SUPPLEMENTARY INFORMATION FOR

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Quantifying biologically essential aspects of environmental light

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Camera hardware and optics

Any digital RGB camera providing RAW-files, fitted with a 180° fisheye lens can be used for ELF measurements given that appropriate radiometric and angular calibrations are performed. We used a Nikon D810 SLR camera body fitted with a Sigma 8 mm f/3.5 EX DG circular fisheye lens. The Nikon/Sigma combination display very small variation between individual camera bodies and lenses, allowing common calibration factors, included with the provided software, to be used without any need to calibrate each individual camera/lens combination. If other digital cameras are used, we suggest RGB cameras with spectral sensitivity curves that display maximum coverage of 400-500 nm for blue, 500-600 nm for green and 600-700 for red pixels, and with minimum overlap between the spectral channels.

Fish-eye lenses are designed to produce different image projections. Any kind of projection would in principle be acceptable. For most of our development we used a Sigma 8 mm f/3.5 EX DG for Nikon. This lens has an equisolid projection (radial image position, $R = 2f \cdot \sin(\theta/2)$, where f is the focal length and θ is the angle to the optical axis). The remapping function in the provided Matlab routines assumes this projection.

Sensitivity and dynamic range

The image sensor size or pixel number is of little consequence for the measurements. The 36 Megapixels (MP) of the Nikon D810 are far more than needed. We have also successfully made measurements with a 1 MP image sensor. For measurements at low light levels, a camera with a large image sensor with low noise is preferred. The Nikon D810/Sigma 8mm combination is sensitive enough to allow measurements at starlight intensities. To avoid artefactual contrasts caused by noise it is advisable not to use very high ISO-settings. For the Nikon D810 we used an upper ISO limit of 1600. For measurements at starlight intensities, this called for exposure times of 8 min. For daylight and indoor lighting, the exposure time could always be kept short enough to allow a handheld camera. It is essential that the camera can store images in a raw format without any image pre-processing or file compression. Noise suppression or noise subtraction may be acceptable or even advisable, but the consequences must be evaluated for each camera model. Tested and recommended settings for Nikon D810 are given last in this Supplementary Information.

At daylight intensities the automatic exposure function of the camera will generate suitably exposed bracketing series, but at late dusk, early dawn, night or other dimly lit conditions, manual exposure based on trial and error is necessary. In dim light levels, when exposure times exceed one second, we recommend taking dark images (e.g. with the lens cap on) to allow compensation for thermal noise on the image sensor. Our software provides an automatic way to integrate these dark measurements.

General calibration procedures and equipment

All calibration measurements were performed in a dark, temperature-controlled room at 20° C. Photographs were taken with a Nikon D810 with a Sigma 8mm fisheye lens attached. The camera was set to Manual mode, and all other settings were left at our default values (see last section of this document) except where otherwise specified below. Stimuli were generated by four Xenon-arc lamps connected to a 30.5 cm diameter integrating sphere (ISV410-UV, Electro Optical Industries, USA), which provided a bright, broadband, white light stimulus of even radiance across its 10 cm aperture. The intensity of this light source is controlled in closed circuit using feedback from a manufacturer-calibrated light sensor inside the integrating sphere. For the spectral calibration, monochromatic light stimuli were created using a TILL Polychrome V monochromator (TILL Photonics GmbH, Germany) with a 150 W Xenon high-stability lamp. The light was guided through a fibre-optic cable into the integrating sphere. To accurately measure the intensity and spectrum of the calibration light sources, we made use of three calibrated spectroradiometers: a RAMSES (TriOS Mess- und Datentechnik GmbH, Germany), a GS-1290 (Gamma Scientific, San Diego, USA) and a PR-680L (Photoresearch, JADAK, New York, USA). These devices have different strengths in terms of spectral range and resolution, acceptance angle and speed of operation, and the combination of all three allowed us to optimally measure our stimulus in all situations.

For each calibration measurement, we aimed to cover the full range of potentially relevant settings. Wherever possible, the order of conditions was balanced or randomised to prevent time- or temperature-dependent and hysteresis-like effects from going undetected. Photographs were imported into Matlab following the procedures laid out in Sumner (2014). The integrating sphere's aperture was detected in the raw image using a simple thresholding algorithm, and its centre determined as the median x- and y-position of all included pixels. Stimulus brightness was then determined for each of the 763 photographs as the mean over a 2-degree radius around this centre point. For measurements where the camera was stationary throughout the measurements, the aperture's position was detected once, in a single image where it was easily visible. For vignetting measurements, where the camera was rotated during each step, the aperture was detected once for each camera position. In all cases, the results of the automatic detection were manually checked for each image set.

Dark signal

In any real camera system, the current through a sensor pixel depends on other factors than light, such as temperature, leading to a noisy signal that only imperfectly represents the radiance of the absorbed light. One important part of this noise is the raw signal that can be measured in the absence of light. Its mean (the *dark signal*) raises the dark level of the image, and can be seen as a reduction in contrast, or fog-like effect in noisy images. Its standard deviation (which we here call the *dark noise*) randomly increases or decreases the value of each pixel, and leads to a speckled noise pattern on the resulting images. We measured the dependence of this dark signal and noise on exposure time and on ISO-speed.

Measurements

To measure the magnitude of the dark signal in the Nikon D810, we took repeated measurements across exposure and ISO values in a completely dark, windowless room, with a lens cap covering the lens mounted on the Nikon D810. We measured across exposure times at low (ISO-100) and high (ISO-6400) gain, and across ISO settings (ISO speeds) at short (1/1000 s) and long (4 s) exposure time. At each setting, 20 images were taken in quick succession (**Table S1**). The internal noise reduction mechanisms ("High ISO NR" and "Long Exposure NR") of the D810 were turned off during these experiments.

Table S1: Dark signal calibration protocol

	apt	ISO	exp (s)	# files
1	f/3.5	100	1/8000, 1/1000, 1/125, 1/15, 1/2, 4, 30, 120, 30, 4, 1/2, 1/15, 1/125, 1/1000, 1/8000	15*20
2	f/3.5	6400	1/8000, 1/1000, 1/125, 1/15, 1/2, 4, 30, 120	8*20
3	f/3.5	6400	4, 2, 1, 1/2, 1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000, 1/2000, 1/4000, 1/8000, 1/6000, 1/3000, 1/1500, 1/750, 1/350, 1/180, 1/90, 1/45, 1/20, 1/10, 1/6, 1/3, 2/3, 1.5, 3, 4	32*20
4	f/3.5	100, 800, 6400, 12800, 3200, 400, 64, 200, 1600, 12800, 100	4	11*20
5	f/3.5	31, 64, 100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600, 51200, 18102, 9000, 4500, 2200, 1100, 560, 280, 140, 72, 45, 100	1/1000	23*20

Analysis

After importing the raw images into Matlab, we calculated the mean (**Fig. S1**) and standard deviation (**Fig. S2**) of all raw pixel values for each image.

We found the *dark signal*, which in a noise-free environment would be set to 600 counts according to the Nikon raw format, to increase only moderately with exposure time at the two ISO values measured (**Fig. S1a,c**). Even at ISO-6400 and 4 seconds exposure time, it is only about 6 counts above the expected 600. Interestingly, we observed a drop-off in dark signal at exposure times greater than 4 seconds, indicating that even with noise reduction mechanisms deactivated, the camera performs some noise reduction algorithms. At higher ISO values than 6400, the signal rapidly increases to a measured maximum of about 80 counts at ISO-51200 (**Fig. S1b**). To be able to correct for this increase in dark signal, we fitted a robust linear model (including ISO value, exposure time, and their product) to the combined data, separately for each channel. We excluded data at exposure times greater than 4 seconds, and ISO values above 6400, as we advise against using these without internal (using the camera NR) or external (using additional software) dark measurements.

For the *dark noise*, we observed a similar picture. The dependence on exposure time was low, at least for exposure times below 4 seconds (**Fig. S2a,c**), while increasing ISO values had a much stronger effect (**Fig. S2b,d**). Again, we found evidence of nose reduction algorithms that reduced the dark noise at ISO-6400, this time for all exposure values above ¼ s.

