpness and the contrast of the character.
- The fact that both the visual performance and the visual comfort were lower for the lower resolution would indicate that the thickness of character involved in the resolution is more important than the resolution itself.
- Mean contrasts higher than 5 are sufficient to reach a visual performance of 90% and a visual comfort rating of 3. The corresponding inner contrast is 1.4.

Acknowledgements

We thank Ing. José Barraza for his help with the software, and Mrs Elena B. Lavanda for the statistical processing results. This work had the support of CIUNT and CONICET from Argentina.

6. References

1 Roufs J, Boschman M. *Vision and visual dysfunction*. New York: MacMillan Press, 1992.
2 Commission Internationale de l'Eclairage. Contrast and visibility. CIE 95, 1992.
3 Commission Internationale de l'Eclairage. *Vision and the visual display unit work station*. CIE 60, 1984.
4 Kokoschka S. Visibility aspects of VDUs in terms of contrast and luminance. *Behaviour Inf. Technol.* 1986; 5: 309–33.
5 Rea MS. Toward a model of visual performance: a review of methodologies. *J. Illuminating Eng. Soc.* 1987; 16: 128–49.
6 Rea MS. Toward a model of visual performance: foundations and data. *J. Illuminating Eng. Soc.* 1986; 15: 41–57.
7 Rea M, Oullette M. Relative visual performance: a basis for application. *Lighting Res. Technol.* 1991; 23: 135–44.
8 Naiman A, Makous W. Spatial non-linearities of greyscale CRT pixels. SPIE vol. 1666. *Human Vision Visual Processing and Digital Display* 1992; III: 44–56.
9 Perry M. *Daylighting for display screen equipment*. BRE, 1993.
10 Haubner P, Kokoschka S. Visual Display Units, characteristics of performance. *CIE Reports* 2 B3/1–B3/8. Amsterdam, Holland, 1983.
11 Colombo E, Raitelli M, Kirschbaum C. Legibility of texts: the influence of blur. *Lighting Res. Technol.* 1987; 19: 61–79.
12 Colombo E, Kirschbaum C. Print quality and visual performance. *Lighting Res. Technol.* 1990; 22: 85–93.
13 Naka KI, Rushton W. S potentials from colour units in the retina of fish. *J. Physiol.* 1966; 185: 536–55.
14 Naka KI, Rushton W. An attempt to analyse colour reception by electrophysiology. *J. Physiol.* 1966; 185: 556–86.
15 Hood DC, Finkelstein MA, Bucckingham E. Psychophysical test of models of the response function. *Vision Res.* 1979; 19: 401–406.

Discussion

Comment 1 on 'Inner contrast and perceptual quality in tasks with video display units' by B O'Donell and E Colombo

Peter Boyce (Lighting Research Center, Rensselaer Polytechnic Institute)

This is an interesting paper based on the idea that saying contrast is what matters to visual comfort and visual performance is inadequate unless you also specify where the contrast is measured. The results are interesting but there are two aspects where more information is needed before the conclusions should be accepted. The first is the performance characteristics of the luminance meter used, specifically, the extent of light scatter in the optics of the luminance meter. Measurements of the minimum luminance for the inner contrast are taken with surrounding pixels activated. Light scatter in the optics of the luminance meter will tend to increase the measured minimum luminance and hence reduce the inner contrast from its true value. The second aspect requiring more information is the correlation between the various measures of contrast; mean contrast, inner contrast and outer contrast, over

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009

the range of conditions examined. If these three measures of contrast are highly correlated, then there is little to choose between the three measures of contrast as predictors of comfort or visual performance.

Finally, it seems to me that calling the change between the number of pixels 'resolution' is somewhat misleading. As shown in Figure 3, changing from 480 × 640 pixels to 768 × 1024 pixels not only changes the number of pixels contributing to a character but also the form of the character. It may be that the size of detail contained in the characters is finer for the 768 × 1024 pixel format than for the 480 × 640 pixel format. If this is so then it would explain why people find the 'normal resolution' condition more comfortable than the 'high resolution' condition. While contrast is undoubtedly important in determining visual comfort and visual performance for a task, so is size of detail, and changes in form of characters represent a change in size of detail.

Comment 2 on 'Inner contrast and perceptual quality in tasks with video display units' by B O'Donell and E Colombo

Owen Howlett (Zumtobel Staff Lighting)

Although the choice of Equation (1) for mean contrast gives rise to a misleading distortion of the curves in Figures 4 and 5 (and how can a value for L_c/L_b be negative?), the mathematical analysis in the paper is very thorough. To accept *prima facie* that because VC and RVP vary as a function of mean contrast, in the same way that inner contrast varies as a function of mean contrast, would be insufficient to demonstrate a relationship between inner contrast and VC or RVP. For example, the frequency of road accidents increases with vehicle speed, and the rate of fuel consumption also increases with vehicle speed, but these two facts taken together are insufficient to prove that road accidents are caused by excessive fuel consumption. The authors go on to show that VC and RVP vary as functions of inner contrast in precisely the way predicted by the Naka and Rushton compression curve, and this analysis provides a much stronger basis for the conclusion that inner contrast is the key determinant of VC and RVP.

The consequences of these results for office lighting practice may (in fact should) be highly significant. The improving affordability of TFT flat-panel displays has seen them become the default choice for many blue-chip companies, especially where space constraints are tight. Although I am not aware of any experimental evidence, I anticipate that the degree of cross-contamination between pixels with these screens is dramatically less than for older CRT screens, and that the inner contrast is correspondingly higher. The consequently higher legibility and comfort of these screens would reduce or even remove the need for highly directional louvred luminaires to control screen reflections and screen veiling luminance. Loosening the grip of this luminaire type on the office lighting market would improve the overall visual environment, and bring ensuing benefits for the satisfaction and productivity of office workers.

I would like to suggest that the authors now turn their attention to the comparatively simple task of measuring the difference in inner contrast between CRT and flat panel displays, at the same level of mean contrast. Standards such as EN9241-7 (Ergonomic Requirements for Display Screen Use) and national guidance on office lighting may have to be revised as a result.

Authors' response to P Boyce and O Howlett

B O'Donell and E Colombo

LMT Luminance Meters L 1009 are suitable for a variety of measuring tasks because of their wide measuring ranges from 0.0001 to 19 990 000 cd/m^2. The influence of stray light is minimised by using a specially designed lens system in combination with proper stray light baffles. The steeply bounded metering profiles enable exact measurements even with the smallest angular field, that is 6′. The minimum measuring area with close up lens is 0.17 mm of

Downloaded from http://lrt.sagepub.com at UNIV DE SAO PAULO BIBLIOTECA on December 2, 2009