Blur tolerance and perceived sharpness in the chromatic and luminance domain

Huw C. Owens, Stephen Westland, and Sophie Wuerger,
Human and Machine Perception Research Centre,
Department of Communication & Neuroscience,
Keele University, Keele, ST5 5BG, UK.

Abstract

We measured blur thresholds for square wave gratings modulated either along the red-green, the luminance or the yellow-blue colour direction. The modulations along the red-green and yellow-blue resulted in zero luminance variation. For all three observers the blur thresholds for red-green and luminance stimuli were very similar. The blur thresholds for yellow-blue were much higher. These results are consistent with the idea that the luminance and red-green channels do not differ in their inherent spatial resolution.

Introduction

When a red-green sinusoidal grating is presented to observers with normal colour vision, observers usually report that the sinusoidal grating looks more like a square wave than a sine wave. The transition from red to green is often described as abrupt. In contrast, a sinusoidal luminance grating of the same spatial frequency is always perceived veridically as a sine wave and the transition from the dark to the white areas is smooth. This 'chromatic sharpening' effect is even more striking for yellow-blue sinusoidal stimuli. The transition between the yellow and blue areas appears to be abrupt and observers usually describe yellow-blue sinusoidal gratings as looking very similar to square waves. This chromatic sharpening effect is largest for isoluminant gratings, for example, for a sinusoidal grating that is modulated between red and green without inducing luminance changes. An isoluminant yellow-blue sinusoidal grating is modulated along a yellow-blue line such that the luminance does not vary.

This phenomenon was first noted by Helmholtz (1909), and has been mentioned by Mullen (1982), and Butler, Carden, and Kulikowski (1993), but to our knowledge it has so far not been studied systematically. Chromatic sharpening is an interesting phenomenon for two reasons. Firstly, it tells us something about the neural mechanisms involved in spatio-chromatic processing. Secondly, it has consequences for image compression and image-encoding applications.

When human observers are asked to resolve fine spatial detail, the performance for luminance-modulated stimuli is usually superior to the performance for isoluminant red-green or yellow-blue gratings. The highest spatial frequency the human visual system can resolve is about 50 to 60 cycles/deg for luminance-defined stimuli and around 20 to 30 cycles/deg for red-green gratings. The cut-off frequency for yellow-blue lies at around 4 cycles/deg (Kelly, 1983). The spatial cut-off frequency is to some extent contrast dependent and also varies with the temporal frequency of the stimulus. Despite the lack of high spatial-frequency information available to the visual system from the chromatic gratings, these gratings appear to have sharp edges.

We investigate a phenomenon related to chromatic sharpening, namely blur discriminability in the various colour directions.

Blur tolerance is relevant for image-encoding and image-compression algorithms. The fact that the visual system can tolerate more blur in the chromatic directions than in the luminance direction can be exploited to achieve efficient image compression. If the visual system tolerates more blur in the purely chromatic directions, there is no need to preserve very high spatial frequencies. A convincing demonstration of the different amount of blur tolerated in different colour directions has been compiled by Hagit Hel-Or (see Wandell, 1995). In the following experiments we attempt to quantify the amount of blur tolerated by the visual system for various colour directions. We use square wave gratings with various amounts of blur added to assess blur thresholds.

Methods

Three subjects with normal colour vision (confirmed with Ishihara plates) and corrected spatial vision served as subjects in our experiment. Each subject took part in 10 sessions. The subjects' viewing distance from the screen was 1.14 m.

Throughout the experiment a grey background of mean luminance (31 cd/m^2) was displayed to ensure stable adaptation. The test patterns were vertical square wave patterns, subtending 6 degrees of visual angle, superimposed upon the uniform background for one second. The stimuli were vignetted by a two-dimensional Gaussian envelope thus depriving the subjects of edge information. The stimuli were modulated along a luminance direction, a red-green direction or a yellow-blue direction. Modulation along the chromatic directions resulted in no luminance change. The CIE coordinates and the cone coordinates are given in Tables 1 and 2.

We used a two-interval forced-choice (2IFC) procedure to measure blur thresholds. Each trial consisted of two intervals. One interval contained the standard (unblurred) square wave grating, the other interval contained the blurred square wave. The task of the observer was to discriminate between the standard and the blurred square wave by indicating via a button press which of the two intervals contained the standard square wave. Depending on the response of the observer, the amount of blur was increased or decreased using a transformed up-down procedure. Each session finished on the completion of ten reversals.

The low-pass filtering 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.

The data of all sessions were accumulated and a Weibull function was fitted to the data using a maximum likelihood criterion. The standard deviation corresponding to 81% correct identification is defined as the blur threshold; chance performance is 50%.

