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Creating correct aberrations: Why blur isn't always bad in the eye

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ABSTRACT

In optics in general, a sharp aberration-free image is normally the desired goal, and the whole field of adaptive optics has developed with the aim of producing blur-free images. Likewise, in ophthalmic optics we normally aim for a sharp image on the retina. But even with an emmetropic, or well-corrected eye, chromatic and high order aberrations affect the image. We describe two different areas where it is important to take these effects into account and why creating blur correctly via rendering can be advantageous. Firstly we show how rendering chromatic aberration correctly can drive accommodation in the eye and secondly report on matching defocus-l generated using rendering with conventional optical defocus.

Keywords: Adaptive optics, vision science, ophthalmic optics

1. INTRODUCTION

Like most optical systems chromatic aberration in the eye is caused by different refracting elements having different refractive indices which gives rise to both lateral and longitudinal chromatic aberration (illustrated in figure 1). In the former off–axis images are smeared out in color and in the latter - which is of interest here

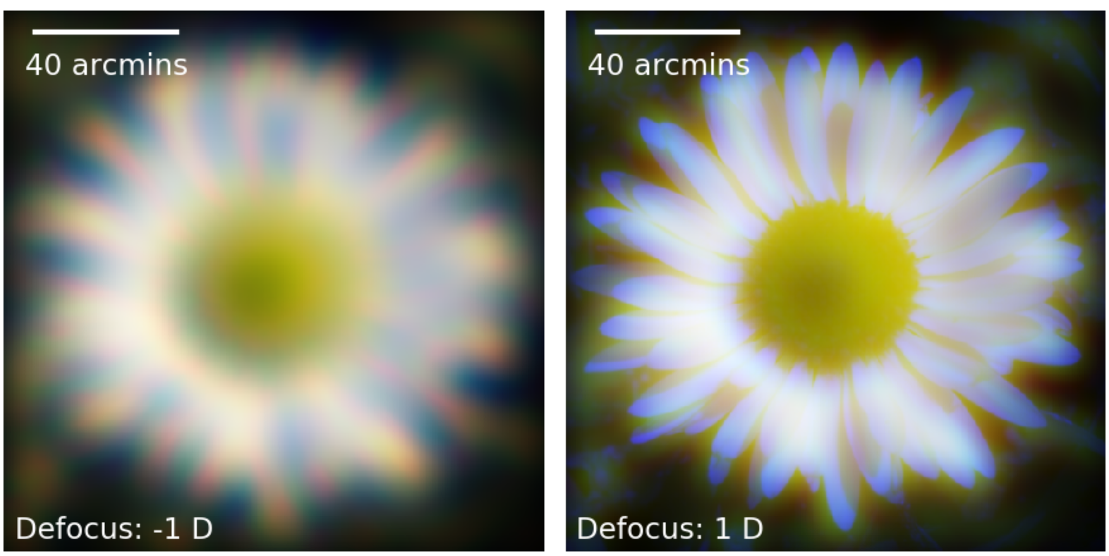

Figure 1. Simulated images on the retina showing a daisy blurred by equal but opposite amounts of 1D. Normally these images would be identical – but the effects of LCA mean that colored fringing appears.

(which we denote as LCA) – different wavelengths have different focal lengths. E.g. shorter wavelengths are

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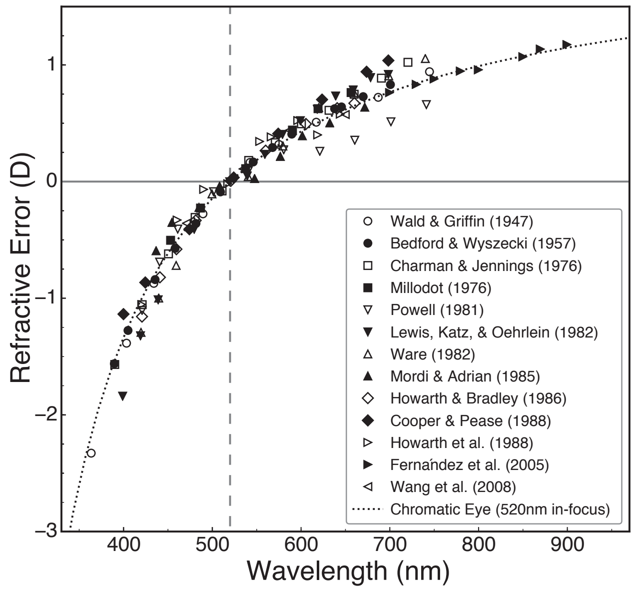

