Modeling discriminable distance and luminance of the colors

To represent the colors in the chick’s receptor space (fig. 1) relative quantum catches $q_i$ (equation s1) for S, M, and L cones were calculated and converted into Cartesian coordinates.

$$ q_i = \frac{q_i}{q_{SW} + q_{MW} + q_{LW}}, \quad \text{(s1)} $$

Here, $i$ refers to the S, M and L cones, respectively. The absolute quantum catches $Q_i$ are given as

$$ Q_i = \int_{350}^{700} S_i(\lambda)R(\lambda)I(\lambda)\,d\lambda, \quad \text{(s2)} $$

where $S_i$ is the spectral sensitivity of the cone type $I$ (figure S1), $R$ is the reflectance spectrum of a color, (measured with an Ocean Optics USB2000 spectrometer), and $I$ is the spectrum of the illuminant (figure S1)

**Figure S1.** The colored lines show the relative spectral sensitivity of the chick’s single cones. The black line shows the normalized radiance spectrum of the long-pass filtered illuminant.

Relative quantum catches are then transferred into Cartesian coordinates $x$ and $y$ as follows
\[
x = \frac{1}{\sqrt{2}} (q_L - q_M),
\]

\[
y = \frac{\sqrt{2}}{\sqrt{5}} \left[ q_S - \frac{(q_L + q_M)}{2} \right].
\]

The perceptual distance of the test stimuli to the rewarded stimulus was calculated using the receptor noise limited model Vorobyev and Osorio (1998). According to this model, the discriminability \( \Delta S \) of two colors, in units of just noticeable differences (JNDs) is given as

\[
\Delta S = \sqrt{\frac{\omega_1^2(\Delta q_3 - \Delta q_2)^2 + \omega_2^2(\Delta q_3 - \Delta q_1)^2 + \omega_3^2(\Delta q_1 - \Delta q_2)^2}{(\omega_1^2)(\omega_2^2) + (\omega_1^2)(\omega_3^2) + (\omega_2^2)(\omega_3^2)}},
\]

with \( \omega_1, \omega_2, \) and \( \omega_3 \) being the noise in the S, M, and L channel, respectively. Noise is given as Weber fractions and was found to be 0.06 for the chicks’ M and L channel in a study by Olsson, Lind, and Kelber (2015) using a 2afc task and a threshold criterion for 1 JND of 75% correct choices. To calculate the noise levels in the other single cone types we used ratios of VS:S:M:L = 1:2:4:4 (Bowmaker, Heath, Wilkie, & Hunt, 1997; Olsson et al., 2015). Another study reported ratios of 1:1.5:2.5:2 (Kram, Mantey, & Corbo, 2010), which leads to slightly different noise levels in the L and S cones and hence predicts slightly different JNDs. However, analysis of the chicks’ choice behavior showed that these slight changes in discriminability have only a negligible effect on the shape of the generalization gradients and the generalization thresholds.

\( \Delta q_i \) is the difference in quantum catches between the two colors \( S1 \) and \( S2 \) for each cone type \( i \) assuming a logarithmic performance of the photoreceptors:

\[
\Delta q_i = \ln \left( \frac{q_{s1}}{q_{s2}} \right).
\]

The luminance of each color was defined by quantum catches of the chicks’ double cones using equation s2. For each experiment colors were chosen to be isoluminant for the double cones (table 1).
References