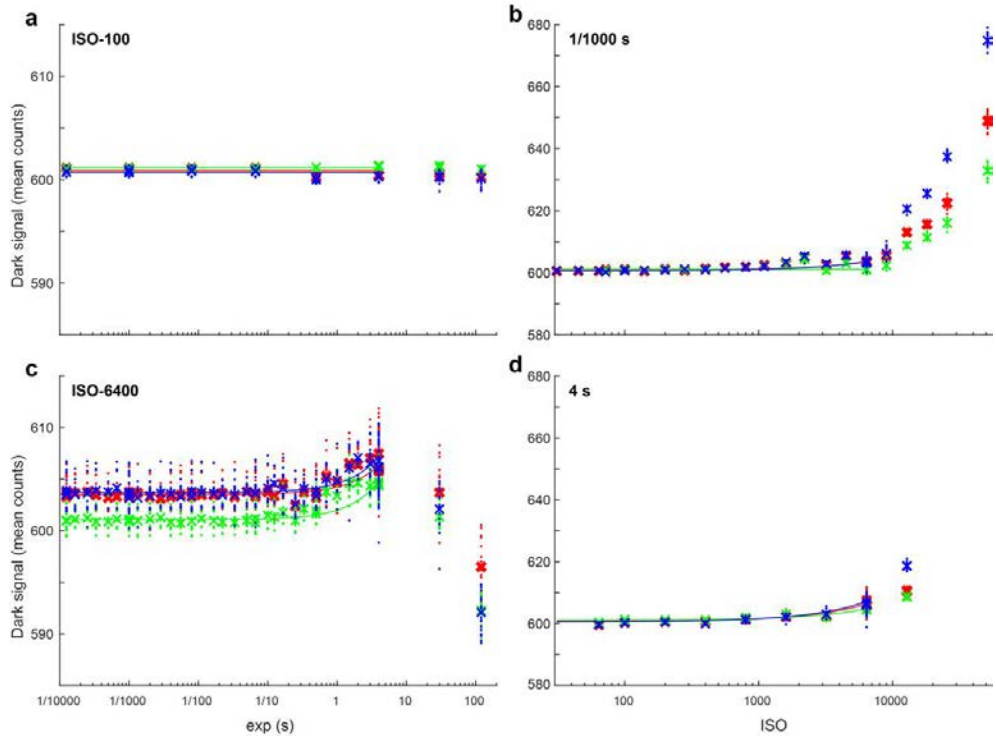

Figure S1: Increase in the Nikon D810's dark signal with exposure time at ISO-100 **(a)** and ISO-6400 **(c)**, and with ISO value at 1/1000 s **(b)** and 4 s exposure time **(d)**. Symbols and colours as in Fig. S1, with lines indicating the predictions of our final noise model. Note that while exposure is below 1 second and ISO below 6400 (the maximum values we suggest using without taking dark images), the dark signal is never more than 10 counts higher than the 600, the manufacturer-set dark level.

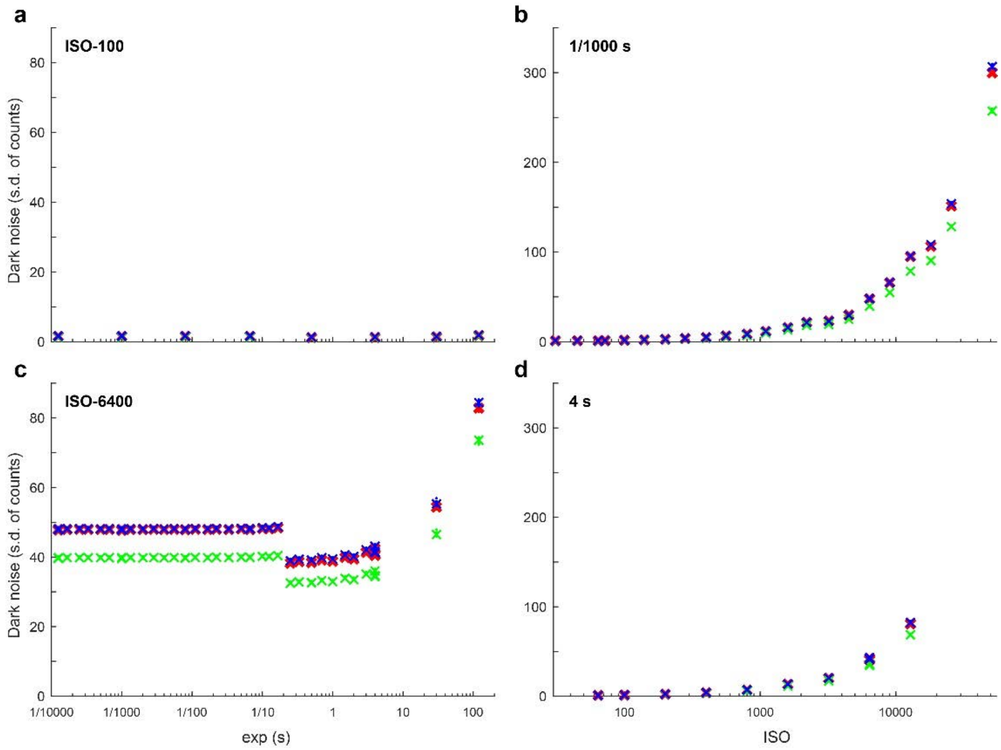

Figure S2: Increase in the Nikon D810's dark noise with exposure time at ISO-100 **(a)** and ISO-6400 **(c)**, and with ISO value at 1/1000 s **(b)** and 4 s exposure time **(d)**, in the red, green and blue channels (colour-coded dots and lines). Dots indicate the mean of a single image, crosses are the mean of a single test condition (averaged over 20 images).

Linearity

Measurements

We tested the range over which the D810's image sensor reacts linearly to the incoming radiance by recording the response to light from the integrating sphere at 13 different brightness levels between 3.4 and 34000 cd/m^2 (**Table S2**). 40 photographs were recorded at each stimulus brightness, and the mean raw pixel value inside the aperture determined as usual. Dark levels were subtracted according to our noise model.

Table S2: Camera chip linearity test protocol

apt	ISO	exp (s)	luminance (ft-lambert = 3.426 cd/m^2)	# files
f/3.5	100	1/8000	10000, 1, 2, 10, 46, 215, 1000, 4642, 2154, 464, 100, 22, 5, 1, 10000	15*40

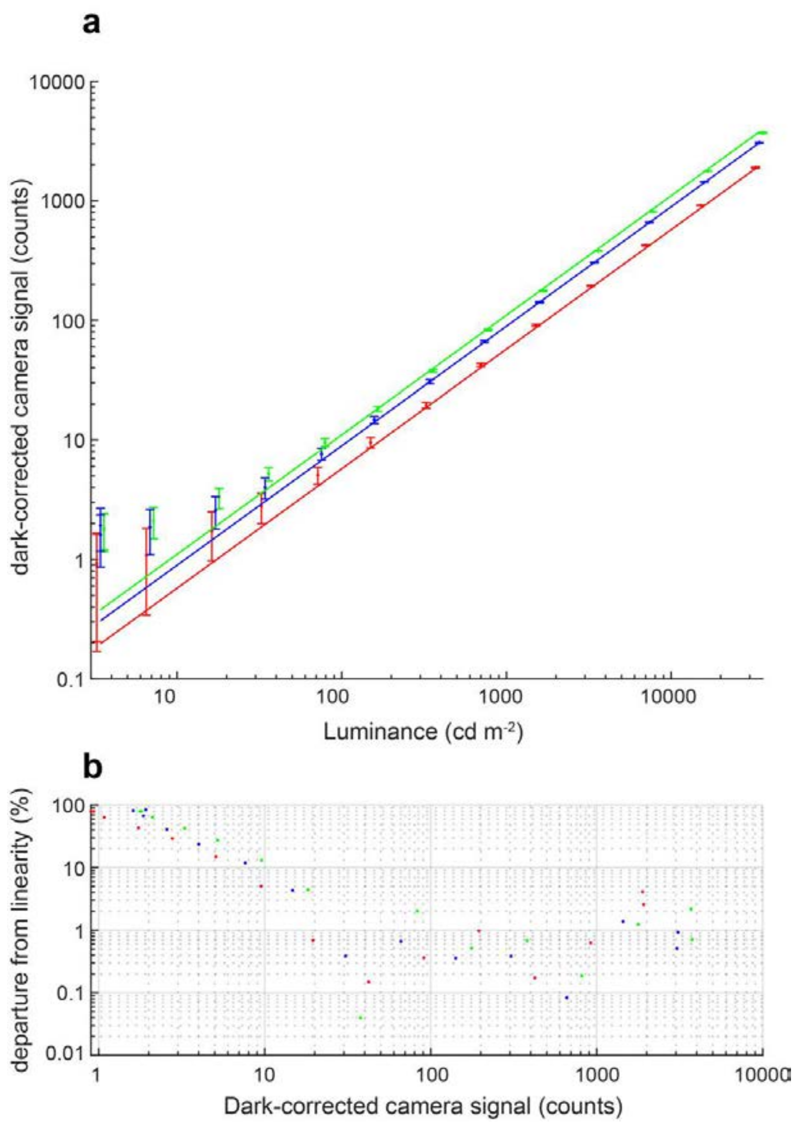

Figure S3: Linearity of the D810's chip. Camera signals were measured in response to 13 different light levels of the integrating sphere lamp **(a)**. Dots and error bars show mean and standard deviation across the 40 images taken at each level (colour-coded for the red, green and blue channels). Red and green channel data were shifted by 5% to the left and right, respectively, for clarity. Solid lines show a robust linear fit (no constant term) for each channel. Errors relative to the linear prediction drop below 5% at 10 counts **(b).**

Analysis

The resulting relationship between luminance and camera raw count was fitted with a robust linear fit, allowing only for a slope coefficient, but no constant term (**Fig. S3a**). Plotting the fit residuals over the raw camera count shows that above as little as 10 counts, the signal rarely strays more than 1%, and never more than 5%, from linearity. Taking this into account, and leaving some extra safety margin for an uncertainty in the determination of the dark signal, we set a minimum threshold of 50 counts for all following calibrations. Signals below this level were considered too noisy to contribute to the calibration.

In a series of separate measurements, we determined the maximum raw count that linearly follows the intensity signal, before camera pixels should be considered to go into saturation. A recommendation for this level can be read from a DNG file's EXIF information, presumably stored there by Adobe during image conversion. For the Nikon D810, this level is at 15220 counts. Since in our measurements, we never found saturation values below 16381 counts, we decided to adopt Adobe's more conservative value for all our calibrations, and for HDR image generation.

