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Perception of High-Contrast Blurred Edges

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Observer sensitivity to edge blur has been examined by experimental measurements of threshold blur as a function of contrast. An extension of previous results from Watt and Morgan for high-contrast blur edges is discussed and analyzed. We propose a psychophysical test based on a two-alternative forced choice test. The results found for three adult observers show a comparable behavior. A tendency for the blur threshold to reach an average value as contrast increases is mainly discussed. These results complement previous ones from other authors for which low- and intermediate-contrast ranges were analyzed. The observed behavior suggests a need to improve algorithms for image quality assessment, extending the actual range of contrast values to high-contrast ones.

1. INTRODUCTION

Detecting, perceiving, and representing intensity changes in images has been the subject of an enormous amount of work during the past few decades. Intensity changes are used by observers as important cues to obtain crucial information about objects in scenes. Some of these cues are related to features such as contrast or blur. Our current interest is to find a relation between blur sensitivity and contrast.

The pioneering discovery in 1865 by Mach describing the relation between boundary locations on brightly illuminated regions and the visual field constituted a first step for later experiments on visual perception [1]. From a later experiment due to O'Brien [2], of recognizing edge-objects or discontinuous objects, it is well accepted that the contours of natural images or scenes are determinants for the human visual perception (HVP) process.

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O'Brien developed several tests based on ramp-objects or two zones of constant luminance (minimum and maximum) connected with a region with a gradient in the luminance. The author observed that perception decreases as a function of the slope of the ramp-object. From Mach band illusions and related experiments it has been demonstrated that the bipartition of a field is detectable, even if the luminance is constant during overall test [1–4].

Studies of edge-blurred perception have been relevant to the theories of detection and location of objects in scenes [5–8] as well as to the analysis of perceptual quality of images [9, 10]. The computational aspects of the location and detection of edges in the context of human vision were first established by Marr and Hildreth [5], based on earlier experiments from Campbell and Robson [11]. These studies were further analyzed by Watt and Morgan [8], who proposed several models. Watt and Morgan's contribution to the computational theories of human spatial vision was derived from results on blur perception and its influence on edge and line location [12–14]. For images containing a large number of edges or boundaries, the general inference is that the higher the contrast, the higher the sharpness. The same law applies as the edge blur spread decreases. This is the conclusion of a considerable amount of work, culminating in a number of algorithms that attempt to determine the ratio between the sharpness of an observer and the physical properties of a natural image [10, 15–18].

It is widely accepted that the blur spread (deviation of a blurring kernel) is the key factor in the perception of sharpness in simple image scenes such as isolated edge maps [9, 10, 15]. Watt and Morgan [13] measured the sensitivity of the human visual system (HVS) to changes in the shape of Gaussian, exponential, and linear blurring kernels over a large range of blur spreads and contrasts. On the basis of results reported by Hamerly and Dvorak [12] and Watt and Morgan [13] on blur just noticeable differences (JNDs), Nijenhuis [9] proposed an empirical relation between the blur spread of the physical blurring kernel and the perceived unsharpness in a single-edge image. Using this relation, an objective measurement for the perceived blur in an image can be obtained from the spread of the blurring kernel. It is shown that fixed variations in the objective measurement are related to approximately equal variations in the perceived unsharpness. This implies that it is a psychometric measurement for sharpness. Kayargadde and Martens [10] incorporated Nijenhuis' relation in an algorithm to estimate the perceived blur image in general images using edge features with excellent results.

The previous analyses were carried out for Michelson contrast lower than 0.8 (be it digital or luminance-based definitions), and images of natural scenes whose contrast usually is not very high. Blur sensitivity measurements require a complete analysis for low, intermediate, and high contrasts, which takes into account possible limits of blur perception. For detecting high-contrast objects limited by blurred contours it is important to have some insight concerning the HVS performance, as for example in the case of some radiological examinations. The main aim of this work is to establish a relationship between blur sensitivity and contrast for very high contrasts, that is, between blur and perception of degradation for high contrast. We propose a generalization of Watt and Morgan's [13] and Nijenhuis' [9] results extended to the upper limits of high contrast (say, Michelson contrast values close to 1.0). To develop a psychophysical test sensitive to blur, we have adopted the design found in Refs. [12, 13].

