Supplementary Material

Coping with copepods: Do right whales (*Eubalaena glacialis*) forage visually in dark waters?

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(1) Calculations of sensitivities of eyes of southern right whales and bowhead whales

Extensive data on ocular morphology exist for *E. australis* (southern right whale), obtained from adults and calves that stranded in Argentina [1]. Of 31 whales whose eyes were categorized (4 adults and 27 calves), we selected all four adults and six calves of various body lengths for characterization of eye dimensions necessary to calculate sensitivity. Of these, two (Ea 19, adult and Ea 02, calf (see [1] and table S1) had measurements that included both the overall eye length (axial dimension, from the outer cornea to the back of the sclera) and the posterior nodal distance (distance from the center of the lens to the retina), taken to be the focal length of the eye. The average ratio of eye length to posterior nodal distance was 0.53. Since all eyes had their overall lengths measured, we estimated their focal lengths using this ratio (table S1). The eye of one calf (Ea 02) had both its corneal dimensions and lens dimensions (height, or vertical diameter and width, or horizontal diameter; both perpendicular to the optic axis) measured, providing a ratio of (lens width + lens height)/(corneal length + corneal height) of 0.46, which we used to estimate pupil diameter, assuming that the fully opened pupil exposed the full dimensions of the lens (see [1] and table S1). Unfortunately, no retinal data were available for *E. australis*.

In addition to these data on southern right whales, Zhu *et al.* [2] provide an extensive data set from the bowhead whale, *Balaena mysticetus*, a balaenid species that is similar in size to right whales. One eye each from six whales, ranging in body length from 7.5 to 17.4 m, had overall eye length as well as lens height and width measured (see [2] and table S2); we estimated pupil diameter as the average of lens height and width. Posterior nodal distance was not measured in this species, but we were able to estimate the ratio of this to overall eye length from a photograph in figure 6 of [2] which shows the cornea, lens, and retina; we used a ratio of 0.6 for (lens center to retina vs cornea surface to back of sclera), which is a bit more than the Southern right whale ratio (table S2). Although retinal data are not given in [2], Schweikert *et al.* [3] provide light and electron micrographs of bowhead rods, from which we estimated rod length to be 30 μm and diameter as 1.4 μm. Absorptance of the rod was computed from absorbance, which is length in μm x absorbance per μm (given in [5] for mammalian rods as 0.015 μm^{-1} at the wavelength of peak absorption, or λ_{max}). We used these numbers in our estimates of sensitivity for both species (tables S1 and S2).

Using these values in Eq. (2) of the main paper, we calculated the optical sensitivity for all selected samples from both species at 493 nm, the λ_{max} of the *E. glacialis* rod visual pigment [4]. We used estimated posterior nodal distance values and rod diameters for *f* and *d* in Eq. (2). The average sensitivity values for the southern right whale (table S1) and the bowhead whale (table S2) differed, with the bowhead being nearly 50% higher in sensitivity than the southern right (3.22×10^{-9} cm^2 sr vs. 2.21×10^{-9} cm^2 sr). This may reflect the Arctic habitat of the bowhead whale, which generally is more dimly lit than the temperate waters inhabited by southern right whales (especially in the winter). (If we used the southern right whale's (focal length)/(eye length) ratio for the bowhead eyes, bowhead sensitivities increased to nearly double the right whales'.) Southern rights were possibly less sensitive as adults (whales > 11 m in length) than as calves (table S1), probably because the F-number increased and the angular diameter of the rods decreased with eye size. (The F-number is the ratio of focal length to aperture, here taken as the PND/average pupil diameter. Sensitivity decreases as the F-number increases.) In bowheads, F-number changes were less important because pupil diameter tended to increase with eye length (table 2). As described in the main paper, we used the sensitivity value for *E. australis* as an estimate for *E. glacialis*, both as a conservative measure and because of the genetic relatedness of the two species.

