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Author for correspondence:
Gábor Horváth
e-mail: gh@arago.elte.hu

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Psychophysical study of the moon illusion in paintings and landscape photos

Zoltán Kovács, Zoltán Udvarnoki, Eszter Papp and Gábor Horváth

Environmental Optics Laboratory, Department of Biological Physics, Institute of Physics, ELTE Eötvös Loránd University, Pázmány sétány 1, 1117 Budapest, Hungary

GH, 0000-0002-9008-2411

The moon illusion is a visual deception when people perceive the angular diameter of the Moon/Sun near the horizon larger than that of the one higher in the sky. Some theories have been proposed to explain this illusion, but not any is generally accepted. Although several psychophysical experiments have been performed to study different aspects of the moon illusion, their results have sometimes contradicted each other. Artists frequently display(ed) the Moon/Sun in their paintings. If the Moon/Sun appears near the horizon, its painted disc is often exaggeratedly large. How great is the magnitude of moon illusion of painters? How different are the size enlargements of depicted lunar/solar discs? To answer these questions, we measured these magnitudes on 100 paintings collected from the period of 1534–2017. In psychophysical experiments, we also investigated the moon illusion of 10 test persons who had to estimate the size of the lunar/solar disc on 100 paintings and 100 landscape photographs from which the Moon/Sun was retouched. Compared to the lunar/solar disc calculated from reference distances estimated by test persons in paintings, painters overestimated the Moon's size on average $Q = 2.1 \pm 1.6$ times, while the Sun was painted $Q = 1.8 \pm 1.2$ times larger than the real one, where $Q = r_{painted}/r_{real}$ is the ratio of the radii of painted ($r_{painted}$) and real (r_{real}) Moons/Suns. In landscape photos, test persons overestimated the Moon's size $Q = 1.6 \pm 0.4$ times and the Sun was assumed $Q = 1.7 \pm 0.5$ times larger than in reality, where $Q = r_{test}/r_{real}$ is the ratio of the radius r_{test} estimated by the test persons and the real radius r_{real} of Moons/Suns. The majority of the magnitude of moon illusion $Q = 1.6$, 1.7, 1.8, 2.1, 2.8, 2.9 measured by us are larger than the Q-values 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8 obtained in previous psychophysical experiments due to methodological differences.

1. Introduction

It is a well-known phenomenon that the disc of the full Moon near the horizon appears larger than when it rises higher within a few hours [1–6]. This is called the moon illusion. The same is true for the apparent angular dimension of the solar disc and constellations of the night sky. As the Moon orbits the Earth, the diameter of the lunar disc seen from the Earth changes by no more than 15% during 27 days [7]. As the Earth orbits the Sun, the diameter of the solar disc seen from the Earth changes <3.4% during a year [8]. Both the Moon and the Sun have an angular diameter of about 0.5° seen from the Earth, that is why total solar eclipses can occur [9]. The celestial bodies constituting constellations of the night sky are so far from the solar system that the change in their angular magnitude over time seen from the Earth is practically negligible.

Since the moon illusion can occur between two different elevation angles of the Moon above the horizon within a few hours while the mentioned changes of the apparent size of the Moon, Sun and star constellations can happen in much longer periods (month–year), the reason for the moon illusion is not astronomical. Hence, the moon illusion is not the result of a physical effect. This can be demonstrated simply by extending ones arm, closing one eye and comparing the observed moon with the extended thumb: the observed moon will immediately shrink, and the illusion will return when once again observed normally.

The moon illusion could be confused with the so-called supermoon. The concept of supermoon was introduced by the astrologer Richard Nolle, who used it first in 1979 to characterize the increased tidal effect of the Moon [10]. At first, it was not used for the increased size of the Moon as it is today. At the time of the new Moon and the full Moon, when the Sun and the Moon stand together, the tide they produce is stronger than in average due to the resultant gravity. Furthermore, if the Moon is close to Earth at this time, the tidal effect is even greater. According to Nolle's original definition, it is a supermoon when the full Moon occurs nearly at the smallest perigee of the Moon. This is because the Moon orbits the Earth in an elliptical path with an average perigee distance of 362 000 km and an average apogee distance of 405 000 km. Thus, in the case of a supermoon, the full Moon or the new Moon coincides in time with the perigee, or they are close to each other in time. It is an astronomical fact that the apparent diameter of the supermoon is only 15% larger than that of the most distant Moon. If these two lunar discs are depicted side by side, the difference is striking. Of course, we do not perceive this in the sky, because these two lunar discs do not appear at the same time, and from memory, we cannot compare the diameter and/or brightness of the lunar disc with that of a full Moon several months earlier. Despite the misconceptions about it, the supermoon is an existing phenomenon and its occurrence can be accurately predicted astronomically. The supermoon, however, should not be confused with the moon illusion, that is, when the rising or setting Moon is perceived to be larger in diameter than when it is high in the sky.

In ancient times, attempts were made to explain the moon illusion by light refraction in the atmosphere, but it later turned out that this refraction had the opposite effect, because it slightly compresses the vertical angular extension of the solar and lunar disc as well as constellations near the horizon. First, the Arabian astronomer, Ibn al-Haytham described between 1011 and 1022 that this illusion may be of purely psychological origin. The deviation of the direction of light rays grazing the horizon due to atmospheric refraction is about 0.5°. Thus, when the lowermost point of the lunar/solar disc (with a diameter of 0.5°) appears to touch the horizon, in reality (without atmosphere) the topmost point of the disc is already below the horizon.