We presented our stimuli on a high quality non-interlaced colour monitor (Mitsubishi Diamond Pro 20X) controlled by a graphics card (Cambridge Research Systems VSG) in a Compaq PC. We corrected for the non-linear relationship between internal specification and luminance by gamma correction. The chromaticity of our stimuli were obtained by spectroradiometric measurements (Photo Research Model Spectrascan PR 650) and correlating them with the tabulated Smith-Pokorny fundamentals.

Colour	x	y	Lum
red	0.397	0.313	31.5
green	0.248	0.389	31.1
blue	0.301	0.279	31.4
yellow	0.403	0.483	31.1
black	0.334	0.345	28
white	0.334	0.345	36.1

Table 1: CIE coordinates

Colour	L	M	S
red	0.032284	0.013475	0.000644
green	0.028066	0.017738	0.000640
blue	0.030364	0.015694	0.001043
yellow	0.030020	0.015268	0.000162
black	0.026995	0.013849	0.000570
white	0.034866	0.017882	0.000738

Table 2: Long wavelength (L), Medium wavelength (M), Short wavelength (S) coordinates

Results

The blur threshold (81% correct) for each observer and for each colour direction was based on ten sessions. Each session contained on average 50 trials or exactly ten reversals of the adaptive procedure.

Figures 1-3 show the relative frequency of correct identification as a function of the standard deviation (minutes of visual angle) of the gaussian kernel. The symbols denote the relative frequencies and the Weibull fit is denoted by a continuous line. Figures 1a-c show the psychometric functions for luminance.

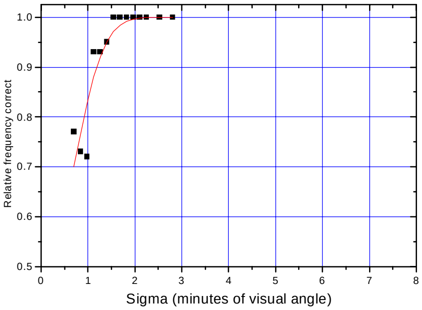

Figure 1a : Observer HO; luminance

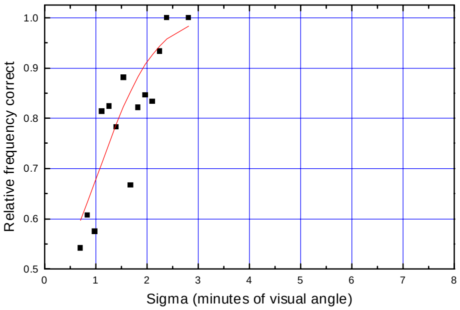

Figure 1b: Observer JH; luminance

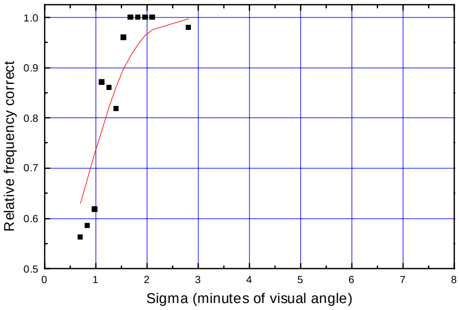

Figure 1c: Observer SMW; luminance

Figures 2a-c show the psychometric functions for red-green.

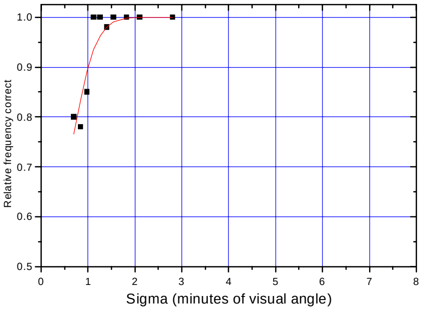

Figure 2a: Observer HO; red-green

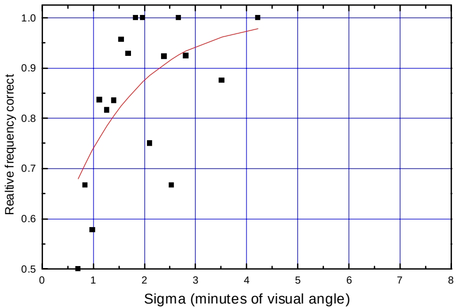

Figure 2b: Observer JH; red-green

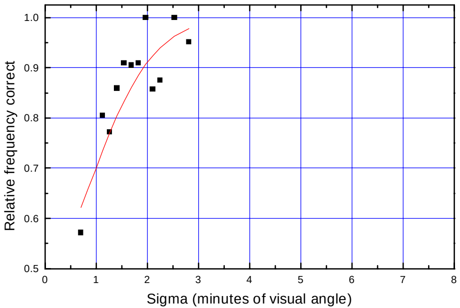

Figure 2c: Observer SMW; red-green

Figures 3a-c show the psychometric functions for the blue-yellow colour direction. The psychometric functions for yellow-blue are shallower than those for red-green and luminance for all three observers.

