Supplemental material: Chromatic properties of horizontal and ganglion cell responses follow a dual gradient in cone opsin expression.

This document contains supplemental material for Yin et al., Chromatic properties of horizontal and ganglion cell responses follow a dual gradient in cone opsin expression.

Supplemental Figures

Supplemental Figure 1. Intensity weight analysis: when background intensity increased, relative cone contribution to horizontal cell responses increased while relative rod contribution decreased.

A, Photoreceptor intensity weights of cells collected at eight background levels. Same data and same format as Figure 3A. The only difference with Figure 3A is that intensity weights are plotted, which were computed by converting the contrast weights shown in Figure 3A with corresponding background isomerization rates (Suppl. Table 1). We fitted all the data of each retinal area with a straight line (red lines). Slopes of the fits describe relative M and S contributions as a fraction of total cone input (superior retina, 0.95/0.05; inferior retina, 0.15/0.85), which are similar to values in Figure 3A. Mean weights obtained in superior retina at main background (green dots, n = 14) were: M = 0.79 ± 0.02 (standard error), S = 0.02 ± 0.01, rod = 0.19 ± 0.02. Mean weights obtained in inferior retina at main background (green circles, n = 8) were: M = 0.12 ± 0.01, S = 0.74 ± 0.02, rod = 0.14 ± 0.02. Rod weights did not differ significantly between superior and inferior retina (t-Test, p = 0.18).

B, Mean intensity weights (± standard error, SE) are plotted against background intensity (M: green line; S: blue line and rod: black line). Upper panel shows data from superior retina while lower panel shows data from inferior retina. Rod contribution decreased with background intensity but did not drop to zero at the highest intensity backgrounds used.
Supplemental Figure 2. Intensity weight analysis: distributions of M and S intensity weights differed between different retinal areas, but were similar across cell types.

A, Intensity weights of horizontal cells estimated from flicker data. Same format as Figure 6A. The only difference with Figure 6A is that intensity weights are plotted. To estimate cone intensity weights, we used the mean rod intensity weights \( w_{Rod} = 0.17 \pm 0.08 \) standard deviation obtained from the horizontal cell flash experiments to set the rod weight used in fitting the LNL model, and fit the model using incremental intensity as the stimulus description, rather than incremental contrast. We also estimated cone weights under different assumptions about rod input. Additional rod weights assumed were no rod input (gray), and \( \pm 1.5 \) standard deviation (SD) away from the mean estimate (red and blue). In the fits, we constrained the cone weights to be positive, which for some cells altered the rod weight to a smaller value when M or S weights equal zero. The rod weights shown in the insets are the mean values used in calculation, which are smaller than the nominal values because of the alteration procedure described in the previous sentence. Across the range of rod weights assumed, clear separation of the data from superior and inferior retina holds. The background produced 4.16 (M), 4.12 (S) and 4.76 (Rod) log_{10} Rh*/photoreceptor/s. The same background was used for all the rest panels in this figure.

B, Summary of cone intensity weights in A. Same format as Figure 6B except that intensity weights are plotted.

C, Intensity weights of ganglion cells. Same format and analysis as described for panel A above.

D, Summary of cone intensity weights in C. Same format as B.
Supplemental Table

Supplemental Table 1. Photoreceptor isomerization rates for all backgrounds used in the experiments.

<table>
<thead>
<tr>
<th>Background</th>
<th>M cone</th>
<th>S cone</th>
<th>Rod</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (The dimmest background)</td>
<td>1.50</td>
<td>1.39</td>
<td>2.08</td>
<td>$\log_{10} \text{Rh}^*/\text{photoreceptor/s}$</td>
</tr>
<tr>
<td>2</td>
<td>2.09</td>
<td>1.99</td>
<td>2.67</td>
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</tr>
<tr>
<td>3</td>
<td>2.89</td>
<td>2.83</td>
<td>3.48</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3.27</td>
<td>3.17</td>
<td>3.85</td>
<td></td>
</tr>
<tr>
<td>5</td>
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<td>3.47</td>
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</tr>
<tr>
<td>6</td>
<td>3.86</td>
<td>3.79</td>
<td>4.45</td>
<td></td>
</tr>
<tr>
<td>7 (The main background)</td>
<td>4.17</td>
<td>4.12</td>
<td>4.76</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4.55</td>
<td>4.48</td>
<td>5.14</td>
<td></td>
</tr>
</tbody>
</table>