Camera parameter calibration

Camera serial number: 6037507

In a perfect camera system, we would expect the number of raw image counts to be linearly proportional to exposure time, ISO setting (representing the gain of the system), and the reciprocal square of the aperture value (representing the area of the entrance pupil). To test whether this was the case for the Nikon D810, we took photographs of the test stimulus across the full range of ISO-settings and aperture-values, and with exposure times up to 1 second.

Measurements

We took photographs with a Nikon D810 set up on a tripod at approximately 2 meters distance from the integrating sphere. Over the course of the experiment, we regularly measured the absolute spectral radiance of the stimulus with the GS-1290 spectroradiometer, and found it (integrated from 300 nm to 800 nm) to have varied by less than 1% within individual measurement blocks, and less than 5% over the total 2-hour period of our measurements.

The design of the 19 measurement blocks can be found in **Table S3**. Within each block, we kept two parameters constant, while sweeping across the full range of the third parameter, as far as over- and underexposure limits allowed.

Table S3: Camera parameter calibration protocol

	ISO	apt	exp (s)	# files
1	100	f/3.5	**1/8000 to 1**	40
2	100	**f/3.5 to f/22**	1/8000	17
3	100	f/8	**1/8000 to 1**	40
4	100	f/22	**1/8000 to 1**	40
5	100	**f/22 to f/3.5**	1/100	17
6	100	**f/3.5 to f/22**	1/400	17
7	100	**f/3.5 to f/22**	1/1600	17
8	**100 to 51200**	f/3.5	1/8000	26
9	400	f/3.5	**1/8000 to 1/100**	20
10	400	f/8	**1/8000 to 1/10**	30
11	400	f/22	**1/8000 to 1**	40
12	1600	f/3.5	1/8000	1
13	1600	f/8	**1/8000 to 1/10**	30
14	1600	f/22	**1/8000 to 1**	40
15	6400	f/8	1/8000	1
16	6400	f/22	**1/8000 to 1/100**	20
17	**100 to 51200**	f/22	1/8000	26
18	**51200 to 100**	f/22	1/800	26
19	**100 to 51200**	f/22	1/80	26

Analysis

For each raw image, we obtained a mean signal for a 4° diameter circle as described above. We discarded any measurement that indicated an overexposed (>15220 counts) or underexposed (<50 counts after dark correction) signal. For each of the three camera parameters, we then plotted the raw camera signal as a function of that parameter, taking into account only measurement blocks where that parameter was altered. For example, to analyse the dependency on exposure time, we included blocks 1, 3, 4, 9, 10, 11, 13, 14 and 16. To cancel out the effect of the aperture and ISO changes between blocks, as well as the small effect of changing light source intensity, we allowed a correction factor for each curve, to align its mean with that of all other exposure curves. We also allowed for a single factor to correct for the sensitivity difference between colour channels. The resulting data was fitted with a robust linear regression model, allowing only for a slope to be fitted, but not a constant term (**Figure S3a**).

For **exposure** (Fig. S4a) and **ISO speed** (**Fig. S4c**), we found a near-perfect linear relationship (residual error (RMSE) of 3.36e-5 and 21.1, respectively), with nearly all measurements lying within 10% and 5% of the value predicted by the model (**Fig. S4b, d**). For **aperture** (**Fig. S4e, f**), we found the relationship to be almost equally well predicted (RMSE: 1.67e-2) once we raised aperture to the power of 2.292 rather than 2 as would have been expected. This effect, resulting in an unexpectedly large entrance aperture at low f-numbers, is likely due to the fact that we only include pixels at the very centre of the camera image in our measurements. The f-numbers, on the other hand, are balanced taking into account exposure across the whole image. Since the effect of vignetting (darkening of the image at the edges) is more pronounced at low f-numbers, these two effects likely balance each other out well enough for the purposes of consumer photography.

Finally, we compared how well our full model of exposure, aperture and ISO speed would predict measurements across the whole experiment (**Fig. S5**), without allowing any correction factors between experimental blocks other than those predicted by the camera parameters. Overall, these findings suggest that we can predict the radiance of a 4° light spot to an accuracy of at least 10%.

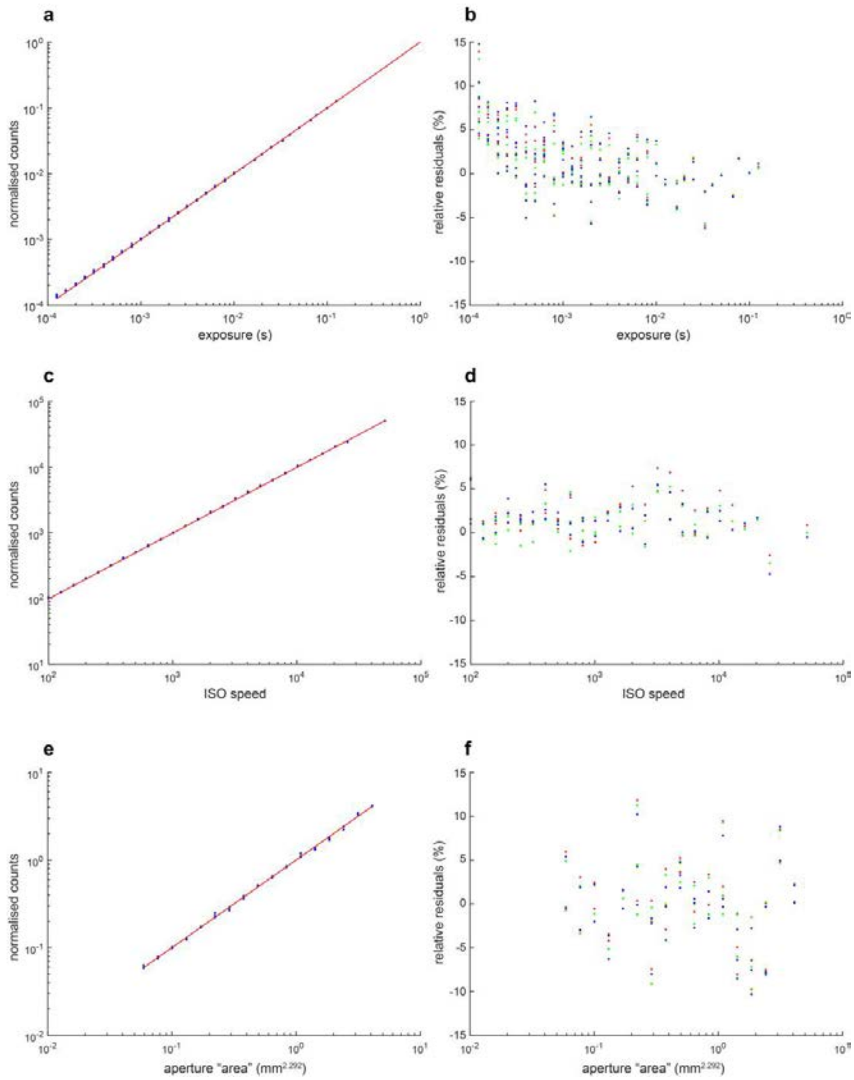

Figure S4: Camera parameter model for exposure time (a, b), ISO speed (c, d) and aperture values (e, f). Blue dots in model panels **(a, c, e)** reflect mean pixel values of one image, whereas red lines reflect a robust linear model. For aperture values, counts are plotted against inverse f-numbers to the power of 2.292, which was found to most accurately predict the camera signal. Residuals **(b, d, f)** are generally within 5% of the predicted value.

