Downwelling spectral irradiance during evening twilight as a function of the lunar phase

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We measured downwelling spectral vector irradiance (from 350 to 800 nm) during evening civil and nautical twilight (solar elevation down to −12°). Nine sets of measurements were taken to cover the first half of the lunar cycle (from the new to full moon) and were also used to calculate chromaticity (CIE 1976 u′v′). The lunar phase had no consistent effect on downwelling irradiance until solar elevation was less than −8°. For lower solar elevations, the effect of the moon increased with the fraction of the illuminated lunar disk until the fraction was approximately 50%. For fractions greater than 50%, the brightness and chromaticity of the downwelling irradiance were approximately independent of the fraction illuminated, likely because the greater brightness of a fuller moon was offset by its lower elevation during twilight. Given the importance of crepuscular periods to animal activity, including predation, reproductive cycles, and color vision in dim light, these results may have significant implications for animal ecology.

OCIS codes: (330.1720) Color vision; (330.4060) Vision modeling; (350.1260) Astronomical optics; (010.1290) Atmospheric optics.

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1. Introduction

Although the dramatic changes in the illumination level that accompany the rising and setting of the sun are well-known, the associated changes in the chromaticity (i.e., color) of the illumination are less appreciated. However, for animals and instruments that can discern it, the chromaticity of the downwelling irradiance during a moonless twilight varies over a far greater range than that observed when the sun is well above the horizon [1–4]. Civil twilight ($-6° < \theta_s < 0°$, where θ_s is solar elevation) is dominated by red-shifted direct light and blue-shifted scattered light from the sun. Nautical twilight ($-12° < \theta_s < -6°$) is intensely blue due to the absorption of long-wavelength visible sunlight by the ozone layer [1]. Astronomical twilight ($-18° < \theta_s < -12°$) is primarily composed of airglow, integrated starlight, zodiacal light, and other dimmer sources, which are mostly richer in longer-wavelength light. Thus, as the sun drops from 20° above the horizon to 20° below it, the color of a moonless, clear sky (defined herein as the chromaticity of the downwelling irradiance) goes from approximately white to reddish to blue to very blue and then back to reddish [5].

This evolution of chromaticity over the course of twilight can also be influenced by the presence of the moon. A moonrise or moonset that occurs at night creates the same temporal pattern of intensity and chromaticity as a sunrise or sunset, albeit with direct moonlight being far dimmer and slightly red-shifted relative to direct sunlight due to the reddish reflectance of the lunar surface [6]. The situation is more complicated when the moon is above the horizon during solar twilight because, in certain cases at least, the combined intensity of direct and scattered moonlight can be comparable to that of scattered sunlight. Because both the brightness and elevation of the moon depend strongly on the lunar phase [7–10],

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the chromaticity of downwelling irradiance during twilight is also likely to be affected by the lunar phase, especially during nautical and astronomical twilight.

Aside from its optical interest, the effect of the lunar phase on the chromaticity of downwelling irradiance during twilight may be important to animals. Many species are especially active during twilight, a period that is often used for hunting, foraging, and mating [11,12]. It is also now known that certain species (e.g., the elephant hawkmoth *Deilephila elpenor* and the nocturnal helmet gecko

Table 1. Conditions during Each of the Nine Sets of Measurements

	Lunar Phase Angle (Degrees)	Fraction Illuminated	Date	Sky Conditions	Solar Elevation (Degrees)	Lunar Elevation (Degrees)
	171.5	0.01	March 1	Mostly clear	−1.0–12.5	7.5–3.5
	140.0	0.12	April 2	Clear	0.0–12.5	37.0–25.0
	120.0	0.25	March 5	Partly cloudy	0.5–12.5	56.0–45.0
	105.0	0.37	April 5	Partly cloudy	0.0–12.0	65.5–55.5
	72.0	0.66	April 8	Partly cloudy	−1.0–13.0	64.0–66.5
	60.5	0.74	April 9	Partly cloudy	−2.5–13.0	57.0–62.5
	49.5	0.82	April 10	Clear	−1.0–12.5	46.5–55.0
	32.5	0.92	February 11	Partly cloudy	0.0–12.5	29.0–41.0
	15.0	0.98	April 13	Partly cloudy	0.0–10.5	14.5–23.5