Figure 2. Longitudinal chromatic aberration of the human eye plotted as relative defocus in diopters as a function of wavelength. The dotted curve is the aberration of the chromatic eye model of 3. The data were adjusted such that defocus is zero at 520nm (dashed vertical line), see Eq. 1. Data have been replotted from 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16.

refracted more than long wavelengths, so blue and red images tend to be focused respectively in front of and behind the retina. In diopters (inverse focal length) LCA is given by,

$$D(\lambda) = 2.071 - \frac{633.46}{\lambda - 214.10} \tag{1}$$

where λ is in nanometers and 520nm is in-focus,[1] as shown in figure 2. LCA is essentially the same in all human eyes[2,3] and its magnitude is quite large – over 2D across the full visible spectrum. A refractive error of this size would certainly be considered as significant and a patient would certainly be prescribed spectacles or contact lenses, but yet we don't tend to see the world with considerable chromatic blur. Why we don't see the effects of LCA when it it is so large remains an interesting question. In figure 1 we show the results of a simulation of the image of an out of focus daisy flower on the retina of the eye taking into account LCA. The image is quite magnified (and hence should be viewed some distance away to simulate the correct angular scaling) but even so the effects of LCA are quite clear.

In this paper we consider rendering aberrations - i.e. creating blurred images which have optical aberrations (in this case defocus) encoded using computer graphics. Building on past work using a process called *chromablur* we derive an approximate equation for calculating the amount of rendered defocus at each wavelength required to produce chromatically correct defocused images on the retina. We then describe progress on produce aberrations using rendering and trying to match them perfectly to aberrations produced optically.

2. CHROMABLUR: ACCOUNTING FOR LCA IN RENDERING DEFOCUSED IMAGES CAN DRIVE ACCOMMODATION

When trying to create out of focus images using rendering (e.g. in computer graphics) then the usual methodology is that a blur kernel is generated (via a number of techniques: e.g. ray tracing or even physical optics) which is convolved (in a generic sense) with the image to produce a blurred final scene. They key point of relevance here is that all the wavelengths in a colored image are normally treated equally and therefore all wavelengths are blurred by an equivalent amount. However, if we are trying to replicate what happens in the eye with real optics this is incorrect – as described in the introduction – as LCA means different wavelengths are blurred by different amounts and, indeed, some wavelengths can even be made less blurred by being out of focus. In reference 17 we proposed a technique for taking the effect of chromatic aberration into account - which we called *chromablur*.

In chromablur we created, via optimization, a look–up table for RGB images which indicated how much each individual wavelength should be blurred for a particular desired wavelength. This is shown in fig. 3. The x axis is the desired defocus and the y axis is how much defocus should be rendered to produce a chromatically approximately correct image. Consider here just the solid lines (the dotted lines are the results of the analytical model described in the next subsection). For the green channel there is zero LCA (assuming a single wavelength) and therefore the green line is simply $y = |x|$. The modulus occurs as defocus is an even function and positive defocus is indistinguishable (in the absence of other aberrations) from negative defocus. Consider now the line for red: here we can see that for a required defocus of +2 D then actually a value closer to +2.5 D is needed, whereas for -2 D a value close to $-1.5D$ is needed. For values between around 0 and -1 D then the image needs to be made more sharp than the original. In general this is impossible – or at least problematic – and therefore these values are set to 0. Similar arguments hold for the blue channel.

