Simulation of EnChroma Glasses with ISETBio

(Teacher's Note: Can you please add the separate spectral curves for, say, the purple and orange. You seem to have plotted just one radiance, the one on the left, when there are two different parts of the scene. Perhaps you can also plot the spectral irradiance after passing through the lens and Enchroma filter. Also, can you please explain the 'Improvement' metric a bit more. The way it is written it seems as if the EnChroma improvement metric should be negative if the glasses are working. Finally, I think one of the graphs is an M cone but labeled L cone.)

Team members: Neeka Nikfar, Abby Lindquist

Contents:

Introduction:

EnChroma lenses, invented by a glass scientist and mathematician named Donald McPherson, are designed to enable people with color vision deficiencies, specifically red-green colorblindness, to see color in ways they have never seen before. These lenses modify the spectrum of the light entering the eye in order to help dichromats experience a wider range of colors. This design takes advantage of the overlap between the L and M cones and a notch filter that separates this overlap. These glasses block certain wavelengths of light to create a more distinct separation between spectral sensitivities of L and M cones. These glasses are said to have little to no effect on 20% of color blind people who have drastic color vision deficiencies [2].

This project focuses on examining the effectiveness of the EnChroma glasses on improving color perception using ISETBio and examines the physical effect of light entering the eye by measuring cone excitations in individuals with normal color vision, individuals with color blindness, and individuals with EnChroma glasses applied. Relative excitation levels will determine if EnChroma glasses are effective in improving color perception.

Background:

The human eye is responsible for transmitting light from the outside world into an image that we are able to understand and perceive. As light gathers in the cornea from our field of view and refracts through the pupil, the lens projects these light rays to an area toward the back of the eye called the retina. The human retina contains around 6 million cones and 100 million rods. Light is detected when photons are captured by pigments in these cells [1]. The concentration of rods and cones differ across the retina. These photoreceptors play a significant role in the way we see, receiving and sending signals to the brain for processing.

While rods are responsible for vision at low levels, called scotopic vision, cones are responsible for color vision. Cone cells contain three photopigments that differ in their sensitivity to light, called the short (S), medium (M), and long (L) wavelength cones. The human eye can detect wavelengths from approximately 400nm to 700nm, where each cone will react to each wavelength differently based on its sensitivity to different parts of the visible spectrum. The normalized sensitivities of the L,M,S cones in the human eye are shown below. These spectral sensitivity curves are widely spread over the visible spectrum [3]. The L and M cones have similar spectral sensitivities, whereas the S cone shows minimal overlap between the L and M cones.

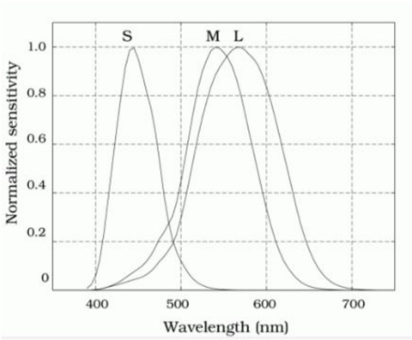
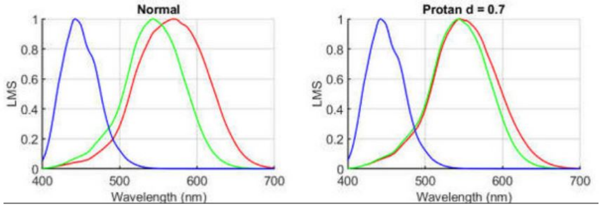


Figure 1. Spectral Sensitivities of L,M,and S cones.

Most individuals can match any color in a color test by adjusting the intensity of three light sources that are superimposed by generating long, medium, and short wavelengths, meaning that color vision is trichromatic. However, for a small group of individuals with color vision deficiencies called dichromats, only two colors of light are needed to match all colors perceived by these individuals. Dichromacy is a rare form of color blindness, affecting about 2% of the population, that occurs when one cone is absent or defective. A more common form of color blindness, called anomalous trichromacy, occurs when there is a shift in the cone absorbance spectrum for one or more cones. Approximately 8% of the US male population are affected by this hereditary form of color blindness often referred to as red-green color blindness [4]. Figure 2 below demonstrates this shift.


Normal

Protan d = 0.7

Figure 2: Spectral Sensitivities of L, M, and S cones for normal vision (left) and red-green color blindness (right) [2]

The increased overlapping of the L and M absorbance spectra mean that light coming in at 500-600 nm will almost equally excite the red and green cones. Thus, the afflicted person will have difficulty telling apart colors within this range. This person would have difficulty distinguishing the numbers in Figure 3 below.

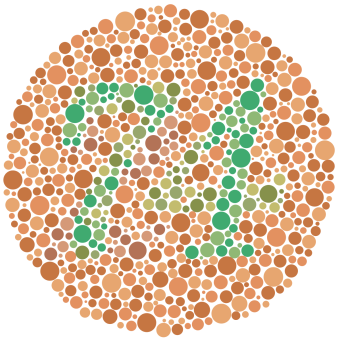


Figure 3: Common red-green color blindness test

As a potential solution to this common problem, a company, called EnChroma, has designed glasses that they say “bring life-changing vibrancy to those with color vision deficiency [5].” Designed to address only red-green color blindness, the EnChroma glasses apply a notch filter to incoming light, modifying the transmittance. This notch filter creates a separation between the highly overlapping L and M cone absorbances, to allow each cone to be individually excited. This technology would allow millions to have increased quality of life with improved visual perception.