The paper is divided as follows: In Section 2 we introduce the definition of images used for measuring blur thresholds. In Section 3 we describe the experimental method for obtaining high-contrast degradation sensitivity curves for different observers. We describe the apparatus, type of stimuli, procedure, and subjects. In Section 4 we present the experimental results and compare them with previous ones obtained by several authors for low and intermediate Michelson contrast. In this section we propose an empirical formula for blur threshold as a function of contrast. We end with discussion and conclusions in Section 5.

2. DEFINITIONS

Although the extent of blur in absolute terms is difficult to define, a given blur may be defined quite precisely by specifying the stimulus blur function. Different extents of blur may be produced by expanding the given blur function, in which case the proportional change in blur may be specified without ambiguity. In general, blur functions related by angular expansion are described as similar, while different blur related to other causes may not be described by angular expansion. Another restriction on the definition of blur unsharpness used in the present work is to consider only symmetric blur functions. At this point we recall that from earlier works of Andrews [19] neural response to spatial distributions is assumed to operate with line detector elements having a Gaussian distribution response. This is a symmetric response function provided that discrimination of relative orientation would not be included in the model.

From various blur definitions that have appeared in the literature [12, 13], it is found that the selection of a predetermined blur function, with the exception of linear kernels, does not influence the results of blur sensitivity. Consequently, only one blur definition has been chosen in this study.

In previous works [20–22], we introduced the following definition for the intensity of a one-dimensional blurred edge (Fig. 1a)

$$\mathrm{Edge}(x, x_0, \sigma) = \mathrm{step}(x - x_0) * \exp\left(\frac{-2 \cdot |x|}{\sigma}\right), \tag{1}$$

where $*$ is the convolution operation; x_0, the edge origin, is the position at which the function has half the value of its maximum; and σ, the blur parameter, is a measure of the transition width or the blur extent. In Fig. 1a we observe that the larger the σ, the larger the edge blur and that it is a measure of the slope of edge intensity in the transition region ($x = x_0$). Using definitions previously given [12], the edge-transition width is defined as the spatial range over which the edge intensity goes from 90 to 10% of its range. With this definition, the edge-transition width is $1.6 \cdot \sigma$.

In Fig. 1b, we describe the parameters considered for the digital implementation of the blurred edges. I_{sup} is the maximum gray level that can be displayed by the monitor. The parameter "com" accounts for the amplitude of the gray scale, i.e., the limits of the gray level used in the representation of the edge. The parameter I_{min} is the minimum gray level of the edge and it is used to choose the region of gray scale at which the edge will be represented. X_{max} is the image size in terms of the number of pixels, and it is obviously limited by the monitor resolution.

The parameter com/σ is the maximum slope in the gray transition. Since σ is the measured value of the transition width, this magnitude accounts for the necessary number of bits (or gray levels) per pixel for displaying the transition. Note that this value is related to the

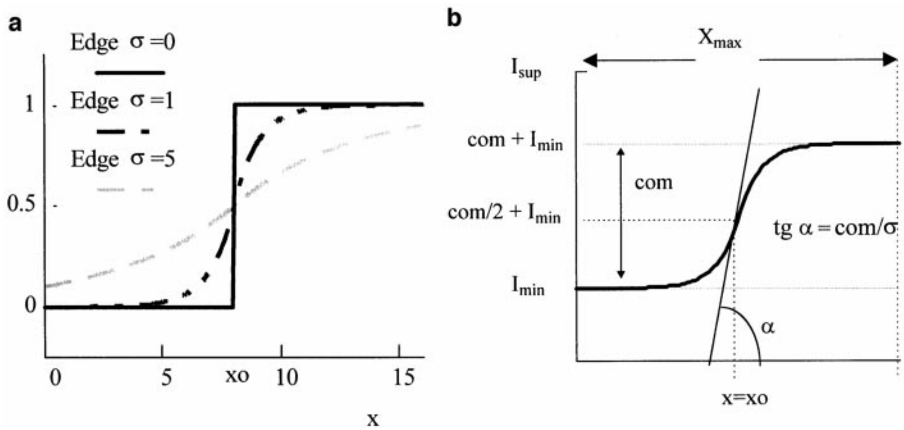

FIG. 1. (a) Edge profiles and interpretations of parameter x_0 and σ. (b) Important parameters used in the digital implementation of the blurred edges. It provides a digital interpretation of the parameter com/σ in terms of transition width.

specific experimental design. σ/com is a useful descriptor of the width of the transition in terms of the number of pixels between regions of constant values of the edge. This rate is a global measure of degradation in the present model. When fixing the number of gray levels this rate is given as the number of gray levels per pixel.