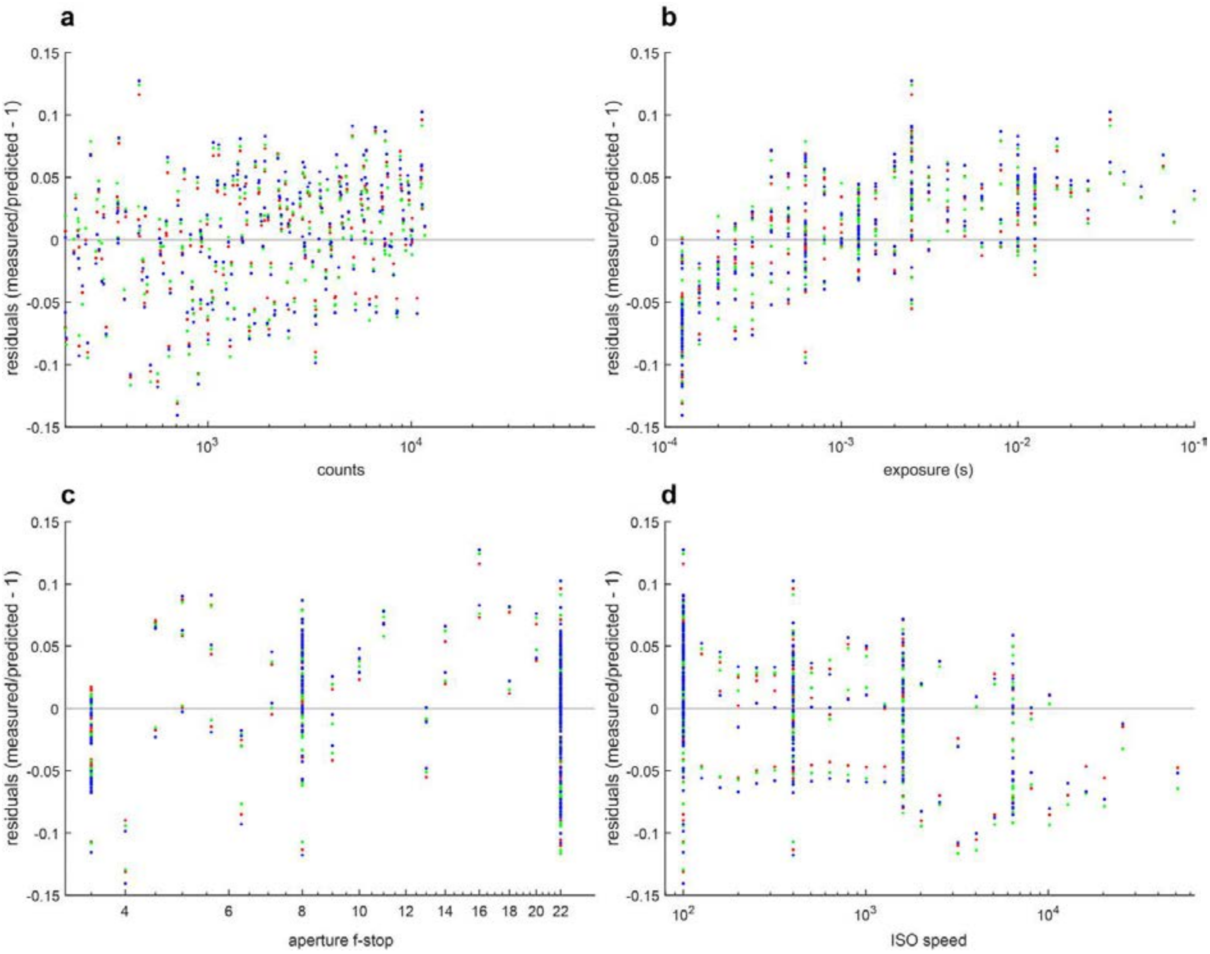

Figure S5: Overall camera calibration residuals. Residuals here are those of all measurements taken in this test versus the final model, allowing for no other correction factors between experiments. All residuals are shown in each panel but plotted against different factors. As in Fig. S4, the majority of residuals were within a 10% error band.

Camera unit repeatability

Camera serial number: 6037507

Some of the remaining variance in our calibration can likely be traced back to technical limitations in the camera, which necessarily limit the accuracy with which camera parameters are set. Especially the mechanical action of the lens aperture cannot be expected to always reliably create the exact same opening. Similarly, we might expect higher variability when consecutive images are taken at high speed in continuous release mode. To test whether we can minimise this unreliability by selecting or avoiding certain parameter settings, we took repeated images of our stabilised light source at different aperture and release mode settings.

Measurements

Our first set of measurements (**Table S4**) was designed to compare inter-exposure variability with a small (f/22), medium (f/8) and fully open (f/3.5) aperture, and its dependence on the degree to which the aperture was changed or reset in between two images. We took 20 identical images at each setting. In this test, we waited for 5 seconds in between each two photographs in order to minimise the effect of vibrations and temperature build-up, but we also included one test condition where we shot the 20 images in high-speed continuous mode, in which the camera takes images at 5 frames per second as long as the shutter-release button is held down.

In a second set of tests (**Table S5**), we specifically compared different shooting speeds (high-speed continuous mode CH, low-speed continuous mode CL, manual exposures every 1 second, manual exposures every 5 seconds), again at the same three aperture settings. To test whether the effects of vignetting (aperture-dependent darkening of the peripheral image; see Vignetting section below) would increase the variability at intermediate apertures, we added a condition where the camera was rotated so that the light stimulus was in the periphery, at 80° from the centre of the image.

Table S4: Exposure repeatability tests with different aperture settings

	ISO	apt	exp (s)	condition	# files
1	100	f/8	1/1250	Took 1 image at f/3.5 before this set	20
2	100	f/8	1/1250	Took 1 image at f/22 before this set	20
3	100	f/8	1/1250	Changed aperture to f/3.5 in between every two images	20
4	100	f/8	1/1250	Changed aperture to f/22 in between every two images	20
5	100	f/8	1/1250	Took 1 image at f/3.5 in between every two images	20
6	100	f/8	1/1250	Took 1 image at f/22 in between every two images	20
7	100	f/8	1/1250	Switched the camera off and back on between every two images	20
8	100	f/8	1/1250	Repeat of 1	20
9	100	f/8	1/1250	20 images as fast as possible in high-speed continuous (C_H) mode	20
10-18	100	f/22	1/125	Equivalent to 1-9, but at f/22	20 each
19-27	100	f/3.5	1/6400	Equivalent to 1-9, but at f/3.5	20 each

Table S5: Exposure repeatability tests at different release mode settings

	ISO	apt	exp (s)	condition	# files
1	100	f/22	1/125	20 images in high-speed continuous (C_H) mode	40
2	100	f/22	1/125	20 images in low-speed continuous (C_L) mode	40
3	100	f/22	1/125	Wait 1 second between images	40
4	100	f/22	1/125	Wait 5 seconds between images	39
5-8	100	f/8	1/1250	Equivalent to 1-4, but at f/8	40 each
9-12	100	f/8	1/1250	Equivalent to 5-8, but with the camera turned to place the light stimulus at 80° eccentricity	40 each
13-16	100	f/3.5	1/6000	Equivalent to 1-4, but at f/3.5	40 each

Analysis

The mean raw count inside the stimulus image was extracted as usual. For each condition, we then calculated the deviation of each image's value from the mean of all repetitions of that condition, and compared the distribution of these values across conditions (**Fig. S6**). We found that the uncertainty is lowest at a fully open aperture (**Fig. S6a**, f/3.5). Whether we left the aperture unchanged, changed it between images, took intermittent images at another aperture or even switched the camera off between images had no influence on the variability. Taking images at 5 frames per second in C_H mode, on the other hand, moderately but significantly increased the variability of our radiance estimate. In the second test series (**Fig. S6b**), we found smaller differences between apertures, and no significant difference between different shooting speeds. However, we found that the effect of higher variability at f/8 is heightened in the peripheral image, likely because a small accidental decrease in aperture opening does not only reduce the amount of light entering the camera in total, but also changes the vignetting profile of the lens.