(2) Attenuation spectra of suspended copepodites

Copepods were collected on May 18, 2013 in the Great South Channel and shipped in a chilled container to Baltimore, Maryland for measurements of attenuation of copepod concentrations. Live copepods (almost all 5th copepodites) were pipetted into 30 ml of water to required concentrations (1 to 10 copepods/ml) and measured in a cylindrical quartz spectrophotometer cell 10 cm in length for attenuation in a dual-beam spectrophotometer. From 10 to 28 measurements were made at each concentration and averaged for a final estimate of attenuation. Because copepods tended to drift to the bottom of the cuvette, they were resuspended by gentle shaking every few scans. Copepodites produced broad and generally flat attenuation spectra from ultraviolet to far red wavelengths. The shapes of these curves suggest that most of the light is lost by broad-spectrum scattering of light rather than absorption by particular pigments in the animals. Some individuals contained reddish carotenoid-containing oil droplets, which probably produced the slight rise in attenuation beyond 500 nm at the highest concentrations, but the overall contribution of these pigments to spectral attenuation was minor. Increasing concentration from 6 to 10 individuals per ml had little effect on attenuation, perhaps due to multiple-path scattering or because at the highest concentrations most copepods sank out of the spectrophotometer path rather quickly (figure S1).

Table S1. Body and eye measurements for the southern right whale, *Eubalaena australis* (L, length; W, width; H, height; D, diameter; *f*, focal length; *F*, F-number). ID number, body length, eye length, and cornea width and height are taken from (1). Pupil diameter is taken as 0.46 times the average of the cornea width and height (see text). Focal length is taken as 0.53 times the eye length (see text). *F* is taken as focal length divided by pupil diameter. Sensitivity is calculated as described in the text and indicates the value at the *Eubalaena glacialis* sensitivity maximum, 493 nm (the peak wavelength of absorption of the rod's visual pigment).

Eubalaena australis ID#	**Body L** (m)	**Eye L** (cm)	**Cornea W** (mm)	**Cornea H** (mm)	**Pupil D** (mm)	***f*** (mm)	***F***	**Sensitivity** (x 10^{-9} cm^2 * sr)
082210-PV-Ea 11	4.9	3.4	28	22	11.4	18.1	1.58	3.13
071210-PV-Ea 02	4.9	3.3	20	26	10.5	17.5	1.67	2.81
082810-PV-Ea 16	6	3.9	32	24	12.8	20.7	1.62	2.98
090210-PV-Ea 17	7.3	4.6	33	22	12.6	24.5	1.95	2.07
092706-PV-Ea 11	7.7	4.6	28	22	11.4	24.5	2.14	1.71
081209-PV-Ea 18	8	4.1	32	22	12.3	21.8	1.77	2.51
102710-PV-Ea 33	11.9	4.6	30	17	10.7	24.5	2.28	1.51
091410-PV-Ea 19	12.5	4.6	32	21	12.1	24.5	2.02	1.92
070910-PV-Ea 01	12.7	5	35	24	13.5	26.6	1.97	2.01
080310-PV-Ea 05	14.9	5.9	35	24	13.5	31.4	2.33	1.45
Mean	**9.08**	**4.4**	**30.5**	**22.4**	**12.07**	**23.4**	**1.94**	**2.21±0.19 s.e.**

Table S2. Body and eye measurements for the bowhead whale, *Balaena mysticetus* (L, length; W, width; H, height; D, diameter; *f*, focal length; *F*, F-number). ID number, body length, eye length, and lens width and height are taken from (2). Pupil diameter is taken as the average of the lens width and height. Focal length is taken as 0.6 times the eye length (see text). *F* is taken as focal length divided by pupil diameter. Sensitivity is calculated as described in the text and indicates the value at the *Eubalaena glacialis* sensitivity maximum, 493 nm (the peak wavelength of absorption of the rod's visual pigment).

Balaena mysticetus ID#	**Body L** (m)	**Eye L** (cm)	**Lens W** (mm)	**Lens H** (mm)	**Pupil D** (mm)	***f*** (mm)	***F***	**Sensitivity** ($\times 10^{-9}$ cm^2 * sr)
84B3	7.5	3.0	12	11	11.5	18.0	1.57	3.20
83H1	8.2	3.0	12	12	12	18.0	1.50	3.49
95B1	8.4	3.9	13	13	13	23.4	1.80	2.42
96B8	12.7	3.3	16	15	15.5	19.8	1.28	4.81
82KK1	16	3.8	16	16	16	22.8	1.43	3.86
95B9	17.4	4.7	13	12	12.5	28.2	2.26	1.54
Mean	**11.70**	**3.62**	**13.67**	**13.17**	**13.42**	**21.7**	**1.62**	**3.22±0.46 s.e.**