Methods:

The ISETBio platform was the central tool for analyzing the effectiveness of the EnChroma glasses. Spectral transmittance of the EnChroma lesses was extracted and loaded into ISETBio. Figure 4 below displays the transmittance data:

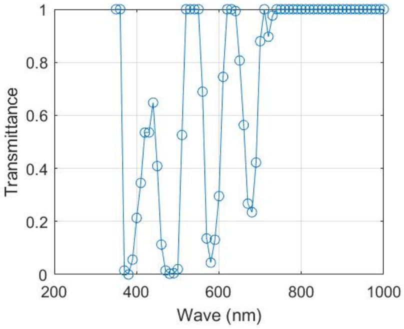
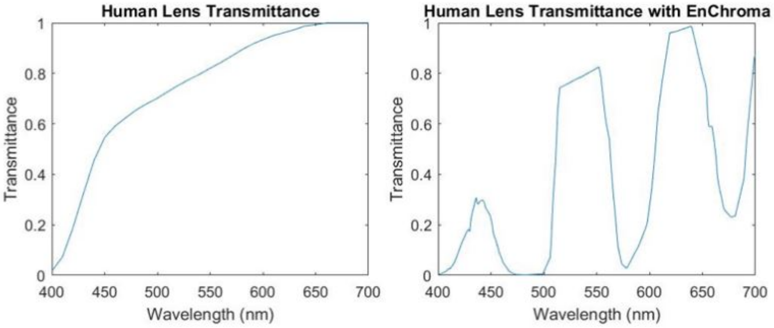


Figure 4: EnChroma lens light transmittance

To model the EnChroma glasses the collected photons from a scene were multiplied by the above transmittance. This gave a final human lens transmittance shown below in Figure 5.


Human Lens Transmittance

Human Lens Transmittance with EnChroma

Figure 5: (Left) Normal human lens transmittance. (Right) Lens transmittance while wearing EnChroma glasses

The ability to linearly or logarithmically shift individual cone absorbances was implemented to allow for the simulation of anomalous trichromacy. To demonstrate red-green colorblindness, the M cone absorbance was shifted 20 nm toward the red cone. This is shown in Figure 6 below.

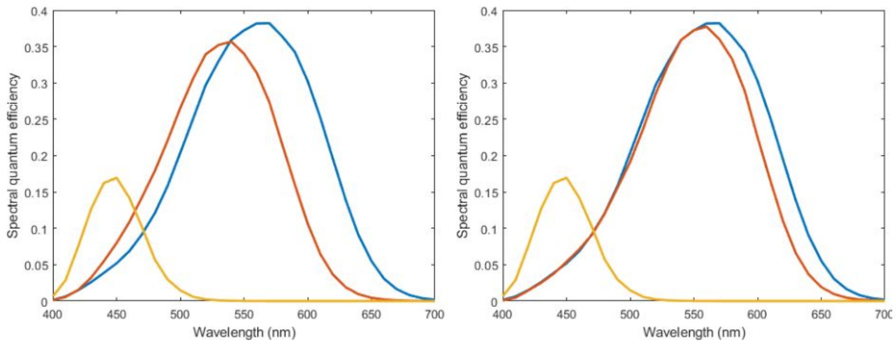


Figure 6: (Left) Standard cone absorbances. (Right) Shifted cone absorbance in MATLAB. Yellow is S cone, red is M cone and blue is L cone.

A. Cone excitations for solid scenes and patterns in different regions of eye

ISETBio was additionally modified to allow for the selection of a specific region of cones in the retina and examine only these excitations. The excitations in the fovea and peripheral retinal were examined by selecting a region extending through the fovea. Figure 7 shows the region of interest examined.

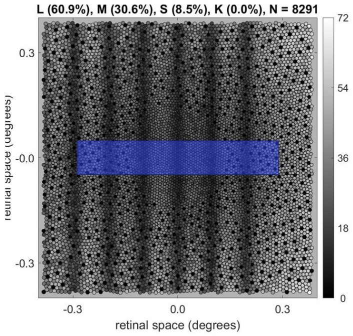


Figure 7: Retinal region of interest.

The excitations in these regions were examined for three scenarios: normal cone absorbance, shifted cone absorbance, shifted cone absorbance with EnChroma filter. The relative LMS cone excitations were compared for each of the three situations. The effectiveness of the EnChroma lens was determined by the ability of the lens to bring relative cone excitations close to those of a person with normal vision.

B. **Relative Cone Excitations for Natural Scenes**

The effectiveness of the EnChroma glasses was further analyzed by examining relative cone excitations in natural scenes. 30 natural scenes shown in Figure 8 below were run through a code that sums all L and M cone excitations in the fovea. All scenes were loaded in with the default LCD display.

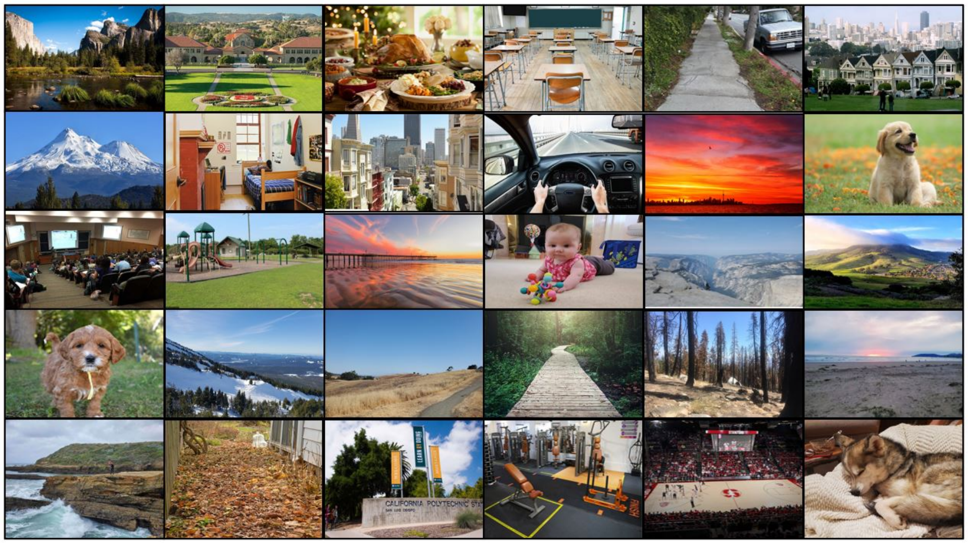


Figure 8: Scenes examined for generalized EnChroma analysis

L and M excitations were normalized to the sum of excitations to allow for comparison of three situations: normal vision, RG color blindness with the M excitation curve shifted as in Figure 5, and RG color blindness with EnChroma transmittance filter. The percent difference from normal was calculated for the colorblind and EnChroma situations. This allowed for examination of improved color vision with the EnChroma glasses.

