Does Chromatic Aberration Hinder or Help?

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Hinder or help what?

Chromatic aberration can affect many aspects of vision:

• Retinal image contrast
• Colored fringing
• Contrast sensitivity
• Visual acuity
• Color perception
• Depth perception
• Diagnostic imaging of the fundus
• The quest for super-vision
What kind of eye?

The impact of chromatic aberration depends on:

- Pupil diameter
- Pupil centration
- Retinal eccentricity
- Magnitude of monochromatic aberrations
The focusing power of the eye varies with wavelength. This phenomenon is called Longitudinal (or axial) Chromatic Aberration (LCA).
The retinal location of the retinal image may vary with wavelength. This phenomenon is called Transverse (or lateral) Chromatic Aberration (TCA).
The size of the retinal image may vary with wavelength. This phenomenon is called Chromatic Difference of Magnification (CDM)
The far point $P$ is that location in object space which is optically conjugate to foveal point $P'$.
Chromatic aberration complicates the “far point”

The presence of longitudinal chromatic aberration in human eyes means a true far-point does not exist.
Human eyes have chromatic aberration

The presence of ocular chromatic aberration =>
the far-point is different for every wavelength.

Far point for red

Far point for blue

No object distance is optically conjugate to the retina for every wavelength simultaneously.
The magnitude of chromatic refractive error

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Refractive Error (diopters)</th>
</tr>
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<tbody>
<tr>
<td>300</td>
<td>0.5</td>
</tr>
<tr>
<td>400</td>
<td>0.25</td>
</tr>
<tr>
<td>500</td>
<td>0.1</td>
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<tr>
<td>600</td>
<td>0.05</td>
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<tr>
<td>700</td>
<td>0.0</td>
</tr>
<tr>
<td>800</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Wavelength (nm) \(\lambda_{\text{ref}} = 589 \text{ nm}\)

Reference:
- Wald & Griffin, 1947
- Bedford & Wyszecki, 1957
- Ivanoff, 1953
- Millodot & Sivak, 1973
- Millodot, 1976
- Charman & Jennings, 1976
- Powell, 1981
- Lewis et al., 1982
- Ware, 1982
- Mordi & Adrian, 1985
- Howarth & Bradley, 1986
- Cooper & Pease, 1988
- Thibos et al., 1991

Water Eye

Chromatic Eye
Effect of chromatic aberration on the retinal image

Object:
white point source

Effects:
• reduced luminance contrast
• errors of hue and saturation

\[ \lambda = 525 \text{ nm} \]
\[ \lambda = 575 \text{ nm} \]
\[ \lambda = 600 \text{ nm} \]

Rings in point-spread function (PSF) are detrimental phase reversals that hinder spatial vision.

Optical model: Indiana Eye (Thibos et al., Applied Optics, 1992)
Effect of chromatic aberration on the retinal image

Object:
white point source

Effects:
• reduced luminance contrast
• errors of hue and saturation

Longitudinal focus errors + transverse position errors combine to produce complex effects on the retinal image

Optical model: Indiana Eye (Thibos et al., Applied Optics, 1992)
Effect of chromatic blur on eye chart

Courtesy of Jim Schwiegerling, U. Arizona
The good news

The wavelengths that are most blurred are also the dimmest.
Polychromatic retinal image, LCA only

Courtesy of Jim Schwiegerling, U. Arizona
LCA reduces contrast sensitivity and acuity

- Polychromatic
- Monochromatic

Spatial frequency (cyc/deg)

Image Contrast

0.001 0.005 0.01 0.05 0.1 0.5 1.0

0.2 log unit loss of CS

Neural Threshold

5% loss of VA

Campbell & Gubisch (1967) J. Physiol. 192:345
• To achieve an optically superior eye requires the correction of monochromatic and chromatic aberrations.

• Correcting one but not the other leaves the eye aberrated and retinal image quality imperfect.
Longitudinal chromatic aberration

\[ \lambda_{\text{ref}} = 589 \text{ nm} \]

Refractive Error (diopters)

-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0

Wavelength (nm)

300
400
500
600
700
800

Data from:
- Wald & Griffin, 1947
- Bedford & Wyszecki, 1957
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Water Eye
Chromatic Eye

Higher-order aberr
Suppose LCA could be eliminated

Correcting longitudinal chromatic aberration (LCA) does not necessarily eliminate transverse chromatic aberration (TCA).

Paradoxically, the deleterious effects of TCA on vision are made worse by correcting LCA!
Effect of TCA when LCA=0

Acuity measured with white-light interferometer avoids LCA but is strongly affected by TCA induced with pupil displacement.

TCA alone can reduce VA from 20/20 to 20/60

LCA and TCA reduce image contrast for different reasons:

LCA => blur

TCA => smear

Smearing (phase shifts) can have a bigger impact.
Effect of chromatic aberration on the retinal image

Loss of image contrast caused by chromatic aberration is due more to transverse (TCA) displacement than to longitudinal (LCA) blur.

No TCA          With TCA

Monochromatic LCA only
LCA + TCA
TCA only

3mm pupil
Population statistics for pupil alignment

Reference position = visual axis (TCA=0)

Population statistics for TCA


red (605 nm) vs. blue (497 nm)
Polychromatic retinal image, LCA + TCA

Courtesy of Jim Schwiegerling, U. Arizona
In addition to losses of luminance contrast, chromatic aberration also affects the hue and saturation of colored objects.
Color artifacts produced by LCA and TCA

Example is for 1mm pupil displacement
In a high-quality optical system, chromatic aberration hinders more than it helps:
- reduces image contrast
- reduces spatial resolution

However, in the presence of other optical defects (e.g. decentered pupil, defocus) LCA can be helpful:
- defeats TCA
- smooths the PSF
Relative importance of mono & chromatic aberration

As technology for correcting higher-order, monochromatic aberrations of the eye develops, the significance of chromatic aberration will grow because it will be the only remaining barrier to “Super Vision” and high-resolution color imaging of the retina.

Correcting either monochromatic or chromatic aberration alone has much less benefit than correction both (Yoon & Williams, 2002)
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