In addition, we define the digital Michelson contrast (DMC) as

$$\mathrm{DMC} = \frac{\mathrm{com}}{\mathrm{com} + 2 \cdot I_{\mathrm{min}}}. \tag{2}$$

This contrast definition depends only on I_{min} and com. By considering the gamma function of the monitor (calibration curve), these two parameters are determinant features for tasks related to the perception of intensity profiles [23]. We have not considered other contrast definitions such as root mean square (RMS), since they depend on the relation between contrast and blur [24]. In consequence, they are not suitable definitions for our experiment, since we are looking for separated dependencies on these two parameters.

3. METHODS

Apparatus

Computer-generated stimuli were presented on a Dell VS15x color monitor. The CRT was driven in a noninterlaced mode with a frame rate of 60 Hz. The spot size quoted by the manufacturer was 0.28 mm. In practice, the whole width of the spot was approximately 0.32 mm. The monitor was calibrated with a photometer (Gossen Panlux Electronic). The monitor calibration curve (see Fig. 2) follows a power law relation between the 8-bit value (g) and the luminance (L): $L = a(g^{\gamma} + b)$, where $\gamma = 2.7$, the constant a depends on the particular display, and the offset b accounts for monitor glare and its value is -4.6.

According to the standard definition of contrast and following the law for L, we have

$$C = g_{\mathrm{MAX}}{}^{2,7} - g_{\mathrm{MIN}}{}^{2,7}/(g_{\mathrm{MAX}}{}^{2,7} + g_{\mathrm{MIN}}{}^{2,7}) - 2 \times 4.6.$$

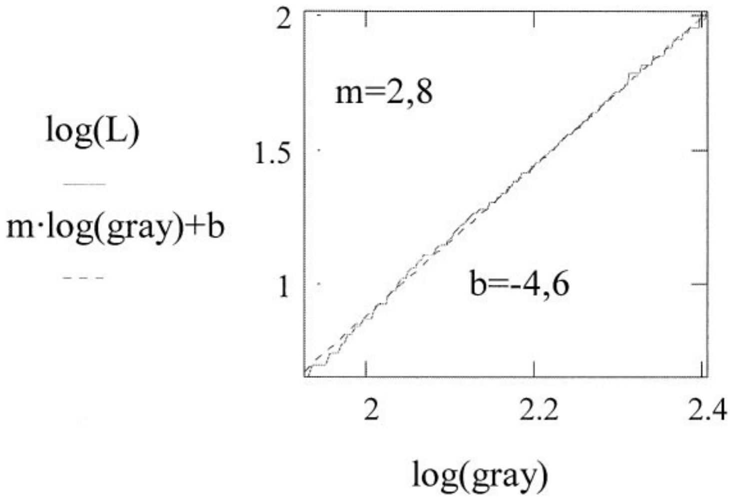

FIG. 2. Calibration curve of the display. It is a logarithmic representation of the ratio between the measured luminous signal(lux) and the gray-level values. Only gray levels between 84 and 255 are represented. The dotted line shows the exponential fit of the data.

If we compare this equation with Eq. (2) it is evident that $g_{\mathrm{MAX}}{}^{2,7} - g_{\mathrm{MIN}}{}^{2,7} = \mathrm{com}$. Then the compression factor of the digitized edge image is equivalent to the luminance range on which the monitor is displaying the image, provided that we are operating under the linear region of Fig. 2. This is the case in the current study.

The luminance ratio displayed by the monitor was 1 cd/m^2:100 cd/m^2. The luminance of the background field in the screen was chosen so as to be equal to that displayed between stimuli (20 cd/m^2). The value of the adaptation field previous to the test was also 20 cd/m^2.

Luminance Perception

The stimuli presented to the observers is defined in terms of luminance levels. Therefore, one first needs to discuss this magnitude for a convenient use and understanding of the luminance range values for which the tests have been designed. It is well known that a number of visual functions, among them contrast sensitivity, are dependent on the luminance of the visual stimuli [25]. Morgan *et al*. [14] pointed out the existence of a nonlinear processing stage in luminance perception affecting the blur perception. As displayed in Fig. 3a luminosity is a function of luminance and exhibits specific values of threshold for certain values of maximum luminance. The influence of the nonlinear state for luminance processing is expressed as $R_L = L \cdot R_{\max}/(L + H)$, where R_L is the amplitude response to a luminous signal of luminance L and $R_{\max}$ represents a constant dependent on the adaptation state. This dependence is shown in Fig. 3b. Also, in Fig. 3c H represents the luminance level at which half the maximum response is reached. As can be seen, this function reaches a constant value for high luminance.

