BLUR TOLERANCE IN DIFFERENT COLOUR DIRECTIONS

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ABSTRACT

We investigated the blur tolerance of human observers for stimuli modulated along the isoluminant red-green, the isoluminant yellow-blue, and the achromatic direction in colour space. The smallest blur difference thresholds are found for slightly blurred images and are about 0.5 arc min for red-green and luminance stimuli and 1.5 arc min for yellow-blue stimuli. The estimated internal blur for luminance-modulated and red-green stimuli is about 1 arc min, for yellow-blue it is about 2 arc min. The contrast dependence of blur tolerance is identical for red-green and luminance. Our blur tolerance estimates may be useful when gaussian lowpass filtering is used for noise removal in colour images.

Keywords: blur; colour; luminance; sharpness; lowpass filtering.

1   INTRODUCTION

The responsiveness of the human visual system to an image depends on a multitude of image features, such as the wavelength (colour) of the visual stimulus and its spatial content. Three main factors limit the spatio-chromatic sensitivity of the visual system: the optics of the eye, retinal sampling, and post-receptoral neuronal factors. In this paper we investigate a specific aspect of the spatio-chromatic sensitivity of the human visual system. We examine how much blur the visual system can tolerate in different colour directions and its dependence on contrast. We will attempt to account for the observed blur tolerance by the known contrast sensitivity function for luminance red-green, and yellow-blue gratings. Our results could be useful as a guideline for image processing applications, such as removal of noise in chromatic and monochromatic images.

2   METHODS

The purpose was to assess the blur tolerance of the visual system for different colour directions and to arrive at an estimate of the internal blur and the contrast dependence of blur thresholds.

Six subjects with normal colour vision (confirmed with Ishihara plates) and normal or corrected-to-normal spatial vision participated in the experiment.

2.1. Stimuli

The test patterns were vertical square wave patterns with a fundamental frequency of 1 cycle per degrees, vignetted by a two-dimensional Gaussian envelope, subtending 6 degrees of visual angle (256 x 256 pixels), superimposed on the uniform grey background for 1 second. The stimuli were modulated along a luminance (black-white) direction, an isoluminant red-green or an isoluminant yellow-blue direction. Isoluminance was defined by photometric luminance and based on the photometric standard observer [1]. The maximum cone contrast used for the black-white and red-green modulations was 10% and for yellow-blue 80%. For red-green and luminance modulatoins, cone contrast is defined as the average incremental LM cone excitation divided by the cone excitation of the background. The L cone contrast is referred to as $c_L=\Delta L/L_{BG}$; the M cone contrast is defined similarly as $c_M=\Delta M/M_{BG}$ where ΔL and ΔM are the incremental cone excitations in the L and M cones respectively. L_{BG} and M_{BG} denote the cone excitations of the grey background. Luminance stimuli are modulations between dark and light grey such that the L and M cone contrast are of equal sign, whereas the red-green chromatic stimuli are modulations between red and green such that the L and M cone contrast are of opposite sign and a 2:1 ratio of L: M cone contrast. We chose this cone contrast metric for several reasons. First, it makes no assumptions about post-receptoral mechanisms. Secondly, for luminance-defined stimuli, our cone contrast measure is identical to Michelson contrast. Finally, for the luminance and isoluminant stimuli used in our experiment, a vector length metric

and a cone contrast metric (RMS) would make almost identical predictions. RMS is also often used as a metric for coloured lights. The yellow-blue colour direction is identical to the tritanopic confusion line; modulations along the yellow-blue direction only stimulate the S cones and do not affect the L or M cones. Cone contrast for yellow-blue is defined as $\Delta S/S_{BG}$.