Actually, the Moon's angular diameter, regardless of its height above the horizon, is always approximately 0.5°, but due to the moon illusion, observers can perceive the Moon on the horizon to be almost twice as large as when it is located on the zenith (table 1). The moon illusion can have

Table 1. Magnitude $Q = \alpha_{perceived}/\alpha_{real}$ of the moon illusion measured in earlier psychophysical experiments, where $\alpha_{perceived}$ is the angular diameter of the retinal afterimage spot or the distance between the projected lunar/solar disc or spot points perceived by the test persons, and α_{real} is the real angular diameter of the lunar/solar disc, or $\alpha_{perceived}$ and α_{real} is the angular diameter of the artificial lunar disc at the horizon and the zenith, respectively.

publications	magnitude Q of moon illusion
Holway & Boring [11,12]	1.8
Taylor & Boring [13]	1.6
Kaufman & Rock [14,15], Rock & Kaufman [16]	1.0, 1.5
Enright [17–20]	1.1, 1.2
Suzuki [21]	1.5
Suzuki [22]	1.0, 1.2, 1.3
Suzuki [23]	1.0, 1.1, 1.2, 1.3, 1.4
Ross & Cowie [24]	1.0, 1.5

several different components and triggers: distance, angular extension and geometric/physical diameter. Over the centuries, several theories have tried to explain the moon illusion, but to date, none has become monopolistic [25–28]. In the electronic supplementary material, we briefly described the most famous theories, on the basis of which one can only state with certainty the following: (i) most people perceive the Moon/Sun to be larger in angular diameter and closer when it is on the horizon than when it is close to the zenith in the sky. (ii) There can be no physical/optical causes for this visual illusion, as the actual angular diameter of the Moon and Sun seen from the Earth is practically constant, which can be clearly demonstrated by photographing them.

Although several psychophysical experiments have been performed to study the moon illusion, their results have sometimes contradicted each other. In the electronic supplementary material, we summarized the most relevant experiments [11–24,29–32], and table 1 lists the magnitude Q of the moon illusion measured in these experiments.

Artists frequently displayed/display the full Moon or the Sun in their paintings. If the Moon/Sun appears near the horizon, its painted disc is often exaggeratedly large, as in many paintings of Vincent Villem van Gogh (1853–1890), or in the painting of Fernando de Gorocica entitled ‘Ella y los Pescadores’ from 2012 (figure 1*b*). This may often be due to the moon illusion, or it might be the choice of artists to paint something different from what they actually see, for example. How great is the magnitude of moon illusion of painters? How different are the magnitudes of size enlargement of depicted lunar and solar discs? To answer these questions, we measured these magnitudes on 100 paintings collected from the period between 1534 and 2017 [33]. In psychophysical experiments, we also investigated the magnitude of moon illusion of 10 test persons who had to estimate the size of the lunar/solar disc on the selected 100 paintings from which the Moon/Sun was digitally retouched, and on 100 landscape photographs without Moon/Sun [33]. We compared our numerical results with those of earlier psychophysical experiments [33].

2. Material and methods

To measure the magnitude Q of moon illusion in 100 paintings and 100 landscape photographs, we conducted three psychophysical experiments with the same 10 test persons of ages 21–63 in a laboratory room with daylight illumination. They were collected among our university colleagues and students as volunteers, who did not know the aim (i.e. studying the moon illusion) of the experiments. The authors of this paper were not among these 10 participants. In our earlier similar

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Figure 1. Selection from the pictures of paintings with a Moon (*a–c*) and a Sun (*d*,*e*) used in our psychophysical experiments studying the moon illusion. (A-4) Thomas Cole (1838): Tower with moonlight (source: oceansbridge.com). (B-31) Fernando de Gorocica (2012): Ella y los Pescadores (Wikimedia). (C-59) Csontváry Kosztka Tivadar (1901): Full Moon over Taormina (Wikimedia). (D-71) Claude Monet (1872): Sunrise impression (Wikimedia). (E-80) Ivan Aivazovsky (1845) The bay Golden Horn (Wikiart). Panels A, B, C, D and E show paintings 4, 31, 59, 71 and 80, respectively, among the 100 paintings listed in the electronic supplementary material. (Online version in colour.)

psychophysical experiments, we used also 10 test persons [34–41]. For every $x_1, x_2, \ldots, x_n$ data series, we calculated the average x and its standard deviation σ as follows:

$$\left.\begin{aligned} x &= \frac{1}{n}\sum_{i=1}^{i=n} x_i, \\ \sigma &= \sqrt{\frac{\sum_{i=1}^{i=n}(x_i - x)^2}{n}} \end{aligned}\right\} \qquad (2.1)$$

(a) Collection of paintings and landscape photographs

Using the Internet, we collected randomly 100 pictures of paintings depicting the (mostly full) Moon or the Sun, without any preconception and independently of fashion. Figure 1 shows five examples for such paintings. Our only attempt was to find such paintings from a period as wide as possible. As a result, this period was 1534–2017. Paintings 1–70 displayed the Moon, while paintings 71–100 depicted the Sun. Electronic supplementary material, appendix SA contains the 100 retouched paintings without lunar/solar discs used in experiment 1. Electronic supplementary material, appendix SB shows the 100 original (unretouched) paintings used for distance estimation in experiment 2. Electronic supplementary material, appendix SC lists the randomly selected 100 landscape photos used in experiment 3. In the majority (91) of landscape photographs, the Moon or the Sun was not visible. In the few (9) photos with Moon/Sun, we retouched the lunar/solar disc without any remaining clue of its original position and size in the picture. Electronic supplementary material, table S1 contains the data of paintings used in experiments 1 and 2, as well as the reference objects with their assumed linear size in metres. Electronic supplementary material, table S2 briefly characterizes the landscape photos used in experiment 3.

