The Moon Illusion*

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Ever since Berkeley discussed the problem at length in his *Essay Toward a New Theory of Vision*, theorists of vision have attempted to explain why the moon appears larger on the horizon than it does at the zenith. Prevailing opinion has it that the contemporary perceptual psychologists Kaufman and Rock have finally explained the illusion. This paper argues that Kaufman and Rock have not refuted a Berkeleyan account of the illusion, and have over-interpreted their own experimental results. The moon illusion remains unexplained, and a Berkeleyan account is still a contender.

1. Introduction. The moon looks bigger when it is near the horizon than when it is higher in the sky. Many observers also report that the horizon moon appears to be closer than the zenith moon. Of course, the moon is a constant size and distance from the earth, so these appearances are illusory.[1] Yet there is little agreement among perceptual psychologists about the cause of the illusion.[2]

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1. In natural viewing conditions the illusion depends on a comparison from memory; however, the illusion also occurs in planetariums, where the time between the two size judgments is compressed to less than a minute, and in laboratories where "artificial moons" are simultaneously compared.

2. Commenting on the current state of research on the moon illusion, Haber and Levin (1989, 299) say "the several dozen perceptual theorists presently writing about the appearance of the moon can barely be categorized into groups larger than two persons each to represent common beliefs about the cause of the moon illusion."

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In fact, the moon illusion may be our most persistent scientific puzzle. It has resisted explanation for over 2500 years. The list of thinkers who have offered accounts of the illusion include many of the most prominent figures in the history of science, mathematics, and philosophy.[3] Unlike other recalcitrant phenomena in the history of science (for example, the apparent retrograde motion of the planets, or the undetectable movement of the luminiferous ether), the puzzle has persisted through massive changes both in our overall physical theory, and in our very conception of the scientific enterprise. Aristotle (in *Meterologica*), Berkeley (in *An Essay Toward a New Theory of Vision*), and the contemporary perceptual psychologists Kaufman and Rock are all working on the same problem.

The earliest accounts of the illusion treat it as a physical phenomenon. One early hypothesis held that the moon actually *is* closer to the earth at the horizon—a *different* heavenly body appears in the sky every day, each spinning off into space to be replaced the next day by another. The most popular explanation in antiquity was the refraction theory, advocated by Aristotle and developed more fully by Ptolemy. It held that the earth's atmosphere scatters the light from the horizon moon, resulting in the horizon moon subtending a larger visual angle at the eye. Physical accounts of the illusion were laid to rest in the 17th century, when astronomers established conclusively that the moon illusion is not an astronomical phenomenon. It has nothing *intrinsically* to do with the moon, or with the earth's atmosphere. Ever since Kepler first characterized the formation of the retinal image, students of the illusion have known that light from the horizon moon and the zenith moon subtend the same angle on the retina. (Though Hobbes (1658, 462) writing 25 years after Kepler's death, still ascribed the illusion to atmospheric refraction, and, to this day, refraction remains the most popular "folk" explanation of the illusion.) Accordingly, recent explanations of the illusion have treated it as a *psychological* phenomenon.

I shall focus in this paper on two explanations of the moon illusion—George Berkeley's account in his *Essay Toward a New Theory of Vision* (1709), and the account advocated by Kaufman and Rock in a series of papers published over the last thirty-five years (Kaufman and Rock 1962a, 1962b, 1989; Rock and Kaufman 1962). Berkeley's explanation appeals to his associationist model of psychological processing, while Kaufman and Rock develop and defend a view popular among 17th-century rationalists, including Descartes and Malebranche. The moon illusion affords an opportunity to see the two general psychological

3. For comprehensive accounts of the history of the moon illusion, see Reimann 1902, Plug 1989, and Plug and Ross 1989.

models—empiricist associationism and rationalist computationalism—brought to bear on a specific phenomenon.

It is not my purpose to defend associationism as a general theory of visual perception, but rather to rescue Berkeley's explanation of the moon illusion from premature burial. I shall argue for two claims: (1) while a key component of Berkeley's explicit account has been refuted, Kaufman and Rock have not refuted a "reconstructed" Berkeleyan explanation, and (2) Kaufman and Rock have over-interpreted their own experimental results—they have *not* explained the illusion. Empiricist psychology has taken a beating since the demise of behaviorism and the ascendancy of computationalism in the 1960s, but it has not yet lost the dispute over the moon illusion.[4]

We can formulate two reasonable constraints that any acceptable explanation of the moon illusion should satisfy. First, and most obviously, it should account for the relevant observational data. Unfortunately, the empirical record is voluminous and riddled with inconsistencies. Theorists cite various experiments in support of their competing accounts—looking at the moon over a wall, or bent over with the head between the legs, or wearing inverted glasses that reverse the orientations of the horizon and zenith moons—but report strikingly different results. Consequently, theories that appear to have been disconfirmed (for example, accounts that appeal to purely physiological processes such as accommodation and vergence) tend to re-emerge sporting fresh empirical support (e.g., Roscoe 1989, Enright 1989).

