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Moon Illusion Explained on the Basis of Relative Size

The moon looks small overhead not because it seems close but because of the broad extent to the horizon.

Frank Restle

The most remarkable natural illusion is the size of the moon. The moon appears larger at horizon, approximately 1.2 to 1.5 times the apparent diameter at zenith. Since the visual angle of the moon is always 0.5°, there is no physical basis for the illusion; it is therefore a perceptual phenomenon.

Of the known illusions, the moon illusion is notably large and reliable. The only artificial illusions of comparable magnitude involve repeated use of the same simple inducing principle or depend heavily on perspective drawing. The moon illusion, however, changes the size of a reasonably simple white circle (there is nothing to indicate that the shadows on the face of the moon affect the illusion) in a plain sky. The usual lines and swirls used to generate artificial illusions are all absent in the case of the moon illusion, which nevertheless is among the greatest in magnitude.

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One unusual characteristic of the moon illusion, as observed in nature, is that the two "apparent sizes" must be viewed at different times, because the moon takes several hours in transit from horizon to zenith. It is possible, however, by use of mirrors or other artificial devices, to obtain more conventional psychophysical comparisons; and the magnitude of the illusion is measured at about 1.3 to 1. The magnitude of the illusion does not depend on the fact that measurement is not ordinarily by direct comparison.

A second unusual characteristic of the moon illusion is that one of the objects viewed (the zenith moon) is overhead and hence is viewed with the eyes turned upward, with the head turned upward, or both. The hypothesis that the moon illusion depends on these factors was given some support by Boring and Holway, but in their psychophysical method the subject matched the apparent size of the moon with the apparent size of a disk that was visible only a few feet away and well enough illuminated to have a visible texture.

Rock and Kaufman (*1, 2*) reported a series of studies that effectively contradicted the Boring and Holway experiments. They established that a moon looks large near the horizon (wherever the horizon is, even if displaced overhead) and looks small when it is far from the horizon and in empty space (even if that space is straight ahead).

Apparent Distance Hypothesis

How do Rock and Kaufman propose to explain the moon illusion? They note that common observation and some experimental studies indicate that the sky appears to have the shape not of a hemisphere but of a flattened soup bowl, so that the horizon seems farther away from an observer than does the sky overhead. How this apparent distance would produce the moon illusion is shown in Fig. 1.

The visual angle subtended by the moon is fixed at approximately 0.5°. To the observer, the moon seems to be on the surface of the sky, and it appears more distant near the horizon than at zenith. When two actual objects subtend identical visual angles but are at different distances from the observer, the more distant object can be calculated to be the larger object. The observer performs this calculation and deduces that the horizon moon must be the larger object; hence, it appears larger.

This apparent distance hypothesis suffers from a number of difficulties. The first objection is that no calculation is required to produce the moon illusion because it is a naive perception. However, the apparent distance theory of visual illusions habitually disregards phenomenology, for it assumes that observers always correct their sense impressions and are not conscious of the process.

Rock and Kaufman (*2*) pinpoint another difficulty: "The zenith moon is at an indeterminate distance and is therefore of indeterminate size. The horizon moon appears very far away, and objects at very great distances also are of somewhat indeterminate size" (*2*, p. 1030). In most applications of the apparent distance hypothesis, the observer is dealing with familiar objects and distances. Because the moon is known to be larger than any terrestrial object, and also farther away, the conscious methods of judging size familiar to surveyors, golfers, and marksmen do not really apply to judging the size of the moon.

If the zenith moon appears smaller because it appears closer, we are entitled to ask why the zenith sky should appear close. If, as it appears, there are no cues to the distance of the sky, then the sky should be indefinite in distance and should not form a definite surface. For example, smaller stars could appear more remote (as indeed they are) and brighter stars closer. In that case, the moon would appear far closer than anything else in a clear sky, and the shape of the sky would have no bearing on either the location or the apparent size of the moon. We obviously cannot apply any simple, systematic principle to all objects in the sky without losing the basis for the moon illusion.

The visual information given to the eye would be perfectly consistent with a hemispherical sky and a moon of constant size. No explanation can adequately account for that simple solution not being chosen by the eye, particularly since there is no definite information as to the remoteness of the zenith sky.

