Bird Colour Vision: Behavioural thresholds reveal receptor noise

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Supplementary information

Table S1, Colour differences between rewarded and unrewarded stimuli in the brightest illumination (250 cd/m^2). Based on a Weber fraction of 0.10 for the LWS channel.

Modeled colour difference between rewarded and unrewarded stimuli

Series 1 (Orange)		Series 2 (Green)	
Stimulus	Colour difference (JND)	Stimulus	Colour difference (JND)
Rewarded O+		Rewarded G+	
Unrewarded		Unrewarded	
O1	0.46	G1	0.39
O2	0.71	G2	0.64
O3	1.34	G3	1.25
O4	1.88	G4	1.65
O5	3.18	G5	3.25

Table S2. Absolute quantum catches for single receptors from colour stimuli at various intensities. Calculated using Eq 5, and values from Table 1. The numbers in bold represent the quantum catch at a stimulus' intensity threshold.

		Quantum catch Intensity (cd/m^2)								
Receptor type	Stimulus	250	10	0.90	0.11	0.09	0.04	0.033	0.025	0.01
LWS	O+	1234	181	23.9	2.73	2.47	1.12	0.93	0.74	0.31
	O1	1190	172	23.1	2.63	2.38	1.07	0.90	0.71	0.29
	O2	1173	170	22.7	2.59	2.34	1.06	0.88	0.70	0.29
	O3	1161	168	23.1	2.63	**2.38**	1.07	0.90	0.71	0.29
	O4	1150	170	23.5	2.68	2.43	1.10	**0.92**	0.72	0.3
	O5	1163	168	24.1	2.75	2.48	1.12	0.94	**0.74**	0.31
MWS										
	O+	492	72.1	9.23	1.05	0.95	0.43	0.36	0.28	0.12
	O1	494	72.9	9.37	1.07	0.96	0.44	0.36	0.29	0.12
	O2	498	74.6	9.4	1.1	0.97	0.44	0.37	0.29	0.12
	O3	509	80.3	10.4	1.18	**1.07**	0.48	0.40	0.32	0.13
	O4	548	87.6	11.4	1.3	1.17	0.53	**0.44**	0.35	0.15
	O5	598	102	14.1	1.6	1.45	0.66	0.55	**0.43**	0.18
S										
	O+	350	51.2	2.38	0.62	0.56	0.25	0.21	0.17	0.07
	O1	345	50.1	2.35	0.61	0.55	0.25	0.21	0.17	0.07
	O2	346	51.4	2.37	0.62	0.56	0.25	0.21	0.17	0.07
	O3	351	53.1	2.46	0.64	**0.58**	0.26	0.22	0.17	0.07
	O4	363	57.2	2.60	0.68	0.61	0.28	**0.23**	0.18	0.08

	O5	391	66.3	3.05	0.80	0.72	0.33	0.27	**0.21**	0.09
VS										
	O+	170	24.9	1.54	0.18	0.18	0.07	0.06	0.05	0.02
	O1	166	24.1	1.51	0.17	0.17	0.07	0.06	0.05	0.02
	O2	164	24.4	1.52	0.17	0.17	0.07	0.06	0.05	0.02
	O3	167	24.0	1.52	0.17	**0.17**	0.07	0.06	0.05	0.02
	O4	164	25.6	1.58	0.18	0.18	0.07	**0.07**	0.05	0.02
	O5	175	29.1	1.80	0.20	0.20	0.08	0.08	**0.06**	0.02

D=0.350, 0.415, 0.466, 0.472, 0.475. 0.477, 0.48, 0.49, 0.499cm; Δt = 0.012s, 0.025s, 0.05s, 0.05s, 0.05s, 0.05s, 0.05s, 0.05s and 0.05s for the intensities, 250, 10, 0.9, 0.11, 0.09, 0.04, 0.033, 0.025 and 0.01 cd/m^2 respectively.

Table S3. Absolute quantum catches for single receptors from colour stimuli at various intensities. Calculated using Eq 5, and values from Table 1. The numbers in bold represent the quantum catch at a stimulus' intensity threshold.