Second, an adequate explanation must cohere with our general knowledge of visual perception. Most theorists have attempted to explain the illusion by reference to a general theory of size perception, claiming that the general theory predicts, and hence is supported by, the illusion. Accordingly, I shall begin in the next section by sketching very briefly the theories of size perception underlying the two accounts of the illusion.

A full explanation of the moon illusion will have two parts: (1) an account of the property(s) of the viewing conditions of the horizon moon that causes its larger apparent size (or, alternatively, an account of the property of the viewing conditions of the zenith moon that causes its smaller apparent size), what I will call the *distal cue*, and (2) an account of the internal process or *mechanism* that is activated by the distal cue and produces the illusory experience. A full account of the illusion will also explain what I call the *secondary aspect* of the illu-

4. Berman (1985) and Schwartz (1994) have recently defended Berkeley against Kaufman and Rock's criticisms, though their discussions of the issue are narrower in scope than mine.

sion—the fact that to most observers the horizon moon appears closer than the zenith moon.

2. Two Theories of Size Perception. George Berkeley, in *An Essay Toward a New Theory of Vision,*[5] argued that our ideas of size, shape, and distance derive not from visual experience, but from tangible experience with objects. The visual field, according to Berkeley, does not present itself as having inherent three-dimensional spatial properties. We acquire ideas of the size and shape of objects by touching them, and ideas of distance from the amount of effort it takes to move to them or reach for them. We see these spatial properties only because we learn to associate visual cues (image size, confusion/clarity of the image, and sensations from the eye muscles) with ideas originally derived from touch and movement. Eventually we learn what objects associated with certain tactile sensations characteristically look like.[6]

A competing theory of size perception, popular in Berkeley's time and in the present day, holds that the visual system computes an estimation of object size from a prior determination of distance (see Figure 1). An object of size s is at distance d from the viewer. Light traveling to the eye from the object forms the visual angle α. Size s varies with distance d as follows: $s = \tan \alpha \times d$. This describes the physical facts. According to the so-called *size-distance invariance hypothesis* (SDIH),[7]

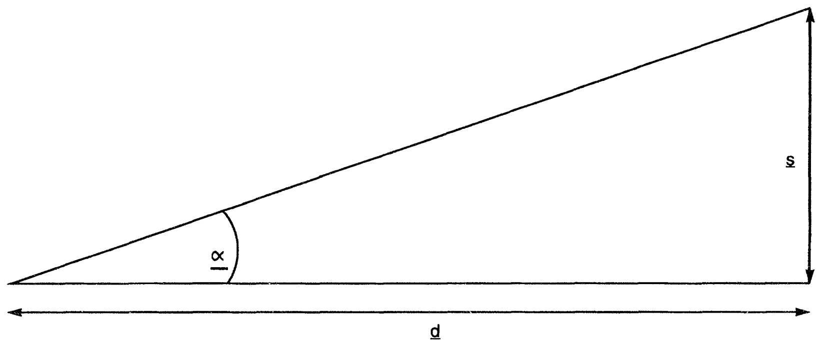

Figure 1.

5. In addition to the *New Theory*, see Berkeley's *Theory of Vision Vindicated and Explained.* For detailed discussion of Berkeley's work on vision, see Armstrong 1960, Pitcher 1977, Hatfield and Epstein 1979, and Atherton 1990.

6. Thus, Berkeley's answer to Molyneux's question—could a newly-sighted man immediately tell a sphere from a cube by sight?—is a resounding "no."

7. The SDIH is a generalization of Emmert's Law, which concerns afterimages. See Epstein, Park, and Casey 1961 and Weintraub and Gardner 1970.

the relationship between *perceived* size S and *perceived* distance D is described by the same function, i.e., $S = \tan \alpha \times D$. *Taking account of distance* (or TAD)[8] models of size perception exploit SDIH, holding that the visual system computes the perceived size S of an object from the visual angle α (defined as the visual stimulus) and previously determined perceived distance D by calculating $\tan \alpha \times D$.[9]

TAD models of size perception were advocated in the 17th century by, among others, Kepler,[10] Descartes,[11] and Malebranche.[12] These theorists can be seen as early proponents of a computational theory of mind. Computational models of size and distance perception are the main target of Berkeley's *New Theory*. In general, he objected to the account of psychological processing presumed by such accounts (unconscious calculation based on innate knowledge of mathematical formulae, rather than association of items derived from experience). With respect to TAD models of size perception, in particular, he argued that there is no reason to think that the visual system determines distance *first* and *then* computes size, because, he claimed, the cues available to the visual system in determining distance—size of the image, confusion vs. clarity of the image, muscular sensations due to accommodation and vergence—are equally cues to the size of objects. These cues are reliably correlated with tangible experiences of size as well as distance. And finally, he claimed that TAD theories could not explain the moon illusion.