(b) Estimation of the size of painted Moons and Suns in experiment 1

In experiment 1, our computer program presented 100 different paintings in a random order for the 10 test persons separately on a monitor (50 cm × 33 cm, horizontal × vertical). For each picture, we previously set the position where a white/yellow disc representing the Moon/Sun appeared. The program read these positions from a data file. At a given picture, the white/yellow disc for Moon/Sun paintings only appeared after the test person turned the mouse wheel. The diameter of the disc could be changed by turning the mouse wheel. After pressing the *enter* key, the program saved the radius of the disc in pixels set by the test person into a text file and presented the next picture.

Using the GNU Image Manipulator Software in each painting, the Moon or Sun was retouched without any remaining clue hinting to its original position and size. Each test person performed experiment 1 ten times, maximum twice per session to avoid memorizing the disc size they set previously.

(c) Distance estimation in paintings in experiment 2

In experiment 2, the unretouched original versions of paintings with Moon/Sun used in experiment 1 were presented for the 10 test persons on the same monitor (50 cm × 33 cm) as used in experiment 1. In these pictures, we previously selected an object (mostly a human, animal, ship, building or tree) with an approximately well-known real height. Electronic supplementary material, table S1 contains these reference objects with their assumed linear size in metres used for distance calibration. In most paintings, these reference objects were standing humans, whose assumed average height was 1.62 m for males, 1.5 m for females and 1.3 m for children. We could also assume well the sizes of different reference animals. The least accurate size estimation happened for ships and trees.

Although the average human height h near 1534 (from which the earliest painting studied by us originated) might have been slightly smaller than that nowadays, we neglected this corporal feature, because (i) the exact temporal change (probably increase) of h as a function of time is unknown, and (ii) the year/decade/century is ambiguous after which h should be considered as enhanced relative to the earlier epoch.

In each picture, the calibration object was marked by a red dot. The test person wrote the estimated distance (in metres) of the calibration object into an input box, which data were saved in a text file after pressing the *enter* key, then the program presented the next picture. Experiment 2 was performed five times by each test person once per session to minimize the possibility of memorizing the distance estimates. If in a painting the linear size (height, length, width) of a reference object is d_{metre} measured in metres, and its distance from the painter is D_{metre} in metres, then the object's angular size is

$$\delta = 2 \cdot \arctan\left(\frac{0.5 d_{\mathrm{metre}}}{D_{\mathrm{metre}}}\right). \tag{2.2}$$

Using the computer program of experiment 1, we measured the radius $r_{\mathrm{pixel}}^{\mathrm{painted}}$ (in pixels) of the lunar/solar disc and the linear size d_{pixel} (in pixels) of the reference objects selected for estimation of their distances in the original, unretouched pictures of paintings. Knowing the assumed linear size d_{metre} (in metres) of the reference objects (electronic supplementary material, table S1) and their distance D_{metre} (in metres) estimated in experiment 2, we calculated the angular size δ of the reference objects with the use of equation (2.2). Then, with the knowledge of the optical fact that the angular diameter of both the Moon and the Sun is approximately 0.5°, we calculated the radius $r_{\mathrm{pixel}}^{\mathrm{real}}$ (in pixels) with which the painters should have depicted the Moon/Sun in order to paint it realistic

$$r_{\mathrm{pixel}}^{\mathrm{real}} = d_{\mathrm{pixel}} \frac{0.5^\circ}{\delta} = \frac{0.5^\circ d_{\mathrm{pixel}}}{2 \cdot \arctan(0.5 d_{\mathrm{metre}}/D_{\mathrm{metre}})} \tag{2.3}$$

Finally, we calculated the ratio $Q = r_{\mathrm{pixel}}^{\mathrm{painted}}/r_{\mathrm{pixel}}^{\mathrm{real}}$, which was considered as the magnitude of moon illusion of painters.

Although the estimation of the distance to reference objects in the studied paintings is itself subjective, there is no other quantitative way to determine the approximate size (angular diameter) of painted moons/suns. The estimation of the distance to reference objects by test persons as performed in our experiment 2 is the usual and proper method, the results of which are averaged distance values judged by the collective experience/knowledge of test persons. In our experiments, the test persons observed the pictures on a monitor with 50 cm × 33 cm horizontal and vertical dimensions, respectively. Since the size of the original paintings and the distance of painters to reference objects were unknown, we could not project the painted sceneries with Moon/Sun on a vertical white wall/screen in order to simulate the original dimensions.