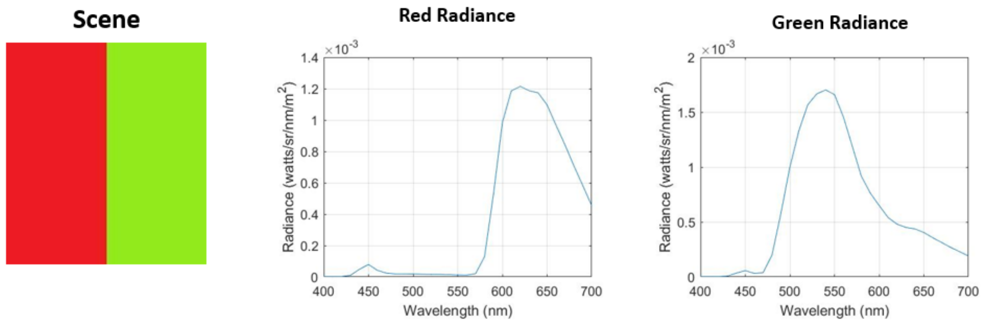
An important metric that was additionally analyzed was the ratio between L and M cone excitations. This ratio was found for all 30 scenes above with the three scenarios mentioned: normal vision, RG color blind, and color blind with EnChroma. The ratio between total L and total M cone excitations in the fovea was measured. The percent difference of this ratio between normal vision and RG colorblind, as well as normal vision and EnChroma glasses was taken. A smaller percent difference would represent more similar color vision to the normal situation.

Results:

A. **Cone excitations for solid scenes and patterns in different regions of eye**

To understand more about how EnChroma glasses distinguish colors, four scenes that show a striped pattern of two solid colors were analyzed. Results show cone excitations across the retina and ROI for individuals with normal vision, individuals who are color blind, and individuals wearing EnChroma glasses who are color blind for a particular scene.

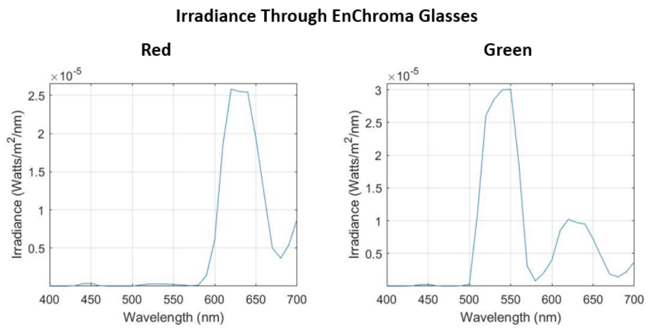
The radiance and the spectral irradiance through the EnChroma glasses of each scene is plotted below. The wavelength is plotted on the x-axis in nm and the radiance in watts/sr/nm/m^2 is plotted on the y-axis.


Scene

Red Radiance

Green Radiance

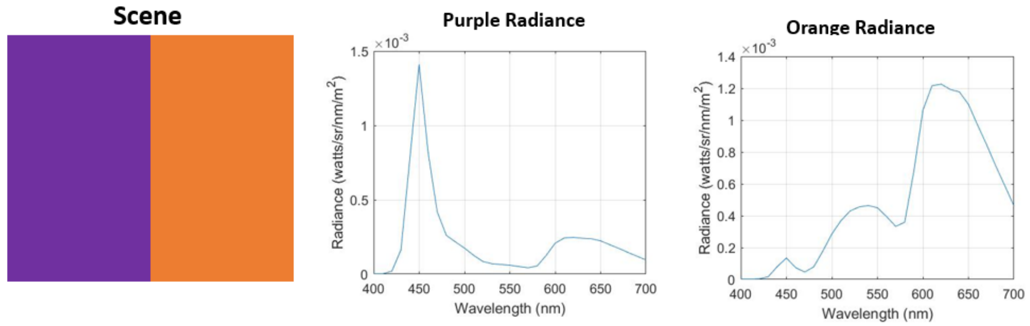
Figure 9: Spectral Radiance vs Wavelength for Red-Green Scene


Irradiance Through EnChroma Glasses

Red

Green

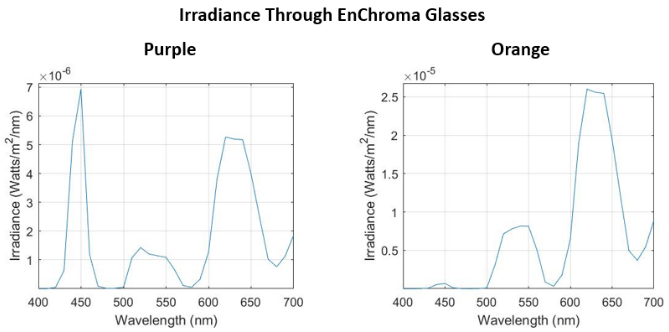
Figure 10: Spectral Irradiance through EnChroma Glasses vs Wavelength for Red-Green Scene


Scene

Purple Radiance

Orange Radiance

Figure 11: Spectral Radiance vs Wavelength for Purple-Orange Scene


Irradiance Through EnChroma Glasses

Purple

Orange

Figure 12: Spectral Irradiance through EnChroma Glasses vs Wavelength for Purple-Orange Scene