		Quantum catch Intensity (cd/m^2)							
Receptor type	Stimulus	250	10	0.90	0.26	0.11	0.08	0.04	0.01
LWS	G+	447	65.5	7.10	2.09	0.81	0.65	0.3	0.09
	G1	455	66.7	7.16	2.10	0.82	0.66	0.33	0.09
	G2	447	65.4	7.13	2.09	0.81	0.65	0.33	0.09
	G3	442	64.8	7.27	**2.14**	0.83	0.67	0.34	0.09
	G4	429	62.9	7.15	2.10	**0.81**	0.65	0.33	0.09
	G5	402	58.9	6.53	1.92	0.74	**0.60**	0.30	0.08
MWS									
	G+	537	78.7	8.06	2.37	0.92	0.74	0.38	0.10
	G1	545	79.9	8.16	2.40	0.93	0.75	0.38	0.10
	G2	532	77.9	8.00	2.35	0.92	0.73	0.37	0.10
	G3	528	77.3	8.08	**2.38**	0.92	0.74	0.38	0.10
	G4	517	75.7	8.00	2.35	**0.91**	0.73	0.37	0.10
	G5	491	71.9	7.52	2.21	0.86	**0.69**	0.35	0.10
S									
	G+	477	69.8	2.86	1.92	0.75	0.60	0.30	0.08
	G1	502	73.6	2.96	1.99	0.77	0.62	0.32	0.09
	G2	507	74.2	3.04	2.04	0.79	0.64	0.32	0.09
	G3	534	78.2	3.26	**2.19**	0.85	0.68	0.35	0.09
	G4	543	79.6	3.37	2.26	**0.88**	0.70	0.36	0.10
	G5	602	88.2	3.80	2.55	1.00	**0.80**	0.40	0.11
VS									
	G+	213	31.2	1.82	0.53	0.21	0.17	0.08	0.02
	G1	232	34.0	1.90	0.56	0.22	0.17	0.09	0.02
	G2	236	34.6	2.00	0.59	0.23	0.18	0.09	0.03
	G3	206	38.1	2.20	**0.65**	0.25	0.20	0.10	0.03
	G4	271	39.1	2.32	0.68	**0.26**	0.21	0.11	0.03
	G5	337	49.5	2.83	0.83	0.32	**0.26**	0.13	0.04

D=0.350, 0.415, 0.466, 0.470, 0.472. 0.477, 0.480 and 0.499cm; Δt = 0.012s, 0.025s, 0.05s, 0.05s, 0.05s, 0.05s, 0.05s and 0.05s for the intensities 250, 10, 0.9, 0.26, 0.11, 0.08, 0.04, and 0.01 cd/m^2 respectively.