Supplementary Figures

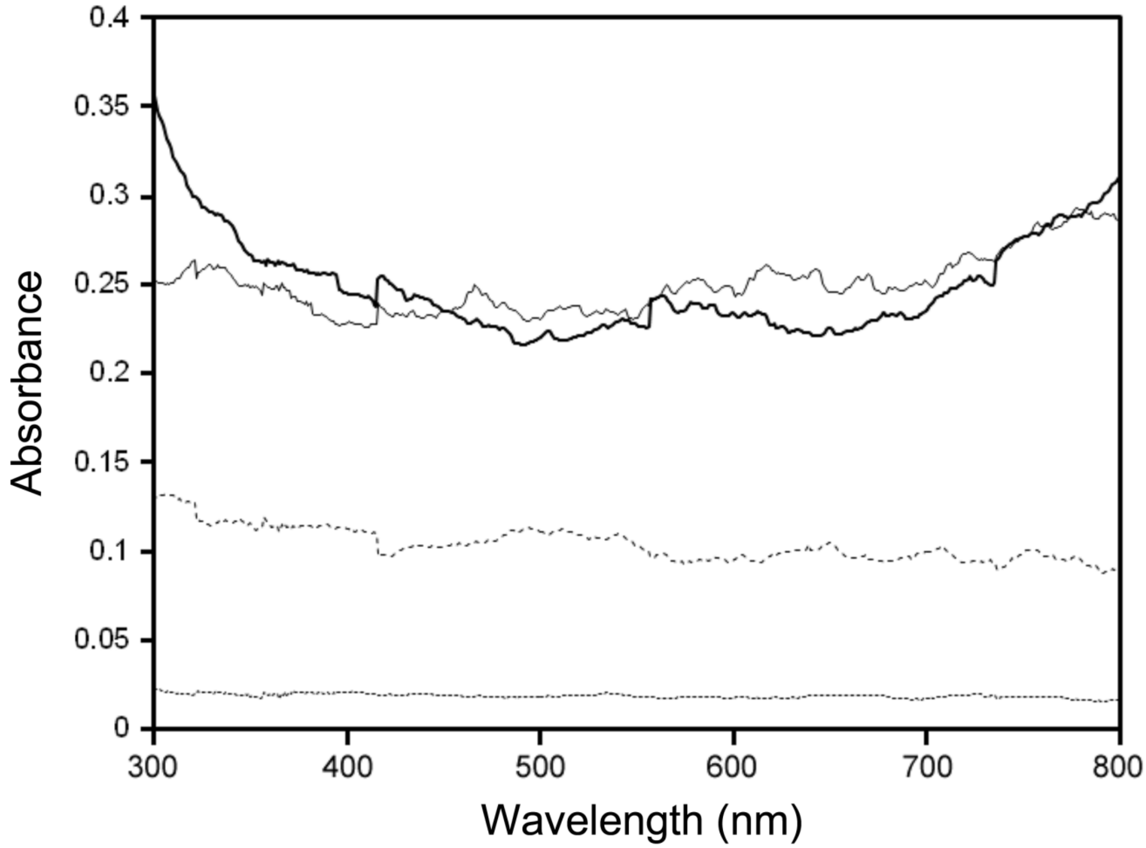

Figure S1. Attenuation spectra of living *Calanus finmarchicus* (5^{th} copepodite) at concentrations of 1 ml^{-1} (dotted line, average of 28 scans), 3 ml^{-1} (dashed line, average of 12 scans), 6 ml^{-1} (thin solid line, average of 10 scans), and 10 ml^{-1} (thick solid line, average of 10 scans). Data were obtained through a 10-cm path length in a quartz cuvette as described above. Original data are available from the first author.