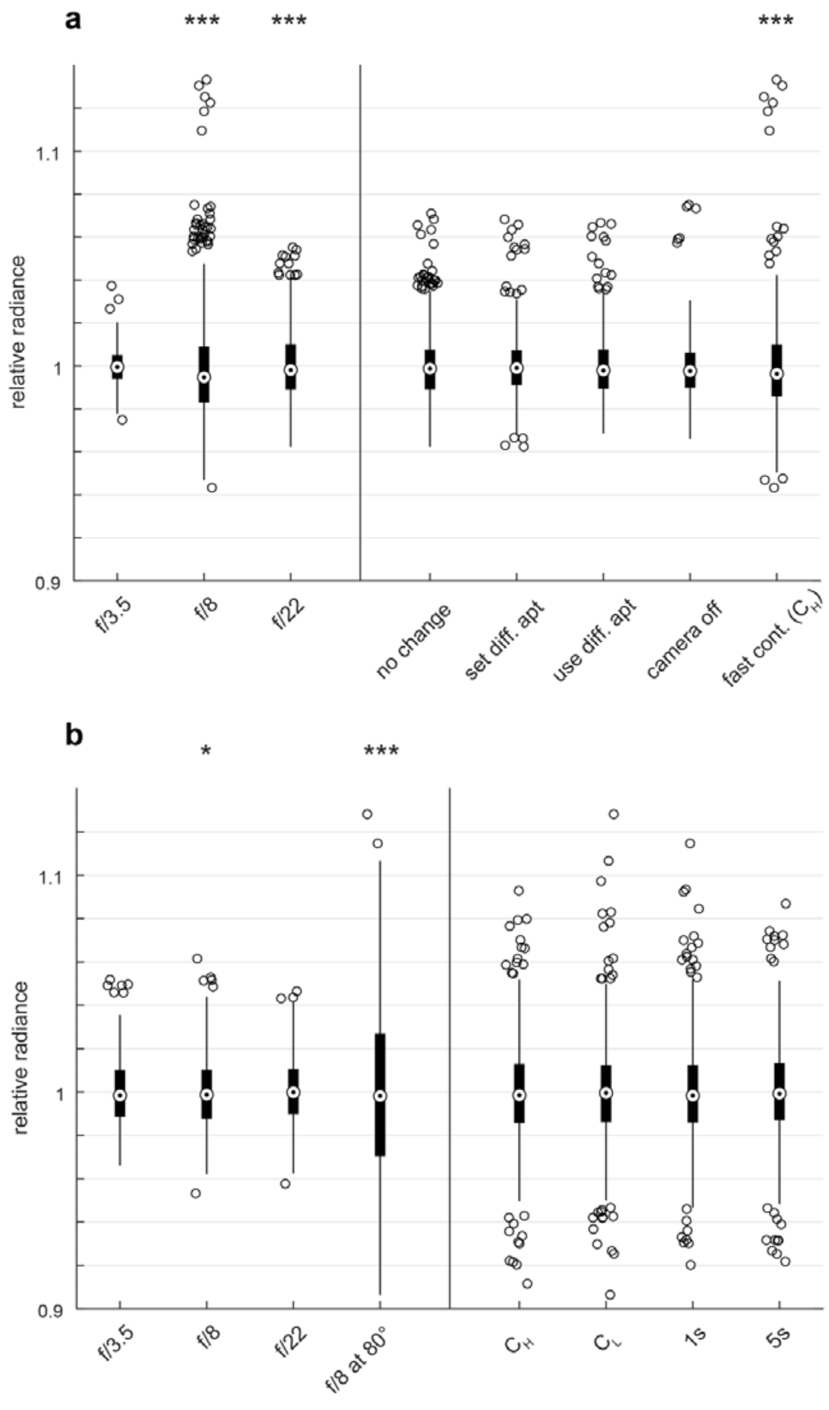

Figure S6: Exposure repeatability with different aperture (a) and burst mode (b) settings. Exposure variability is significantly higher with partially closed apertures (f/8 and f/22) than with a fully open aperture (f/3.5). We found no difference in variability depending on whether the aperture was changed or the camera was switched off in between two images or not, but in an initial test found that taking images quickly in high-speed burst mode (C_H, panel a) was disadvantageous. In a second test **(b)** designed to detect a difference between burst mode settings, we found no difference between CH and CL burst mode, or manual exposures with 1s or 5s breaks between images. We confirmed that a partially open aperture (f/8) creates higher variability than a fully open one, and further confirmed that this effect is exaggerated in the peripheral image (f/8 at 80° eccentricity). All statistical tests are two-sample F-tests comparing a condition to the left-most condition in that block (* $p<0.05$, *** $p<0.001$).

Overall, it should be noted that the variability we found associated with repeated measurements was small. In almost all conditions (except at 80° eccentricity), 50% of the variability data lay within ±2% of the mean, and virtually all data was within ±10% of the mean. While we cannot rule out larger effects over longer periods, for example due to temperature or wear of the camera, this variability should usually be insignificant for normal ELF analysis.

Spectral calibration

Camera serial number: 6037507

To determine the absolute spectral sensitivity of the Nikon D810's CMOS sensor, we took a series of photographs of monochromatic stimuli between 320 nm and 700 nm wavelength, while at the same time monitoring the absolute spectral photon radiance of the stimulus with a calibrated spectroradiometer.

Measurements

For this measurement, light from the monochromator was guided into the integrating sphere to create a 10 cm, monochromatic stimulus at the sphere's aperture. The monochromator's entrance slit was set to produce a spectral half-width (full width at half maximum) of 5 nm. We first measured the spectrum of the calibration stimuli with the RAMSES spectroradiometer placed at the integrating sphere's aperture. The RAMSES measures over a range from 280 nm to 950 nm, which allowed us to fully characterise the light output at each target wavelength (**Fig. S7a**). The sequence of wavelength measurements was the same as in the following measurements with the D810 (see below).

After characterising the light output, we took photographs of our monochromatic stimuli with the D810 set up on a tripod at approximately 2 meters distance from the integrating sphere. To control for changes in the monochromator lamp's intensity over the experiment, we measured the spectrum of each stimulus also with the PR-680L spectroradiometer mounted on a second tripod beside the D810. The 1° acceptance angle of the PR-680L allowed us to measure the centre of our stimulus at the exact same time and from the same vantage point as the D810, although at a limited spectral range of 420 nm to 680 nm. Measurements with the PR-680L were performed in parallel to the RAMSES measurements, as well as in parallel to the D810 measurements.

In a first sweep across the wavelength spectrum, we set the camera to a fully open aperture (f/3.5) and low ISO setting (ISO-100). At each wavelength, we then took seven consecutive images at exposure times of 1/100, 1/50, 1/25, 1/13, 1/6, 1/3 and 0.67 seconds, which ensured that at each wavelength above 400 nm, we had acquired several photographs that were not under- or overexposed. We scanned the wavelengths in an order designed to minimise the effect of changes in lamp or camera over time, by first scanning up and down the spectrum at coarse resolution, and then repeating this at a finer resolution until we had achieved an overall resolution of at least 5 nm (**Table S5**).

Table S6: Camera settings and wavelength order during spectral calibration

	Aperture	ISO	Exposure	Wavelength order
Sweep 1	f/3.5	100	1/100, 1/50, 1/25, 1/13, 1/6, 1/3, 0.62	300:50:650 694 675:-50:325 350:20:690 694 680:-20:360 350 355:20:675 694 685:-20:355 350
Sweep 2		10000		350:10:410 405:-10:305 300

To capture the range between 350 nm and 400 nm, we performed a second sweep in this wavelength range with the same settings as before, but at ISO-10000.

Analysis

Camera raw images were downloaded and converted as usual and corrected to exposure time and ISO setting as per our camera parameter calibration.

To account for the effect of stray light from other light sources in the room (status LEDs, computer screens and light from the monochromator's Xenon lamp escaping through the cooling vents, photos were dark-corrected using images that were taken with the monochromator's lamp running, but its fibre disconnected from the integrating sphere. We also checked this against images taken with the monochromators set to 300 nm (where its Xenon lamp provides no light), and images taken with the aperture closed by a plastic lid.

To guard against the effects of saturation and excessive noise, we removed from the analysis any images where the raw signal was greater than 15520 counts or lower than 50 counts after dark correction.

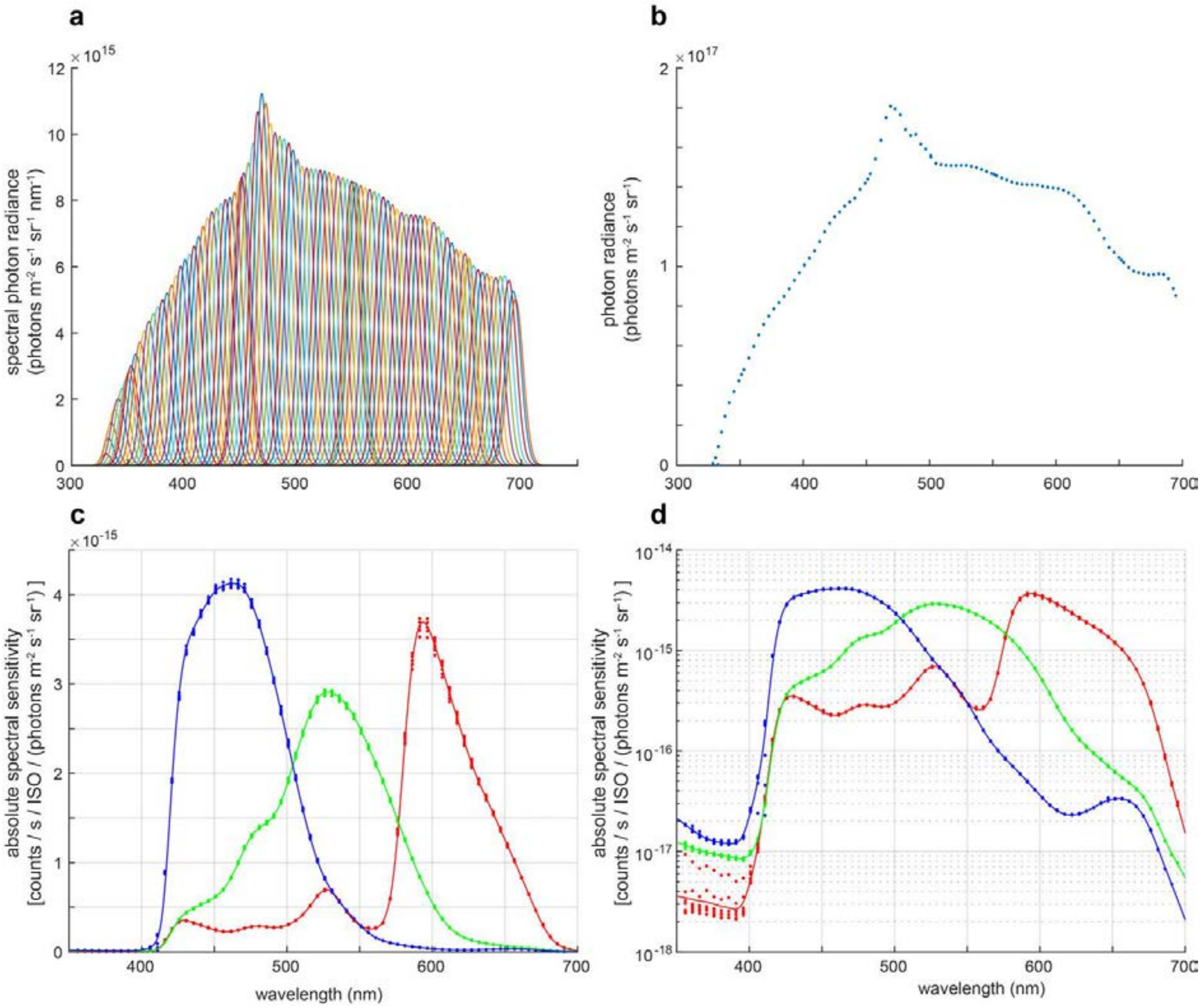

Figure S7: Spectral sensitivity of the Nikon D810 with a Sigma 8 mm fisheye lens. (a) Spectrum overlay of all individual monochromatic stimuli. **(b)** Total photon radiance of monochromatic stimuli at each wavelength. Dividing the camera's response signal by this radiance results in each channel's spectral sensitivity curve **(c)**: linear y-axis, **(d)**: logarithmic y-axis). Dots represent repeated measurements, which were then fitted with a smoothing spline (solid line). Colours in **(c)** and **(d)** indicate red, green and blue colour channels.