Tarentola chazaliae) have the ability to see color under far lower levels of illumination than humans can, with some able to discern hues under dim starlight [13,14]. Other species, while unable perhaps to see color at these low light levels, may be better able to discern shades of blue than humans and thus distinguish the scatter-dominated blue of early twilight from the absorption-dominated blue of later twilight. Thus, the phase of the moon during twilight, which affects both the appearance of objects and the ability to distinguish colors, may influence animal vision and behavior. Perhaps most important, at least as far as the lunar phase is concerned, is that many animals, both terrestrial and aquatic, mate during twilight at certain phases of the moon [15]. A number of these animals (e.g., corals, various echinoderms) have—at best—quite poor spatial vision, and it has been suggested that particular spectra of downwelling irradiance are cues for reproductive behavior [15].

Relatively few spectral measurements of downwelling irradiance have been made during twilight. While there are a number of long-term monitoring stations that measure downwelling irradiance, they are typically not sensitive enough to capture the illumination when the sun is more than a few degrees below the horizon. Also, the physicists, astronomers, and engineers who have equipment sensitive enough to measure spectra during this period tend to be less interested in global measurements such as downwelling irradiance and instead measure the spectra of select celestial objects or regions of the sky [3,7]. Finally, the majority of the universities that contain the equipment and expertise to make these measurements are in populated regions with skies dominated by light pollution, which greatly affects downwelling irradiance [16,17]. While underwater downwelling irradiance during twilight has been measured several days before and after the full moon [15], to our knowledge, a systematic set of measurements of the effect of the lunar phase on twilight irradiance has not been made.

This paper describes nine sets of measurements of twilight (evening) downwelling spectral irradiance (from 350 to 800 nm) taken at a remote site chosen to minimize light pollution. The measurements were done on evenings selected to cover a range of lunar phases during the first half of the lunar cycle (when the moon is above the horizon during the evening). These measurements were then used to calculate human-based chromaticity (CIE 1976 u′v′) and generate images of the average color of the sky and the appearance of objects.

2. Materials and Methods

A. Measurements of Downwelling Irradiance

Downwelling spectral irradiance was measured on nine evenings in an open field at Medoc Mountain State Park in Hollister, North Carolina (36°15′28′N 77°52′42″W), a remote site specifically chosen using a map of artificial night sky brightness [18] to minimize light pollution. Data were collected on February 11, March 1, March 5, April 2, April 5, April 8, April 9, April 10, and April 13, 2014, during which the fraction of the lunar disk that was illuminated (f) ranged from 0.01 to 0.98 (Table 1; Fig. 1A). All measurements were restricted to the first half of the lunar cycle (i.e., the new to full moon), during which the moon was above the horizon for at least part of the time after sunset. It was expected that measurements taken at dawn during the second half of the lunar cycle would be similar although somewhat affected by the different atmospheric parameters found during the morning versus the evening and by the fact that lunar radiance in the second half of the lunar cycle is slightly different from that in the first half due to the inhomogeneity of the lunar surface [7]. Sky conditions ranged from clear to partly cloudy, with the lunar disk unobscured during all measurements.

Spectra were taken using a USB2000 spectrometer (Ocean Optics Inc., Dundein, FL, USA) that was fitted with the largest possible entry slit (200 μm) and an L2 collector lens (Ocean Optics) over the detector array to increase sensitivity. The spectrometer was coupled to a 1000-μm-diameter fiber optic cable that was fitted with a CC-3 cosine corrector (Ocean Optics). Ten to 13 spectra of downwelling irradiance were taken each night, with the solar elevation ranging from 0.5 to −13°, to cover both civil and