(d) Magnitude of moon illusion versus lunar/solar elevation in experiment 2

One of the characteristics of moon illusion is that the size of the Moon/Sun perceived by observers decreases with increasing elevation angle above the horizon. To test the possible occurrence of this tendency, we studied the magnitude Q of moon illusion of painters and test persons in experiment 2 as a function of the elevation angle θ of the lunar/solar disc centre above the horizon. Elevation θ was calculated from the following equation:

$$\theta = \delta \frac{h_{\mathrm{pixel}}}{d_{\mathrm{pixel}}} = \frac{2 h_{\mathrm{pixel}}}{d_{\mathrm{pixel}}} \arctan\left(\frac{d_{\mathrm{metre}}}{2 D_{\mathrm{metre}}}\right), \tag{2.4}$$

where h_{pixel} (in pixels) is the height of the lunar/solar disc centre above the horizon, d_{pixel} (in pixels) is the linear size (height) of the reference object used for distance estimation, d_{metre} (in metres) is the assumed size (height) of the reference object in metres (electronic supplementary material, table S1), D_{metre} (in metres) is the distance of the reference object estimated in experiment 2 and δ is the angular size of the reference object expressed by equation (2.2).

(e) Estimation of the size of Moon and Sun in landscape photographs in experiment 3

In experiment 3, 100 landscape photographs were presented in a random order on the same monitor (50 cm × 33 cm) in the same way as in experiment 1. In most of the photos, there was no Moon or Sun. In the few exceptions with Moon/Sun, we retouched the lunar/solar disc, just as we did with the paintings. Experiment 3 was performed 10 times, maximum twice per session to avoid memorizing the size of the white/yellow lunar/solar disc set by test persons previously.

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3. Results

(a) Estimated size of painted Moons and Suns in experiment 1

Figure 2 shows the average r_{ave} and standard deviation Δr of the lunar/solar disc radius r set by test persons as a function of the painting number N in experiment 1. In Moon paintings, r_{ave} was smaller (33.8 ± 13.0 pixels) than in Sun paintings (37.3 ± 14.0 pixels). The r_{ave} of lunar discs was the smallest in painting 45 and the largest in painting 10, while r_{ave} of solar discs was minimal and maximal in paintings 74 and 83, respectively. Electronic supplementary material, figures SD1–SD10 in appendix SD show $r_{ave} \pm \Delta r$ of lunar/solar discs estimated by test persons in 100 paintings in experiment 1 as a function of the painting number N. Δr was the smallest for test person 7 and the largest for test person 9.

(b) Estimated reference distances in paintings in experiment 2

Figure 3 shows the average ± s.d. of distance d of the reference objects as a function of the painting number N set by test persons in 100 paintings in experiment 2. In general, longer reference distances had larger standard deviations.

(c) Estimated size of the Moon and Sun in landscape photos in experiment 3

Figure 4 shows the average r_{ave} and standard deviation Δr of radius r of lunar/solar discs as a function of the photo number N set by test persons in 100 landscape photos in experiment 3. r_{ave} of the Moon was smaller (25.9 ± 9.2 pixels) than that of the Sun (27.8 ± 8.0 pixels). The r_{ave} of the lunar disc was the smallest in photo 21 and the largest in photo 3, while r_{ave} of the solar disc was minimal in photo 99 and maximal in photo 79. Electronic supplementary material, figures SE1–SE10 in appendix SE show $r_{ave} \pm \Delta r$ of lunar/solar discs estimated by test persons in 100 landscape photos in experiment 3 as a function of the photo number N. Δr was the smallest for test person 5 and the largest for test person 9.

(d) Measured magnitudes of moon illusion

(i) Moon illusion of test persons measured in paintings (experiment 1)

In experiment 1, we measured the radius $r_{painted}$ of painted Moons/Suns in 100 paintings and compared it with the radius r_{test} of lunar/solar discs set by test persons. Figure 5 shows the average ± s.d. of the magnitude $Q = r_{test}/r_{painted}$ of moon illusion as a function of the painting number N. Test persons set the lunar disc $Q = 1.6 \pm 0.6$ times larger than the painted Moon and estimated the solar disc $Q = 1.7 \pm 0.4$ times larger than the painted Sun (table 2).

(ii) Moon illusion of painters and test persons measured in distance-calibrated paintings (experiment 2)

Since the moon illusion might have also affected painters—that is they might depict the Moon/Sun with an angular diameter larger than the real 0.5°—, we compared the sizes of painted lunar/solar discs with those calculated on the basis of the estimated distances of reference objects in paintings. Figure 6 shows the magnitude $Q = r_{painted}/r_{real}$ of moon illusion of painters as a function of the painting number N, where $r_{painted}$ is the radius (in pixels) of painted Moons/Suns, and r_{real} is the real radius (in pixels) of lunar/solar discs calculated on the basis of the average reference distances set by test persons in 100 paintings in experiment 2. The painters depicted the Moon $Q = 2.1 \pm 1.6$ times larger than the reality, and the Sun was painted $Q = 1.8 \pm 1.2$ times larger than its real size (table 2). It is remarkable that Q of painters was predominantly higher than 1 (figure 6): among the 100 studied paintings, there were only 11 ones with $Q \ll 1$, Q approximated 1 in 18 cases, and 71 paintings had $Q \gg 1$. These data demonstrate that painters may be very often subjected to the moon illusion.