The Commission Internationale De L'Éclairage (CIE) also considers this characteristic of luminance perception. CIE [26] defined the magnitude *luminosity* (L^*) for converting the luminance into a perceptual response according to the expression $L^* = 116\,(L/L_{\mathrm{n}})^{1/3} - 16$, whose validity range is $0.008856 < L/L_{\mathrm{n}}$, where L_{n} is the maximum reference luminance and L^* defines a range from 0 to 100. Thus, human vision has a nonlinear response with

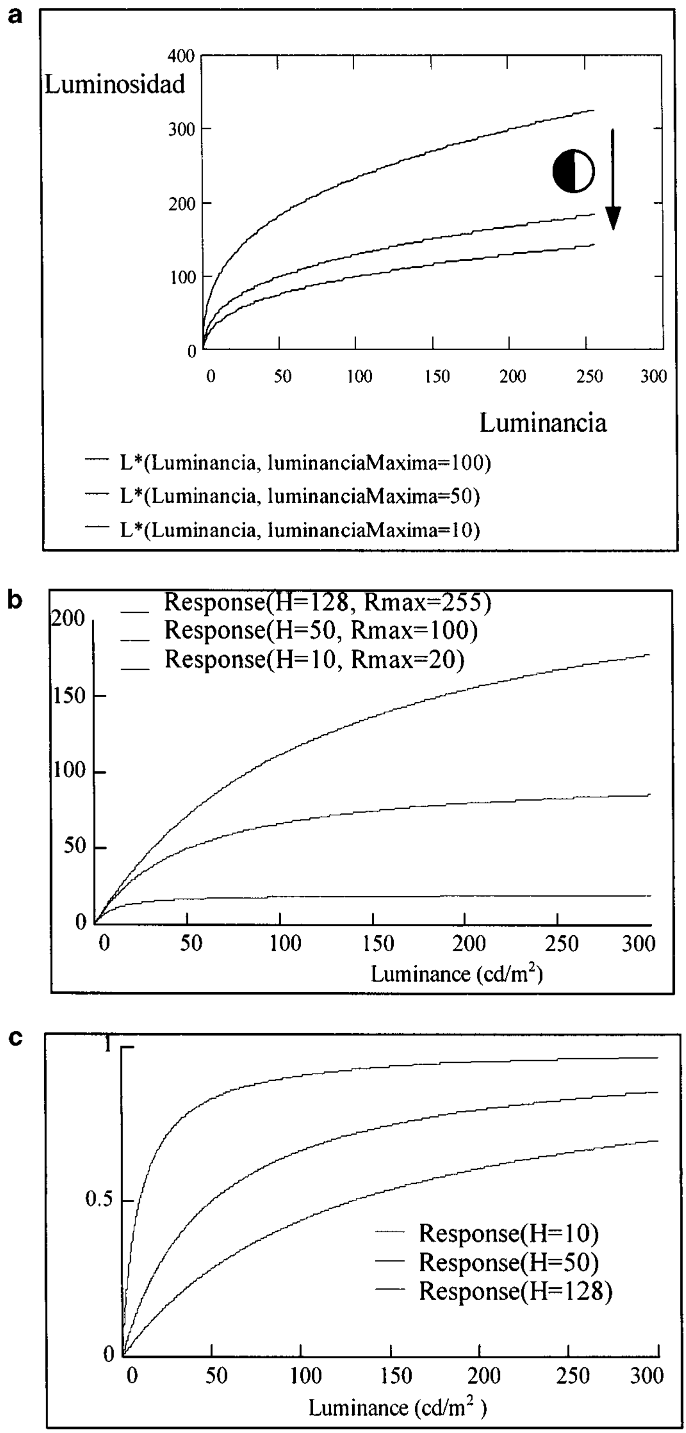

FIG. 3. (a) Luminosity perception scale for the human visual system (HVS) from [14]. Regions of saturation in luminance appear fixed by the adaptation process for certain luminance values. (b, c) CIE relations between luminosity (perception) and luminance (stimulus) showing the dependence on the maximum luminance.

respect to luminance, and the luminosity perception follows approximately a logarithmic behavior.