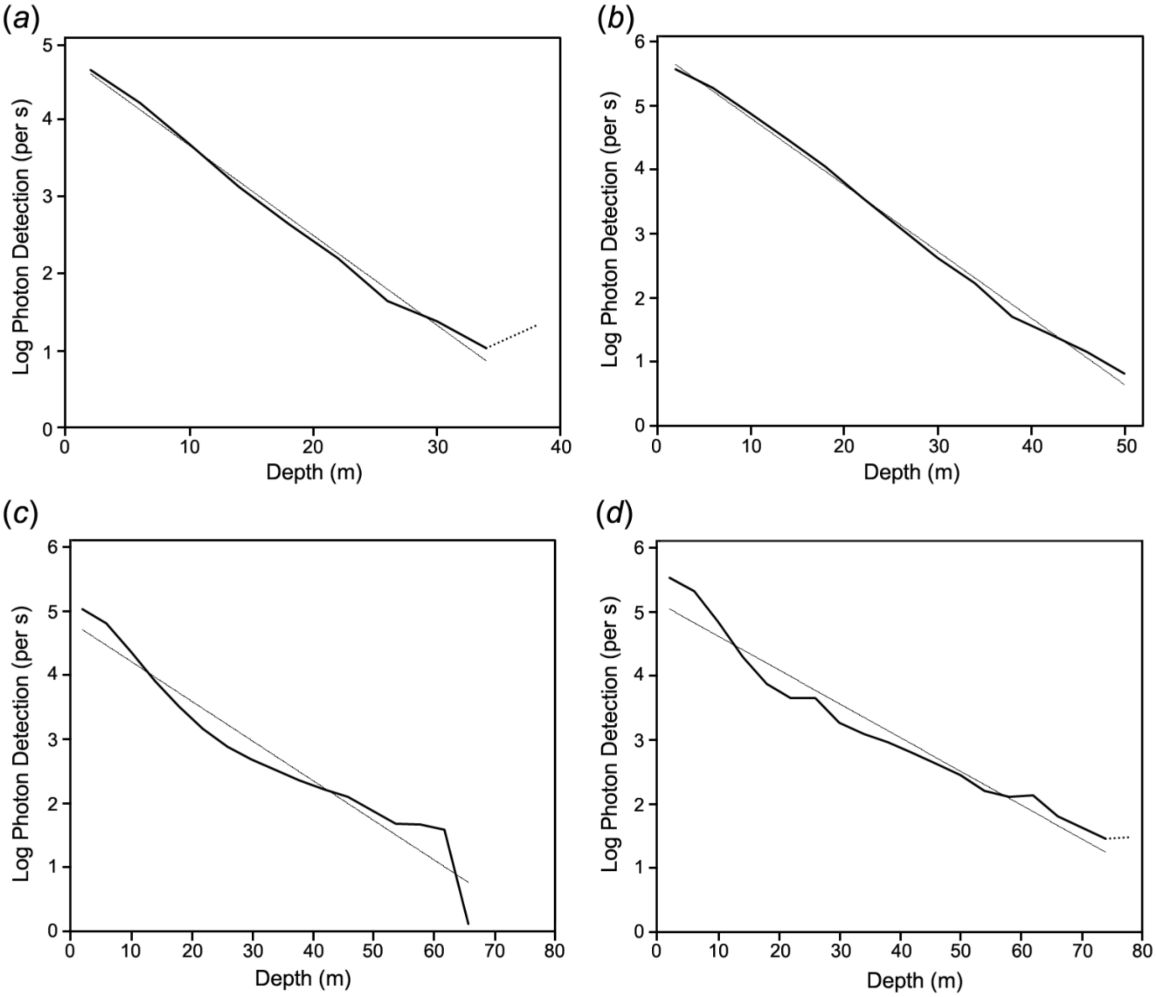

Figure S2. Log photon detection per rod photoreceptor per second vs. depth for eyes of *Eubalaena glacialis*, computed as described in the main paper (multiplying visual sensitivity by horizontal radiance, summed at 1-nm intervals from 400 to 700 nm) for the four data series collected in the vicinity of foraging whales. (*a*) Wilkinson Basin, April 4, 2012, near 13:00 EDT (total depth 209 m), (*b*) entrance to Cape Cod Bay, near 17:00 EDT (total depth 58 m), (*c*) Great South Channel, May 8, 2013, near 14:15 EDT (total depth 75-68 m), (*d*) Great South Channel, May 9, 2013, near 4:55 EDT (total depth 83 m). Computations based on raw data are plotted in thick lines and log-linear fits to the computed photo catches are plotted in thin lines (these were required to compute contrasts described in the main paper at depths below the deepest measurements). The dotted line segment in panel (*a*) was probably a measurement error and was not used in the log-linear fit. Equations of these fitted relationships: (*a*) $y = 144{,}000\, e^{-0.268x}$, (*b*) $y = 1{,}460{,}000\, e^{-0.241x}$, (*c*) $y = 137{,}000\, e^{-0.142x}$, (*d*) $y = 269{,}000\, e^{-0.121x}$. Original data are available from the first author.

Supplementary References

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