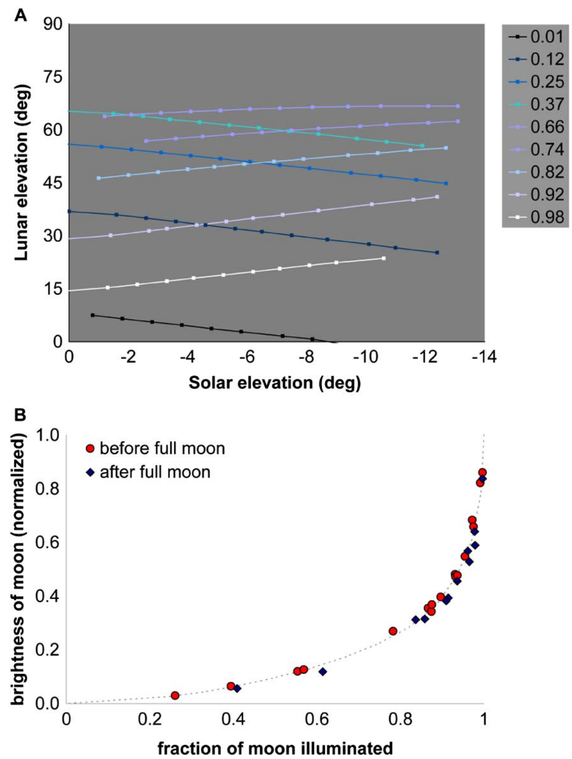

Fig. 1. A, lunar elevation as a function of solar elevation θ_s and fraction of the lunar disk illuminated for the nine sets of measurements; B, brightness of the moon (at 500 nm and normalized to 1 for a full moon) as a function of the fraction of the lunar disk illuminated. Data in B are from [7]. Dotted line is Eq. (4) from the text.

nautical twilight (the spectrometer was not sufficiently sensitive for measurements far into astronomical twilight).

The solar and lunar elevations during each measurement were acquired from the U.S. Naval Observatory's astronomical applications website [19]. The lunar phase angle ϕ (0° for a full moon; 180° for a new moon) was also taken from the same website and used to approximate the fraction of the lunar disk illuminated f via

$$f = \frac{1}{2}(\cos\phi + 1). \quad (1)$$

The average value of the spectra from 200 to 250 nm (where natural light is negligible) was subtracted to account for the dark noise of the spectrometer, and the resulting values were then corrected for the spectral sensitivity of the detector to give spectra in quantal units (which are more relevant for vision than energy units). These spectra were then averaged over 10-nm intervals from 350 to 800 nm and normalized so that their integrals over this wavelength range were equal to 1000 so that the change in the shape of the spectra could more easily be discerned. These spectra (converted back to energy units) were then used to calculate the chromaticity (CIE 1976 u′v′) for each spectrum to show how the human-perceived chromaticity of the downwelling irradiance evolved over the course of civil and nautical twilight as a function of the lunar phase. This measure of chromaticity was chosen over the