In Figs. 3b and 3c, we observe that both expressions for the luminace response behave similarly, except at high luminance values. Adaptation to a specific luminance range presented to an observer is established by the highest luminance value processed in the visual field of the observer. The relationship blur–contrast defined in previous studies should be modified for high luminance. The conditions of stimulus response in this study deal with photopic vision [27].

Experimental Conditions

The viewing distance was 114 cm to avoid corrections for stimulus contrast [28]. Viewing was with natural pupils and in a completely dark environment (absent of any emissions source except for the monitor), avoiding possible stray light due to reflections on the screen and ensuring that only emissions energy coming from the monitor was received. The monitor was surrounded by a black background.

Stimuli

The stimulus arrangement for the experiment was a 2D gray-scale representation as illustrated in Fig. 4. In this experiment, we followed the arrangement proposed by Watt and Morgan [13]. A near-perfect edge and a blurred edge of opposite polarity but equal luminance were placed well separated in a single, long ribbon of light. The number of available displayed images was 120 (10 blur levels per contrast level).

Procedure

The observers were required to judge which edge appeared to be the more sharply focused. Since the edges were side by side rather than on top of one another, the observer could not use Vernier alignment cues. Also, the location of each edge was varied slightly from trial to trial within a region of uncertainty so that the subject could not use distance cues. The mean separation of the edges was 90 arcmin.

The method used to determine thresholds consisted of a two-alternative forced choice (2AFC) procedure. The observer was instructed to select which edge appeared to be less

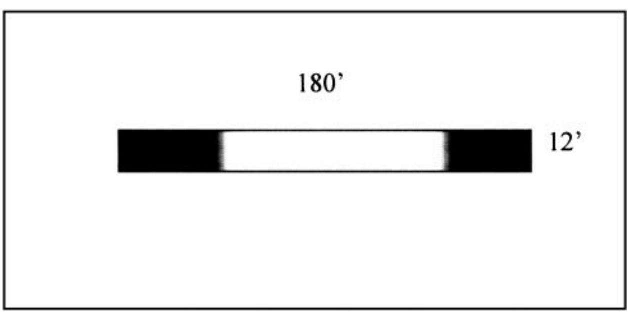

FIG. 4. The stimulus arrangement for the test. The numbers, 180′ and 12′, represent the visual angle (arcmin) subtended by each image dimension in horizontal and vertical directions, respectively. The mean separation of the edges is 90 arcmin. (See text for details).

blurred. The time considered sufficient to get a good adaptation to the screen and to other parameters involved in the test was 10 min. Each trial began with the stimulus presentation and the exposure lasted until the observer responded. With this procedure we chose a long option time response to ensure a correct answer. Eye movements occurred at the time of the judgement since it is well known that saccadic latency is 225–275 ms. Thus, there are about three eye movements per second. Avoiding eye movement to give a reasonable good fixation target would limit the exposure to 200–225 ms. This is obviously a very short response time. After each response, an adaptation interlude was presented, lasting 2 s. A typical trial took approximately 1 h. In order to measure the blur threshold as a function of contrast, the total observer's task was separated into subtasks, each one having a predetermined constant contrast. The performance order of each constant-contrast subset was randomly chosen in order to avoid any possible bias of the observer's behavior in the high-contrast region. Also the blur index was selected randomly from a number of preset magnitudes using the method of constant stimuli [28]. Probit analysis [29, 30] was used to determine the standard deviation of the resultant psychometric function, and the threshold defined as 75% correct point. Probit analysis also estimates the standard error of this statistic.

Observers

The observers were three adults and experienced in psychophysics observations, being either 45 years old (M.C.R.) or between 25 and 30 years (A.S.P. and I.S.R.). They either had normal uncorrected vision or wore corrective lenses (A.S.P.).

4. RESULTS

Table 1 summarizes the values of the important parameters from the earlier studies of Hamerly and Dvorak [12], Watt and Morgan [13], and the present study. Although a direct comparison with the parameters from Watt and Morgan is not possible, we have included them since we have used the same experimental arrangement. Poynton [23] established that a human observer is able to perceive luminous stimuli for values of luminance ranging from a maximum value (100 cd/m^2 in our study) to a 1% of this luminance value (see Table 1). This is an important requirement to avoid the unpredictable effects due to luminance adaptation.