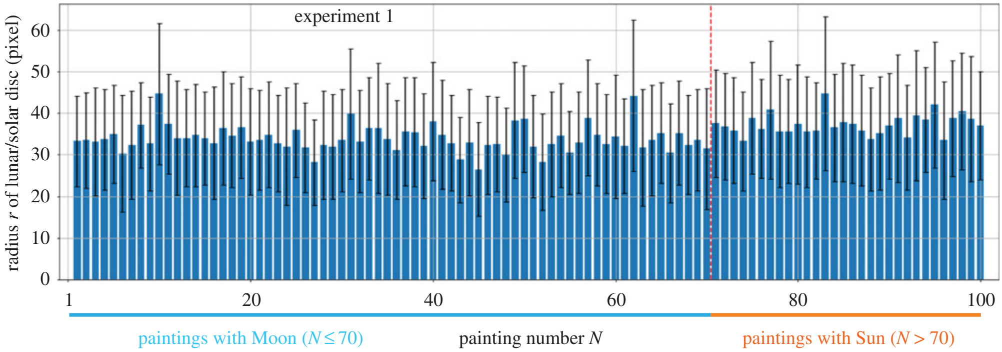

Figure 2. Average $\pm$ s.d. of radius r (in pixels) of lunar/solar discs averaged for 10 test persons and 10 tests versus the painting number N ($1 \le N \le 70$: paintings with Moon, $71 \le N \le 100$: paintings with Sun) set by test persons in 100 paintings in experiment 1. (Online version in colour.)

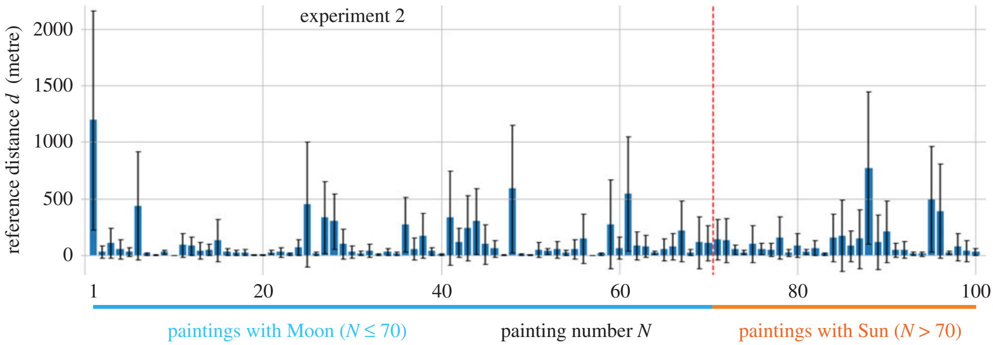

Figure 3. Average $\pm$ s.d. of distance d (in metres) of the reference objects averaged for 10 test persons and 5 tests versus the painting number N ($1 \le N \le 70$: paintings with Moon, $71 \le N \le 100$: paintings with Sun) set by test persons in 100 paintings in experiment 2. (Online version in colour.)

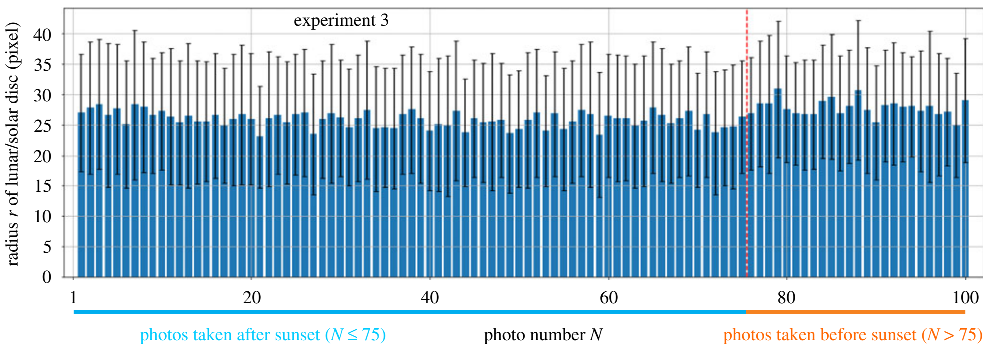

Figure 4. Average $\pm$ s.d. of radius r (in pixels) of lunar/solar discs averaged for 10 test persons and 10 tests versus the photo number N ($1 \le N \le 75$: photos taken after sunset, $76 \le N \le 100$: photos taken before sunset) set by test persons in 100 landscape photos in experiment 3. (Online version in colour.)

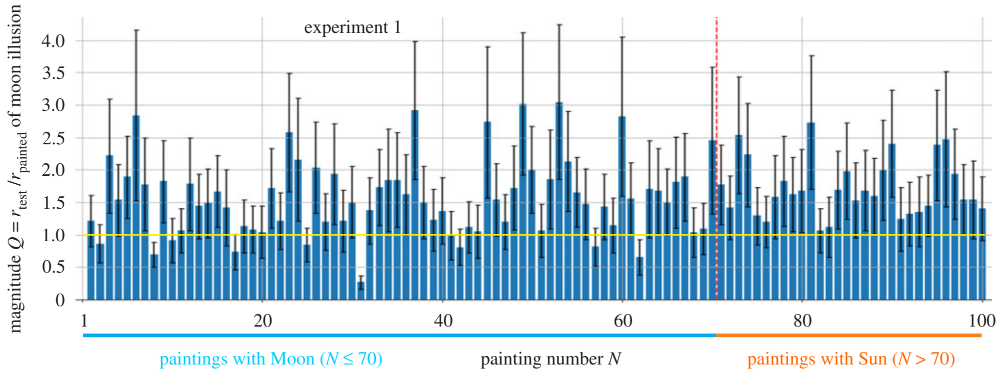

Figure 5. Average ± s.d. of the magnitude $Q = r_{test}/r_{painted}$ of moon illusion averaged for 10 test persons and 10 tests versus the painting number N ($1 \leq N \leq 70$: paintings with Moon, $71 \leq N \leq 100$: paintings with Sun), where r_{test} is the radius of lunar/solar discs set by test persons, and $r_{painted}$ is the radius of painted Moons/Suns in 100 paintings in experiment 1. (Online version in colour.)