The absolute photon radiance of each stimulus was determined by fitting the RAMSES-measured spectrum with a Gaussian function and integrating over wavelengths. This absolute intensity was then corrected slightly (less than 6%) using the PR-680L measurements (**Fig. S6b**). We also recorded the central wavelength of this Gaussian fit and used it, rather than the wavelength set on the monochromator, for any further analysis, even though it never differed by more than 2 nm in the relevant wavelength range. By dividing the camera signal (in counts/s/ISO) in each colour channel by the absolute photon radiance (in photons/s/sr/m^2) delivered by the stimulus at that wavelength, we then obtained the camera's absolute spectral sensitivity (**Fig. S6c, d**).

We considered two strategies for applying this information to the raw camera signal:

A) Simple method: Each channel's raw signal is individually divided by the integrated sensitivity of that channel. The resulting number then indicates the number of photons (per s, per sr, per m^2) absorbed across the whole sensitivity function of that channel.
B) Deconvolution method: By comparing the signal in all three channels, it is easily possible to construct a hypothetical spectrum, with constant radiance across three bins (400-500 nm, 500-600 nm, 600-700 nm) that would result in the observed camera signal.

While the second method results in more easily interpretable numbers, it has a major drawback: Flawed data, due to noise or saturation, "spreads" across channels. For example, if the blue channel is at or near saturation (which, despite all precaution, occasionally happens), this will naturally result in an incorrect value in the blue channel for both methods; for method B, however, it will lead to an incorrect value in *all* channels. We therefore decided to apply method A as a standard in ELF processing.

Vignetting calibration

Camera serial number: 6037507

Due to mechanical and optical limitations in lens design, and the angular dependence of camera chip pixels, the brightness of a raw camera image generally decreases towards the image periphery. This *vignetting* effect depends strongly on lens aperture.

To measure vignetting in the Nikon D810 / Sigma-fisheye combination, we took images at our three standard apertures at a variety of angles. The camera was mounted at approximately 2 meters distance to the integrating sphere, on a panoramic tripod head (Nodal Ninja Ultimate M2, Fanotec, USA), which allowed us to rotate the camera precisely around all three rotational axes. We then took repeated images at a number of angles covering the whole horizontal, and part of the vertical, field of view of the camera (see **Table S7** for details).

As we were expecting successively larger spread at higher f-numbers (see Repeatability section above), we took 20, 30, and 40 successive images at each position for f/3.5, f/8, and f/22, respectively. These repetitions were triggered automatically, 1 second apart, by an attached remote to reduce the chance of any accidental camera movement during measurements. Before each set of repetitions, we acquired a dark image, which was used in the analysis to get a better estimate of noise levels. At the same time as the dark image, we also measured the radiance of our test stimulus with the PR-680 spectroradiometer.

Table S7: Vignetting calibration design

	ISO	apt	exp (s)	eccentricity	# files
1	100	f/3.5	1/6400	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*20
2	100	f/3.5	1/6400	-30° to +90° elevation in 10° steps, in random order. Then, repeat in reverse.	26*20
3	100	f/8	1/1250	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*30
4	100	f/22	1/125	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*40
5	100	f/22	1/125	-30° to +90° elevation in 10° steps, in random order. Then, repeat in reverse.	26*40

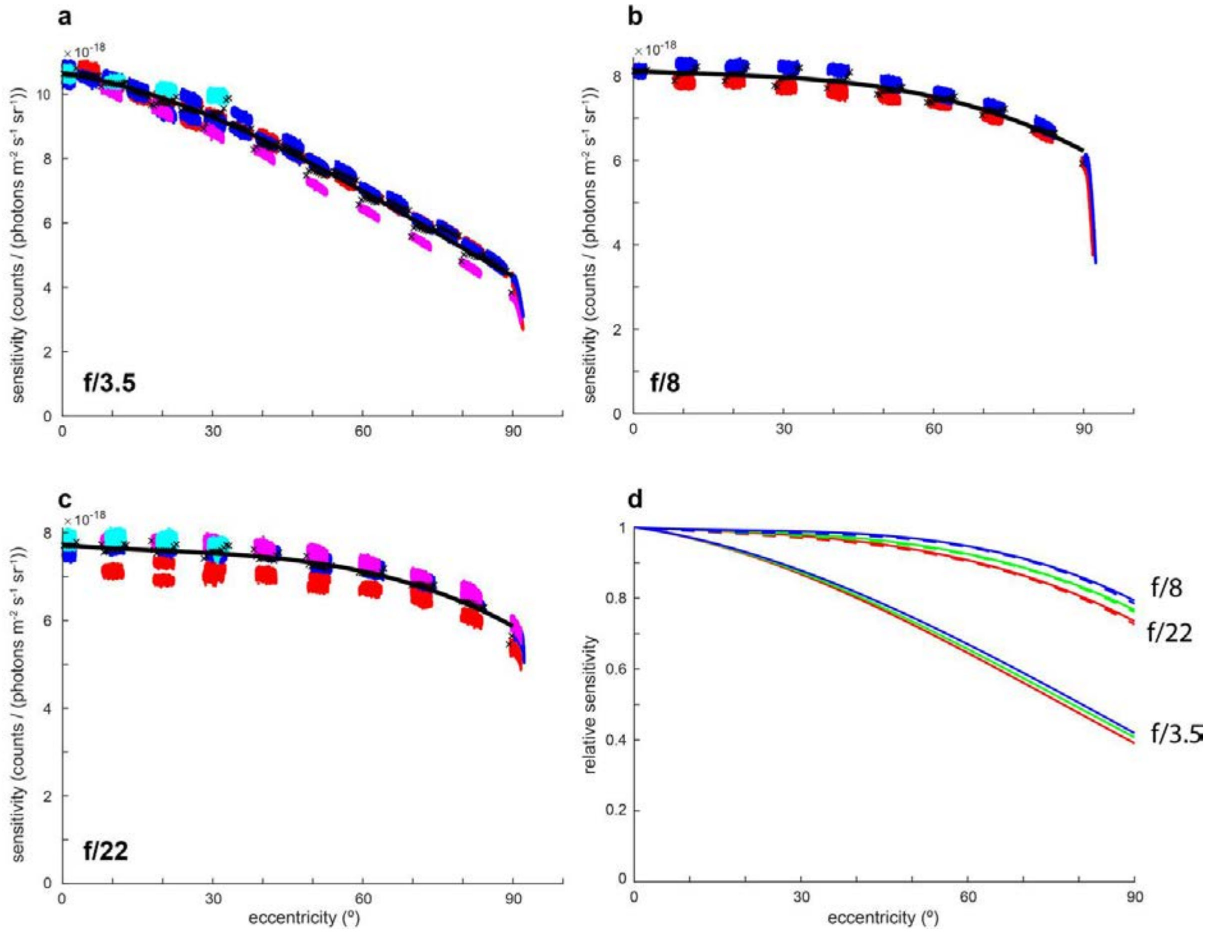

Figure S8: Results of the vignetting calibration for apertures f/3.5 (a), f/8 (b) and f/22 (c). Point clouds indicate the sensitivity estimates for individual pixels within a 2° radius circle around stimulus centre. Colours indicate the part of the camera's visual field: red – left; blue – right; purple – upper; cyan – lower. Black crosses are means for each 0.5° eccentricity bin, which were then fitted using a cubic polynomial (solid line). Panels **a**, **b**, and **c** show data for the green channel, while panel **d** shows fitted vignetting correction functions for all three channels for f/3.5 (lower lines), f/8 (upper solid lines) and f/22 (upper dashed lines).

Analysis

For each aperture, we calculated a sensitivity estimate for each individual pixel inside the detected light stimulus. Using our spatial calibration, we also calculated the eccentricity of each pixel. Plotting sensitivity over eccentricity, we get an estimate of how much sensitivity falls off towards the periphery (Fig. S8a-c). As at least part of this effect is due to optical effects inside the lens, it is dependent on wavelength, and we therefore analysed the three colour channels separately. For each aperture and channel, we then fitted a cubic polynomial to the obtained data (**Fig. S8d**).

Interestingly, vignetting curves at f/8 and f/22 are essentially identical (**Fig. S8d**), meaning that this curve can be used to calibrate any aperture values between those two. Vignetting between f/3.5 and f/8, on the other hand, changes drastically, indicating that these aperture values should not be used in ELF processing with this camera without additional calibration measurements.

Calibration for other camera models

The camera model used for developing the ELF method, Nikon D810, is as of 2020 no longer in production. A similar current model, Nikon D850, has spectral sensitivities similar to the D810, and in daylight or normal interior lighting, the calibration for Nikon D810, included in our software, provides correct measurements. But for low intensities, the D850 has very different (and better) noise characteristics which will require a calibration specific for that model. It is our intention to calibrate the Nikon D850 and include this calibration in the free software we provide.

Data processing

Extraction of radiometric data from the RAW images follows the steps listed in table S8 below. General principles for processing RAW images in Matlab are given by Sumner (2014).