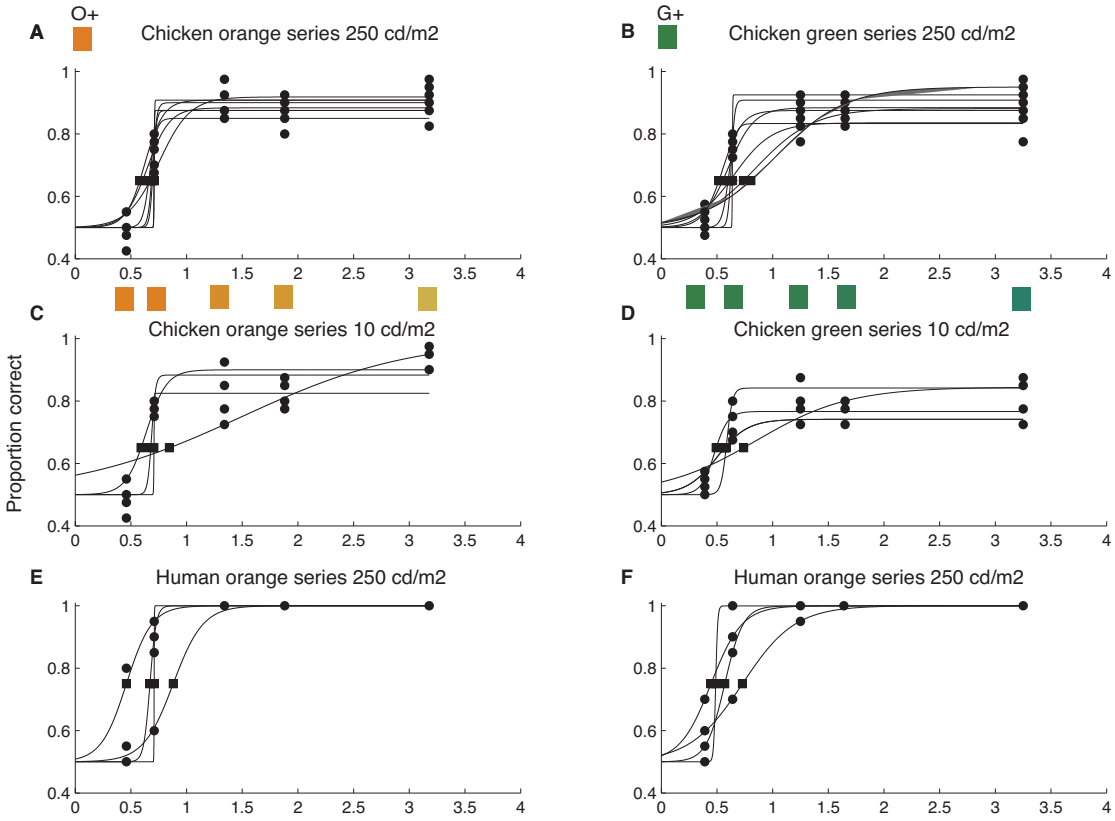

Figure S1. Individual colour discrimination performance of chickens and humans. (A,B) Colour discrimination of chickens (n=8) to colour differences in bright light (250 cd/m2) for the Orange (A) and Green (B) series. Thresholds were found to be 0.66±0.04 and 0.66±0.12 JND for the Orange and Green series respectively. (C,D) Colour discrimination of chickens (n=4) to colour differences in dimmer light (10 cd/m2) for the Orange (C) and Green (D) series. Thresholds were found to be 0.70±0.11 and 0.65±0.15 JND for the Orange and Green series respectively. (E,F) Colour discrimination of humans (n=4) to colour differences in bright light for the Orange (E) and Green (F) series. Thresholds were found to be

0.68±0.15 and 0.56±0.11 chicken JND.