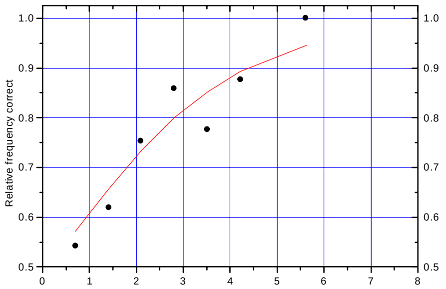

Figure 3a: Observer HO; blue-yellow

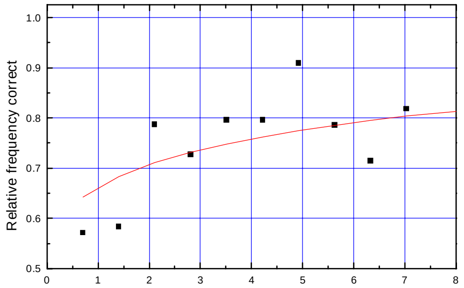

Figure 3b: Observer JH; blue-yellow

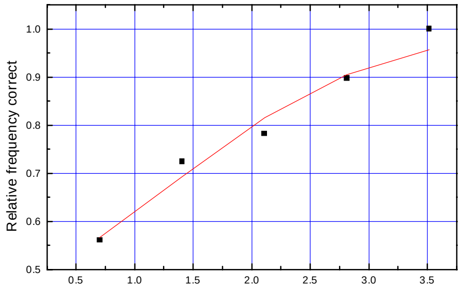

Figure 3c: Observer SMW; yellow-blue

The results are summarised in Figure 4. Blur thresholds are plotted as a function of colour direction for each observer.

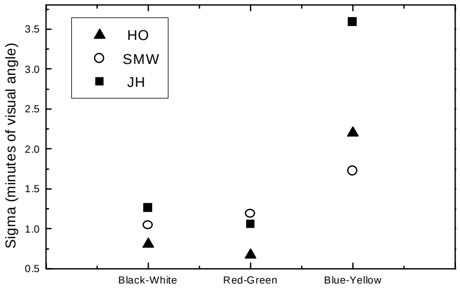

Figure 4: Summary of blur thresholds

Blur thresholds for yellow-blue are always higher than for red-green and luminance. We do not find a consistent distinction between luminance and red-green (Table 3).

Subject/ Colour direction	HO	SMW	JH
Black-White	0.96	1.24	1.41
Red-Green	0.80	1.49	1.48
Yellow-Blue	2.81	2.11	8.18

Table 3: Blur thresholds

Conclusions

We investigated how much blur the visual system can tolerate in different colour directions. We found that blur thresholds are similar in red-green and luminance and significantly larger in yellow-blue.

We found the similarity between the red-green and luminance directions surprising considering that the spatial cut-off frequency is lower for red-green than for luminance; from the difference in spatial cut-off we would have predicted higher blur thresholds for the red-green direction.

It is conceivable that the similar blur thresholds are due to a residual luminance contrast in the nominally isoluminant red-green stimuli. We will test this hypothesis by determining the isoluminant points for each observer using heterochromatic flicker photometry and re-measuring blur thresholds for empirically determined isoluminant points.

Various tasks that measure spatial acuity demonstrate contrast dependence (Krauskopf & Farell, 1991; Wuerger & Morgan, 1995); hence the difference in the blur thresholds could be due to a difference in effective contrast and not to an intrinsic difference between the channels. Further experiments will determine the contrast dependence of blur thresholds.

Our goal is to predict blur tolerance for stimuli of arbitrary spatial content and colour. To achieve this we will measure blur thresholds for simple sinusoidal stimuli.

An important question to ask is whether the amount of blur tolerated by the visual system is due to the optics of the eye or due to limitations in post-receptoral mechanisms. We will attempt to answer this question by using a model of the optical transfer function (OTF) of the eye that incorporates chromatic aberration for each wavelength (Marimont & Wandell, 1994) and for each spatial frequency. Applying Marimont and Wandell's OTF will allow us to determine how much of the 'blur tolerance' can be explained by optical factors.

References

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