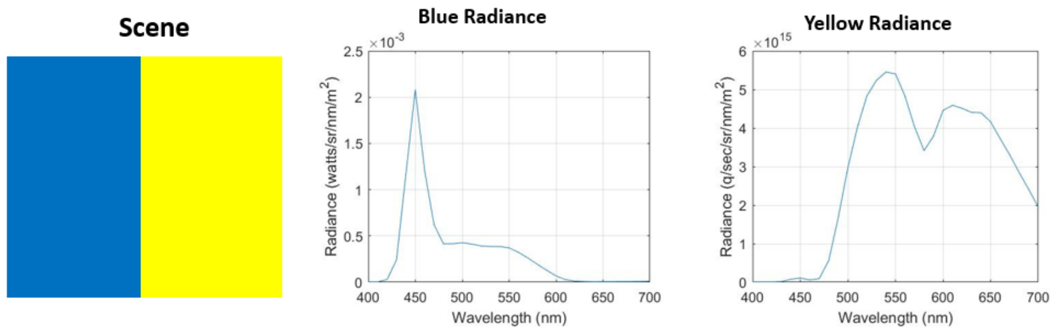


Figure 13: Spectral Radiance vs Wavelength for Blue-Yellow Scene

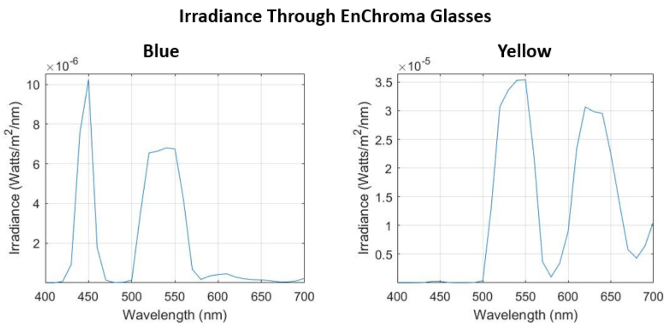


Figure 14: Spectral Irradiance through EnChroma Glasses vs Wavelength for Blue-Yellow Scene

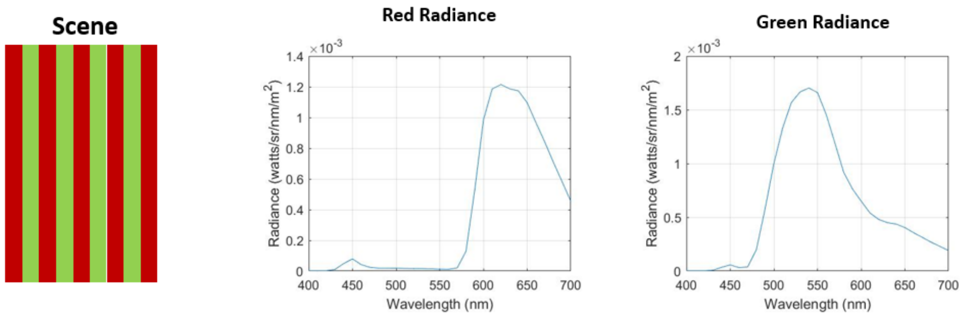


Figure 15: Spectral Radiance vs Wavelength for Red-Green High Frequency Scene

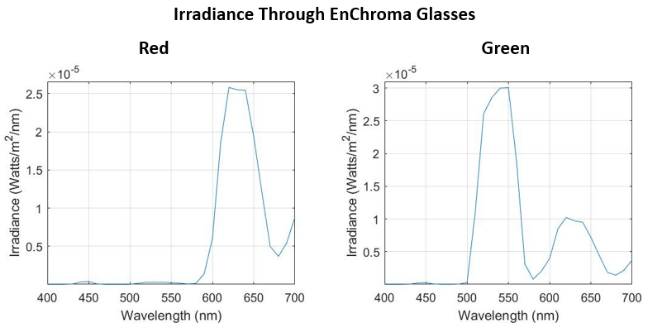


Figure 16: Spectral Irradiance through EnChroma Glasses vs Wavelength for Red-Green High Frequency Scene

If the EnChroma glasses have an effect in terms of excitation response for a color blind individual, then we should be able to see a difference between the responses with and without the glasses. If the EnChroma glasses help correct color deficiencies, then we should be able to see a similarity between excitation responses with normal vision and with the glasses.

Figure 17 shows L,M, and S cone excitations for each vision type. There is a noticeable difference between the excitation response for color blinded individuals and color blinded individuals wearing the glasses. This shows that EnChroma glasses should have some effect on the way color blinded individuals visualize this scene, although there is no way to determine exactly how these individuals visualize these colors. EnChroma glasses for this particular scene bring the L and M cone excitation responses closer together, which shows a similar shape to the normal vision response, indicating a resemblance. However, the overall excitations for each cone across the retina is shifted down.

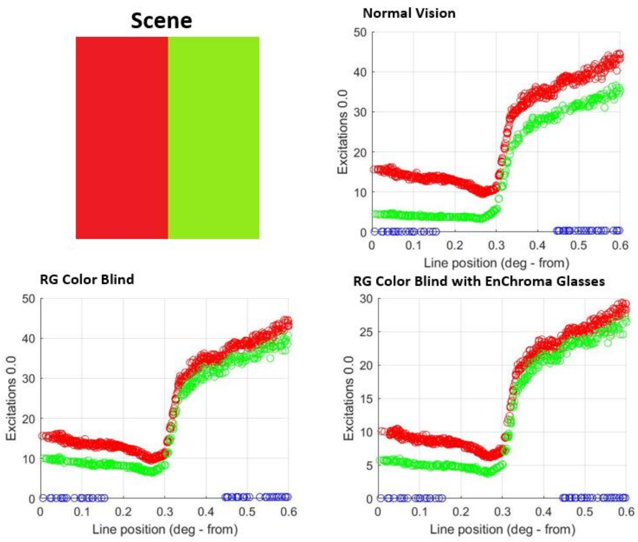


Figure 17: Cone excitations across center of retina for red-green edge

From Figure 18, the scene analyzed depicts a stripe of purple and orange colors. From the normal vision and color blind case, the significant difference occurs with the way the M cone is excited across the retina. This particular scene for color blindness causes the M cones to shift up by around 5 excitations at around 0.05 degrees from the fovea (Plot shows M cone shift at 0.35 degrees, but with respect to ROI, this corresponds to 0.05 to the right of the fovea, shown in Methods). Comparing the excitation responses of the bottom two plots in Figure 10, we can see a downward shift in M cones using the EnChroma glasses to the right of the fovea at 0 to 0.3 degrees. The response under normal vision and under color blindness with enchroma glasses are not significantly similar, which shows that these glasses might not have a large effect on a scene primarily with these two colors. The similarity between the two has to do with the M cone response, which was fixed (downward shift) by adding the EnChroma glasses.