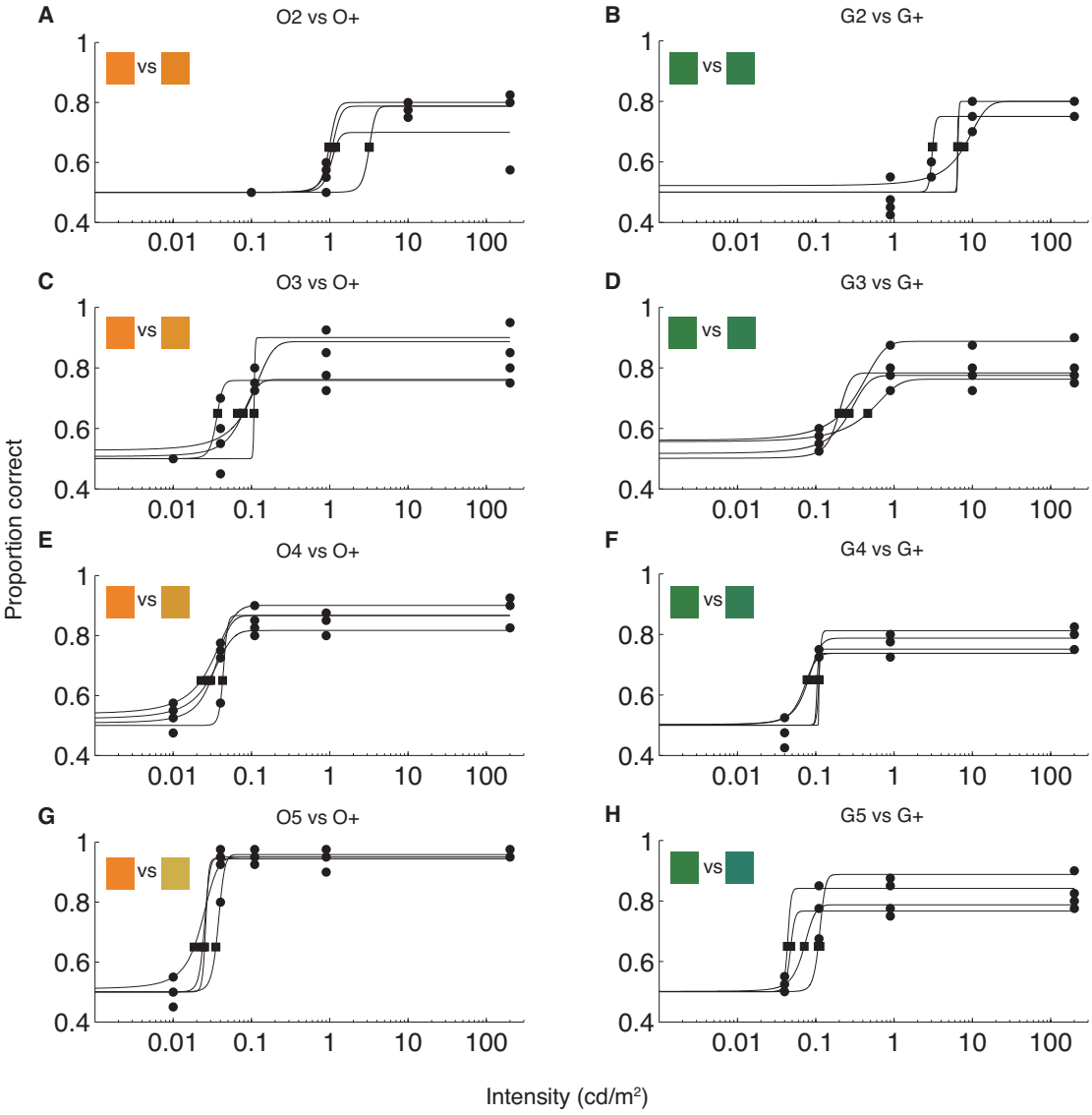

Figure S2. Individual colour discrimination at various intensity levels in chickens. (A, C, E and G) Colour discrimination in dim light in the Orange series. (B, D, F and H) Colour discrimination in dim light in the green series.

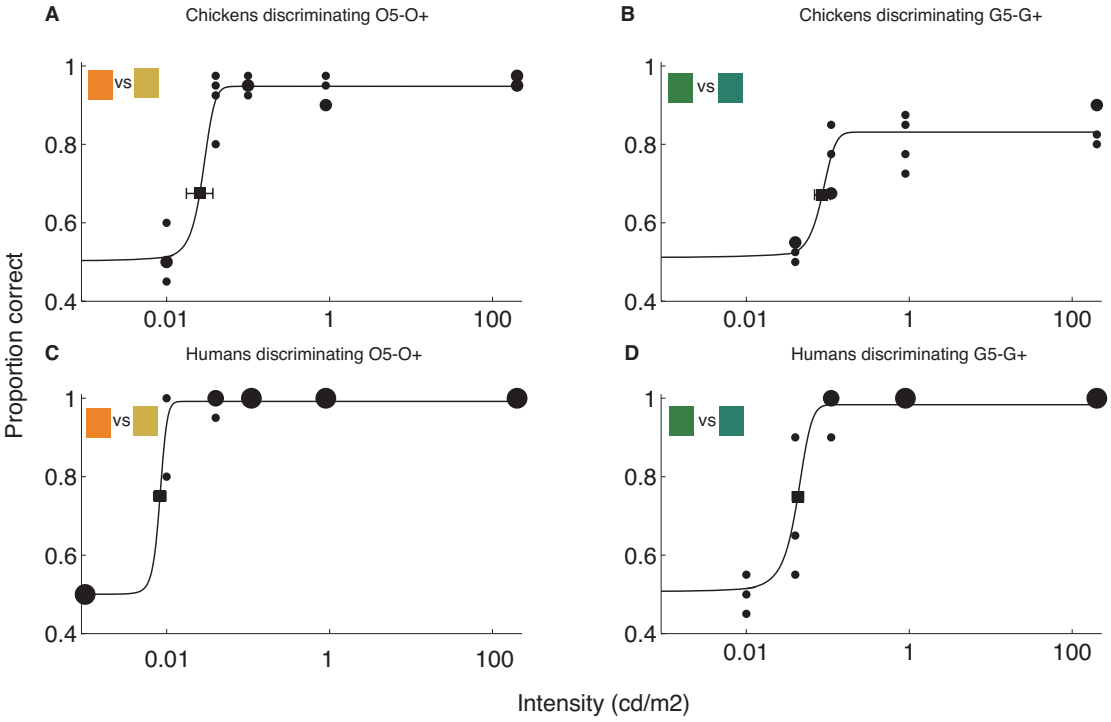

Figure S3. Comparison between the absolute intensity threshold in chickens and humans. (A-B) The discrimination performance of chickens (n=4) between O5-O+ and G5-G+ at various intensities. Thresholds were 0.025±0.008 and 0.08±0.027 cd/m^2 for O5-O+ and G5-G+ respectively. (C-D) The discrimination performance of humans (n=4) between O5-O+ and G5-G+ at several intensities. Intensity thresholds were found to be 0.010±0.002 and 0.052±0.01 for O5-O+ and G5-G+ respectively.