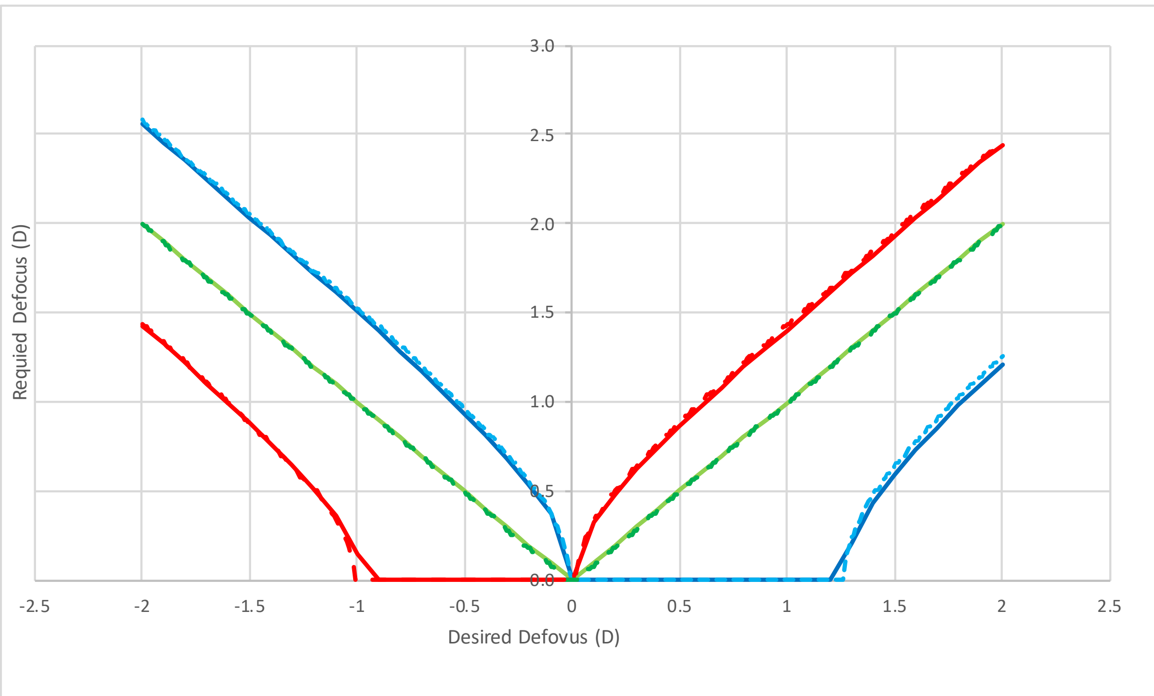

Figure 3. Required rendered defocus (y-axis) needed to produce a chromatically (approximately) correct rendered image for a particular defocus value (x-axis). The solid lines show the results of the optimization algorithm - as described in reference 17. The dotted line shows the results of the approximate analytical calculation - as described in this paper. For green light there is no chromatic aberration and therefore the graph is simply $y = |x|$. The wavelengths for the R, G, and B primaries are assumed to be 617, 520, and 449nm, respectively. The flat parts of the graph for red and blue along $y = 0$ show areas where image sharpening is required and therefore the best value is simply set to be zero blur.

Figure 4 shows an example image generated using this procedure. The central image at 0D is unaberrated and all three colour channels are identical. The left and right panel are blurred by ± 1.4 D. Normally these would be identical but with chromablur the differential effects of the red and blue channels can be seen and the images are slightly colored.

In references 17 and 18 we show that accommodation in the eye is not driven by rendered out of focus images without chromablur (i.e. conventional rendering whereby each of the three channels is blurred by the same amount) but with chromablur images - as shown in figure 4 then the eye accommodates, and furthermore accommodates in the correct direction. We also show that the eye continues to accommodate after some time - even though the change in accommodation actually makes the image less sharp (unlike the real optical case).