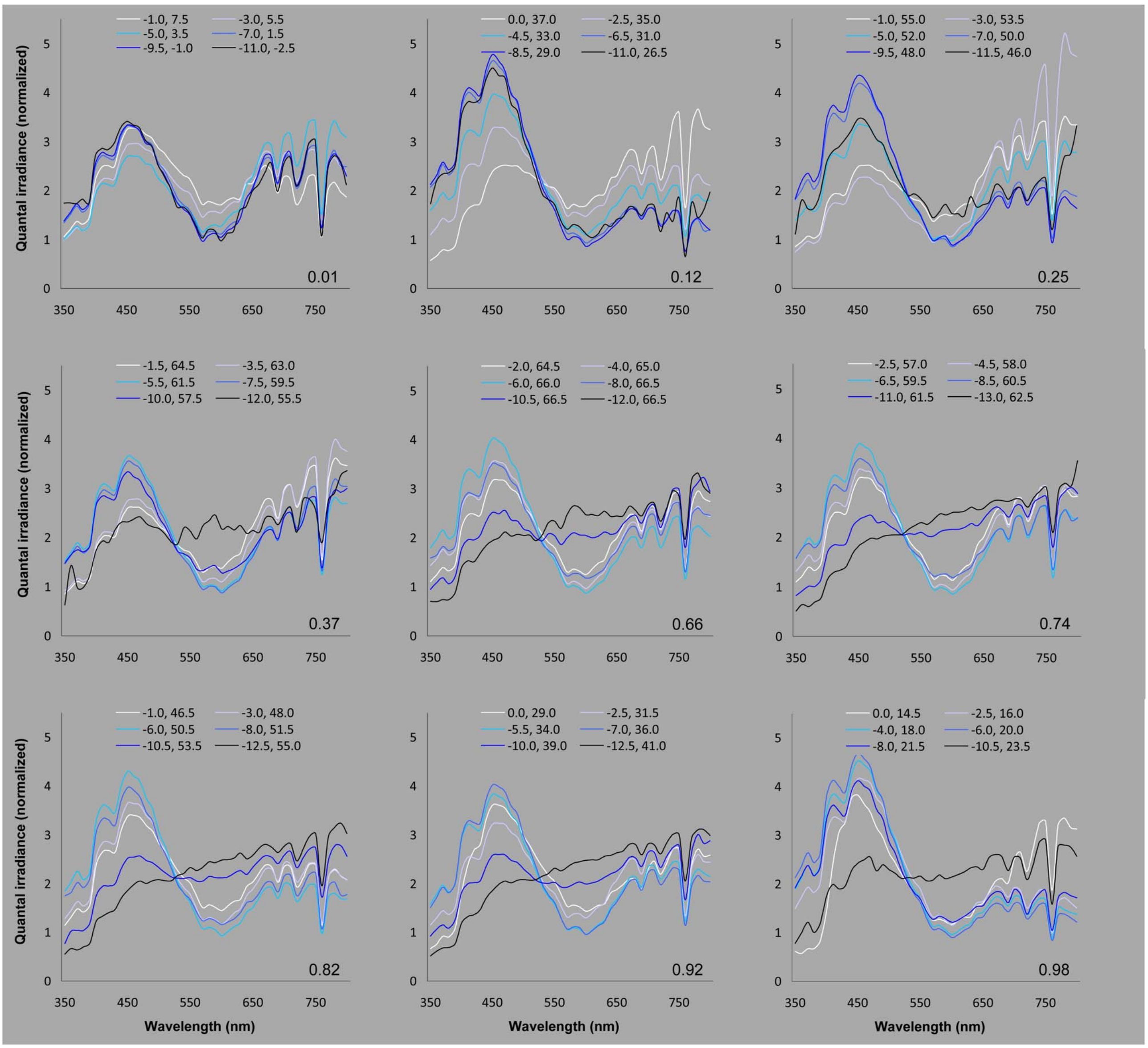

Fig. 2. Measured spectral quantal irradiance as a function of solar elevation and fraction of the lunar disk illuminated (normalized to an integral of 1000 over 350–800 nm). First and second numbers in the legend for each plot are the solar and lunar elevations, respectively (to the nearest 0.5°). Fraction of the lunar disk illuminated is the lower right-hand corner of each graph. Each spectrum is averaged over 10-nm intervals.

more typical CIE 1931 xy because it is more perceptually uniform.

B. Model of the Contribution of Moonlight to Total Downwelling Illuminance

We estimated the contribution of moonlight to the total downwelling illuminance as a function of illuminated lunar fraction f, lunar elevation θ_m, and solar elevation θ_s using previously published data and

$$C_{\mathrm{moon}}(f,\theta_m,\theta_s) = \frac{E_{\mathrm{moon}}(f,\theta_m)}{E_{\mathrm{moon}}(f,\theta_m) + E_{\mathrm{sun}}(\theta_s)}, \qquad (2)$$

where $E_{\mathrm{moon}}(f,\theta_m)$ and $E_{\mathrm{sun}}(\theta_s)$ are the downwelling illuminance (in lux) due to direct and scattered moonlight and sunlight, respectively, (the far dimmer airglow and integrated starlight were not considered). The term $E_{\mathrm{moon}}(f,\theta_m)$ is in turn given by