Table 2. Average ± s.d. of the magnitude Q of moon illusion measured in our psychophysical experiments in the case of N_{Moon} paintings with Moon and N_{Sun} paintings with Sun as well as 100 landscape photos for test persons and painters.

experiment	magnitude Q of moon illusion			
1.	test persons: $Q = r_{test}/r_{painted}$			
$N_{Moon} = 70$	Moon painting	Sun painting		
$N_{Sun} = 30$	1.6 ± 0.6	1.7 ± 0.4		
2.	test persons: $Q = r_{test}/r_{real}$		painters: $Q = r_{painted}/r_{real}$	
$N_{Moon} = 69$	Moon painting	Sun painting	Moon painting	Sun painting
$N_{Sun} = 30$	2.9 ± 1.4	2.8 ± 1.6	2.1 ± 1.6	1.8 ± 1.2
3.	test persons: $Q = r_{test}/r_{real}$			
$N_{Moon} = 75$	Moon photo	Sun photo		
$N_{Sun} = 25$	1.6 ± 0.4	1.7 ± 0.5		

Figure 7 shows the average ± s.d. of $Q = r_{test}/r_{real}$ as a function of the painting number N, where r_{test} is the radius (in pixels) of lunar/solar discs set by test persons in experiment 1, and r_{real} is the radius (in pixels) of Moons/Suns calculated on the basis of the average reference distances set by test persons in 100 paintings in experiment 2. Test persons set the lunar disc radius $Q = 2.9 \pm 1.4$ times larger than the reality, and the radius of the solar disc was set $Q = 2.8 \pm 1.6$ times larger than its real value (table 2).

Considering the magnitude $Q = r_{painted}/r_{real}$ of moon illusion as a function of the elevation angle θ of the centre of painted lunar/solar discs in paintings with Moon/Sun, we found that the regression lines fitted to the (Q, θ) data pairs did not show the expected decreasing $Q(\theta)$ function: in paintings depicting the Moon (electronic supplementary material, figure S1) or the Sun (electronic supplementary material, figure S2), Q more or less increases with increasing θ. Among the investigated 69 Moon paintings only in painting 69 with the largest $Q = 8.5$ was θ of the Moon larger than 20° (electronic supplementary material, figure S1). If we removed the three Moon paintings with the largest Q-values (69: $Q = 8.5$, $\theta = 30^o$; 55: $Q = 7.8$, $\theta = 10.64^o$; 56: $Q = 7.4$, $\theta = 11.22^o$) from the analysis, the increasing tendency of the regression line remained, though with a smaller slope (electronic supplementary material, figure S1). In the case of the studied 30

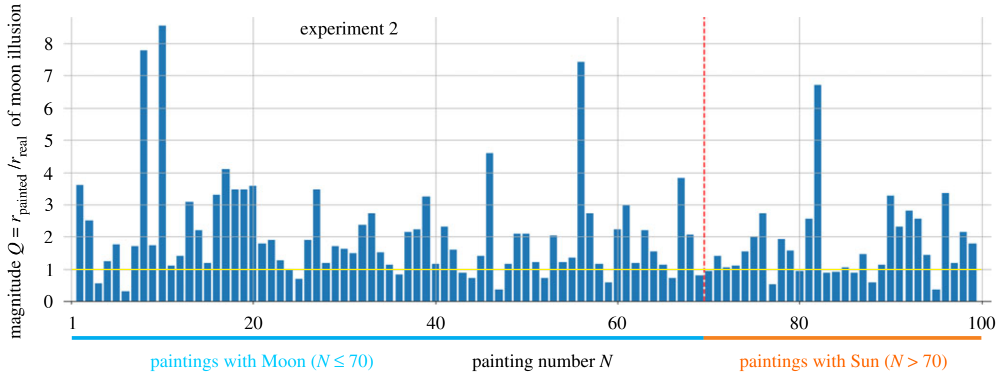

Figure 6. Magnitude $Q = r_{\text{painted}}/r_{\text{real}}$ of moon illusion of painters versus the painting number N ($1 \le N \le 70$: paintings with Moon, $71 \le N \le 100$: paintings with Sun), where r_{painted} is the radius (in pixels) of painted Moons/Suns, and r_{real} is the real radius (in pixels) of lunar/solar discs calculated on the basis of the average reference distances set by test persons in 100 paintings in experiment 2. (Online version in colour.)