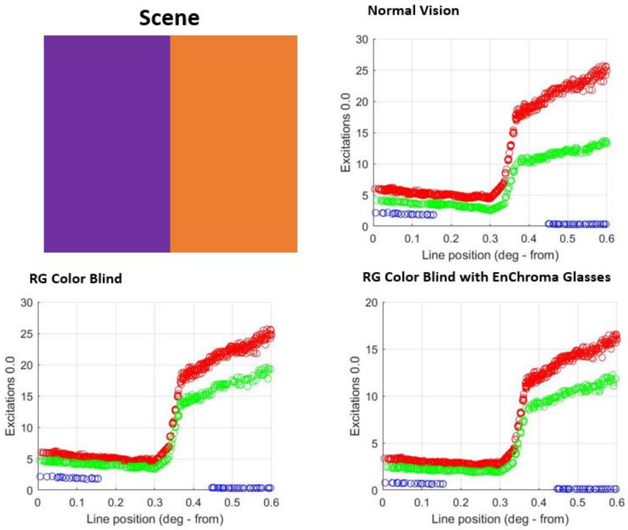


Figure 18: Cone excitations across center of retina for orange-purple edge

The next scene that was analyzed is a stripe consisting of blue and yellow. From the bottom two plots, we can see that the EnChroma glasses don't have a significant effect on the cone excitation responses, only shifting each of the three cones downward by a small amount. Under normal vision, we see a large separation of L and M cones from 0 to 0.3 degrees to the right of the fovea. The response under normal vision and under color blindness with EnChroma glasses for this scene are not significantly similar, since the glasses don't seem to correct this separation or show similar excitation values.

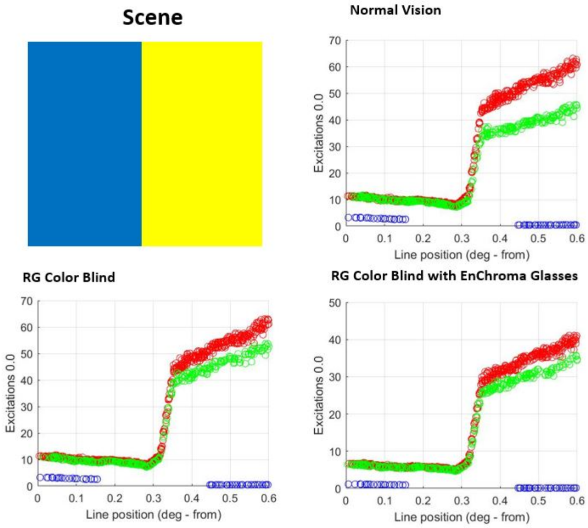


Figure 19: Cone excitations across center of retina for blue-yellow edge

The last scene that was analyzed is similar to the first scene, but shows multiple stripes to create a high frequency pattern of red and green. The only noticeable difference between the excitation response for color blinded individuals and color blinded individuals wearing the glasses is the excitation value across the retina. While the response of normal vision shows a clear separation between the L and M cones, the EnChroma glasses don't widen this separation for color blinded individuals. This shows that the response under normal vision and under color blindness with EnChroma glasses for this scene are not similar in terms of shape, since the glasses don't seem to correct this separation. However, these two responses are similar in terms of excitation values across the retina, which is something to note.

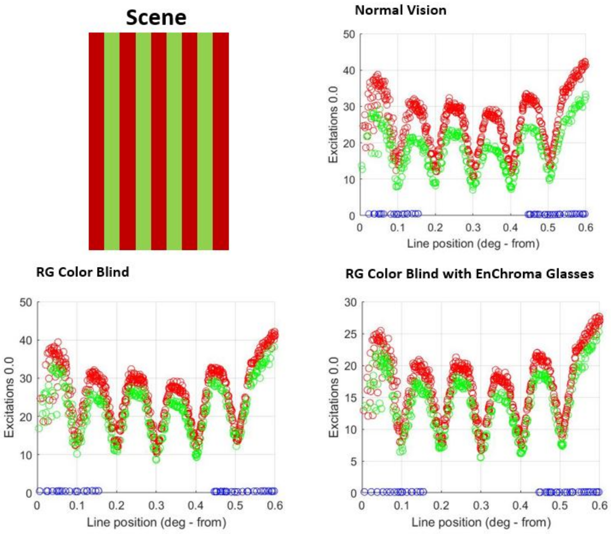


Figure 20: Cone excitations across center of retina for red-green high frequency transitions

B. **Relative Cone Excitations for Natural Scenes**

The results of the examination of the effectiveness of the EnChroma glasses on relative excitations are summarized in Figure 21 below.

