

## **The Moon Illusion, An Unsolved Mystery.**

by Donald E. Simanek

**Disclaimer.** The following review of this long-standing problem is not a research paper. The author is not trained in psychology or cognitive science. Consider it a semi-critical review of the common competing hypotheses about the moon illusion, and some experiments relevant to that problem. Consider it merely an opinion piece if you wish.



### ***What is the moon illusion?***

The so-called "moon illusion" or "moon effect" has perplexed people since earliest historical times, at least as early as the 7th century BCE. It is described in early Greek and Chinese writings. Aristotle mentions it in 350 BCE.

The moon seems larger in angular size when it is near the horizon than when it is high in the sky. Some people judge it to be as much as twice as large, but the average estimate is 50% to 75% larger.

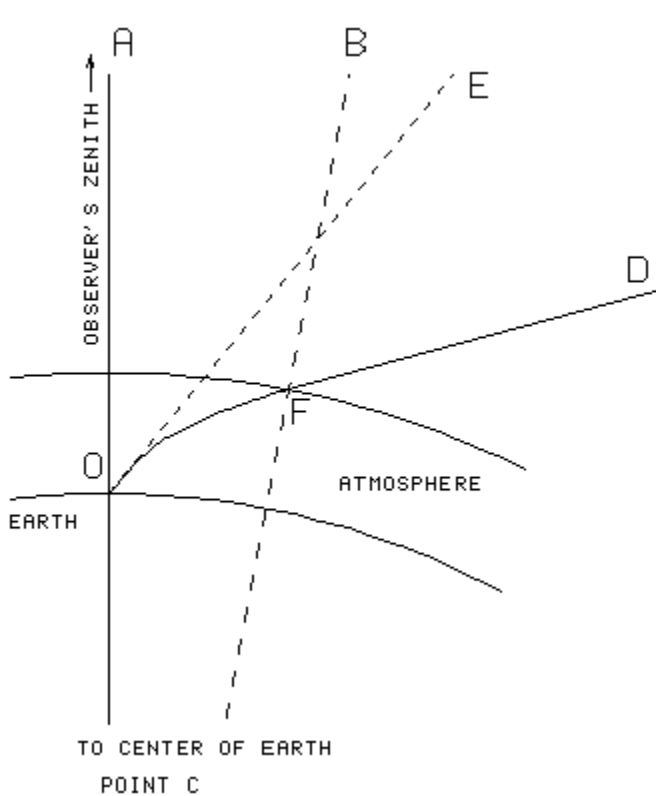
It's not a small effect. The Sun displays the same illusion, but viewing the Sun directly with the eye is hazardous without proper precautions, so let's leave that out of this discussion. The same illusion is observed with any extended object in the sky, such as a constellation.

### ***What it's not.***

We know that this phenomenon is not a physical or atmospheric effect, as may be easily demonstrated by photographing the moon in the sky at various elevations and comparing its size on the negatives. The moon's angular size is nearly constant as it moves across the sky, the moon subtending about 0.5 degree in the sky. One may also verify this with sighting instruments.

The moon does vary in angular size due to the eccentricity of its orbit. When the moon is closest to earth its angular size is about 11% larger than when it is most distant. The moon illusion describes the variation of apparent size during a much shorter time period of a few hours between its maximum elevation in the sky and its rising and setting.

Another real physical effect causes the angular size of the moon's image on the retina to be about 2% smaller when the moon is near the horizon, compared to its size near the zenith. This is due to the fact that the moon is one earth radius farther away when observed on the



horizon. This size change from zenith to horizon is much smaller, and in the opposite sense to the moon illusion. A change of such a small amount is not large enough to be noticed with our unaided visual system.

Some people suppose the moon illusion to be due to atmospheric refraction. Refraction effects can be measured with instruments or cameras, and we find that refraction actually makes the moon's disk subtend a **smaller** angle in the sky than it would have if the atmosphere were not present. These refraction effects make the moon's apparent horizontal angular diameter still smaller (by

about 1.7 percent) when the moon is near the horizon! These physical effects can be confirmed with telescopes and cameras.