3. Two Explanations of the Moon Illusion. The two accounts of size perception are implicated in competing explanations of the moon illusion. According to Berkeley (§67–78 of the *New Theory*), the light from the horizon moon is "intercepted" by the thick layers of atmosphere along the viewer's line of sight. Atmospheric factors do not cause a larger image—Berkeley did not advocate the discredited refraction theory—but they do cause the horizon moon to appear fainter

8. I borrow this terminology from Schwartz 1994. For elaboration and discussion of the model see Ittelson 1960, Kaufman 1974, and Haber and Hershenson 1980.

9. The simple model described here only applies to objects that lie on a fronto-parallel plane.

10. For discussion of Kepler's work on vision, see Lindberg 1976 and Hatfield and Epstein 1979.

11. See *Optics*, Sixth Discourse. For general discussion of Descartes' views on vision, see Pastore 1971 and Hatfield and Epstein 1979.

12. See *The Search after Truth*, Book 1, Ch. 6 for Malebranche's endorsement of the TAD model of size perception, and Book 1, Ch. 7 and 14 for his application of the account to the moon illusion. For general discussion of Malebranche's views on vision, see Pastore 1971.

and less distinct than the zenith moon. Because faint images are typically correlated in experience with large, remote objects, we see the horizon moon as larger than the zenith moon.

According to Berkeley, the thickness of the atmosphere (causing the horizon moon to look faint) is the *distal cue* for the larger appearance of the horizon moon. The *mechanism* is learned association. We learn to see faint-looking objects as bigger because faint images are correlated with tangible experiences of large, distant objects.[13]

Berkeley's explanation of the illusion has several obvious problems. It fails to account for the secondary aspect of the illusion: most people judge the horizon moon to be *closer* than the zenith moon. (Schur 1925 notes that of the 100 subjects tested by Zoth (1899) and 20 subjects tested by Claparède (1906), a total of 116 reported that the horizon moon appears closer than the zenith moon.) Berkeley's account predicts that the horizon moon should appear *farther away*, since faintness of the image is a cue for both large size and greater distance. (Berkeley did not discuss the secondary aspect of the illusion; he may well have been unaware of its existence.)

Second, the experiences of the Apollo astronauts on the moon suggest that faintness caused by the earth's atmosphere is *not* the cue for the larger appearance of the horizon moon. The astronauts reported a corresponding "earth illusion"—the rising earth appearing larger than the zenith earth—although the moon has no atmosphere. However, as Berkeley noted, atmospheric changes would account for the day-to-day variability of the moon illusion. The extent of the illusion appears to vary with humidity levels, pollution, and general quality of the atmosphere. But Berkeley's claim that atmosphere is the main distal cause of the illusion is almost certainly wrong.

The most popular TAD explanation of the moon illusion appeals to the "intervening objects" theory, which can be traced to the 11th-century Arabic physicist Alhazen.[14] The idea is that the horizon moon appears to be at a great distance because it lies behind distant objects

13. The renowned 18th-century mathematician Leonhard Euler agreed with Berkeley that faintness of the image caused by atmospheric factors produces the illusion, but he coupled this account of the distal cue with a TAD account of the mechanism. Euler claimed that the faint image causes the horizon moon to appear more distant than the heavenly bodies at the zenith; the visual system then makes use of SDIH to compute a larger perceived size for the horizon moon. (For Euler's discussion of the moon illusion, see Euler 1762, vol. 2, letters 110–115.)

14. See the discussion of the moon illusion in the *Optics*, Book VII. See also Sabra 1987, where the section discussing the moon illusion is excerpted from Sabra's translation of Alhazen's *Optics*. For a general discussion of Alhazen's theory of vision, see Sabra 1978.

such as buildings and trees at the horizon. By contrast, there are no distance cues for the zenith moon. As Descartes put it in the sixth Discourse of his *Optics*:

> usually, when [heavenly bodies] are very high in the sky . . . they seem smaller than they do when they are rising or setting, and we can notice their distance more easily because there are various objects between them and our eyes. And, by measuring them with their instruments, the astronomers prove clearly that they appear larger at one time than at another not because they are seen to subtend a greater angle, but because they are judged to be farther away. (1985, 174)

Astronomers proved only that light from the horizon moon and from the zenith moon subtends the same angle on the retina—ruling out refraction as a possible explanation for the illusion—and not that the visual system initially judges the horizon moon to be more distant. Astronomers' measurements cannot establish the truth of a psychological model. The passage reflects Descartes' own commitment to the TAD model of size perception, which was widely accepted at the time. According to Descartes, intervening objects increase the apparent distance to the horizon moon; the visual system then computes a larger apparent size relying on principles of natural geometry. The presence of intervening objects is the distal cue for the moon illusion, and the TAD model explains the mechanism.[15]