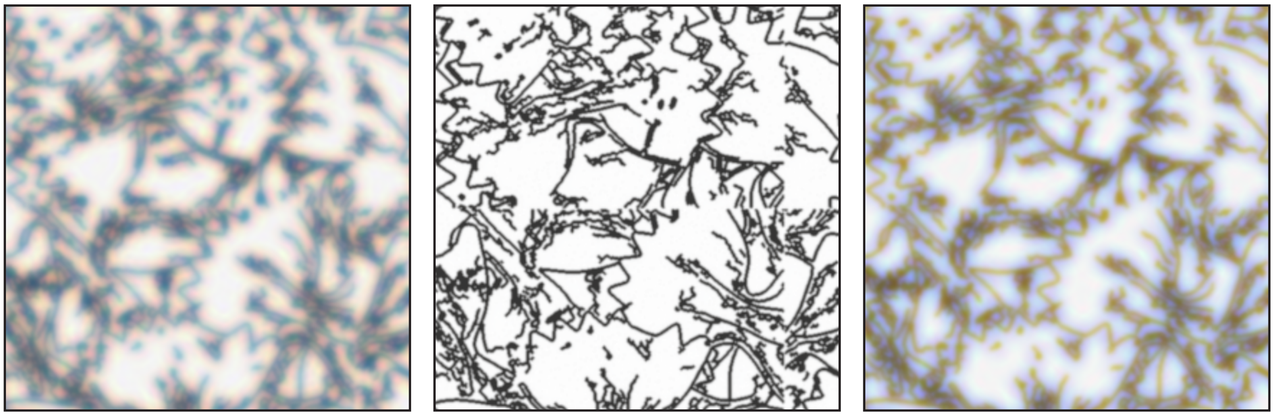

Figure 4. Images blurred in order to give the correct chromatic stimuli on the retina. The panels should be viewed with a pupil of $\sim m6$ mm from a distance of 5.6 times the height of the individual panels. Note how the left and right images are slightly colored.

As described above - in order to calculate the required defocus values in chromablur we used a number of optimization algorithms. Here we describe a simpler analytical approximation in order to calculate the required defocus values.

2.1 An analytical approximation for calculating chromablur values

In order to optimize speed and simplicity ideally an analytical solution to calculate the required defocus values for chromablur is needed - which is described in this subsection. Take a specific example: imagine that we wish to render an image such that it is sharply focused. If the eye is sharply focused on the screen and has no aberrations then the solution is simple: the image is rendered with a blur kernel appropriate for 0D (ignoring the more detailed debate on the shape of the blur kernel). The effects of LCA will be "automatically introduced" by the act of viewing with the eye. What magnitude of blur kernel should we use if instead for a defocus of, say, 1D? Now we need to include the effects of LCA, and in general we can not calculate the result simply by adding the LCA to the required defocus value, wavelength by wavelength. This is because optical and rendered blur do not combine linearly (to take an extreme example, imagine the rendered blur is 1D and the eye has an focus error of -1D then these do not combine to produce a perfect image of 0D on the retina). In[18] the answer to this problem was shown in figure 6, reproduced by the solid lines in Fig. 3. These results were calculated using an optimization algorithm.

In order to answer this problem we make some simple assumptions which give good agreement with the numerical results shown in fig 3. Consider first the case where retinal blur is generated optically. If we wish to generate a blur of magnitude B_{desired} then the blur on the retina, given by $B(\lambda)_{\text{ret}}$ is given by

$$B(\lambda)_{\text{ret}} = B_{\text{desired}} + LCA(\lambda), \tag{2}$$

where LCA is longitudinal chromatic aberration which is shown as a function of λ. All the terms must be in units of inverse length (normally diopters). Consider next the case where the retinal blur is generated via rendering, in which case the blur is given by the convolution of the required blur, B_{required} and the LCA. Just to be clear on terminology - B_{desired} is the actual blur we are trying to generate and B_{required} is the blur needed to generate the desired blur. We make the assumption that the blurs are quasi-Gaussian and also use the result that the convolution of two Gaussians is also a Gaussian whose variance is the sum of the individual variances. We also assume that the width of the Gaussian is linearly proportional to the dioptric blur. So we can write

$$B(\lambda)^2_{\text{ret}} = B^2_{\text{required}} + LCA(\lambda)^2. \tag{3}$$

Equating equations 2 and 3 and rearranging gives

$$B_{\text{required}} = \sqrt{[B_{\text{desired}} + LCA(\lambda)]^2 - LCA(\lambda)^2}. \tag{4}$$

Finally we just need to modify the equation to ensure the argument of the square root can not be negative (which corresponds to the flat horizontal parts in figure 3), to give the final expression.

$$B^2_{\text{required}} = \begin{cases} \sqrt{[B_{\text{desired}} + LCA(\lambda)]^2 - LCA(\lambda)^2}, \text{if } [B_{\text{desired}} + LCA(\lambda)]^2 > LCA(\lambda)^2 \\ 0 \qquad \text{otherwise} \end{cases} . \tag{5}$$

The results from this equation are shown in figure 3 showing very good agreement with fig 3.