2.2. Apparatus

Stimuli were presented on a Mitsubishi Colour Monitor (19 inch) that was driven by a Cambridge Research VSG 2/3 graphics board with a refresh rate of 100 Hz non-interlaced. The output of the two 8-bit-digital-to-analog converters were combined to produce an intensity resolution of 12-bits. A spectroradiometer (Photo Research PR650) was used to measure the spectral power distribution of the three phosphors. The spectra were multiplied by Judd's 1951 colour matching functions to derive the chromaticities and the luminance values of the three phosphors[2,3]. The derived luminance values were used to construct a look-up table that linearised the relationship between the pixel values and the light output of the monitor. The CIE co-ordinates (x,y, maximum luminance in cd x m^{-2}) of the phosphors were as follows: (0.623, 0.352, 22) for the red gun, (0.285,0.585,52) for the green gun, and (0.145, 0.067, 6) for the blue gun. The background was kept constant at a grey with CIE co-ordinates of (0.34, 0.36, 40). The viewing distance in all experiments was 114 cm.

2.3.Procedure

We used a 2-interval-forced-choice (2-IFC) procedure to measure blur thresholds. One interval contained the standard square wave (with a fixed reference blur), the other interval contained the square wave grating with a variable amount of blur. The amount of reference blur applied to the standard ranged between 0 and 3.5 arc minutes, with 0 representing a sharp square wave and 3.5 representing a highly blurred square wave grating. The task of the observer was to indicate which of the two intervals contained the sharper stimulus.

The lowpass filtering (blurring) of the square wave grating was achieved by on-line spatial convolution with a Gaussian mask. The amount of blur was controlled by varying the standard deviation of the Gaussian kernel; a large standard deviation resulted in a large amount of blurring.

Psychometric functions were obtained for each reference blur in each session, a Weibull curve was fitted to the psychometric function and blur threshold was defined as the 81% on the psychometric function. Chance performance was 50%.

3. RESULTS

3.1. The 'dipper' function for blur discrimination

Fig. 1 shows the blur thresholds as a function of the external reference blur for all three colour directions.
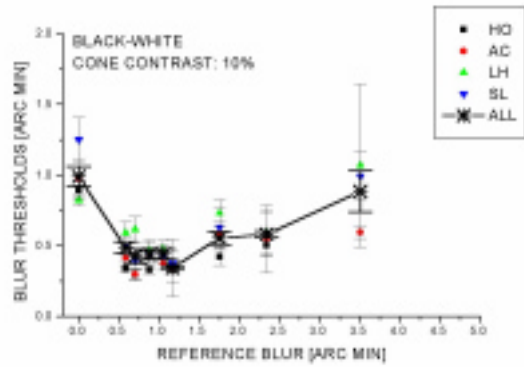

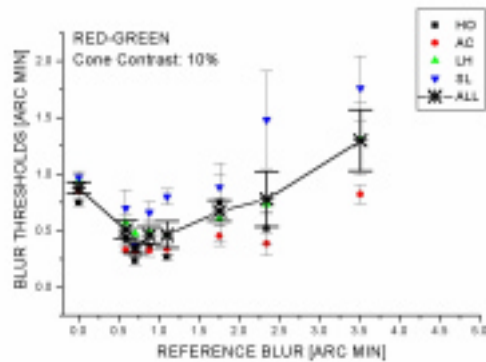FIG. 1a. Blur thresholds for black-white stimuli.
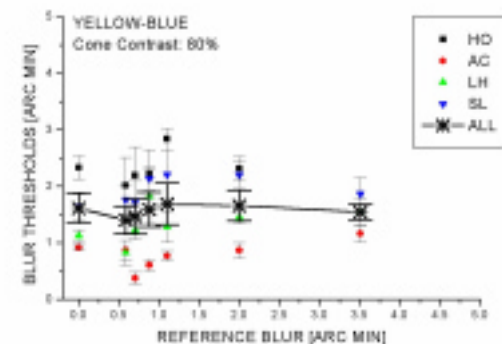

FIG. 1b. Blur thresholds for red-green stimuli

FIG. 1c. Blur thresholds for yellow-blue stimuli.