Kaufman and Rock's account of the illusion is essentially the same as Descartes'. Unlike earlier proponents of the intervening objects theory (coupled with the TAD model), they support the theory with an impressive array of experimental evidence involving moon watching in natural conditions and experiments with artificial moons. As a result, the Kaufman and Rock account today enjoys the status of the "received view" on the moon illusion.[16]

4. Some Experimental Evidence. Experiments confirm that the presence of intervening objects along the line of sight has something to do with the illusion. Kaufman and Rock's subjects found that the moon looked unusually large when observed atop a building in midtown Manhattan, where it was framed by New York's skyscrapers (Rock and Kaufman 1962).

15. Euler offered an interesting argument against the intervening objects thesis. He claimed that the far wall of a large room looks *further away* when the room is empty than it does when it is filled with people. (vol. 2, letter 111)

16. Though see Hershenson 1989 for dissenting opinions from perceptual psychologists.

But intervening objects need not be present for the horizon moon to look big. It looks big when viewed across an expanse of water or terrain, with no intervening objects.[17] An experiment by Kaufman and Rock (1962a, 1962b) confirms that visible terrain is a significant cue for the illusion. Using artificial moons and a mirror device attached to the head they were able to project an image of terrain under a zenith moon. Subjects reported that the moon looked unusually large.[18]

Experiments by Wolbarsht and Lockhead (Wolbarsht and Lockhead 1985; Lockhead and Wolbarsht 1989, 1991) reveal the significant aspect of these cues. They report that when the horizon moon is viewed from an airplane at an altitude of thirty thousand feet, it looks no bigger than the zenith moon looks under normal conditions. Seen from above, there is an expanse of unfilled or empty space (i.e., sky) between the viewer and the horizon moon.[19] The astronaut John Young reported that the rising earth, seen from the command module of Apollo 10 in orbit around the moon, looked no bigger than usual. When Young later observed the rising earth from the surface of the moon (as a crew member on Apollo 16), he experienced it to be significantly larger.[20] In the former situation, orbiting the moon at an altitude of some 60 miles, he was observing the earth rise from above, across unfilled or empty space; on the moon's surface, he saw it across an expanse of rocky terrain. The most significant cue for the moon illusion seems to be the "filled space" between the viewer and the horizon moon. By contrast, there are no objects or visible terrain along the viewer's line of sight when she is looking at the zenith moon. There is nothing but black sky.

Why should filled space make the horizon moon look larger? I will postpone discussion of the mechanism underlying the illusion for the moment, but one point is worth noting. In general, filled space—the presence of intervening objects, visible terrain, or a visible expanse of water—increases the apparent distance between the viewer and the moon. It seems, then, that the cue for the larger appearance of the horizon moon is anything that increases the apparent distance between

17. Sailors commonly report that the moon looks very big when rising (or setting) over the ocean.

18. The significance of this result has been questioned on methodological grounds. Apparently, the subjects were able to see the mirror. (Arnold Trehub, personal communication)

19. Wolbarsht and Lockhead call this the "toy illusion", claiming that when objects are viewed across unfilled space, they look like toys.

20. J.W. Young, as cited in W. Braden, "What is Moon Illusion?," *Durham Sun*, Durham, NC, June 29 1982, 7–8. (Reported in Lockhead and Wolbarsht 1989)

the viewer and the moon. Space filled by intervening objects, or visible ground or water increases apparent distance more effectively than atmosphere. We know now, from observations in planetariums, and by extrapolating from the Apollo astronauts' experience, that the horizon moon would look bigger than the zenith moon even if there were no atmosphere. The modern experimental evidence seems to refute Berkeley's account of the illusion. At the very least, Berkeley appears to have been mistaken about the cue for the illusion.

According to Kaufman and Rock, and TAD models generally, the visual system computes a larger perceived size for the horizon moon based on its greater perceived distance, and tacit knowledge of geometrical principles. There are no distance cues for the zenith moon—it is surrounded by empty sky—and in the absence of distance cues, Kaufman and Rock claim, its distance is indeterminate, and so therefore is its size. It is what is called a *reduction object*. In their latest paper on the moon illusion, Kaufman and Rock say

> For whatever reason (some unknown mechanism underlying a tendency to see reduction objects as being at some relatively nearby distance), a reduction object appears to be *closer* and therefore smaller than does an object at an equal distance but seen through filled space. (1989, 229)

In Section 6 I will consider the evidence for the TAD account of the mechanism underlying the moon illusion. First, though, Berkeley's account of the illusion deserves another look.