$$E_{\mathrm{moon}}(f,\theta_m) = E_f(f) \cdot E_\theta(\theta_m) \qquad (3)$$

where $E_f(f)$ is the brightness of the moon as a function of the illuminated lunar fraction (normalized to 1 for a full moon), and $E_\theta(\theta_m)$ is the downwelling illuminance (in lux) of the full moon as a function of elevation. The former term has been measured as a function of the lunar phase angle [7]. If one combines these data with Eq. (1), $E_f(f)$ is well-approximated by

$$E_f(f) = 1 - \left[\cos\left(\frac{\pi}{2}f\right)\right]^{0.29} \qquad \text{(Fig.1B)}, \qquad (4)$$

which has a maximal value of 1 for a full moon. The latter term in Eq. (3), $E_\theta(\theta_m)$, along with $E_{\mathrm{sun}}(\theta_s)$, was taken from published data [20].

3. Results

A. Quantal Spectral Irradiance during Twilight

None of the spectra showed the 590-nm sodium peaks typical of light pollution, suggesting that the site was relatively free of artificial light. The evolution of the downwelling irradiance spectra during civil twilight was relatively independent of the lunar phase, with the primary feature being the broad ozone absorption band (Chappuis band) centered at approximately 600 nm that became increasingly prominent as twilight advanced [2] (Fig. 2). Thus, the primary components of the visible portion (400–700 nm) of the irradiance spectra of civil twilight were a broad, blue peak centered at approximately 450 nm and a lesser amount of light from 600 to 700 nm that increased with wavelength. Outside the visible region, in the near-infrared, the spectra were characterized by narrow absorption bands due to water vapor and molecular oxygen, with a particularly prominent O_2 band centered at approximately 760 nm.

In contrast to the spectra during civil twilight, the spectra during nautical twilight were strongly influenced by the phase of the moon. Even illuminated fractions as low as 0.25 affected the spectra of late nautical twilight, and fractions greater than 0.5 strongly influenced the spectra of twilight for solar elevations below −8°. The spectra in these latter