The moon's **vertical** angular diameter at the horizon is even smaller, causing the moon to appear "flattened." At the horizon the light must pass through a greater distance in our atmosphere than when the moon is higher in the sky. This size change is also opposite (and much smaller than) the psychological moon illusion!

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**The reason that the atmosphere makes the moon's disk appear smaller is interesting in itself. Consider looking at a star directly overhead. The ray from this star takes the path AO to the observer at O. It passes through the atmosphere without refraction, along the radial line AC. Another star at lower elevation sends light along the line DF. This light is continuously refracted along the curved line FO, its path bending toward the radial line BC, finally reaching the observer at O. But the observer judges the direction of this ray to be along the line OE, which makes a smaller angle with AO than does the line DF. Therefore the angular separation of the stars seems smaller than it would be if the atmosphere were not present. This diagram is exaggerated. In the case of the moon, the angular separation of the edges of the moon is *much* smaller (about half a degree), but the same principle applies.**

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Astronomers understand these atmospheric refraction effects quite well, and



must precisely account for them as they interpret data from telescopes aimed at various elevations in the sky.

### ***Inadequate proposed explanations.***

To return to the moon illusion, many armchair speculators have proposed explanations for it. Some of these explanations, long ago discredited, still appear in textbooks. Many of these invoke visual or cognitive mechanisms that do have some relevance to the moon illusion. Some of these mechanisms modify the moon illusion, making it stronger and weaker, but are not in themselves sufficient to account for the full and strong moon illusion that most people experience.

Note: Some people report that they do not experience the moon illusion at all.

The literature on the illusion is largely silent on the reasons for this fact.

Explanations of illusions must be taken with appropriate skepticism. Many are of the nature of "plausible hypotheses." Most are not (as yet) such that they can be independently verified in terms of physical processes in the brain. Also, we know that our visual perceptions arise because our brain synthesizes multiple cues. Our brain weighs these cues; some dominate in certain conditions, while others are "weaker" and are ignored. But the weightings shift in strength according to the nature of the stimuli. Many classic visual illusions arise from conflicting sensory cues of nearly equal "strength". By controlled experiments, we may often rule out some of the inadequate hypotheses about particular illusions. But when one devises a test for one specific illusion hypothesis, it's difficult to avoid introducing some other type of illusion into the procedure.

Let's consider some of the proposed hypotheses about the moon illusion. Each will be presented, followed by evidence and arguments for and against it.

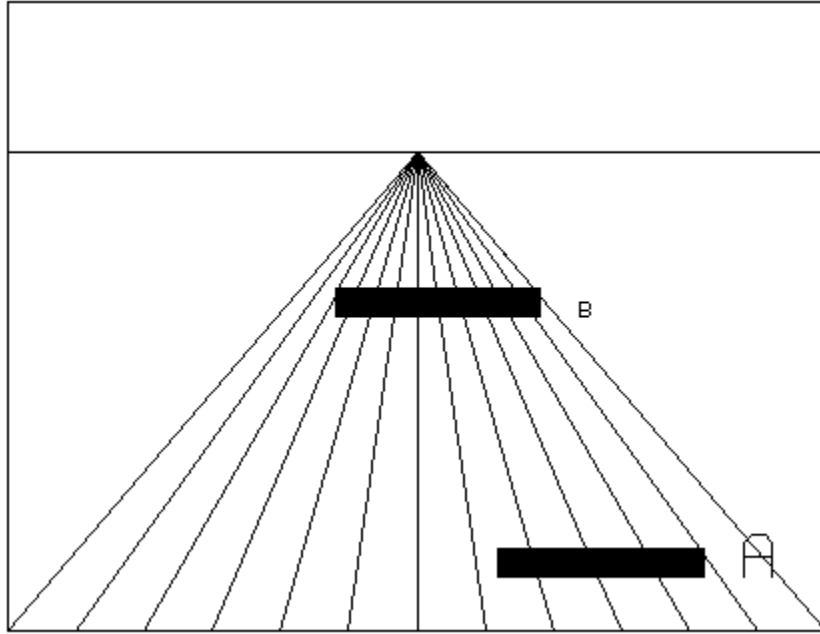
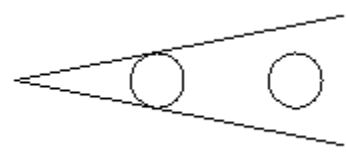
### **A Ponzo illusion.**