5. Revisiting Berkeley's Account. Berkeley explicitly denies that the presence of intervening objects has anything to do with the moon illusion, pointing out (§77) that if the moon is observed rising over a wall that obscures other objects from sight, it looks as big as ever. In the first edition of the *New Theory* (published in 1709) he claims that his own account of the illusion, appealing to atmospheric factors, is supported by the following consideration:

> [that which suggests the greater magnitude of the horizon moon] must not lie in the external circumjacent or intermediate objects but be an affection of the very visible moon itself; since by looking thro' a tube, when all other objects are excluded from sight, the appearance is as great as ever. (§70)

Berkeley deleted the reference to looking through a tube from the second edition, published in 1710. Whether he tried the experiment and found that the horizon moon did *not* look as big when viewed through a tube is not known.[21] But by the publication of the third edition of the *New Theory* in 1732, the entire passage (the third of Berkeley's original four considerations in support of his account) had been eliminated. Berkeley may have reconsidered his opposition to the intervening objects explanation, although his criticism of the view in §77 appears in all four editions.

In any event, it is not clear why Berkeley objected to the intervening objects explanation *per se*, rather than to the TAD explanation of psychological processing that usually accompanies it. What Berkeley *should* have said (and could have said consistent with his general theory of visual perception) is that the presence of intervening objects is as much a cue for (greater) size as for (greater) distance; therefore, there is no reason to suppose that the visual system needs to compute perceived size from perceived distance as the TAD model claims. In other words, Berkeley's real objection is not to intervening objects as the cue for the illusion, but rather to the TAD model as the correct account of the mechanism underlying the illusion. The TAD model is inconsistent with Berkeley's general account of psychological processing as the association of ideas derived solely from experience, and so he must reject it. But the intervening objects hypothesis (as an account of the relevant cue) is not wedded to the TAD model of psychological processing.

In fact, there is good reason to think that Berkeley himself is committed to the intervening objects hypothesis, his objection to it in §77 notwithstanding. In §3 of the *New Theory*, where Berkeley is explicitly concerned with our perception of distance, he says

> when I perceive a great number of intermediate objects, such as houses, fields, rivers, and the like, which I have experienced to take up a considerable space, I thence form a judgement or conclusion that the object I see beyond them is at a great distance. (7)

Though Berkeley does not mention the presence of intermediate objects in the later sections devoted to his account of size perception (§52–87), he explicitly says there (§53) that the same visual cues that suggest that objects are at a great distance also suggest that they are of large size. These cues are correlated in experience with objects that are *both* far away *and* big.

21. The results of this test, as reported in the early literature on the moon illusion, are inconclusive. Molyneux and Euler report that obscuring intervening objects does not eliminate the illusion, while Malebranche and Reimann claim that it does. I have found that the illusion disappears when the horizon moon is observed through a tube, contrary to Berkeley's claim.

Furthermore, in §73 of the *New Theory*, Berkeley offers a second explanation of the moon illusion:

> upon the change or omission of any of those circumstances which are wont to attend the vision of distant objects, and so come to influence the judgements made on their magnitude, they shall proportionably appear less than otherwise they would. For any of those things that caused an object to be thought greater than in proportion to its visible extension being either omitted or applied without the usual circumstances, the judgement depends more entirely on the visible extension, and consequently the object must be judged less. (33)

Berkeley explicitly mentions the angle of the head and eyes ("angle of regard") as one of the "circumstances" that is changed when viewing the zenith moon.[22] But the absence of intervening objects is another. The horizon moon is often viewed in the presence of intervening objects and visible terrain; the zenith moon never is. On Berkeley's account, when the typical clues to the size (and distance) of distant objects are missing, the object will appear to be smaller. Thus, Berkeley is committed to the claim that intervening objects and visible terrain are a relevant factor (cue) in the illusion. In fact, any cue that serves to increase the apparent distance of the horizon moon can be incorporated into Berkeley's explanation of the moon illusion. On his account of size perception all cues for greater apparent distance are, ipso facto, cues for greater apparent size as well, since these cues correlate in experience with large, faraway objects. It is precisely because distance cues are also size cues that the assumption that size is computed from distance is unnecessary.

To summarize the point: Berkeley's theory of size perception commits him to the view that anything that increases the apparent distance to the horizon moon will increase its apparent size. The modern experimental evidence, while refuting Berkeley's explicit account of the cue for the moon illusion (atmospheric factors), actually supports a reconstructed Berkeleyan explanation of the cue that appeals to intervening objects and visible terrain.