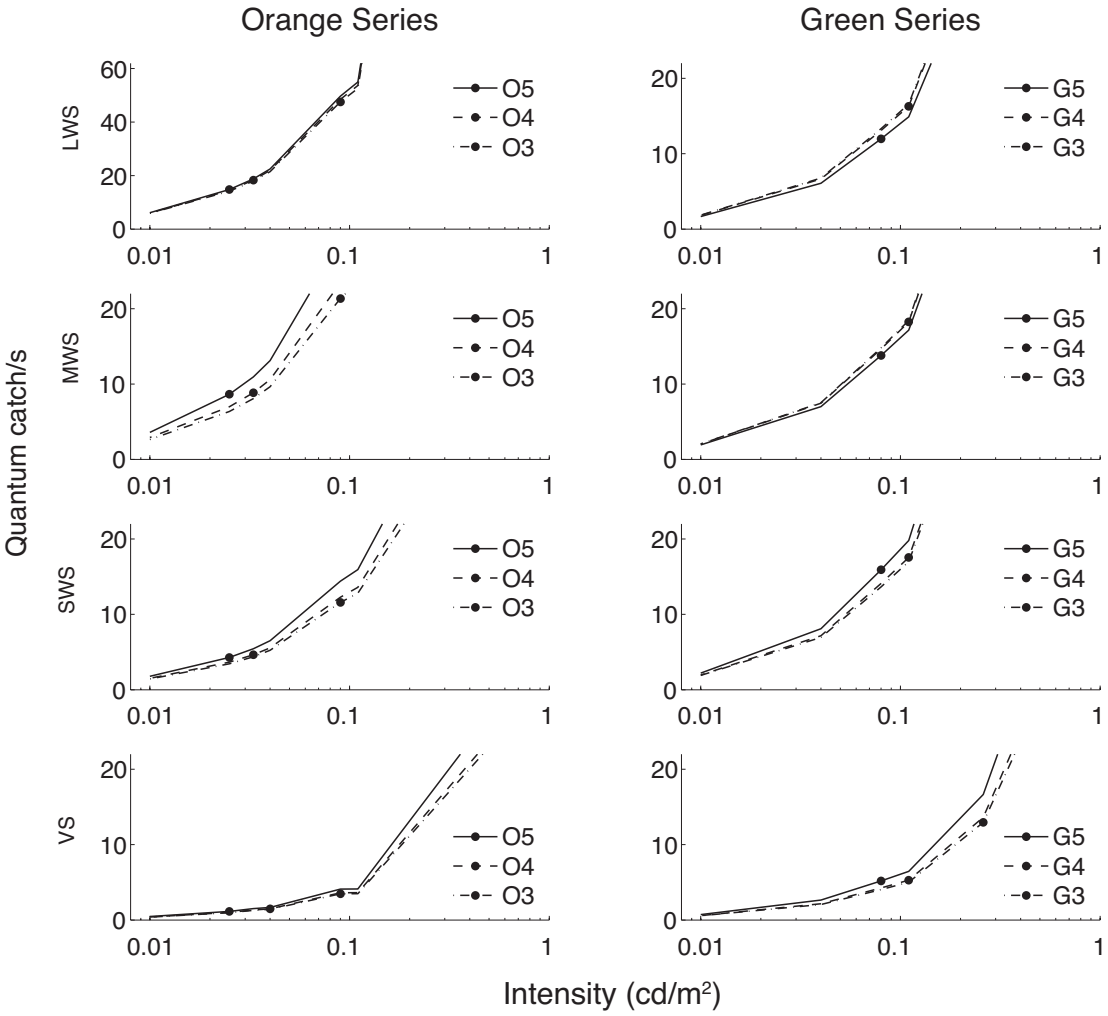

Figure S4. Quantum catch of individual cones from unrewarded stimuli. Taken from Tables S2 and S3, then scaled to quantum catches per second. Filled circles refer to the intensity threshold between a given unrewarded stimulus and the rewarded stimulus. Three unrewarded stimuli in each series are plotted, orange and green series to the left and right, respectively. In the orange series the three stimuli differ most in how much they stimulate the MWS cone, in the green series the stimuli differ most in how much they stimulate the VS cone.