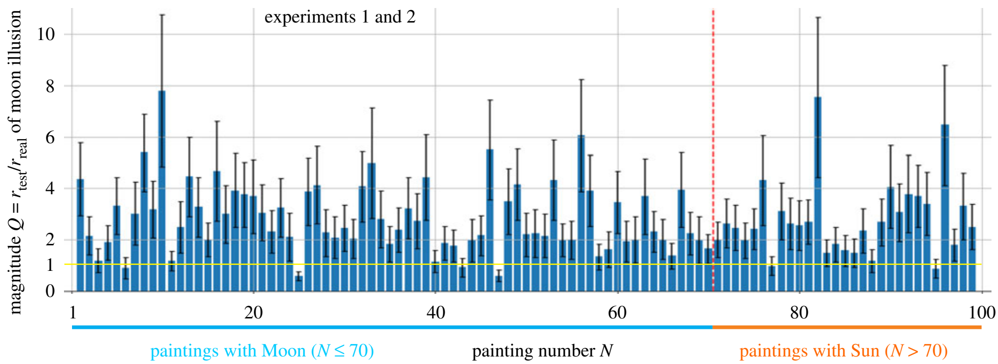

Figure 7. Average ± s.d. of the magnitude $Q = r_{\text{test}}/r_{\text{real}}$ of moon illusion averaged for 10 test persons versus the painting number N ($1 \le N \le 70$: paintings with Moon, $71 \le N \le 100$: paintings with Sun), where r_{test} is the radius (in pixels) of lunar/solar discs set by test persons in experiment 1, and r_{real} is the radius (in pixels) of Moons/Suns calculated on the basis of the average reference distances set by test persons in 100 paintings in experiment 2.

Sun paintings, the $Q(\theta)$ regression line was almost horizontal (electronic supplementary material, figure S2), thus its expected decreasing tendency did not occur either.

Considering the magnitude $Q = r_{\text{test}}/r_{\text{real}}$ of moon illusion as a function of the elevation angle θ of the lunar/solar disc centre set by test persons in paintings with Moon/Sun, the regression lines fitted to the (Q, θ) data pairs were similarly more or less increasing (electronic supplementary material, figures S3 and S4) as in the case of the painters (electronic supplementary material, figures S1 and S2).

(iii) Moon illusion of test persons measured in landscape photos (experiment 3)

In experiment 3, we measured the real radius r_{real} (in pixels) of the Moon/Sun, as well as the height h (in pixels) above the horizon and the radius r_{test} (in pixels) of lunar/solar discs set by test persons in 100 landscape photos. Since the angular radius of the Moon/Sun is always approximately 0.25°, the angular height of the lunar/solar disc above the horizon is $\theta = 0.25° h/r_{\text{real}}$. Figure 8 shows the average ± s.d. of the magnitude $Q = r_{\text{test}}/r_{\text{real}}$ of moon illusion as a function of the photo number N in experiment 3. Test persons set the radius of the Moon 1.6 ± 0.4 times larger than the reality, and the radius of the Sun was set 1.7 ± 0.5 times larger than its real value (table 2).

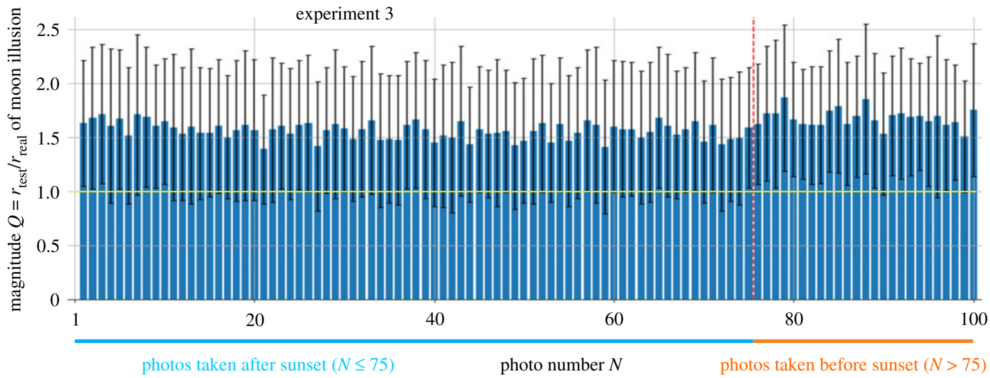

Figure 8. Average $\pm$ s.d. of the magnitude $Q = r_{test}/r_{real}$ of moon illusion averaged for 10 test persons and 10 tests versus the photo number N ($1 \leq N \leq 75$: photos taken after sunset, $76 \leq N \leq 100$: photos taken before sunset), where r_{test} is the radius of lunar/solar discs set by test persons in 100 landscape photos in experiment 3, and r_{real} is the real radius of the Moon/Sun.

The regression lines $Q(\theta)$ fitted to the data points slightly increased in the case of both kinds of landscape photographs taken after and before sunset (electronic supplementary material, figures S5 and S6). Thus, we did not find decreasing Q with increasing θ, being characteristic of the moon illusion.

4. Discussion

In this work, we developed a novel technique for assessing the extent of the moon illusion and reported a non-direct measure Q of the moon illusion as observed in art. We emphasize that we do not know if the artists—whose paintings were studied—were only painting while observing the Moon/Sun, or if their paintings were created in part based on their memory of the size of the Moon/Sun. We acknowledge that moon/sun size in some of the investigated paintings may be based on direct observation, whereas in others, the size portrayed may be based on an artist's memory.

From our psychophysical experiments, we concluded that the moon illusion appeared in paintings and landscape photographs, too. While most theories explaining the moon illusion expect the perceived size of the lunar/solar disc to increase as they approach the horizon, we did not experience such an effect. One of the bases of the apparent distance theory of moon illusion is that the angular diameter of the Moon is constant and only the perceived diameter changes, which we could not study in our experiments due to the lack of spatial effect. The effect of the elevation angle of the ocular axis in the skull can be disregarded, because on the screen used in our experiments, the test persons could always observe the lunar/solar disc with a nearly horizontal ocular axis.

The reasons why painters illustrated the Moon larger than the Sun are probably aesthetic [42]: in paintings, the larger Moon may be less distracting and could fit better into a dark environment, while an oversized solar disc may become distracting due to its brightness.