We will turn our attention now to the mechanism underlying the moon illusion. Recent work on object recognition in infants has undermined Berkeley's claim that perception of spatial properties depends

22. The angle of regard hypothesis has remained popular. Next to Berkeley, E.G. Boring is probably its best-known advocate (see Boring 1943). See Kaufman and Rock 1962a and Rock and Kaufman 1962 for criticism of Boring, and Enright 1989 and Trehub 1991 for arguments in support of new variations on the angle of regard hypothesis.

upon tactile acquaintance with objects[23] (see, for example, Spelke 1990). But the fact that Berkeley's particular brand of associationist explanation of spatial perception is not well-regarded does not impugn his explanation of the moon illusion. Whatever the source of our ideas of size, shape, and distance—whether or not they depend upon tactile experience—the central idea in Berkeley's account of the mechanism underlying the moon illusion is that the visual system learns to see the horizon moon as larger because the cues available to it are associated in experience with large objects. The question is whether the available evidence supports the TAD model over a learning-based associationist account of the mechanism.

6. Evaluating the TAD Explanation. According to TAD theorists (e.g., Descartes, Kaufman and Rock), the visual system initially perceives the horizon moon to be at some distance greater than that perceived for the zenith moon, and then determines, by a process of calculation, a greater perceived size for the horizon moon. In support of the model, TAD theorists typically cite the SDIH, which predicts that an object with a greater perceived distance will have a greater perceived size.

But the evidence does not support the claim that the TAD model describes the mechanism underlying the moon illusion. In the first place, while the horizon moon does look larger whenever there are cues that increase its apparent distance, it often looks very large *without* any cues that increase apparent distance. The framing effect of large buildings on the horizon moon has already been noted; however, the presence of buildings (or trees) framing the horizon moon makes it appear very large without these intervening objects conveying a sense of significant distance. In other words, they function as size cues even when the observer is very close to the framing objects. In fact, Kaufman and Rock admit that "this frame of reference might very well affect the moon's apparent size" (Rock and Kaufman 1962, 1025), suggesting that apparent size need not be computed or inferred from apparent distance.

This evidence suggests that there may not be a single mechanism underlying the moon illusion. The empirical evidence is consistent with the claim that perceived size is computed from perceived distance in many cases; however, in other cases the visual system ascertains greater perceived size in the absence of information indicating greater distance.

But even where the cues for the illusion do increase the apparent distance of the horizon moon, the evidence for the TAD model is weak. The SDIH does not, by itself, support the claim that the visual system

23. I owe this point to an anonymous referee.

computes perceived size from perceived distance. SDIH simply describes a functional relationship between the two variables. Perceived size S covaries as a function of perceived distance D as follows: $S/D = \tan \alpha$ (the visual angle). Berkeley could accept the SDIH; what he objected to was the claim that the visual system tacitly *knows* the functional relationship described by SDIH and employs this knowledge to infer perceived size from perceived distance, as the TAD model claims. When intervening objects and filled space increase the apparent distance of the horizon moon, the horizon moon will look bigger, as the SDIH predicts, but the SDIH, and Kaufman and Rock's experiments, do not tell us *how* this occurs. The experimental evidence on moon-watching does not support the TAD model over experience-based association as the correct account of the processing underlying the illusion, or of size perception in general.

A problem with the TAD model will no doubt have occurred to the reader. TAD explanations claim that the greater perceived size of the horizon moon is computed from its greater perceived distance, but most observers report that the horizon moon looks *closer* than the zenith moon, not farther away. This "secondary" aspect of the illusion violates SDIH and gives rise to the so-called *size-distance paradox*.

Kaufman and Rock attempt to explain the secondary aspect of the illusion by appeal to a distinction between "perceived distance" and "registered distance." As a result of various distance cues (i.e., filled space) the visual system *registers* a greater distance value for the horizon moon than it does for the zenith moon. This value serves as the input to the process that computes a larger perceived size for the horizon moon. The viewer is not consciously aware of this information in the proximal stimulus, or of using it to determine perceived size. And so, because the horizon moon appears larger, it is *subsequently* judged to be closer, and the viewer's report reflects this reasoned judgment. The idea here is that the latter process is a different type of process than the computation of size from registered distance. It is based on the knowledge (much of it derived from experience) that when things look large they are nearby. It is probably accessible to consciousness. Though Kaufman and Rock do not put it this way, it might be described as a "cognitive" rather than a "purely perceptual" process. The idea that perceived size is computed from registered distance, and then used as a premise in a judgment about perceived distance is known, somewhat disparagingly, as the "further-larger-nearer hypothesis."[24]

24. Plug and Ross (1989) seem to have coined this term. It is also used by Enright (1989), Kaufman and Rock (1989) and Day and Parks (1989).