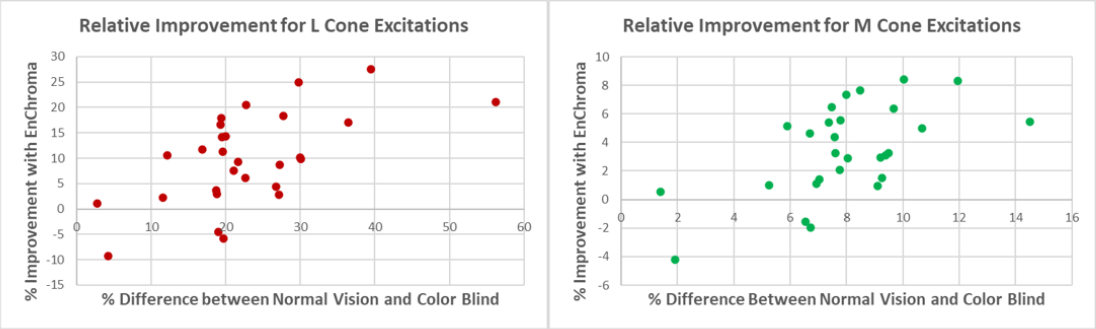


Figure 21: Improvement in relative number of excitations using EnChroma glasses for L cones (Left), and M cones (Right)

Figure 21 above shows the initial percent difference from normal vision for a person with color blindness. The y axis shows how much this percent difference was improved when putting on the EnChroma glasses. A positive value represents the relative excitations becoming that percent closer to the number of excitations for a person with normal vision while negative represents getting further from normal vision. Not all points are positive meaning an improvement in color vision was not seen for all scenes. Equation 1 below explains the math used:

%difference_ColorBlindNormal - %difference_EnChroma_Normal

Note that a positive value represents an improvement while a negative value represents worsening.

Interestingly, this same pattern was not seen when looking at the ratio between L and M cones. Figure 22 below shows that the EnChroma glasses were often ineffective at bringing this ratio closer to the L/M ratio seen with normal vision.

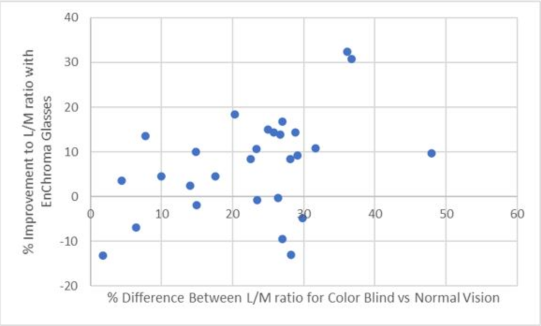


Figure 22: Percent difference between L/M excitation ratio from normal vision and RG color blind with EnChroma glasses

The x axis represents the percent difference between L/M ratio in normal vision and Color Blind vision. The y-axis represents how much this percent improved when putting on the EnChroma glasses. For example, a y value of 5 would mean putting on the EnChroma glasses made the L/M ratio 5% closer to normal vision from color blind vision. A negative value would mean the L/M ratio got worse putting on the EnChroma glasses so a person's ability to perceive color would be worse. Results seem to be scattered, indicating that EnChroma glasses might not make a significant difference to individuals with RG color blind.

Conclusions:

Simulation and analysis of the effectiveness of EnChroma glasses on color blind individuals show that there is some improvement in relative excitation value for L and M cones when comparing normal vision and color vision deficiencies with EnChroma glasses. While our results show mostly improvements, there were some scenes that caused a response that differed more from normal vision. This is expected since the glasses won’t be perfect in all cases. The results also show that while the glasses seemed to improve responses for scenes with primarily red and brown, it seems to have little to no effect on other scenes, such as scenes that were dominantly blue or white.

Individuals with color blindness typically have trouble articulating what they perceive, which makes it hard to understand how effective these glasses really are. The color purple might look different to individuals with color vision deficiencies and individuals without. Image simulations typically try to give an impression to people what colorblind people perceive, but these simulations are not completely accurate, since there is no way to simulate a realistic understanding of what a colorblind individual sees.

EnChroma glasses are reported to have little to no effect on 20% of color blind people who have drastic color vision deficiencies. From MATLAB simulation and analysis, we have shown that there is a difference in the way these glasses allow individuals to see and prove to show improvements for some cases, but not all.

A typical pair of these glasses cost around $300, so buying these glasses is an investment. From the results it appears that these glasses are effective and will in most cases, alter how a RG colorblind individual perceives color. Although color vision won’t be completely fixed to normal vision, there still seems to be noticeable differences between cone excitation responses in a variety of scenes.

Comparing the L/M excitation ratio from normal vision for RG color blind and color blind with EnChroma glasses, we saw very scattered results, indicating that this ratio does not show much difference or improvement. Future improvements to this project could be further analyzing these L/M ratios, instead of focusing on relative excitation levels. This will help us understand more about how effective these glasses are. Due to time, we were not able to analyze this ratio extensively as we wanted to.

Next steps to this project include testing on a large spectrum of scenes as well as analyzing the data in different ways other than the excitation responses. By comparing more parameters, we will be able to get a better understanding of the effectiveness of EnChroma glasses on color blind individuals.

References:

[1] Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Neuroscience. 2nd edition. Sunderland (MA): Sinauer Associates; 2001. Cones and Color Vision. Available from: https://www.ncbi.nlm.nih.gov/books/NBK11059/

[2] *Enchroma eyewear for color blindness*. EnChroma® Color Blind Glasses. (n.d.). Retrieved December 8, 2021, from https://enchroma.com/.

[3] Wandell, B. A. (n.d.). *Chapter 3: The photoreceptor mosaic*. Foundations of Vision RSS. Retrieved December 8, 2021, from

https://foundationsofvision.stanford.edu/chapter-3-the-photoreceptor-mosaic/.

[4]Morgan, M. J., Adam, A., and Mollon, J. D., “Dichromats Detect Colour-Camouflaged Objects that are not Detected by Trichromats”, <i>Proceedings of the Royal Society of London Series B</i>, vol. 248, no. 1323, pp. 291–295, 1992.

[5] Martínez-Domingo, Miguel & Valero, E. & Gómez-Robledo, Luis & Huertas, Rafael & Hernández-Andrés, Javier. (2020). Spectral Filter Selection for Increasing Chromatic Diversity in CVD Subjects. Sensors. 20. 2023. 10.3390/s20072023.