Table S8: The sequence of image processing steps from raw file to HDR scene

1	Convert to DNG	Images are converted to linear, uncompressed DNG files using Adobe's DNG Converter
2	Crop to active pixels	The raw image is cropped to the active pixels according to EXIF information (DefaultArea and DefaultCropSize)
3	Demosaicing	Image is transformed from the Bayer Colour Filter Array to a standard RGB format
4	Linearisation	For some camera models, a linearization function needs to be applied, which is included in the EXIF information (LinearizationTable)
5	Dark correction	For exposures below 1 second, and ISO values up to 6400, the noise model is applied. For larger values, the dark value included in the EXIF information (BlackLevel) is used
6	Absolute sensitivity	Images are multiplied with a sensitivity factor to convert pixel values into radiances
7	Vignetting correction	Images are corrected according to the vignetting calibration
8	Spatial projection	Images are remapped from equisolid (fisheye) to equirectangular projection (Bettonvil 2005)
9	Detect bracketing	To detect the bracketing pattern, the ELF software searches for repetitive patterns in the EV values. This reliably detects patterns if bracketing was performed automatically, but often fails when manual bracketing was necessary (e.g. with long exposures at night). In this case, a brackets.info file can be supplied, which is a simple text file (located in the DNG image folder) containing the start and end of each bracket (see software for example files).
10	Exposure scaling	Inter-exposure differences are eliminated by calculating the median radiance value for each exposure in the bracketing set, and scaling each image to match its radiance to the average across exposures
11	HDR combination	Each pixel in the output HDR image is assigned the value that it holds in the "brightest" (highest EV) image of the bracketing set, ignoring any saturated pixel values
12	Colour correction	Images are corrected according to colour calibration
13	Gamma correction	Standard gamma correction is applied to each image (purely for display purposes)

Comparison of real and 'ideal' spectral sensitivities

The spectral sensitivity of the camera's RGB channels are not ideal for acquiring radiometric data. The spectral curves of the individual channels are bell shaped (with different sensitivity to different wavelengths) and there is significant overlap between the channels (**Fig. S7C**). Another problem is that different models and makes of cameras do not have identical spectral sensitivities. Especially different makes often have rather different spectral sensitivities, with different peak wavelengths, different widths and different amount of spectral overlap. Despite perfect calibrations, such difference may result in somewhat different readings if the cameras are used for ELF measurements in markedly coloured environments. An obvious solution would be the definition of a standard spectral sensitivity.

However, to define a standard based on a specific model of a consumer camera is clearly unsatisfactory, and would only make sense as long as that model is available on the market. Instead, we define an ideal spectral sensitivity that is better suited as a standard, and estimate the expected difference in ELF measurements between the ideal spectral sensitivity and that of the currently used consumer camera. We thus define the 'ideal' spectral sensitivity as 100 nm wide top-hat functions: 400-500 nm (blue), 500-600 nm (green), 600-700 nm (red). Optical filters that come close to these bandpass characteristics are possible to manufacture and available on the market, although not as Bayer masks on image sensors. ELF measurements with ideal spectral sensitivities would call for custom-made cameras, possibly using a spinning disk of filters in front of a monochrome camera (as in Tedore and Nilsson 2019).

To estimate the expected difference between the ideal spectral sensitivities and the calibrated consumer camera (Nikon D810), we used a spectroradiometer (Stellar-Rad UVN Handheld SpectroRadiometer, equipped with a 10° Gershon tube) to record the spectral photon flux from different scene features (**Fig. S9**). For white light (equal quantal flux at all wavelengths), the radiometric calibration takes care of the problem, but for elevation angles that are dominated by strongly coloured light, the spectral mismatch will generate errors. Multiplying RGB channel spectra with environmental radiance spectra reveals that blue is underestimated in blue dominated elevation angles and red is underestimated in red dominate elevation angles. In extreme conditions the total radiance errors may approach 0.1 Lit. For individual RGB channels the error may exceed 0.2 Lit, although most scenes will contain a mixture of differently coloured fields where errors largely cancel. Errors due to the non-ideal spectral sensitivity of typical RGB image-sensors are thus generally small compared to the radiance range within scenes and the variation between different environments. As a consequence, these errors are insignificant for ELF analysis of environmental light.

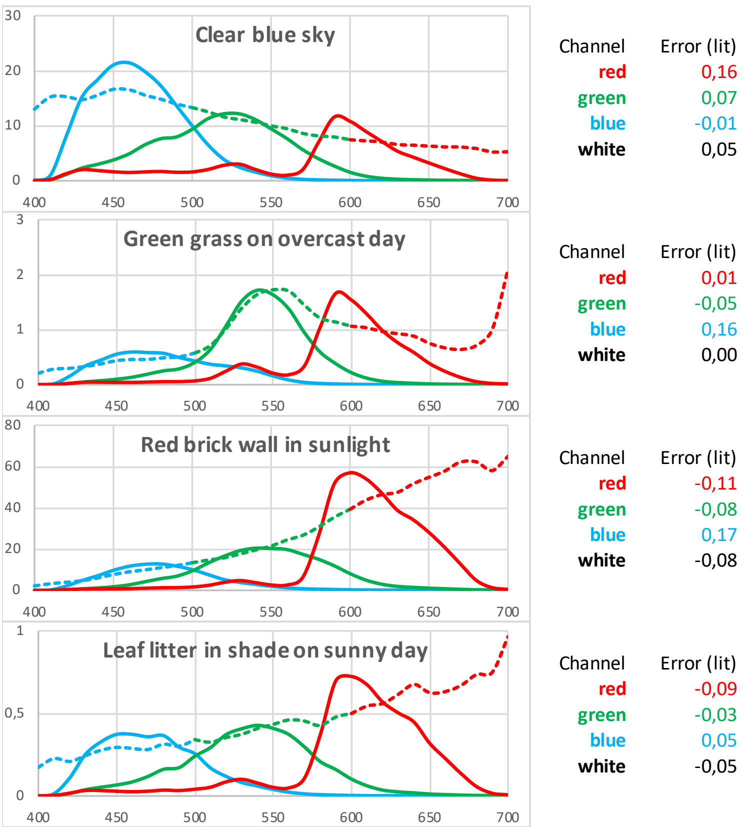

Fig. S9 The difference (error) between ideal spectral channels and those of the Nikon D810. Curves to the left show radiance spectra (dashed curves) for different scene features, and the corresponding signal contributions these spectra generate in each of the three colour channels of the Nikon D810 image sensor (solid curves). For each colour channel, the difference (error) is calculated by comparing the area under the complete solid curve with the area under the band-specific part of the environmental spectrum (corresponding to the ideal spectral sensitivity).

Single and multiple scene measurements

Multiple scene measurements are needed to capture the general features of a light environment. The smooth curves of the environment reveal features that are characteristic for the environment. Single scenes from an environment provides measurements that are obviously similar to the entire multi-scene environment (**Fig. S10**), but the ELF curves of single scenes have numerous quirks and wiggles resulting from specific objects or shadows that are occurring in a partly random fashion in each individual scene. As much as these kinks and wiggles are legitimate parts of the reality we are quantifying, they are specific to the single vantage point and not characteristic features of the entire environment. Instead, the jagged curves of single scenes often mask features that are characteristic of the environment (such as the dark horizontal band in **Fig. S10b**, which cannot be discriminated from other bumps in **Fig. S10 a**). In some cases, such as for visual ergonomics or measurements of changes over time, single scenes are the obvious choice, but for characterizing or reproducing light environments, multiple scene measurements are better.