In fact, the argument can be reversed in direction, with incorrect results. Rock and Kaufman assume that the overhead sky appears closer than the horizon and thereby explain the moon illusion. If it is assumed, instead, that the moon looks smaller overhead than near the horizon, then, in the absence of conflicting cues to remoteness, it follows that the sky should appear more remote overhead than at the horizon, for it is well known that smaller

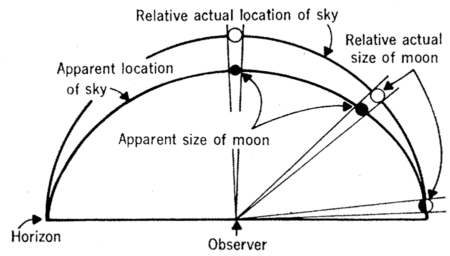

Fig. 1. Relation of apparent distance of the moon to its apparent size. (Top arc) Projected position of the moon based upon (i) its constant visual angle of 0.5° and (ii) the hypothesis that it is of constant size. (Bottom arc) Apparent size of the moon, reduced at zenith because of the large angular separation from horizon; and apparent remoteness, also reduced for the same reason. The effect is calculated with $b = 0.05$. [After Kaufman and Rock (*1*)]

objects appear farther away. In this way, it can be predicted that the sky will appear not as a flattened soup bowl but instead like a ten-gallon hat, higher at zenith.

The effort to handle this theory leads Rock and Kaufman to some mysterious assertions; for example, "In the case of the moon illusion we have to . . . say that the distance influences size perception (in the sense that one moon looks larger than the other) despite the fact that neither moon appears to be of any specifiable size. That is, in the case of the moon illusion it would seem that distance affects the relative-extensity experience, not a relative-linear-size experience" (*2*). If this statement means what it seems to mean, it is entirely out of harmony with the apparent distance theory, because it is the linear size of an object that is calculated from its visual angle and known distance.

Finally, the logic of the situation reveals that the apparent distance hypothesis is not a useful explanation of the moon illusion, because we cannot calculate the actual magnitude of illusion to be expected except with prior knowledge of apparent distance. The apparent distance is itself illusory, however, and is in fact the dependent variable of a perceptual experiment. Therefore, to attribute the apparent size of the moon to the apparent remoteness of the sky is merely to shift the burden of explanation from one phenomenon to another of the same type, without explaining either. Although there is theoretical merit in relating two such variables, the result is not an explanation but a simplification.

Relative Size Hypothesis

The alternative hypothesis does not depend on impressions of remoteness or other interpretations that the observer may put on the information in his visual field. It deals instead with the content of the visual field itself (*3*). In this respect, the relative size hypothesis is an "objective" rather than an "egocentric" theory of the moon illusion, and it agrees with the position established experimentally by Kaufman and Rock (*1*).

The basic assumption of this relative size hypothesis (*3*, *4*) is that a size is always judged relative to other extents in the visual field. Thus the judged size of an object will depend not only on the extent of that object itself but also on the extents in its visual surround and in other, past visual fields with which the present object may be compared. The most elementary demonstration of this theory is the perception of the length of a line within a box of varying size, when the remainder of the visual field is completely without structure (dark) (*4*). In such a field, the judged length of the line should depend on the ratio of line length to box height (*5*, *7*, *8*).

In a more complex field, there are many stimuli with which the test object can be compared. A mathematical treatment of this problem can be drawn from adaptation level theory (*6*), in which the influences of various objects in the field are summarized by their weighted geometric mean. This summary value is called the adaptation level (A), and the judgment of any stimulus depends on the ratio of the stimulus to A.

Let M be the magnitude (diameter) of the moon to be judged. Then

$$J(M) = M/A \qquad (1)$$

where $J(M)$ is the judgment of M and where A is the adaptation level. The adaptation level is calculated as the weighted geometric mean of all relevant influences. An influence is a distance or magnitude, with the same dimensions as M, which exists somewhere in the visual field or memory. In a typical experiment, the field consists of one background object (with value B) used to influence judgment and of the conglomerate of other factors (with net value K) that do not vary systematically during the experiment. Then

$$A = B^b K^{1-b} \qquad (2)$$

The weight b is the probability that M will be compared with the inducing background object, and it indicates the magnitude of illusory effects; and $1 - b$, the weight of constant factors, indicates the degree to which $J(M)$ is based on a constant frame of reference and therefore approximates being objectively correct.

From this point of view, an illusion simply represents a change in adaptation level A. Therefore, to explain the moon illusion this approach must assert that A is larger when the moon is near zenith than when the moon is near the horizon.

In a complex field the adaptation level for extent is different in different parts of the field. If x is a point in a region surrounded by large figures, A_x will be relatively large; if y is a point in a region surrounded by smaller figures, A_y will be small. The moon illusion is explained by saying that A_z, the adaptation level near the zenith position, is much larger than A_h, the adaptation level in the same field near the horizon. But why should A_z be larger than A_h?