TABLE 1
Values of the Important Parameters Used in the Different Experiments

	Hamerly and Dvorak [12]	Watt and Morgan [13]	Present study
Viewing distance (m)	2.6	1.14	1.14
Contrast	0.81, 0.35, 0.1[a]	0.80, . . . , 0.10[b]	≈1.00, 0.96, . . . , 0.50[a]
Blur (arcmin)	0.30–2	0–10.0	0.6–2.1
Image size	2°	180 × 12 arcmin.	180 × 12 arcmin.
Luminance (cd/m^2)	Max.: 87.3	Max.: 522 Min.: 63	Averaged: 20 Max.: 100 Min.: 1
Threshold (%)	75	84	75

Note. In order to compare values it is necessary to consider the adaptation process [23].
[a] Digital based definition.
[b] Luminance based definition.

We have taken into account DMC values belonging to the intermediate region (0.5–0.8) in order to calibrate the psychophysical procedure (to give some reference about stimuli to observers. High DMC values (0.8–≈1.0) were also selected to explore blur perception for these high contrasts and to complete previous studies.

The blur threshold values (75%) estimated with probit analysis from data collected for each observer and contrast values are displayed in Table 2 together with the standard deviation (SD, %) or confidence range of the probit estimation. The blur threshold (BTh_0) values are also plotted against the DMC in Fig. 5. We have also plotted the blur threshold values adapted from Ref. [12]. Although the BTh_0 of the three observers are very scattered, they show a similar tendency; that is, the thresholds have a light decreasing tendency for medium-contrast values and a noticeable increase for high-contrast values. In this region, small variations in contrast cause changes in the thresholds stronger than those in the low-contrast region. From this result it seems that the perception of luminance in the presence of very low blur values is being modified. Of course, the blur perception will be affected in the same way.

Threshold Curve Fitting

Watt and Morgan [13] proposed the expression

$$S_b = \frac{0.05 \cdot \sigma_g^{1.5}}{C^{0.5}}, \tag{3}$$

which relates the blur difference threshold S_b (i.e., the minimum difference in blur extent that is detected when one blurred edge is compared with a reference blurred edge) to contrast

TABLE 2

Blur Threshold Values and Standard Deviation (SD) Estimated by Probit Analysis of Data Collected for Each Observer with Specification of DMC Contrast Values (13 Implemented Values According to Eq. (2))[a]

	$BTh_0 \pm$ SD (%)		
DMC Contrast	A.S.P.	I.S.R.	M.C.R.
1.0000	1.0732 ± 20	0.9597 ± 17	0.9860 ± 35
0.9600	1.2804 ± 30	0.5951 ± 40	0.9132 ± 20
0.9200	0.8937 ± 20	0.5957 ± 40	0.7316 ± 25
0.8800	0.8343 ± 30	0.4892 ± 30	0.7792 ± 17
0.8400	1.0084 ± 20	—	0.7581 ± 17
0.8000	0.7046 ± 30	0.3310 ± 16	0.2001 ± 30
0.7600	—	0.3671 ± 20	—
0.7200	0.6002 ± 20	0.3530 ± 30	—
0.6800	—	0.3455 ± 40	—
0.6400	0.6163 ± 30	0.1117 ± 17	—
0.6000	—	0.4611 ± 18	—
0.5600	0.7253 ± 30	—	—
0.5200	0.5586 ± 40	0.5297 ± 20	—

[a] Note that the nonavailable data are due to some restrictions apparent for each particular observer at the time of running the test, in particular, tiredness due to the long duration of the test (on the order of 1 h per observer sited on the bar with eye fixation). To calculate the curves in Fig. 6 we have considered the following ranges: 0.7200–1.000 for A.S.P. and I.S.R., 0.8400–1.000 for M.C.R., corresponding to the searched behavior for high contrast response versus blur threshold. We recall that the contrast ranges measured in the papers of Hamerly and Dvorak [12] and Watt and Morgan [13] were 0.81–0.10 and 0.80–0.10, respectively (see Table 1).