This modification of the TAD model raises some addititional problems for Kaufman and Rock's account. The distinction between registered distance and perceived distance, upon which the further-larger-nearer hypothesis depends, is ad hoc unless registered distance, the input to the TAD process, can be given a precise specification. But the issue is not simply whether the modified TAD model provides a genuine explanation of the moon illusion. As Robert Schwartz (1994, 65) notes, unless registered distance is interpreted as a distance value itself, and not merely the registration of cues *about* distance, then TAD theorists are very close to conceding Berkeley's main point—that perceived size need not be computed from a prior determination of distance. In their last paper on the moon illusion, Kaufman and Rock say,

> the term *registered distance* . . . was meant to imply that the perceptual system automatically takes sensory information correlated with distance into account when computing distance. (1989, 199)

It is not clear what Kaufman and Rock mean by "sensory information correlated with distance." (They cite accommodation as an example, but most theorists, including Kaufman and Rock themselves, agree that accommodation plays a very minor role in the moon illusion, given that the moon is at optical infinity.) At a minimum, they must mean 'sensory information correlated with *apparent* distance', since no sensory information is correlated with the sort of distances involved in the perception of astronomical bodies. But if the SDIH is correct—if perceived size covaries with perceived distance—then sensory information correlated with apparent distance is also correlated with apparent size. To call this information 'registered *distance*' (rather than, say, 'registered *size*', or, better yet, some more neutral term) is to assume that the TAD model is correct in this case: it is to assume that perceived size of the moon is computed from a prior determination of its distance. But the application of the TAD model is particularly suspect in this case. By their own account, the information that Kaufman and Rock call 'registered distance' is radically at odds with the *perceived* distance of the moon. The latter is the output of a different process. Hence, there is no justification for calling this information 'registered distance'. And what remains of the "further-larger-nearer" account, once this point is appreciated, is the following: as a result of certain cues (perhaps texture cues caused by filled space[25]) the visual system, by some un-

25. It is plausible to take texture to be a distance cue in the normal case, since it is reasonable to suppose that texture (normally) plays a direct role in the determination of perceived distance. But in the "further-larger-nearer" account, texture cues are not involved directly in the determination of perceived distance. To insist that texture is a distance cue in the present case is to beg the question in favor of the TAD model.

known process, determines the perceived size of the moon. A subsequent process, using this size information, determines the moon's perceived distance. But this is *not* a TAD explanation—perceived size is not computed from a prior determination of distance.

It is difficult to see how the secondary aspect of the moon illusion can be adequately explained by a theory that remains committed to the TAD model. The TAD theorists Gogol and Mertz (1989) hold that the horizon moon is perceived to be both larger and *more distant* than the zenith moon, in agreement with SDIH, but contradicting subjects' reports that the horizon moon appears to be closer. Gogol and Mertz claim that observers reason that since the horizon moon looks larger it must be closer, but that this judgment, reflected in their verbal reports, does not reflect the way the horizon moon actually *looks* to them. Unlike Kaufman and Rock's account, Gogol and Mertz's explanation preserves the TAD model—it holds that perceived distance determines perceived size. But it does not provide an adequate explanation of the secondary aspect of the illusion. Let me elaborate.

When Gogel and Mertz claim that the perceived distance of the horizon moon is greater than the perceived distance of the zenith moon, they clearly mean that the horizon moon *looks* farther away:

> Because the perceived distance to the horizon often is considerably larger than that provided . . . for the zenith moon, the horizon moon usually *appears* more distant than the zenith moon. (1989, 245; my emphasis)

and

> the horizon moon is *conciously perceived* to be both larger and more distant than the zenith moon . . . . (1989, 252; emphasis on "consciously" added)

According to Gogol and Mertz, then, observers say that the horizon moon looks closer when in fact it looks farther away. Are subjects lying about the way the moon looks to them? Well, no—they engage in a reasoning process based on consciously accessible information (the fact that things that look larger than normal are usually closer) and then convince themselves that the moon really looks closer, not farther away. But there is no reason to think that anything like this is going on. Since the reasoning process that Gogol and Mertz postulate is supposed to be conscious, subjects should know about, and be able to report, its occurrence. Yet there is no evidence of it.

I know from my own experience that the horizon moon, when viewed above buildings and trees, can look very close. It does *not* look farther away than the zenith moon. I am not assuming that subjects' reports (including my own) are to be taken as absolutely authoritative on this matter. It is possible that the claim that the horizon moon looks closer is an alternative way of saying that it appears more *salient* in some way, or that it fills more of the visual field. So I am not assuming that the secondary aspect of the moon illusion must be explained by appeal to processes actually involved in distance perception. But the report that the horizon moon looks closer is not plausibly construed as a way of saying that the horizon moon looks farther away! Gogol and Mertz's reinterpretation of subject's verbal reports about the way things look to them is perilously close to a denial of the experimental data, not an *explanation* of it. (I suggest that Gogol and Mertz try looking at the moon themselves.)

In summary, the TAD theory has no plausible explanation of the secondary aspect of the moon illusion. Accounts offered by TAD theorists either abandon commitment to the TAD model (Kaufman and Rock) or refuse to take seriously the phenomenological data (Gogol and Mertz).