As remarked by Rock and Kaufman, there are many "cues to distance" at the horizon. In other words, in many visual fields the stimuli below the horizon are relatively complex, with a receding gradient or "ground" and with trees or bushes, buildings, or other objects at or near the horizon. At zenith, on the contrary, there are no definite objects or contours near the moon. Only the stars are visible, and they are obscured by the brightness of the moon. Such considerations do not provide a secure basis for asserting that A_h will be smaller than A_z.

In a recent experiment in our laboratory (*7*) we studied the effect of boxes of height B at the ends of a test line of length L. We found, as expected, the size contrast illusion: larger boxes B produce smaller judgments $J(L)$ for a line of given length. Then we varied the gap G between the boxes and the line (*8*). As G increased and the boxes became more remote from the line, the effect of the boxes decreased as expected. A second, equally reliable effect was that, as G increased, the judgments of the line systematically decreased. The reason soon became obvious; when the boxes were far from the line, the line was surrounded by relatively great extents, namely, the gaps between boxes and line. Although G was thought of merely as a gap in the figure, it entered into the adaptation level. The theory fit the data quite adequately when we entered G into the formula for adaptation level:

$$A = B^b G^g K^{1-b-g} \quad (3)$$

This observation provides the basis for an explanation of the moon illusion. A major difference between the horizon moon and the zenith moon is the space between the moon and the nearest horizon. The simplest case, when the moon is seen over the ocean on a clear night, is illustrated in Fig. 2. Assuming constant factors K, the only difference between A_h and A_z must be in the space S between moon and horizon.

In the moon illusion, all factors are constant except the space S between moon and horizon. Therefore, all constant factors can be represented by C, and the adaptation levels at horizon and at zenith are

$$A_h = S_h^s C^{1-s}$$
$$A_z = S_z^s C^{1-s}$$

By using these formulas to replace A in Eq. 1, we obtain

$$J_h(M) = M C^{s-1} S_h^{-s}$$
$$J_z(M) = M C^{s-1} S_z^{-s} \quad (4)$$

Since S_z is much greater than S_h, $J_z(M)$ will be smaller than $J_h(M)$, the moon illusion. This explanation does not require interpretations of the field by the observer, it does not depend on the particular stimulation near the horizon, and it provides a quantitative theory of the effect. In these respects, the present hypothesis of relative size compares favorably with the Rock and Kaufman theory of apparent distance.

There remains, however, the fact that the sky does look farther away near horizon than at zenith, that is, that the sky looks like an inverted soup bowl. In the relative size theory, this fact merely constitutes an informal statement that subjects judge apparent remoteness of the sky by depending on cues to remoteness (R) and the adaptation level for extents. If an observer is asked to judge how far away a certain point x of the sky appears to be, his response is

$$J(R) = R / A_x$$

by Eq. 1. The adaptation level for remoteness should depend on the same factors as the adaptation level for size, in particular on the space S between x and horizon. If so, the adaptation level A_x will be smaller near the horizon than at zenith for judgments of remoteness, and the sky should be judged to be more remote near the horizon than overhead, producing the appearance of an inverted soup bowl. If the sky is visually homogeneous (as it is to a fair approximation on a clear starry night), the judged remoteness of a point a space S above horizon will be

$$J(R) = R C^{s-1} S^{-s}$$

a decreasing power function of S. This formula is used to produce the apparent sky in Fig. 1.

According to the relative size hypothesis, the apparent remoteness of the sky does not cause the moon illusion; it is a second effect of the prime causal variable, namely, the space S between a point x and the horizon.

The formulas derived above are of little interest unless the detailed experimental measurements of the moon illusion and comparable laboratory measurements agree in sufficient detail with the calculated predictions. In the following sections, the abstract symbols are replaced with measurements, and the theory is compared with experimental findings.

Our laboratory measurements have indicated that the effect of an adjacent extent on a test line is in the range of 0.03 to 0.09. In the moon illusion, the space S is adjacent to the moon; hence its effect should be within this range. In their studies, Rock and Kaufman apparently consider that a horizon moon is approximately 1° above horizon and that zenith is 90° above horizon. Therefore, the ratio S_z/S_h is approximately equal to 90.

Combining the two parts of Eq. 4, we obtain

$$J_h(M)/J_z(M) = (S_z/S_h)^s$$
$$\doteq 90^s$$

If s varies from 0.03 to 0.09, the illusion varies over the interval

$$1.15 < J_h(M)/J_z(M) < 1.50$$

Thus, the moon illusion should be very large, with a magnitude near 1.33. This prediction is in general agreement with the findings of Rock and Kaufman, who found values from 1.15 to 1.75.