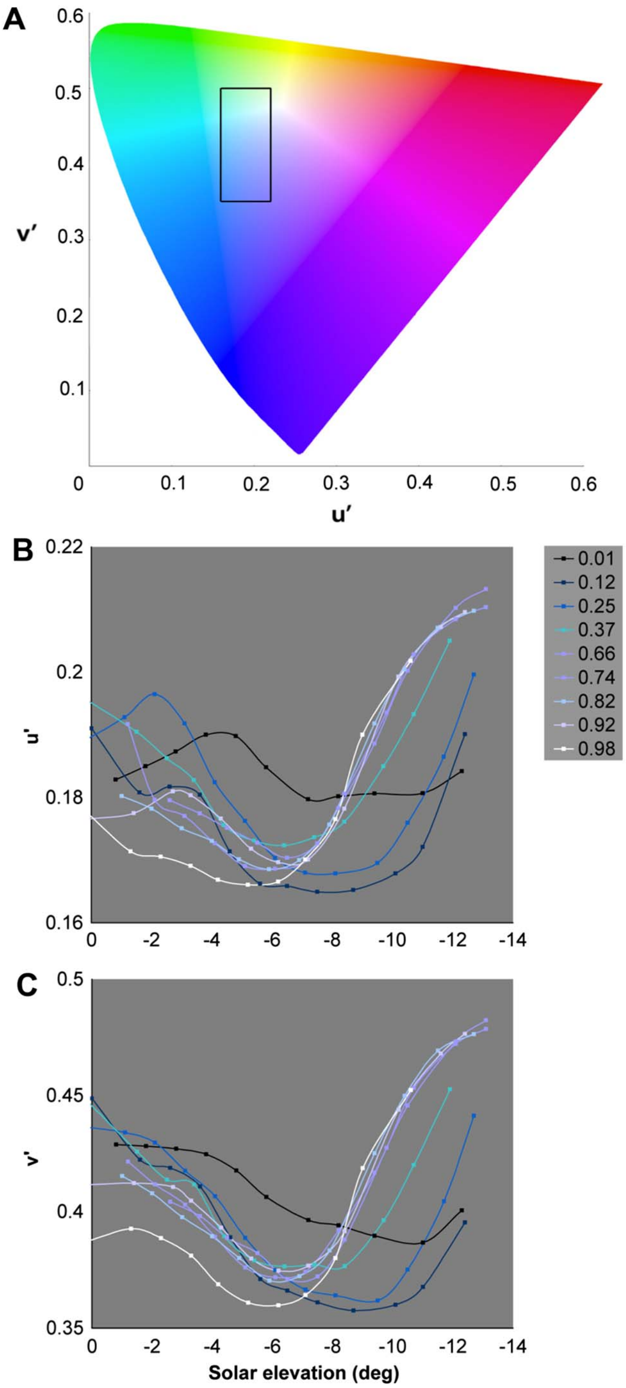

Fig. 3. A, CIE 1976 u′v′ chromaticity diagram, with the region of the chromaticity variation during twilight shown in black; B, u′ as a function of solar elevation and the fraction of the illuminated lunar disk; C, v′ as a function of solar elevation and the fraction of the illuminated lunar disk. Parameters u′ and v′ are shown separately as functions of solar elevation, rather than in the usual combined format, to better show the effect of the lunar phase during different portions of twilight.

cases showed that the downwelling irradiance was essentially dominated by moonlight, with scattered sunlight (and its modification by visible ozone absorption) playing a minor role. In addition, the late nautical twilight spectra for which $f > 0.5$ tended to group together, with the nearly ten-fold greater brightness of the full moon relative to the quarter moon [7] being offset by its lower elevation during twilight.

B. The CIE 1976 u′v′ Chromaticity during Twilight

The chromaticity during civil twilight was somewhat variable but had no discernible relationship to the lunar phase (Figs. 3 and 4). As would be expected from the irradiance spectra, the general evolution