We obtain a u-shaped function for all three colour directions and for all observers. This counter-intuitive finding that human observers are most sensitive to incremental blur when added not to very sharp images

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but to slightly blurred images, has been reported before for luminance edges[4,5]. We have replicated this finding for luminance edges and found the same u-shaped function for red-green and yellow-blue gratings. Black-white (Fig. 1a) and red-green stimuli (Fig. 1b) were presented at 10% cone contrast, yellow-blue stimuli (Fig. 1c) were presented at the maximum available contrast, namely 80% cone contrast. On the x-axis the reference blur of the standard stimulus is plotted, on the y-axis the blur difference thresholds are plotted. Blur discrimination thresholds for black-white (Fig. 1a) and red-green (Fig. 1b) are very similar and show a minimum at a reference blur between 0.5 and 1 arc min. The blur thresholds for sharp square waves (0 reference blur) are about 1 arc min for red-green and for black-white. Blur thresholds for yellow-blue gratings are much higher (1.8 arc min; Fig. 1c). The minimum blur thresholds for yellow-blue also occur at a reference blur between 0.5 and 1 arc min.
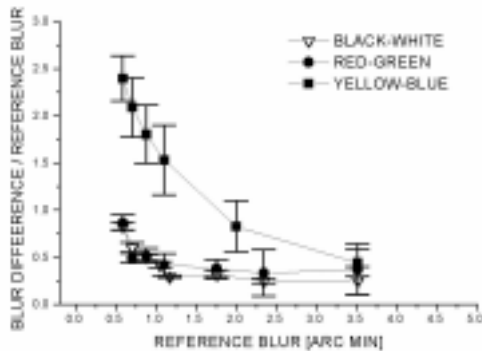

FIG. 2. Blur thresholds are re-plotted as Weber Fractions.

In Fig. 2 the data are replotted as Weber fractions, that is, as the ratio of the blur difference thresholds and the external reference blur. The Weber ratio for black-white (open triangles) is constant at 0.28 for external blurs larger than 1 arc min; the Weber ratio for red-green is only slightly higher and it levels at 0.35 for external blurs larger than 1 arc min. Hence, for red-green and black–white blur discriminations, Weber's law holds when the stimulus is slightly blurred (>1 arc min). These results differ from previous findings on luminance targets where the blur difference thresholds did not follow Weber's law and an exponent of 1.5 rather than 1 had be postulated for the external blur[4]. However, subsequent experiments on luminance edges confirmed the validity of Webers law for external blurs larger than 3 arc min[5]. For yellow-blue gratings (closed squares) the Weber ratio converges to a constant value at much larger external blur values, i.e above 3.5 arc min. The Weber ratio is about 0.5 for a reference blur of 3.5 arc min.

3.2. Contrast dependence

To assess the contrast dependence of blur discrimination sensitivity we measured blur thresholds at several contrast levels (3%, 5% and 10% cone contrast for red-green and black-white; 25% and 80% cone contrast for yellow-blue). Figs. 3a-c show the thresholds for a reference blur of 0 arc min for all three colour directions for all observers. In Fig. 3d (lower right corner), the contrast dependence is compared for the three colour directions. Regression lines have been fitted and the resulting slopes (in log co-ordinates) are as follows: -0.147 for black-white, -0.161 for red-green, and –0.758 for yellow-blue. We compared the regression lines for the different colour directions[6] and found the following: neither the slopes (P=0.35) nor the intercepts (P=0.56) are statistically different for the black-white and the red-green directions. The slope for yellow-blue is also not different from the slope for red-green and black-white (P=0.34). Hence we conclude that the contrast dependence for all three colour directions is the same. The intercept for yellow-blue differs from the intercept for red-green and black-white (P=0.013). When testing for the overall coincidence of the red-green and the black-white regression lines, we find that they do not differ significantly from each other (P=0.342). Overall, the yellow-blue regression line differs significantly from the red-green and the black-white regression lines (P<0.001) reflecting the fact that the thresholds for yellow-blue are twice as high as the thresholds for red-green and black-white stimuli.
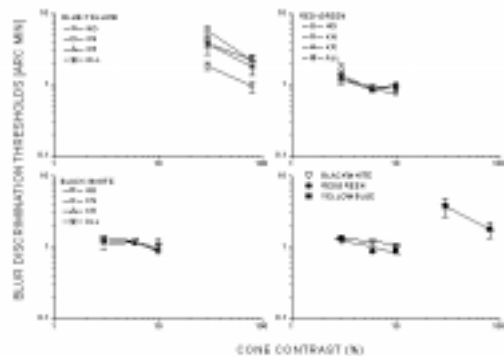

FIG. 3. Blur thresholds as a function cone contrast.