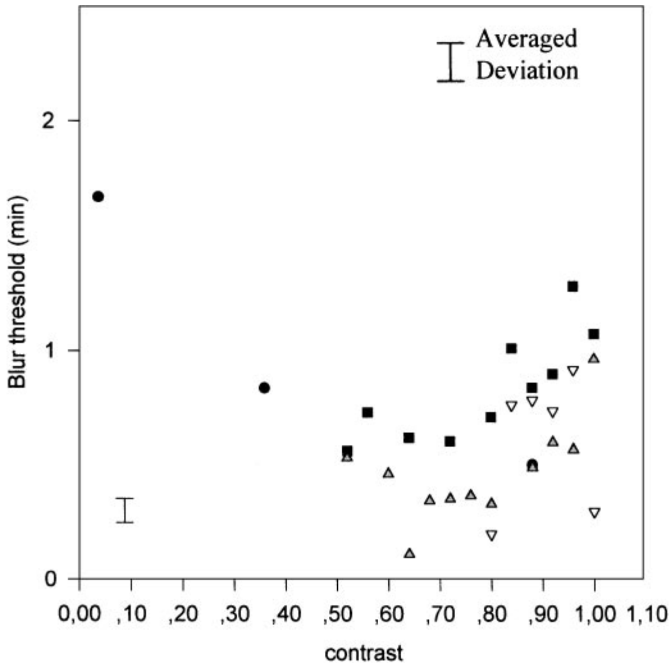

FIG. 5. Blur threshold as a function of digital Michelson contrast (DMC). The results plotted are from the three observers I.S.R.▲, A.S.P. ■, and M.C.R.▽ and the results obtained by H.P.L.● [12].

C and Gaussian reference blur extent σ_g. This expression was developed by assuming that the blur perception task and edge location are related to the position of the stationary points of the second derivative distribution of the retinal stimulus. Therefore, Eq. (3) defines the location of the origin of a blurred edge. The theoretical expression proposed by Watt and Morgan was also in agreement with their experimental results [13]. Equation (3) was derived from fitting results for low- and medium-contrast values (up to 0.8) with reference blur values higher than 2.5 arcmin. Later, Nijenhuis [9] and Kayargadde and Martens [10] proved the validity of this relation by considering it in algorithms for the calculations of image perceptual quality. Such algorithms show a close agreement with the results obtained with psychophysical tests.

Despite the differences among experiments, we have considered the above expression since it is already well established and accepted as the relationship between degradation sensitivity and contrast [9, 10]. By accepting that this relation also describes qualitatively the blur sensitivity data (up to 0.8), in experiments with zero reference blur, we have generalized it for high-contrast values. In a first approximation, we have linearly fitted our data to the expression given in Eq. (4) below. The goodness of the fit expressed in terms of the regression coefficient is 22% as the SDs of the individual BTh_0 are high. The BTh_0 (with zero reference blur) as a function of DMC is

$$\mathrm{BTh}_0 = 0.9 \cdot \mathrm{DMC} - 0.07. \tag{4}$$

The coefficient multiplying DMC is a measurement of the BTh_0 increment per DMC. A maximum value is obtained for $\mathrm{DMC} = 1.0$.

In Fig. 6 the linear fit for each observer is plotted. It can be appreciated that there is a similar tendency for the three observers. For each observer, the values of the increasing

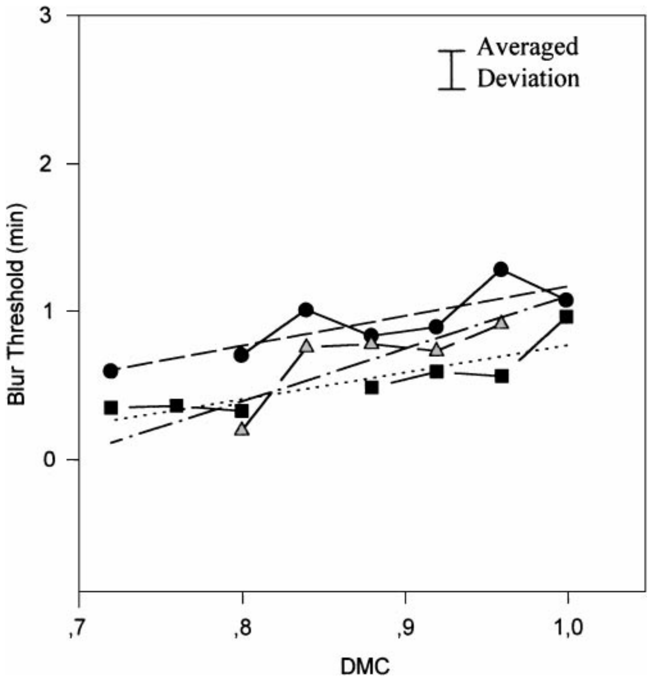

FIG. 6. Fits of the threshold data for the three observers I.S.R. ■, A.S.P. ●, and M.C.R.▲.