Considering our results obtained for landscape photos, test persons can be divided into two groups: (i) some of them assumed the Sun larger than the Moon, and (ii) others imagined both celestial bodies with nearly the same size. The reasons for this may be the following: (i) the Moon is easy to observe on cloudless evenings/nights, because its relatively dim light does not dazzle our eyes despite the darkness. Thus, the size of the lunar disc can be well estimated. By contrast, because the Sun is not easy to observe in the daytime sky due to its dazzlingly bright light, it is difficult to estimate the boundary of the solar disc, which can result in an overestimation. (ii) At sunset or sunrise, a dim orange or red solar disc can be observed with the naked eye for an extended period. Because the Sun is on or near the horizon at this time, we perceive it larger because of the moon illusion. This may affect the internal image of the Sun in humans, which appeared in our experiments as a larger solar than lunar disc.

According to the moon illusion, we expected that as the elevation angle above the horizon increases, painters and test persons overestimate the size of the Moon/Sun to a gradually decreasing degree. Our results (electronic supplementary material, figures S1–S4) differing from this expectation may be mainly explained by the limited range of the elevation angle θ of the Moon/Sun in the studied paintings.

5. Conclusion

The conclusions of our three psychophysical experiments performed on 10 test persons aged between 21 and 63 years—meaning 10 (test persons) $\times$ 100 (paintings/landscape photographs) $\times$ 25 (experiment 1 performed 10 times + experiment 2 performed 10 times + experiment 3 performed 5 times) = 25000 individual measurements—are the following:

— Test persons in experiment 1 overestimated the imaginary size of the lunar disc and the solar disc $Q = 1.6 \pm 0.6$ and $Q = 1.7 \pm 0.4$ times, respectively, relative to the size painters originally depicted. Test persons thus assumed the Sun on average 1.1 times larger than the Moon.

— In experiment 2, test persons overestimated the size of the Moon $Q = 2.9 \pm 1.4$ times and the size of the Sun was assumed to be $Q = 2.8 \pm 1.6$ times larger compared to the real lunar/solar disc calculated from the reference distances estimated by test persons in unretouched paintings.

— Compared to the actual lunar/solar disc calculated from the reference distances estimated by test persons in unretouched paintings in experiment 2, painters overestimated the size of the Moon on average $Q = 2.1 \pm 1.6$ times, while the Sun was painted $Q = 1.8 \pm 1.2$ times larger. The Moon was thus depicted by painters on average 1.2 times larger than the Sun.

— In landscape photos, test persons of experiment 3 overestimated the size of the imagined Moon $Q = 1.6 \pm 0.4$ times, and the imaginary Sun was assumed $Q = 1.7 \pm 0.5$ times larger than the real one. In these photographs, test persons imagined the Sun 1.08 times larger than the Moon.

— The majority of values 1.6, 1.7, 1.8, 2.1, 2.8 and 2.9 measured in our experiments for the magnitude Q of moon illusion (table 2) are larger than the values 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 and 1.8 measured in previous psychophysical experiments (table 1). The magnitudes $Q = 1.8$, 1.6 and 1.5 measured by Holway & Boring [11,12], Taylor & Boring [13] and Ross & Cowie [24] are the closest to our results. The methodology of experiment conducted by Ross & Cowie [24] was the most similar to our experiments, while the methods of the other previous experiments differed significantly from those of ours.

— Due to the narrow range of Moon/Sun heights in the paintings and landscape photographs studied in our experiments, the height dependence characteristic of the moon illusion was not observed by us: we did not find a decrease in the size (i) of the lunar/solar disc depicted in paintings and (ii) assumed by test persons in paintings and landscape photos with increasing elevation angle of the Moon/Sun.

Ethics. For our psychophysical experiments, no institutional permission, licence or approval was necessary. The director of the Institute of Eötvös University, Prof. Zsolt Frei has confirmed that our institute does not require formal ethical approval for studies of this nature. Furthermore, all 10 participants of our psychophysical experiments gave verbal consent.

Data accessibility. Our paper has the following electronic supplementary material: Theories of the moon illusion; Earlier psychophysical experiments studying the moon illusion; electronic supplementary material, table S1: data of paintings (1–70: depicting a Moon, 71–100: displaying a Sun) used in experiments 1 and 2, and the chosen reference objects with their assumed linear size in metres; electronic supplementary material, table S2: brief characterization of the landscape used in experiment 3; electronic supplementary material, figures S1–S6; electronic supplementary material, appendix SA: 100 retouched paintings without lunar/solar discs used in experiment 1; electronic supplementary material, appendix SB: 100 paintings used for distance

estimation in experiment 2; electronic supplementary material, appendix SC: 100 landscape photos used in experiment 3; electronic supplementary material, appendix SD: radii of the lunar/solar discs estimated by the test persons in paintings in experiment 1 with electronic supplementary material, figures SD1–SD10; electronic supplementary material, appendix SE: radii of the lunar/solar discs estimated by the test persons in landscape photos in experiment 3 with electronic supplementary material, figures SE1–SE10.

Authors' contributions. All authors gave final approval for publication and agree to be held accountable for the work performed therein. Z.K., Z.U., E.P. and G.H.: substantial contributions to conception and design, performing psychophysical experiments and drafting the article and revising it critically; Z.U.: software development; Z.K. and G.H.: collecting paintings; E.P.: taking landscape photos; Z.K. and G.H.: data visualization and data analysis and interpretation.

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