4. DISCUSSION

We show that blur discrimination sensitivity is optimal for slightly blurred images rather than for sharp images. Our findings are in agreement with previously reported blur discrimination thresholds for luminance edges and extend the results to chromatic gratings.

4.1. Comparison of blur tolerance for luminance and red/green stimuli

Our psychophysical experiments show that the blur tolerance for luminance and isoluminant red-green stimuli is very similar when the stimuli are stationary and of identical LM-cone contrast. For both colour directions, Weber's law holds for external blurs larger than 1 arc min and the absolute blur difference thresholds are almost identical. These findings are consistent with the hypothesis that, in our visual tasks, luminance and chromatic stimuli are mediated by the same mechanism. Furthermore, the contrast dependence is similar for both luminance and isoluminant red-green targets, which also supports this hypothesis. The most likely pathway is the parvocellular pathway, which responds to luminance and isoluminant chromatic modulations, is sensitive to high spatial frequencies but rather insensitive to high temporal frequencies.

4.2. Blur tolerance for yellow-blue stimuli

Blur thresholds for yellow-blue are about twice as high than for the red-green and black-white gratings when yellow-blue gratings are presented at the maximum contrast (80% cone contrast) and red-green and black-white gratings are presented at 10% cone contrast. Webers law does not hold for yellow-blue stimuli for the range of external blurs we have measured (up to 3.5 arc min). This suggests that little masking or normalisation takes place in the yellow-blue pathway. .

Blur difference thresholds are lower than expected from the retinal sampling of the blue cones. Only approximately 5% of the cones are sensitive to short-wavelength light and the yellow-blue modulations employed in this experiment are chromatic modulations that only stimulate the blue cones. Hence, if the performance in this task was only limited by the retinal sampling mosaic we expect the blur thresholds for yellow-blue to be higher than by a factor of 2.

4.3. Computations underlying blur discrimination

We will now consider two possibilities to account for the blur discrimination thresholds. The first possibility is the model proposed by Watt & Morgan which is based upon the idea that blur discrimination performance is based on the output of the most sensitive spatial filter.

4.3.1. Watt & Morgan's Blur Model

The purpose of our experiment was to assess how much blur the visual system tolerates in different colour directions. To obtain a quantitative estimate of the internal blur in the visual system associated with

the different colour directions, we used a simplified version of the model proposed by Watt & Morgan[7] which has been used successfully to predict blur discrimination data for luminance edges. The two main assumptions are:

A1. The internal blur of the visual system maybe modelled as a Gaussian spatial filter. Hence the internal blur representation is given by the convolution of the real edge of blur B with the filter of space constant s (internal blur). If the blur is Gaussian, then the internal blur representation (B') is given by:

$$B' = \sqrt{s\ + B^2}\ .$$

A2. The main source of error in a 2-IFC blur discrimination task is the comparison of the internal blur representation in the two intervals. We assume a Weber law for the internal blur comparison: $\Delta B'/B' = k$.

Based on these two assumptions blur difference thresholds (ΔB) can be expressed as a function of the Weber constant, the internal blur constant, and the external reference blur[7]. We estimated the two parameters, that is, the standard deviation of the internal blurring function (s) and the Weber constant (k), using a weighted least-squares fit:

$$\chi^2(s,k) = \sum_{i=1}^{N}\left[\frac{\Delta B_i - \Delta B(B_i;s,k)}{\sigma_i}\right]^2$$

$\Delta B(B_i;s,k)$ is the predicted blur threshold as a function of B,s,k; s is the internal blur, k is the Weber constant, B_i is the external reference blur, ΔB_i is the observed blur difference threshold, σ_i is the standard deviation of the relevant data point and N is the number of data points.
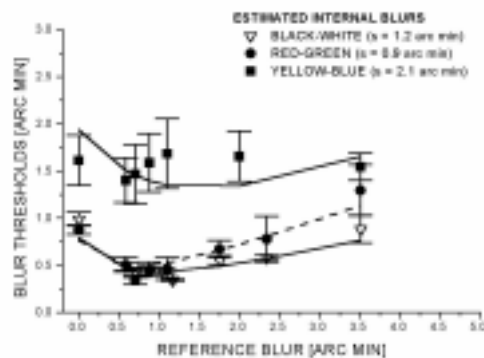

FIG. 4. Model fit and estimated internal blur.