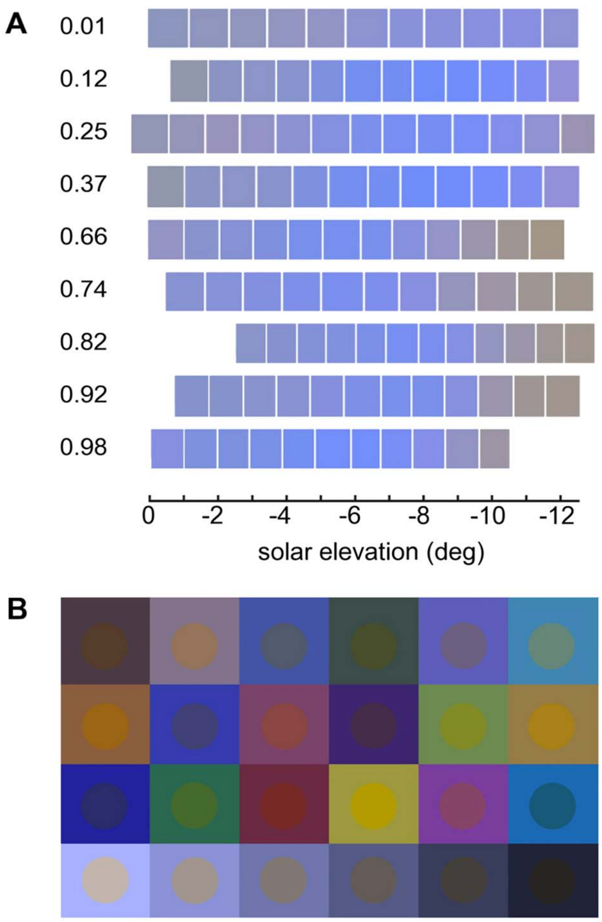

Fig. 4. A, chromatics in Fig. 3 converted to sRGB to show the average color of the twilight irradiance as a function of solar elevation and the fraction of the illuminated lunar disk; B, GretagMacbeth Colorchecker viewed under both a new moon ($f = 0.01$) and a nearly full moon ($f = 0.92$), both when the solar elevation equals −12° (a full moon was not used because there was no measured spectrum for a solar elevation of −12°). Square for each color indicates the appearance under a new moon, and inset circle indicates the appearance under a nearly full moon, both during late nautical twilight, when the effect of the moon is largest. Two sets of colors were normalized to have the same human-perceived brightness for the white square (lower left-hand corner). Figure was made using the measured spectra and published values of the reflectance spectra of the ColorChecker, both to a resolution of 5 nm. Both A and B are best viewed on a monitor calibrated for sRGB.

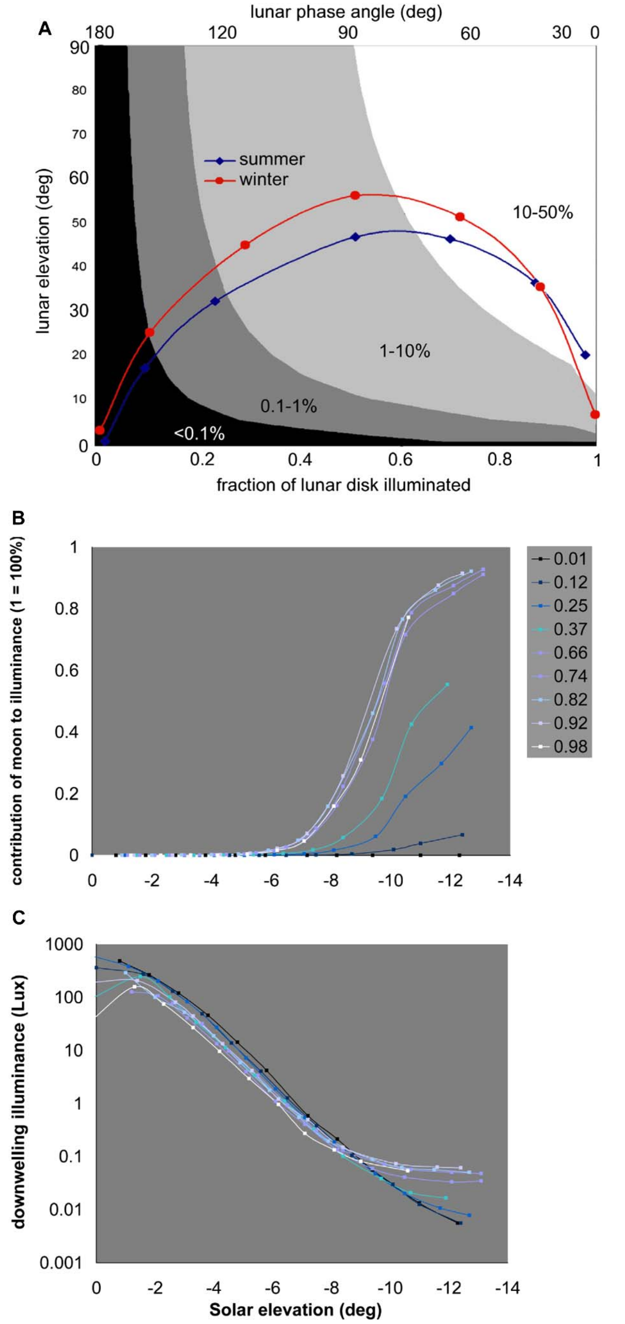

Fig. 5. A, contour plot of the contribution of moonlight to the total downwelling illuminance (when $\theta_s = -8°$) as a function of lunar elevation θ_m and the fraction of the lunar disk illuminated f. Superimposed on this plot are θ_m and f (when $\theta_s = -8°$) for the latitude of the study site (~36°N). Blue curve depicts the parameters for the first half of the lunar cycle closest to the summer solstice in 2014. Red curves depict the parameters for the first half of the lunar cycle closest to the winter solstice in 2014. Contribution to the total illuminance is relatively constant once $f > 0.5$ because, as the moon waxes beyond this point (and thus brightens), it also sits lower in the sky during evening twilight; B, modeled contribution of moonlight to the total downwelling illuminance as a function of solar elevation, lunar levation, and fraction of the illuminated lunar disk for the nine sets of measurements in this study; C, measured downwelling illuminance (in lux) as a function of solar elevation and fraction of the illuminated lunar disk. Again, the data for which $f > 0.5$ tend to group together, with the effect of the moon becoming increasingly apparent during nautical twilight.