Obtaining the intensity weights

For the horizontal cell flash data, the intensity weights were derived from the contrast weights obtained in the fits to the action spectra. For the flicker data, the intensity weights were obtained by refitting the data with the stimuli expressed in intensity rather than in contrast units. We describe both procedures here.

Horizontal cell flash data

Let $A(\lambda)$ be the action spectrum of a cell. Denote the photoreceptor contrast sensitivities as $S_M^c(\lambda)$, $S_S^c(\lambda)$, and $S_{\text{Rod}}^c(\lambda)$. These are derived from the corresponding intensity sensitivities $S_M^i(\lambda)$, $S_S^i(\lambda)$, and $S_{\text{Rod}}^i(\lambda)$: $S_M^c(\lambda) = S_M^i(\lambda) / R_{\text{M,bg}}$, for the M-cones (where $R_{\text{M,bg}}$ is the M-cone isomerization rate produced by the background), and similarly for the S cones and rods.
The fitting procedure described in Appendix B is equivalent to finding the relative contrast weights \( w_M^c \), \( w_S^c \) and \( w_{Rod}^c \) that best describe the action spectrum \( A(\lambda) \) as the weighted sum of the photoreceptor contrast sensitivities:

\[
A(\lambda) = w_M^c S_M^c(\lambda) + w_S^c S_S^c(\lambda) + w_{Rod}^c S_{Rod}^c(\lambda). \tag{S1}
\]

We obtain from \( u_M^c \), \( u_S^c \) and \( u_{Rod}^c \) the relative contrast weights \( w_M^c \), \( w_S^c \) and \( w_{Rod}^c \) reported in the paper according to Equation B4.

To find intensity weights that describe the action spectrum as the weighted sum of the intensity sensitivities, we note that from Equation S1

\[
A(\lambda) = w_M^c S_M^c(\lambda) + w_S^c S_S^c(\lambda) + w_{Rod}^c S_{Rod}^c(\lambda) \\
= w_M^c S_M^i(\lambda) / Rh_{M, bg}^i + w_S^c S_S^i(\lambda) / Rh_{S, bg}^i + w_{Rod}^c S_{Rod}^i(\lambda) / Rh_{Rod, bg}^i \tag{S2}
\]

where the intensity weights \( u_M^i \), \( u_S^i \), and \( u_{Rod}^i \) are obtained from the relative contrast weights as (e.g.)

\[ u_M^i = w_M^c / Rh_{M, bg}^i. \]

To get normalized intensity weights we then have (e.g.)

\[
w_M^i = u_M^i / (u_M^i + u_S^i + u_{Rod}^i) \\
= (w_M^c / Rh_{M, bg}^i) / (w_M^c / Rh_{M, bg}^i + w_S^c / Rh_{S, bg}^i + w_{Rod}^c / Rh_{Rod, bg}^i). \tag{S3}
\]

We used Equation S3 to convert from contrast to intensity weights for the horizontal cell flash data.

**Flicker data**

Obtaining cone weights from the flicker data requires an assumption about the intensity weight of rod input and involves enforcing a constraint in the fit that no obtained weights be negative. The latter constraint is not easily captured analytically, and to obtain intensity weights from the flicker data we simply refit the LNL model after converting the stimuli to intensity units by multiplying the stimulus contrast seen by each photoreceptor class by the background isomerization rate for the
corresponding class. For the strength of rod input in the analysis in terms of intensity rates, we took the values obtained from the intensity weight analysis of the horizontal cell flash data.