One of the problems that any theory of the moon illusion must handle is the remarkably great magnitude of the illusion. The illusion depends on the visual distance between the test magnitude and the horizon, however, and the night sky provides a unique expanse of unstructured visual space. The moon moves from the edge to the middle of this space. Most artificial illusory displays drawn on paper use only a relatively small part (perhaps 20°) of the visual field and, therefore, cannot produce illusions based on large empty expanses.

Another factor increasing the size of the moon illusion is the simplicity of the field at night, which provides the viewer with no fixed framework. In experiments performed in a room indoors, the viewer has an ample supply of constant magnitudes, which increase the relative weight of constant factors and thus reduce the relative weight of any illusion-producing figures.

The relative size theory not only accounts for the magnitude of the illusion when viewed under "standard" conditions but also provides explanations of some of Rock and Kaufman's detailed results.

Rock and Kaufman approximated the simple field conditions posited here in an experiment in which they measured the moon illusion at an airfield. They took measurements when the sky was clear, obtaining an illusion ratio of 1.39, and also when the sky was cloudy, obtaining a ratio of 1.56. Why this difference? Rock and Kaufman give little explanation for the effectiveness of clouds in increasing the illusion, but the explanation is easy to find. Unlike the "sky," the clouds do not provide a blank or even texture. Clouds directly overhead are actually much closer than clouds near the horizon. If the cloud cover is physically more or less homogeneous, any texture arising from cloud structure will be coarser (that is, larger) at zenith and distinctly smaller near the horizon. Since the cloud texture makes an excellent and relevant background for judging relative size of a moon image, it is natural that the illusion will be great. A simple calculation should indicate the approximate variation in visual angle of cloud structure. The radius of the earth is approximately 6120 kilometers. Consider a cloud cover 3 kilometers high. Clouds at zenith are 3 kilometers away, whereas clouds near the horizon are 192 kilometers away (*9*). The texture therefore varies by a factor of 64/1, and can be the basis of a very great illusion.

In another part of the same experiment, Rock and Kaufman shifted their artificial moon to a direction where trees and shrubbery obscured the horizon at a distance of about 640 meters.

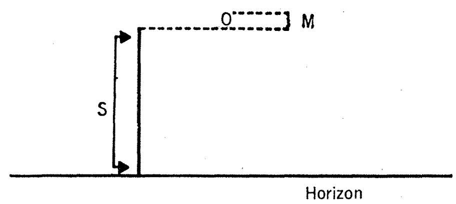

Fig. 2. Moon of diameter M suspended a distance S above horizon.

At that distance a 16-meter tree, such as might be found in a fence row, subtends an angle of 1.5°, a high bush about 0.5°. The shrubbery sets up a texture of 0.5°, somewhat larger than the moon itself. The trees and shrubbery possibly set up an adaptation level larger than the level at the horizon of the open field, where the texture of grass presumably diminished below detectability at 3 kilometers.

By this analysis we find that A_h is larger when the moon is near the shrubs and trees than when it lies at the horizon at the end of the grassy field, and, since A_z is presumably the same and relatively high in both cases, we expect a greater illusion for the grassy field (observed, 1.39) than for the short, shrubby ground (observed, 1.27). The experimental result agrees with Rock and Kaufman's hypothesis, for the shrubby hedge and trees looked closer than the horizon at the end of the airfield and, therefore, should make the moon look closer at the horizon, as well as smaller.

The above discussion may seem purely academic, for a stimulus pattern theory was considered and rejected by Rock and Kaufman on the basis of one experiment. In that experiment the visual field was inverted, so that the sky seemed below rather than above the ground, and an artificial moon was projected in this inverted sky. The moon appeared somewhat larger than it appeared at zenith (illusion of 1.28) but much less so than when the field was viewed through a similar framework but right side up (illusion of 1.66). Thus, although Rock and Kaufman admit that some sort of "framing" or relative size factor may have operated, they hold that field effects cannot explain the weakening of the illusion in the inverted field.

First, inspection of the quantitative results of the experiments shows that the illusion in the inverted field is perhaps slightly smaller than usual but that the main anomaly is the very large value of illusion when the field is right side up (1.66). The field of view is extremely complex, being a city street in Manhattan with 10- to 40-story buildings, and the "horizon" is a point far down 57th Street between tall buildings. The test moon is nestled between buildings near this "horizon." Rock and Kaufman found that the magnitude of illusion is far greater when this scene is viewed upright than when it is seen upside down, or when a set of lines that is similar but that does not induce apparent depth surrounds the test moon.