was toward an increasingly saturated shade of blue that tended to reach the highest saturation at the end of civil twilight, with the data for the new moon having less saturation for unknown reasons. The evolution of the chromaticity during nautical twilight, however, was strongly influenced by the lunar phase. For an illuminated lunar fraction less than 0.5, the effect of the moon—which brought the chromaticity back toward white—depended on f. However, for $f > 0.5$, the effect of the moon was essentially independent of f.

C. The Contribution of Moonlight to the Total Downwelling Illuminance during Twilight

The modeled contribution of moonlight to total downwelling illuminance during twilight showed that it depends strongly on both lunar elevation and the fraction of the illuminated lunar disk (Fig. 5A). For example, when the sun is 8° below the horizon, a crescent moon ($f \sim 0.2$; $\theta_m \sim 30°$) contributes less than 1% to the twilight illuminance, while a waxing gibbous moon ($f \sim 0.75$; $\theta_m \sim 50°$) contributes approximately 15%. In theory, a full moon at the zenith of a clear sky would contribute approximately half of the total illuminance, though a full moon is never this high in the sky when $\theta_s = -8°$. In general, when $f > 0.5$, moonlight contributes 7–15% to the total illuminance at this solar elevation. Atmospheric conditions can, of course, alter these values considerably.

The contributions of moonlight to the total illuminance during the nine sets of measurements in this study were essentially negligible during civil twilight but rapidly increased during nautical twilight, reaching nearly 100% when $f > 0.5$ and $\theta_s = -12°$ (Figs. 5B and 5C). Again, the data fell into two regimes, with the contribution being proportional to f when $f < 0.5$ but approximately independent of f when $f > 0.5$.

4. Conclusions

This data set, while relatively small, leads to several conclusions. First, the moon has little effect on either the brightness or the color of downwelling irradiance during civil twilight and early nautical twilight. Thus, for an animal to be influenced by the light of the moon during early twilight, it would either need the visual acuity to image the moon itself or—in the case of the rising full moon—possess a non-imaging photoreceptive surface that faces the lunar azimuth. Neither of these is likely for corals and many other aquatic invertebrates, which have non-imaging photoreception and are found at depths greater than 10 m but nevertheless release their gametes during twilight at distinct lunar phases [15]. This suggests that late nautical twilight, when the effect of the moon is large and there is still enough light to see by, may be a key time for animals with lunar-based reproductive cycles.

Second, the effect of the moon on downwelling irradiance appears to be fairly constant once at least half of the lunar disk is illuminated. This is due to the brightness of a fuller moon being offset by its lower position in the sky during twilight and thus contributing less to downwelling irradiance due to both geometry and a longer optical path through the atmosphere. Therefore, animals with non-imaging photoreception may have a difficult time distinguishing a quarter moon ($f = 0.5$) from a full moon. When the fraction illuminated is less than 0.5, however, the effect of the moon depends significantly on fraction, suggesting that reproductive timing may be easier during these periods, at least for animals with non-imaging photoreception.

Finally, for those animals that have spatial color vision during late twilight, the phase of the moon significantly affects the colors of objects. The color constancy that many animals possess [21] may be able to compensate for this, though the compensation required is large compared to that required during daylight. If not, then visual signals, camouflage, pollination, and other tasks that require accurate color perception may be affected. In general, reliable color vision for crepuscular animals is significantly more difficult than it is for diurnal animals, and further research may turn up physiological adaptations to this dynamic and colorful period of the day.

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