BTh_0 ratio (slope of the curve), with corresponding SD, are 1.8 ± 0.4, 2.0 ± 0.5, and 3.1 ± 1.2 for A.S.P., I.S.R., and M.C.R., respectively. The analogous behavior presented for the two first observers is very noticeable (see Fig. 6) as their threshold have only a shift. The third observer presents a major dependency with regard to the DMC.

5. DISCUSSION AND CONCLUSIONS

Based upon previous mathematical models for blurred edge representations we have carried out a psychophysical test for blur sensitivity. For that purpose we followed the main characteristics of an earlier test developed by Watt and Morgan. The interest of the present study is that it extends the previous results to a wider range of contrasts by including high-contrast values (ranging from 0.8 to 1.0). The experimental data obtained from three adult observers show an increase in the blur threshold values for this extended contrast range. Comparisons with previous results would be valid for the low and intermediate regions of contrast. A possibility to extend these comparisons could be carried out via blur sensitivity for grating-type objects [31].

The results given in Figs. 5 and 6 differ noticeably from those deduced for high contrast from the Watt and Morgan expression (Eq. (3)). With the aim of achieving a better explanation of our results, we have also considered Watt and Morgan's theory on the existence of a nonlinear stage in luminance perception. This transformation takes place after the light reaches the retina and prior to the location of the stationary points in the second derivative of the retinal light distribution. It constitutes another important mechanism involved in blur perception and edge location. This mechanism would also explain certain optical illusions as the Mach bands and the Chevreul effect. For the former, the greater the contrast differences, the greater the effect. Through this nonlinear transformation, the luminance (stimuli) is related to the luminosity (perception) as standardized by CIE. Basically, a nonlinear transformation in the luminance perception implies a shift in the edge location without modifying the blur extent. Moreover, when the maximum luminance (L_n) increases, the perceived luminosity is only shifted. From these considerations, it seems that the nonlinear stage does not explain a change in the tendency for blur perception for high contrasts such as that displayed in Fig. 6. For this reason we have considered the need for a new mechanism that would be associated with compression in response to the high luminance [27] that appears in the test when the high contrasts are analyzed.

We have characterized this effect by the ratio increase and the maximum value for the threshold in a first approximation. This effect will be investigated in order to obtain a more generalized expression. In this sense, it is also possible to take into account other factors not considered in this work that could affect the behavior of the blur threshold for high contrast such as the influence of age and training of the observers. In fact, from results not displayed here we have found some disparity for an observer aged 50 for which there was a constancy in threshold for high-contrast values. Further experiments for age factor are required [32, 33].

The interpretation of experimental results obtained for blur perception in images is conditioned by the formulation of mathematical models. The definitions of mathematical operators representing different visual mechanisms are limited by the specific mathematical properties of the operators used in the model. As natural biological processes cannot be entirely described in terms of mathematical models one must restrict the search to interpreting partial mechanisms [34]. For example, the application of the formula $S_\mathrm{b} = 0.05 \cdot \sigma_\mathrm{g}^{1.5}/C^{0.5}$, established for the blur difference threshold, could be proved with the implementation of algorithms. Kayargadde and Martens have also discussed this aspect to ensure objective measurement estimation and interpretation.

In summary, the interpretation of the results suggests the presence of a certain state of saturation or overload in luminance perception. Note that with the Mach effect the results observed correspond to normal behavior. Also, the statistics applied for data analysis may play a role in the results described. In fact, a tendency of the three observers to an average value (close to 1.0 for DMC = 1.0) is clearly evident in Fig. 6 [34].

Blur sensitivity measurements require a complete analysis of low, intermediate, and high contrast, accounting for possible limits of blur perception. This aspect is of particular importance in the analysis of high-contrast images. The authors are now continuing this study by extending the analysis to include other possible parameters (i.e., age, luminance level) not considered in the present work.

An application of this analysis on the behavior of blur sensitivity to high-contrast values, enlarging the luminance range, should be of interest, for example, when setting up techniques for image compression, i.e., reducing contrast for improving perceived quality.

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