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**Illusion of shape. The two figures are exactly the same size, yet many people judge the upper one to be smaller. But not all persons do. This illusion illustrates how our judgment of shape and size of an object can be influenced by the shapes and sizes of other objects nearby in the field of view.**

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Illusions of shape are well known, as in the above example. Multiple cues in the field of vision can modify our judgments of shape, size, alignment, and even straightness of straight lines. Some claim the moon illusion is nothing



more than this. One particular version of this explanation invokes the Ponzo illusion. I wouldn't even consider this worthy of mention here, but for the fact that is still commonly seen in popular books on this subject.

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**The Ponzo illusion. The two circles are the same angular diameter. Yet many people judge the right one to be smaller. The two converging straight lines nearby influence our judgment. If the lines are replaced with solid black areas, the illusion remains.**

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When we view a drawing of, say, a straight railway track receding to the horizon in the distance, we interpret it as stretching from near to far even though it is only a pattern of radial lines drawn on a flat paper at constant distance from our eyes. This is relevant here because our experience with railway tracks and roadways has conditioned us to so interpret these patterns in this way. This is the mental map or model against which we interpret other things. We can draw two small identical figures on such a drawing, say a couple of plain (featureless) disks of equal size, the one placed where the tracks are well-separated on the paper (interpreted as near) and the other placed where the tracks converge to the vanishing point on the horizon (interpreted as far). The brain tells us that the disk where the tracks are narrow is the larger disk. Some writers liken this to the Ponzo illusion, but it is more than that.

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**The figure shows convergent lines that we imagine as parallel lines converging to a common "vanishing point" on the horizon. The two black bars are the same angular size, but we think that the one labeled B is farther away, and therefore many people think it is "larger". Not all persons perceive this size difference, but very few think A is larger. Remove the convergent lines, and nearly everyone judges the bars to be equal length.**

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In my opinion this illusion is not sufficient in magnitude to account for the

moon illusion, only to modify it (and confound attempts to experimentally study the moon illusion). But consideration of such illusions does remind us that other objects in the local field of view may affect judgments of size and shape. By "local" I mean "visually contiguous or adjacent".

### **Contextual effects; reference cues in the field of vision.**

When we judge the size of an object near the horizon our perception is influenced by familiar terrestrial objects in the field of view (trees, houses, roads). We know from everyday experience that many of the recognizable things we see in the distance are quite far away. But when our gaze is upwards, we have no reference cues for distance, and judge things near the zenith to be closer than those on the horizon. Ibn Alhazan proposed this explanation for the moon illusion around 1000 CE.

Some experiments seem to support this explanation.

- After-images of bright objects may be produced on the retina. Their apparent size depends upon where you look, being smaller when you look at a blank wall, or up into the sky, but larger when there are comparison objects in your visual field.
- When one looks at the moon near the horizon through a hole in a piece of paper held some distance in front of the eye the moon appears smaller. The "horizon effect" largely disappears. One interpretation of this experiment is that the paper tube obscures any familiar reference objects. It seems to show that the moon illusion is due to direct comparison with reference objects of known size. Another interpretation is that the paper tube provides a visually dominating reference object already judged to be "near".

Some experiments cast doubt that these explanations are complete.