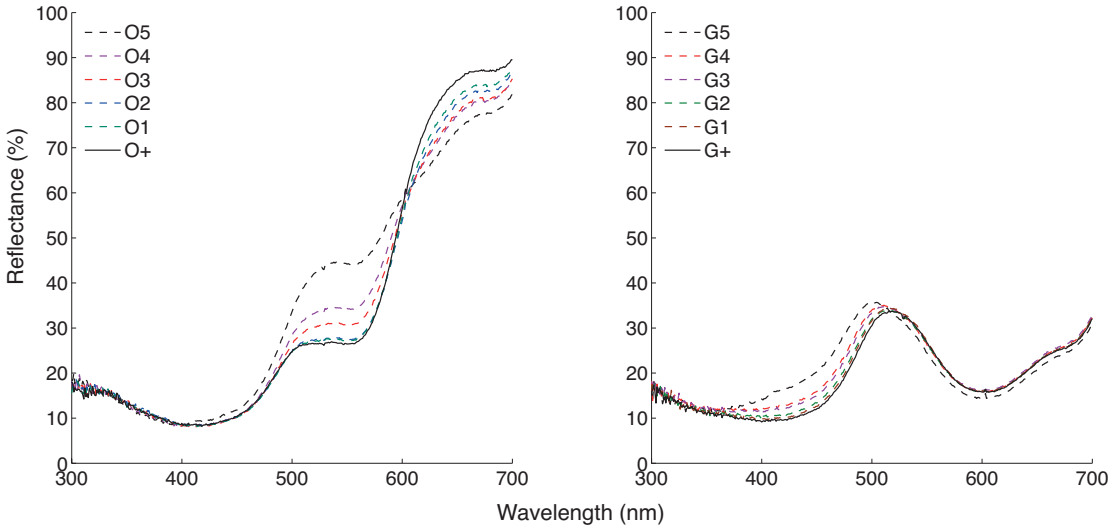

Figure S5. Reflectance of stimuli. Average reflectances from three measurements of the brightest versions of each stimulus.

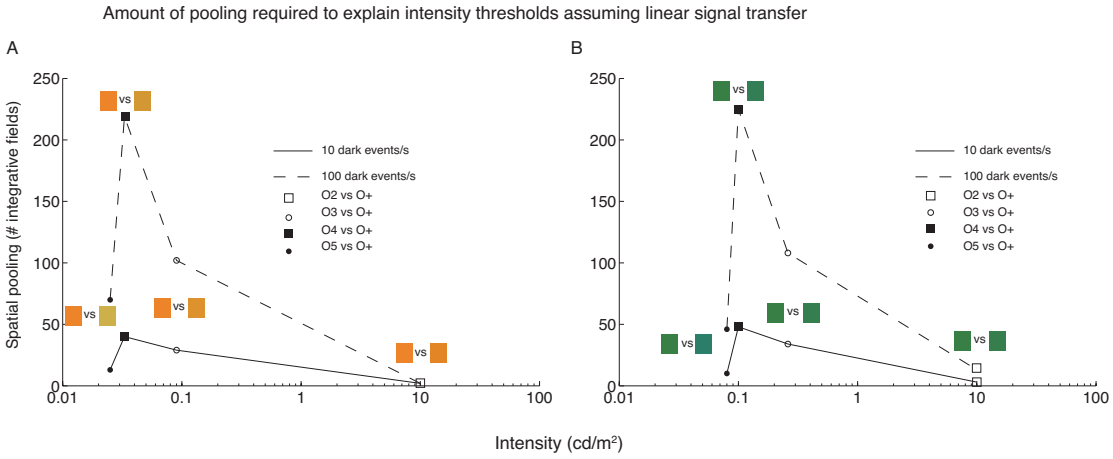

Figure S6. Spatial pooling required to explain the intensity thresholds, assuming photon-shot noise and dark noise in linear spatial pooling (both photons and dark events are pooled). (A) The amount of pooling required to explain the intensity thresholds in the Orange series. (B) The amount of pooling required to explain the intensity thresholds in the green series.