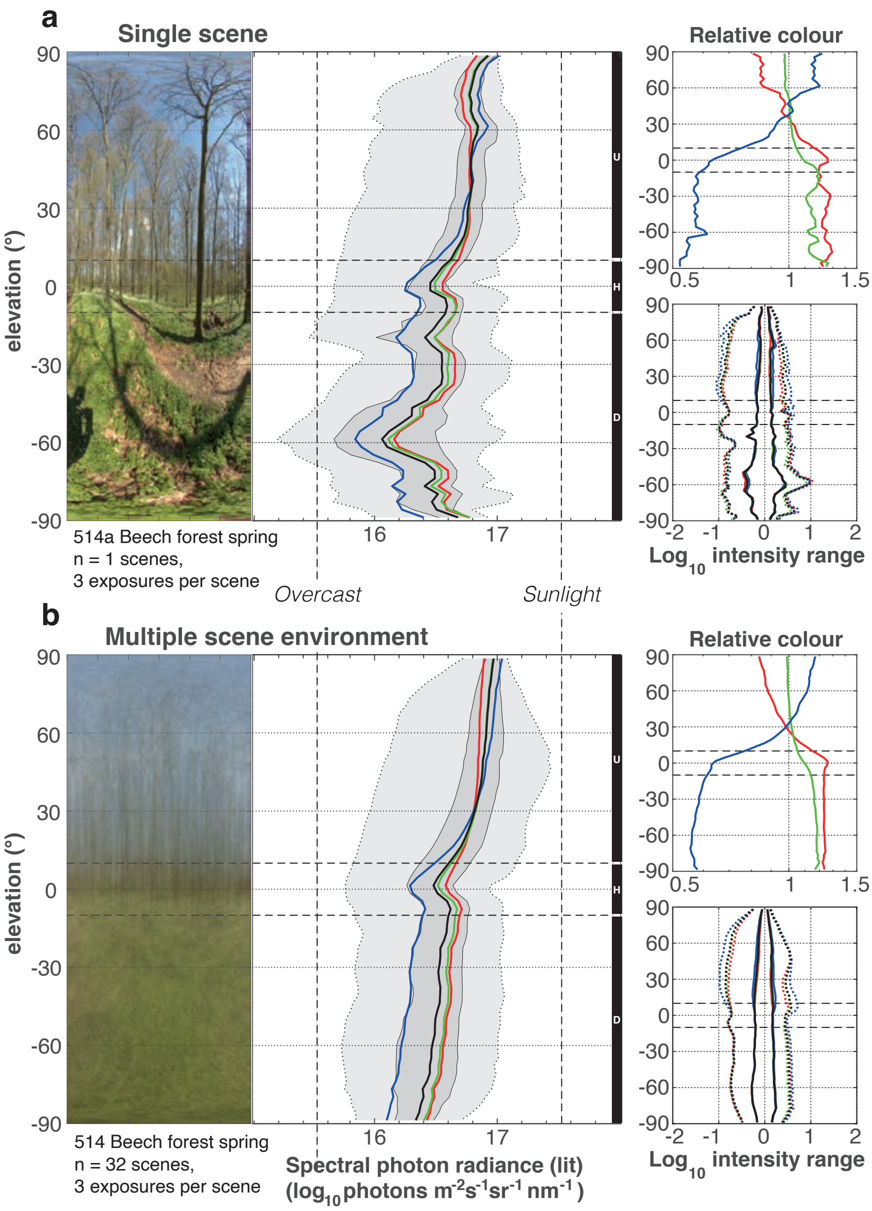

Fig. S10 A single scene versus a multiple scene environment. Chart **a** is from a single scene, which is part of the environment in chart **b,** composed of 32 scenes.

ELF measurement practices and camera settings

When working out the practices for ELF measurements, we mostly used Nikon 810 with a Sigma 8 mm F3.5 fisheye lens. Other camera models and other fisheye lenses may have different controls, options and menus, and the information here will then have to be adapted accordingly. It is important that the camera can store images in RAW format. Cameras without this ability cannot be used. It is also necessary to have an intensity calibration for the camera model used This is a complicated and advance procedure, but since Nikon D810 and the Sigma 8 mm/3.5 fisheye vary so little, it is possible to use our calibration for that particular camera and lens combination. The Matlab script provided here is made for Nikon D810, and we intend to update it with a calibration also for Nikon D850, which is a very similar camera. Cameras from Canon unfortunately have colour channels with less suitable spectral sensitivities – these would deviate more from the ideal spectral sensitivities, but not so much that a camera could not be used for ELF after correct calibration.

Lens

For Sigma fisheye lenses, older lenses have a two part lens-cap and it is important to remove both parts before measurements, or else the photos will only cover 140° (newer lenses has a single-piece lens cap that uncovers the full 180° field when removed).

Procedure

Take photos of at least 15, ideally 40 scenes within the habitat (type of environment) that you want to evaluate. All 15-40 scenes should be photographed in as rapid a succession as possible, such that time of day and weather remains roughly the same. If there are windows, this applies also to indoor scenes. Try to choose scenes randomly in different horizontal directions, and such that the set of scenes makes a representative random sample of the habitat. To represent human vision, keep the camera at typical eye height and select vantage points where head of people would potentially be located. On open sunlit areas your own shadow will be visible in all photographs that do not include the sun.

For each measurement (multi scene environment or single scene), note the location, time, weather and other circumstances of possible importance. Make sure the camera's date and clock and time-zone are correctly set (take a note about daylight savings such that astronomic time can be reconstructed).

Always confirm that the measurement photos are taken with the camera exactly horizontal in both tip and tilt angles. The most important end result is the relation between luminance and vertical angle. It is thus essential that the midpoint as well as the straight line connecting the extreme right and left edges of each image are in the horizontal plane. Do not be fooled by sloping terrain. A bubble level mounted on the camera is an ideal solution, which also makes it unnecessary to look through the finder.

Free hand photography works fine in daylight and early dusk intensities. Under darker conditions a tripod is necessary. Because the dynamic range of a single photo is often not large enough to capture the entire range of radiances within a scene, it is necessary to use "bracketing" (a series of different exposures instead of a single photo of each scene). This can be done automatically by most cameras.

Camera settings

For the photos to be usable for ELF, it is essential that images are stored in RAW format, and no white balance adjustment are turned on (use daylight setting) and no automatic image enhancement functions are turned on. The images must also be taken with a fixed (predetermined and calibrated) aperture, and without flash. It is essential that the bracketing series of exposures cover the full dynamic range of the scene.

Exposure (settings for Nikon D810)

Use automatic exposure with fixed aperture (A) for intensities where the exposure meter works (all, except night, late dusk, early dawn or similar).

Use the only the calibrated apertures, F3.5, F8, or F22 depending on light level (assumes use of the provided Matlab routines, which include calibrations only for these apertures). Use F3.5 for indoor or twilight measurements, F8 for outdoor overcast or shaded areas and F22 for sunny environments (see below under Lens settings).

Set ISO to Manual or Auto. Because of the fixed aperture, the ISO value effectively determines the shutter speed that the camera will use. The ISO setting should be in the range 64-1600. High ISO values generate noise, which pollutes the measurements.

Set bracketing to 3 exposures differing by 3 EV between each. If possible, set bracketing order to go from – to + (rather than starting with the middle exposure).

Make test exposure to confirm that exposure is not too dark or washed out. In the brightest photo of the bracketing series there should be no completely black pixels, and in the darkest exposure in the series there should be no fully white pixels (except for light sources such as the sun or lamps). If necessary, make a general exposure correction + or – to avoid parts of the picture being completely black or completely white through the entire bracketing series.

At late dusk, early dawn or dimmer conditions, the exposure meter will under-expose significantly. Manual exposure and trials are recommended in these conditions.

If the brightness of a light source in view (sun or lamp) is important to know, the exposure considerations above must include also the light source. This may call for very long bracketing series (the sun's disc is about 5 log units, or 16.5 EV binary units brighter than the scene it illuminates. Auto ISO may help here.

If possible, set the camera to take the entire bracketing series with one push on the release button, and then stop (C_H on Nikon D810). Make sure shutter speeds are not hitting the roof of 1/8000 s in any part of the bracketing series, and that they are no longer that about 1/8 s for a handheld camera. Typical settings for daylight is ISO 200 and F8, for indoor ISO 400 and F3.5.

Set exposure meter area to centre integration, Centre area 20 mm (in tools menu)

Use exposure lock with release button pressed halfway (not continuous sports exposure setting)

Lens (settings for Sigma 8 mm f/3.5 EX DG, on a Nikon D810)

Autofocus: off (on camera body)

Set aperture to fully open (3.5; on camera upper display) for dim conditions, twilight, night or indoor use. In bright daylight, use an aperture setting of 8. If the sun or other bright light source is to be correctly assessed, aperture 22 is necessary. Aperture 22 can also be used to obtain maximum depth of focus of objects are close. Do not use any other than these three settings because the others are not calibrated.

Set focus on the lens to ∞ at R (on Sigma 8 mm Fish Eye), unless important objects are closer than 0.5 m. For scenes with close objects, set aperture to 22, and ∞ to 22 setting, which makes sharp from infinity to 13.5 cm).

To avoid unintentionally changing the focus, use a piece of tape to lock the focusing ring.

If the camera refuses to take an exposure, it is likely that the autofocus has been accidentally turned on and it fails to focus because the tape is locking the focus ring. Just turn autofocus off to solve the problem.

Picture storage format (settings for Nikon D810)

Image quality RAW (NEF).

Store RAW image: RAW L (large), NEF compression OFF, Bit depth 14-bit

Image area: 5:4 (30x24) or FX (36x24). The smaller format will have less unused space, with smaller files as a result.

There is no point in using double storage formats (such as RAW + JPEG). It will only slow the camera down and fill up the data storage cards.

Other camera settings

Set White balance to daylight (direct sunlight). Do not use automatic white balance. This is very important!!

Nikon: Picture control: Flat or Neutral (although this does not change RAW files)

Colour space: use sRGB (although this does not change RAW files)

Active D-Lighting: off (very important)

HDR: off (very important)

Vignetting control off

Noise reduction for long exposures: On

Noise reduction for high ISO: High

Flash: off

Finder grid: on (if it exists, will help orient the camera horizontally)

Virtual horizon in the tools menu is not as good as a real bubble level mounted on the camera.

Show ISO on (if it exists, will make ISO selection easier to see)

Because the astronomic time of day may be important information, it is advised that the camera clock and time zone is correctly set, preferably without using daylight savings correction.

Night measurements with Nikon D810

Use tripod and external timer connected with a cable. Avoid wireless timers as they frequently loose contact and interrupt long exposures.

Change ISO from Auto to 1600 for starlight or 800 for moonlight.

Change Mode from A to M

Alt 1 (moonlight or brighter): Use normal bracketing (3 x ±3EV), Set exposure time to 4s (F3.5, 4")

Alt 2 (less than full moonlight): Turn off bracketing, set time to BULB, and use remote to expose a manual series with the long, and make three separate exposures 8s, 1min, and 8 min. If there is no moon or other concentrated light sources, it is sufficient to use a single exposure (no bracketing), although it has to be confirmed that each single image is not overexposed or underexposed. Please note that with such long exposures the camera automatically makes a dark noise expose of equal length after each shot. So, for the 8 min shot, the camera will be busy for another 8 minute after completing the real 8 min exposure (in effect requiring 16 min for the longest exposure in starlight).

References

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