The smaller illusion in the inverted field is sufficient to disprove the idea that the apparent size of the moon depends solely on the size of its surroundings. However, in the present version of adaptation level theory, the observer has some choice as to what he is to use as frame of reference for the moon. When a clear impression of depth is conveyed by the visual field, each object in the field, if it has a specific depth, can be compared primarily with other objects judged to be the same depth. In the rather complex visual field on 57th Street, the horizon "moon" can then be compared selectively with objects near the horizon—that is, with tiny retinal angles of windows, ledges, cars, and other objects at great distance down the street. The adaptation level is therefore very low, and the moon is judged very large. When the scene is inverted, the impression of depth is weakened and the moon will be compared with a somewhat wider variety of objects and extents near the moon. Since these objects will be closer than the horizon, they will tend to be larger in visual angle. Thus the adaptation level will be somewhat larger with this inverted field, the horizon moon will be judged proportionately lower, and the illusion will be reduced.

Individual Differences in Illusions

Rock and Kaufman wrote that different observers give consistently different readings or magnitudes of illusion but are "reluctant to accept the notion that the actual sensory experience of the moon's size differs for different individuals viewing the moon at the same time and in the same place" (*2*, p. 1030). Their alternative hypothesis, which unfortunately bears no relationship at all to their apparent distance hypothesis of the cause of the illusion, is that subjects will initially choose a certain response and will then continue to choose values near that original choice.

The adaptation level theory permits more detailed investigation of these individual differences. In the adaptation level formula, A is given as a weighted geometric mean of the various extents in the field. No complete theory of the weights is available, but it seems evident that the weight of an extent Y on the judgment of the magnitude of the moon M should depend not only on the propinquity of Y and M but also on the degree to which the observer uses Y as a standard in judging M. Some subjects may with high probability choose the magnitude of objects on the horizon, others may use the space from moon to horizon, and still others may use the total extent of the visual field, the size of their own noses, or other values. These different subjects would all be trying to fulfill the requirements of the task but would show quite different illusions, and they might even be quite differently sensitive to other variables, like cloudiness or the nature of the horizon.

If, as suggested here, judgment of the moon is always relative to other stimuli, it must be realized that the observer has no instructions as to what frame of reference he is to use in his judgments. Different observers may use different strategies, each with as good reason as the next, and for that reason make consistently different judgments. If an observer makes heavy use of the space around the moon, staring at the moon itself, then he should show a large illusion. If, instead, he compares the moon with constant factors such as a house or his outstretched thumb, he will show little, if any, illusion.

Summary and Conclusions

Rock and Kaufman showed that the moon illusion depends not on the position of the moon relative to the observer's body but on objective characteristics of the visual field. The present discussion builds on this basic conclusion.

Rock and Kaufman interpreted their many experimental results as the effects of the apparent distance of the moon in its various orientations. This interpretation is faulty because the cues to distance are ambiguous and cannot logically be responsible for the moon illusion.

The apparent size of the moon, like all other visual objects, depends on the magnitude of extents near the moon. The judgment of the moon $J(M)$ is proportional to the diameter of the moon (0.5°) divided by the adaptation level A, which is calculated as the weighted geometric mean of extents in the field, each extent being weighted according to its relative importance or attention value as a frame of reference for M.

The moon appears small at zenith because it is in a uniquely large empty visual extent, being surrounded by the large (90°) space to the horizon. When the moon is near the horizon, it may be compared with the small (1°) space to horizon. The distance from moon to horizon is a fairly important factor in this adaptation level, having weight near 0.06.

This formulation gives a quantitative account of several of the detailed experimental results reported by Rock and Kaufman and also explains the soup bowl shape of the night sky. The adaptation level theory has additional advantages: it need not use the complicated and indirect arguments regarding apparent and registered distances, and it need not skirt the apparent contradictions in the apparent distance hypothesis of Rock and Kaufman.

Is the moon illusion an isolated curiosity, or does it illustrate some general principle of perception? I believe that the moon illusion provides a dramatic, naturally occuring example of the relativity of perceived size; it shows how the same object may appear large in one context and small in another, provided that the two contexts pit the object against different adaptation levels. Normal visual perception is effective over an enormous range of sizes, distances, brightnesses, and so forth, mainly because the judgmental scale is always adjusted to the relevant range of stimulation. In the case of the moon illusion this process of adjustment is caught in a flagrant misapplication, which appears, however, to incur no substantial biological disadvantage.

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