7. Some Evidence Against the TAD Model. TAD explanations of the moon illusion are attractive in part because of the plausibility of the TAD model as a general account of size perception. But there is evidence concerning the effect of size perception on distance judgment that suggests that the TAD model does not enjoy unequivocal support as a general account of size perception. Predebon (1979) conducted a series of experiments in which observers were asked to judge the distance of a normal chair, an unusually large chair, and several stakes all situated at a distance of 25.3 meters from the observer in a large open field. Subjects judged the large off-sized chair to be closer than the normal chair presented at the same distance. They perceived the off-sized chair to be at approximately the distance it would have to be at to account for the angular size of the image, *if the object had its characteristic size*. Familiarity with the characteristic size of the object appears to have played a more significant role in the determination of perceived size, and on judgments of distance, than any distance cues (for example, texture) present in the scene. The stakes—objects that lack a characteristic size—were judged to be at the same distance as the normal chairs. Experiments by Carlson and Tassone (1971) and Leibowitz and Harvey (1967, 1969) also indicate that observer judgments concerning the size and distance of familiar-sized objects rely less on retinal size, or extent in the visual field, and more on knowledge of the characteristic size of the objects.

The evidence suggests that familiarity with the characteristic size of objects may play a significant role in their perceived distance. This evidence is consistent with the SDIH, but it undermines the TAD model, which holds that distance is determined first and is subsequently used to compute perceived size. For objects of familiar size the order of processing may be exactly the reverse. Given that many of the objects that we encounter are objects of familiar type (and hence have characteristic sizes), the evidence undermines the plausibility of the TAD model as a general account of size perception.

This evidence has an interesting further implication. It indicates that the determination of size may be subsequent to, and dependent upon, object recognition. To the extent that it is, then perceived size would not play a role in object recognition itself. Many familiar objects may be recognized on the basis of their overall shape, the configuration of their parts, and perhaps their color, rather than their size. This seems independently plausible. We have no trouble recognizing giant reptiles and miniature buildings as reptiles and buildings respectively.

How does this evidence bear upon the moon illusion? I am not suggesting that the same mechanism that underlies size perception of familiar objects explains our perception of the moon, or that the moon has a "familiar size." The point is rather that there may well be multiple mechanisms at work in size and distance perception.[26] The plausibility of the TAD explanation of the moon illusion derives from the plausibility of the TAD model as a general account of size perception. But the TAD model does not enjoy sufficient empirical support on its home ground—our perception of the size of objects around us—to justify confidence in its application to the moon illusion.[27]

8. Summary and Conclusion. I have argued that a Berkeleyan explanation of the moon illusion has not been refuted. The experimental evidence generally assumed to refute Berkeley bears only on the distal cue for the illusion. While the evidence does refute Berkeley's explicit explanation of the cue, it actually supports a reconstructed Berkeleyan account of the cue, and is compatible with an associationist account of the underlying mechanism. The most popular competing account of the mechanism, the TAD model, does not enjoy any significant empirical support. Moreover, it is doubtful that the secondary aspect of the illusion can be explained by the TAD model.

So the moon illusion remains unexplained. While we have a fairly

26. An anonymous referee has suggested that the visual system may solve problems of size and distance perception by employing mechanisms that are capable of satisfying multiple constraints, i.e., mechanisms of the sort that connectionist theorists are developing.

27. See Schwartz 1994 for criticisms of the attempt to apply the TAD model to objects not on the fronto-parallel plane.

good understanding of the cue for the illusion—roughly, the filled space between the observer and the horizon moon—we are still in the dark about the underlying mechanism. What are the prospects for a solution to the puzzle? There is no reason to think that a general theory of visual space perception would yield, in any straightforward way, an explanation of the mechanism underlying the moon illusion. Illusions typically arise from complex interactions among various levels of visual processing—involving both fixed or structural features of the visual system as well as "higher-level" or "cognitive" processes (see Coren 1989). Explaining an illusion requires disentangling and independently specifying each contributing factor. This will be especially difficult for the moon illusion, because we do not even have a clear specification of the explanandum. When observers judge that the horizon moon looks larger than the zenith moon, are they reporting that it appears to be a larger *object*, or that it fills more of one's visual field?[28] It simply is not clear. Even more problematic, as we have seen, are distance judgments. We have no way of measuring or specifying the apparent distance of the moon. How far away does the zenith moon look? Of course, nothing can *look* 250,000 miles away. How much further does the zenith moon look than the horizon moon? The question has no sensible answer. Given these difficulties, the moon illusion's status as our longest-standing scientific puzzle seems to be secure.

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28. See McCready 1986 for an account of the distinction between perceived *size* and perceived *extensity*. McCready argues that for most people the horizon moon has a larger perceived extensity rather than a larger perceived size.

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