The solid and dashed lines in Fig. 4 show the predicted blur difference thresholds as a function of the external reference blur for the three colour directions. The fits were performed over the accumulated data of all observers. (i) For black-white and red-green

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modulations the internal blur estimates are very similar and around 1 arc min (Fig. 4) when the stimuli are equated in terms of cone contrast (10% cone contrast). The estimated Weber-Fraction (for the internal blur representation) is slightly higher for red-green (Weber constant = 0.3) than for black-white (Weber constant = 0.2) (ii) Yellow-blue stimuli produce internal blur estimates that are twice as high (2.1 arc min) as luminance and red-green blur estimates (Fig. 4). The estimated Weber fraction for yellow-blue is 0.36 and is higher than for red-green and for luminance stimuli. For all three colour directions, the thresholds predicted from the model do not differ significantly from the observed data; in all three cases the probability that the deviations from the model fit are due to chance is larger than 0.1.

Our estimate of 1 arc min for the internal blur in the luminance pathways is in agreement with a previous study on motion blur[8]. Watt and his collaborators[4] have reported internal blur filters of larger sizes (2.8 arc min) than we find in our experiment. However, the external blur at which blur discriminability is optimal is very similar to ours, namely at around 1 arc min. Assuming that Watt & Morgan's model is correct, the filters used in our blur discrimination task are centered at higher spatial frequencies than the spatial filter derived from their experiments. The estimated filters for luminance and red-green in our blur discrimination derived from our experiment are centered at around 10 cpd, the centre frequency of the yellow-blue filter is at around 5 cpd. These estimates are higher than the ones derived by Watt and his colleagues: the best-fitting filter for luminance edges was centered at around 5 cpd[4,5,7].

4.3.2. Contrast sensitivity and blur tolerance

Blur tolerance thresholds were assessed by convolving the square wave grating with a Gaussian kernel. Blurring the image with a Gaussian mask attenuates the higher frequencies. We tested the simple hypothesis that blur discriminability can be accounted for by the contrast sensitivity of the human visual system. We made the simplifying assumption that the human visual system can be modeled by a single channel whose modulation transfer function is described by the contrast sensitivity curve. The predictions of the single channel model are shown in Fig. 5 and the following steps are involved in the simulations. All calculations were performed with MatLab Version 5.

(1) The original square waves are blurred with the reference blurs as in the actual experiment (reference blurs used in the simulations: 0, 0.5, 1, 2, and 3.5 arc min). This is done by convolving the waveforms with Gaussian kernels of the appropriate standard deviations. Then the Fourier transform of the blurred waveforms was performed and the amplitude spectra are computed (*Reference Spectra*)

(2) The blurred waveforms that are just noticeably different from the reference waveforms are simulated. Again, this is done by convolving the original square waves with Gaussian kernels. The blur applied to these comparison stimuli is the sum of the reference blur and the (measured) blur difference threshold (see Fig. 1). By definition, the comparison stimulus is one JND apart from the reference blur. E.g. for luminance stimuli (see Fig. 1a), for a reference blur of 0, the difference blur (at threshold) is 1 arc min and the resulting comparison blur is 1 arc min; for a reference blur of 0.5 arc min the difference blur (at threshold) is 0.5 arc min and the resulting comparison blur is also 1 arc min. The Fourier Transform of the comparison stimuli is then computed and we refer to the amplitude spectra as *comparison spectra.*