Appendix:

A. Code to measure excitations of scene across region of interest

```
ieInit;
clear all

%prompt for color blindness and glasses
```

```
prompt = {'Are you color blind? (y/n)','Put on Enchroma glasses? (y/n)'};
dlgtitle = 'Input';
dims = [1 35];
definput = {'n','n'};
answer = inputdlg(prompt,dlgtitle,dims,definput);

%Create optics
oi = oiCreate('wvf human');
oi = oiSet(oi, 'wavelength', 400:10:700);

%Load Enchroma Data
load('EnchromaInput','EnchromaInput');
load('EnchromaThroughLens','EnchromGrabThroughLens');
wave = (350:10:1000);
enchromIn = interp1(EnchromaInput(:,1), EnchromaInput(:,2),wave);

enchromOut = interp1(EnchromGrabThroughLens(:,1), EnchromGrabThroughLens(:,2),wave);
ieNewGraphWin;
% plot(EnchromGrabThroughLens(:,1),EnchromGrabThroughLens(:,2));
transmittance = enchromOut./enchromIn;
transmittance = min(transmittance,1);
transmittance = max(transmittance,0);

% wave_interp = 350:1:1000;
% transmittance = interp1(wave, transmittance, wave_interp);

%plot transmittance
ieNewGraphWin;
plot(wave, transmittance, '-o')
grid on;
xlabel('Wave (nm)');
ylabel('Transmittance');

%Get current Optics Transmittance
transmit_oi = oi.optics.lens.transmittance;
%Recompute tranmittance with enchroma glasses
transmit_enchroma = transmit_oi.* transmittance(6:36)';
%Set new optical transmittance
%oi.optics.lens.transmittance = transmit_enchroma;
% oi = oiSet(oi, 'lens Transmittance', transmit_enchroma);


%set Scene
scene = sceneCreate('macbethd50');

%Upload own scene to test
% scene = sceneFromFile('test_scene4.jpg','rgb');
% scene = sceneSet(scene, 'wavelength', 400:10:700);
% rgb=sceneShowImage(scene); %Will display scene
%sceneWindow(scene); %Another way to display scene

wave=sceneGet(scene,'wave'); %professor's suggestion
oi = oiCompute(oi, scene);

if answer{2} == 'y'
    %Set new optical transmittance
    photons = oiGet(oi,'photons');
    [photons, row, col] = RGB2XWFormat(photons);
    photons = photons*diag(transmittance(6:36)');
    photons = XW2RGBFormat(photons,row,col);
    oi = oiSet(oi,'photons',photons);
end


cm = cMosaic('sizeDegs',[0.8, 0.8],'eccentricityDegs',[0,0]);
cm.visualize();
%
if answer{1} == 'y'
    %change cone absorbance
    mAbsorbance = cm.pigment.absorbance_(:,2);
```

```
    wave = cm.pigment.wave_;
    absorbance = ShiftPhotopigmentAbsorbance(wave(:),mAbsorbance',20,'linear');
    cm.pigment.absorbance_(:,2) = absorbance;
    cm.plot('spectral qe');
else
    cm.plot('spectral qe');
end

allE = cm.compute(oi);
noiseFreeExcitationResponse = cm.compute(oi, 'opticalImagePositionDegs', [0 0]);
activationRange = prctile(noiseFreeExcitationResponse(:), [1 99]);
excitations = cm.compute(oi);

hFig = figure(1);
%
% cm.visualize(...
%     'activation', excitations, ...
%     'visualizedConeAperture', 'geometricArea', ...
%     'verticalActivationColorBarInside', true, ...
%     'domain', 'degrees', ...
%     'backgroundColor', [0 0 0], ...
%     'colorbarTickLabelColor', [0 1 0], ...
%     'plotTitle', 'Excitation Response');

sConeResponses = noiseFreeExcitationResponse(cm.sConeIndices);
% ieNewGraphWin; histogram(sConeResponses,'FaceColor','b');
% xlabel('Excitations'); ylabel('Number of S cones');
% fprintf('%d S cones\n',numel(sConeResponses));
% stotal = sum(sConeResponses);

lConeResponses = noiseFreeExcitationResponse(cm.lConeIndices);
% ieNewGraphWin; histogram(lConeResponses, 'FaceColor','r');
% xlabel('Excitations'); ylabel('Number of L cones');
% fprintf('%d L cones\n',numel(lConeResponses));
% ltotal = sum(lConeResponses);

mConeResponses = noiseFreeExcitationResponse(cm.mConeIndices);
% ieNewGraphWin; histogram(mConeResponses, 'FaceColor','g');
% xlabel('Excitations'); ylabel('Number of M cones');
% fprintf('%d M cones\n',numel(mConeResponses));
% mtotal = sum(mConeResponses);

%roiLine_perif = regionOfInterest('shape', 'line', 'from', [-.13 .3], 'to', [.13,.3],'thick', 0.1);
roiLine_all = regionOfInterest('shape', 'line', 'from', [-.3 0], 'to', [.3,0],'thick', 0.1);
%cm.plot('roi',allE, 'roi',roiLine_perif);
cm.plot('roi',allE, 'roi',roiLine_all);
%cm.plot('excitations roi',allE, 'roi',roiLine_perif);
cm.plot('excitations roi',allE, 'roi',roiLine_all);
```