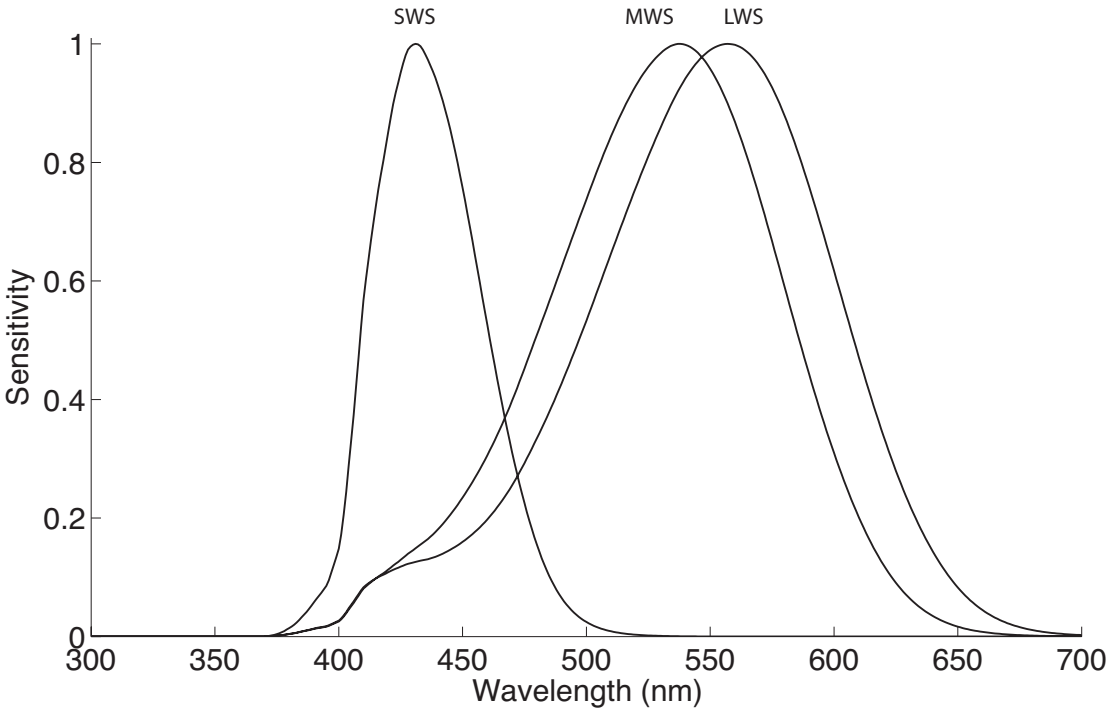

Figure S7. Spectral sensitivity of human visual pigments. Modelled using the Govardovskii template (Govardovskii et al. 2000), known human pigment absorbance peaks (Dartnall et al. 1983), ocular media transmittance and macular pigment transmittance (Wyzecki and Styles). S, M and L receptor from left to right.

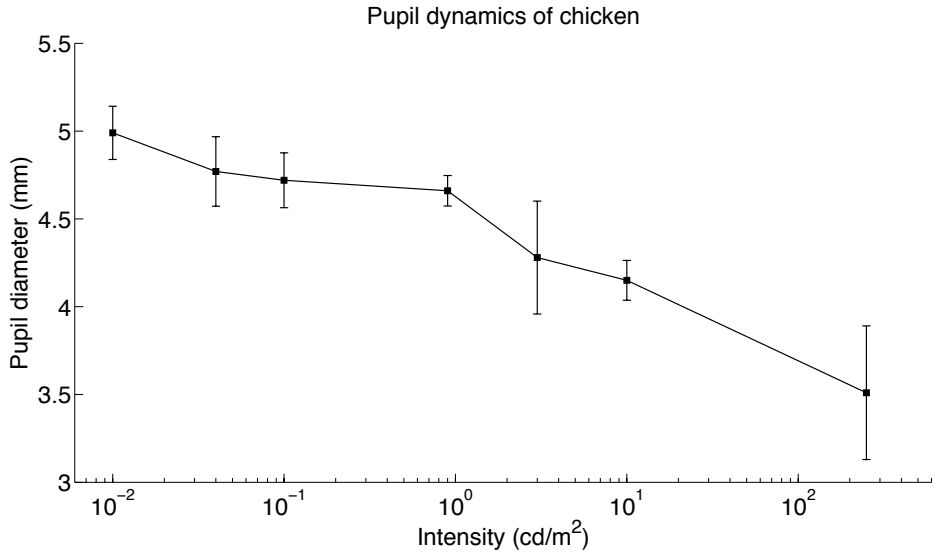

Figure S8. Pupil dynamics in chicken. The average pupil diameter of chickens (n=3) at the various intensities tested. Error bars refer to standard deviations.