(3) The next step is to multiply the reference and the comparison spectra with the contrast sensitivity functions for luminance, red-green, and yellow-blue modulations. The contrast sensitivity data were taken from Mullen[9]. We expressed the contrast sensitivity for red-green and luminance in cone contrast units; the units for yellow-blue contrast sensitivity are arbitrary. It is worthwhile noting that, for a 0.3 cpd grating, the cone contrast required for detection is 0.00245 for red-green and 0.0124 for luminance modulations; hence the red-green grating detectability is *20 times higher* than the luminance one for this low frequency. For a 3 cpd grating the threshold is 0.015 for red-green and 0.00635 for luminance modulations; hence, for 3 cpd, the detectability of a red-green grating is *2.5 times lower* than the detectability of a luminance grating. For frequencies above 3cpd the relative sensitivity (luminance vs. red-green) is fairly constant and about 2.5 times lower for red-green compared to luminance modulations. Based on Mullen's data the contrast sensitivity curves for luminance and red-green cross over between 1 and 2 cpd when sensitivity is expressed as the inverse cone contrast.

(4) We then take the inverse Fourier transform of the respective reference and comparison spectra, and compute the root-mean-square (RMS) contrast of the difference between the filtered images (reference and comparison stimuli) . The RMS contrast is a measure of the visible difference between the two stimuli.

(5) The final step is to normalise the RMS contrast of the difference image with the RMS contrast of the filtered reference image.

Fig. 5 shows the predictions derived from steps 1 to 5. If the blur tolerance is based upon detecting the overall

contrast difference (via a single channel described by the contrast sensitivity function) then the RMS contrast should be constant when plotted as a function of the reference blur. We report three main findings: (1) For luminance and red-green waveforms (open triangles and open circles), the contrast of the difference image is constant for reference blurs ranging from 0 to 1 arc min. For higher reference blurs, the contrast available in the difference image is too large to account for the measured blur tolerance. In other words, the visual system does not utilise the available information when performing the blur discrimination task. However, for small external blurs (up to 1 arc min) the dipper function for blur discriminability is predicted by the RMS contrast of the difference image. In this range, the contrast in the filtered difference image is constant. (2) The RMS contrast for luminance modulations is consistently higher than for the red-green modulations. Since the difference images are chosen to be one jnd apart from the reference image, the RMS contrast should be identical for the red-green and the luminance modulations. Our calculations show that, difference images with identical RMS contrast, will lead to *lower* blur discrimination thresholds when modulated along red-green than along a luminance direction. (3) The single-channel model does not predict blur tolerance for yellow-blue modulations (open squares) for reference blurs larger than 0.5 arc min. The RMS contrast for yellow-blue is in arbitrary units. With increasing reference blur, the contrast in the difference image is used to a lesser degree than predicted by the contrast sensitivity function.
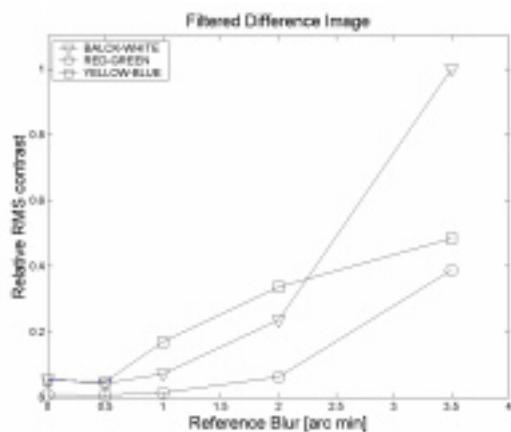

FIG.5. RMS contrast available at blur discrimination threshold.

In summary, a single-channel model based on the contrast sensitivity of the visual system does not predict blur discrimination thresholds for chromatic or luminance gratings. A possible explanation for this mismatch is that blur thresholds are determined by the output of one or a few selected filters or that interactions between different spatial filters are important in this task. A similar conclusion was reached by Watt and his colleagues[4,5,7]. The filters most likely involved in our blur discrimination task are centered at 10 cpd for red-green and luminance, and at 5 cpd for yellow-blue waveforms.

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