3. RENDERING CORRECT BLUR

In adaptive optics, some form of wavefront sensor is important in order to provide the necessary correction, but since most systems work in closed loop it is not always necessary to precisely measure the aberrations. Clearly in other areas in optics it is important to accurately measure aberrations. Here we turn to the problem of trying to render the effects of defocus (and other aberrations). How can we render a blurred image such that it appears to be identical to an equivalently optically defocused image? Ignoring the effects of chromablur, as described in the previous section, it would seem as if the answer to this question is simple: we know how to render images and therefore it should be simple to produce an out of focus image using computer graphics. However, there have been a range of experiments which show that, in general, reproducing optical blur with rendering is not simple and the amount of blur needed to subjectively match optical and rendered blur is not the same. Furthermore - the detailed results are often contradictory - as described in references 19, 20,21,22,23,24. The papers tend to show that aberrations generated optically have a different effect than aberrations rendered on a display. Generally the visual acuity is better for optical defocus than rendered defocus. Possible explanations for the differences are the effects of LCA and/or high order aberrations (HOAs). The full solution is not clear but here we describe progress on investigating the effects of HOAs.

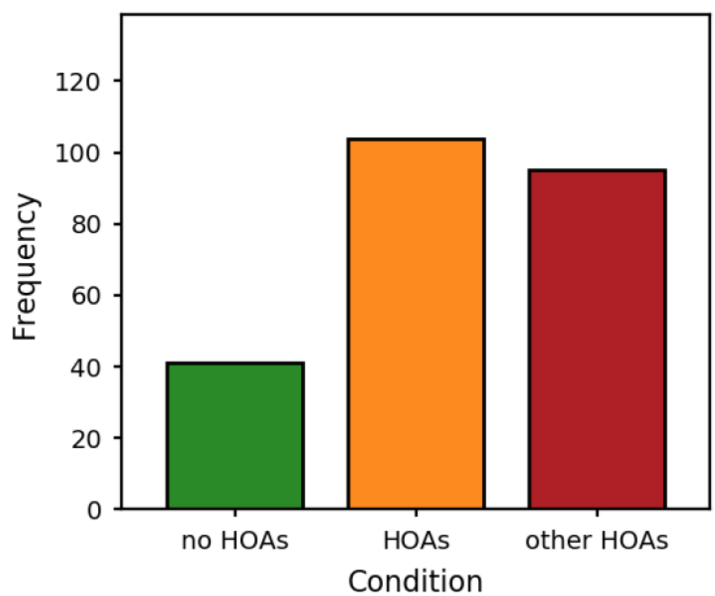

Figure 5. Results of a psychophysical experiment where subjects were asked to compare the visual similarity of images rendered either with or without higher order aberrations (HOAs) using either their own HOAs (central bar) or an average value (right bar).

We carried out a psychophysical experiment and subjects were presented with a forced choice experiment to try and match optical and rendered blur. We induced optical blur by moving lenses in the experiment (unknown to the observer) and we induced rendered blur using narrowband light (to remove the effects of LCA). Subjects were asked to select rendered images which most closely matched optically blurred images. In addition we separately measured the HOAs in the subjects' eye so that when we rendered images we could choose to take these into account. Initial results are shown in figure 5. The y-axis shows the frequency of agreement (i.e how often the subjects thought the optical and rendered stimuli matched). The 3 bars show 3 experimental conditions. For "no HOAS" (green) the effect of HOAs in the subjects' eyes were ignored and it can be seen that the agreement is the worse for this condition. For the "HOAs" (orange) bar the effects of the subjects' HOA were taken into account in the rendering and the agreement was considerably improved. Interestingly the final "other HOAs" (red) condition also shows improvement over the simple "no HOAs" condition. In this case an average value for HOAs across a number of subjects was used. We will present more details of this experiment in a future paper.

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