B. **Code to compare excitations of L and M cones in fovea**

```
ieInit;
clear all

prompt = {'What curve do you want to shift? (L/M/S)','By how much? (+/-# or off)'};
dlgtitle = 'Input';
dims = [1 35];
definput = {'M','20'};
answer = inputdlg(prompt,dlgtitle,dims,definput);
shift = str2double(answer{2});
%shift = 20;

%Create optics
oi = oiCreate('wvf human');
oi = oiSet(oi, 'wavelength', 400:10:700);
oi_enchroma = oiCreate('wvf human');
oi_enchroma = oiSet(oi_enchroma, 'wavelength', 400:10:700);
```

```
%Load Enchroma Data
load('EnchromaInput','EnchromaInput');
load('EnchromaThroughLens','EnchromGrabThroughLens');
wave = (350:10:1000);
enchromIn = interp1(EnchromaInput(:,1), EnchromaInput(:,2),wave);

enchromOut = interp1(EnchromGrabThroughLens(:,1), EnchromGrabThroughLens(:,2),wave);
ieNewGraphWin;
% plot(EnchromGrabThroughLens(:,1),EnchromGrabThroughLens(:,2));
transmittance = enchromOut./enchromIn;
transmittance = min(transmittance,1);
transmittance = max(transmittance,0);


%set Scene - Custom or pre-set
% scene = sceneFromFile('nature1.jpg','rgb');
% scene = sceneSet(scene, 'wavelength', 400:10:700);
scene = sceneCreate('macbethd50');
spectrum = sceneGet(scene, 'spectrum');
oi = oiCompute(oi, scene);
oi_enchroma = oiCompute(oi_enchroma, scene);


%Set new optical transmittance
photons = oiGet(oi_enchroma,'photons');
[photons, row, col] = RGB2XWFormat(photons);
photons = photons*diag(transmittance(6:36)');
photons = XW2RGBFormat(photons,row,col);
oi_enchroma = oiSet(oi_enchroma,'photons',photons);



cm = cMosaic('sizeDegs',[0.15, 0.15],'eccentricityDegs',[0,0]);
cm_shift = cMosaic('sizeDegs',[0.15, 0.15],'eccentricityDegs',[0,0]);
cm_enchroma = cMosaic('sizeDegs',[0.15, 0.15],'eccentricityDegs',[0,0]);


%change cone absorbance
if answer{1} == 'L'
    lAbsorbance = cm_shift.pigment.absorbance_(:,1);
    wave = cm_shift.pigment.wave_;
    absorbance = ShiftPhotopigmentAbsorbance(wave(:),lAbsorbance',shift,'linear');
    cm_shift.pigment.absorbance_(:,1) = absorbance;
    cm_enchroma.pigment.absorbance_(:,1) = absorbance;
elseif answer{1} == 'M'
    lAbsorbance = cm_shift.pigment.absorbance_(:,2);
    wave = cm_shift.pigment.wave_;
    absorbance = ShiftPhotopigmentAbsorbance(wave(:),lAbsorbance',shift,'linear');
    cm_shift.pigment.absorbance_(:,2) = absorbance;
    cm_enchroma.pigment.absorbance_(:,2) = absorbance;
else
    lAbsorbance = cm_shift.pigment.absorbance_(:,3);
    wave = cm_shift.pigment.wave_;
    absorbance = ShiftPhotopigmentAbsorbance(wave(:),lAbsorbance',shift,'linear');
    cm_shift.pigment.absorbance_(:,3) = absorbance;
    cm_enchroma.pigment.absorbance_(:,3) = absorbance;
end

cm.compute(oi);
cm_shift.compute(oi);
cm_enchroma.compute(oi_enchroma);

excitations = cm.compute(oi);
excitations_shift = cm_shift.compute(oi);
excitations_enchroma = cm_enchroma.compute(oi_enchroma);

% roiLine_perif = regionOfInterest('shape', 'line', 'from', [-.13 .3], 'to', [.13,.3],'thick', 0.1);
% roiLine_fovea = regionOfInterest('shape', 'line', 'from', [-.13 0], 'to', [.13,0],'thick', 0.1);

hFig = figure(1);
```

```
sConeResponses = excitations(cm.sConeIndices);
stotal(1) = sum(sConeResponses);
sConeResponses_shift = excitations_shift(cm_shift.sConeIndices);
stotal(2) = sum(sConeResponses_shift);
sConeResponses_enchroma = excitations_enchroma(cm_enchroma.sConeIndices);
stotal(3) = sum(sConeResponses_enchroma);

lConeResponses = excitations(cm.lConeIndices);
ltotal(1) = sum(lConeResponses);
lConeResponses_shift = excitations_shift(cm_shift.lConeIndices);
ltotal(2) = sum(lConeResponses_shift);
lConeResponses_enchroma = excitations_enchroma(cm_enchroma.lConeIndices);
ltotal(3) = sum(lConeResponses_enchroma);

mConeResponses = excitations(cm.mConeIndices);
mtotal(1) = sum(mConeResponses);
mConeResponses_shift = excitations_shift(cm.mConeIndices);
mtotal(2) = sum(mConeResponses_shift);
mConeResponses_enchroma = excitations_enchroma(cm_enchroma.mConeIndices);
mtotal(3) = sum(mConeResponses_enchroma);

params = cm.visualize('params');
% cm.visualize('help');   X = categorical({'Normal','Abnormal','Abnormal with Enchroma'});

X = reordercats(X,{'Normal','Abnormal','Abnormal with Enchroma'});
lsum = stotal(1) + mtotal(1) + ltotal(1);
msum = stotal(2) + mtotal(2) + ltotal(2);
ssum = stotal(3) + mtotal(3) + ltotal(3);
exc = [stotal(1)/lsum mtotal(1)/lsum ltotal(1)/lsum; stotal(2)/msum mtotal(2)/msum ltotal(2)/msum; stotal(3)/ssum
rel = [ltotal(1)/mtotal(1); ltotal(2)/mtotal(2); ltotal(3)/mtotal(3)];
pdif_rel = [(rel(1) - rel(2))/rel(1),(rel(1) - rel(3))/rel(1)];
pdif_rel = pdif_rel.*100;
color = [1,1,1];

g = bar(X, exc, 'stacked');
title('Normalized Excitations for Three Visual Cases');
ylabel('Relative Excitations');
g(1).FaceColor = [0 0 1];
g(2).FaceColor = [0 1 0];
g(3).FaceColor = [1 0 0];

pdif = [(exc(2,2)-exc(1,2))/exc(1,2), (exc(3,2)-exc(1,2))/exc(1,2);(exc(2,3)-exc(1,3))/exc(1,3), (exc(3,3)-exc(1,3)
pdif = abs(pdif.*100);

T = array2table(pdif,'VariableNames',{'RG Blind % Dif','EnChroma % dif'},'RowName',{'M','L'});
disp(T)

M = array2table(pdif_rel,'VariableNames',{'LM Ratio Dif RG Blind','LM Ratio Dif EnChroma'});
disp(M)
```