- The moon illusion persists even when viewed on a dark night on a featureless plain, on the ocean, and even by airline pilots flying high above clouds. So reference objects of known size aren't the only basis for the illusion.
- The moon illusion disappears (for most people) when they bend down and look at the moon between their legs. [Is it merely coincidence that this is the position used for "mooning"? Disregard that.] Or, if so inclined, one can view the moon by hanging from one's heels! At least two hypotheses have been proposed to account for this. (1) Familiar

- objects in the field of view may become useless as distance references because of their unfamiliar appearance when viewed upside-down. (2) The illusion may have something to do with our inner-ear's balance mechanism that tells us whether the head is upright or upside-down.
- The method of viewing the moon through a hole in a piece of paper may also be used to view other objects. They too, appear smaller when viewed through the hole. Is our brain using the paper and the hole as a strongly dominant reference object? The nearby reference object is the paper; distant reference objects are hidden.

### ***Hypotheses with some merit.***

Some proposed explanations clearly have merit and are based on experimentally verified visual phenomena. But they also have "problems" that prevent any one of them being pronounced the "final answer".

### **A memory map.**

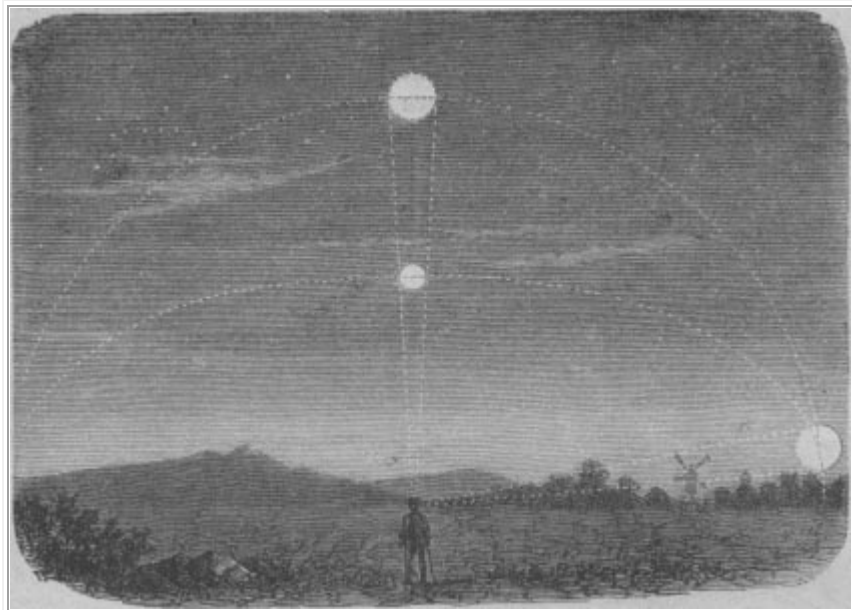
Perceptions are influenced by our past experience. One model of visual perception postulates that when we perceive a new and unfamiliar phenomenon our brain interprets it by comparing it to a mental map or model of our memory of previous sensory experiences. Of course, this represents just one of the cues that the brain must sort out, weighing it against other cues. Conflict between sensory cues is the basis of many common visual illusions.

When we observe the horizon moon and think, "My, that moon seems unusually large," we are comparing it to past experience of moons seen higher in the sky. The moon illusion, seen "in the wild" always involves a comparison of the horizon moon being seen **now** with a **memory** of an overhead moon seen earlier, or vice versa. There's about six hours between the horizon moon and the overhead moon (more or less, depending on the tilt of the moon's orbital plane and the season). Too often discussions bury this important point in a lot of moonshine. Perhaps it's more accurate to say that we are comparing our immediate perception of the moon with all of our memories of moons seen in the past, under a variety of conditions. We have only one moon, and cannot observe it in two positions at the same time.

Most of the studies done under controlled conditions ask human subjects to compare sizes of two objects seen simultaneously. And yet these studies clearly show that the illusion of size difference between overhead objects and objects on a level with the head is still present.

This alone does not discredit the mental map idea, but does show that if such a map, cognitive mechanism, or mental model is involved it does not **require** long-term memory. But it also is perceived even without simultaneously present comparison objects. The distinction between these two manifestations of the moon illusion is often blurred in the literature.

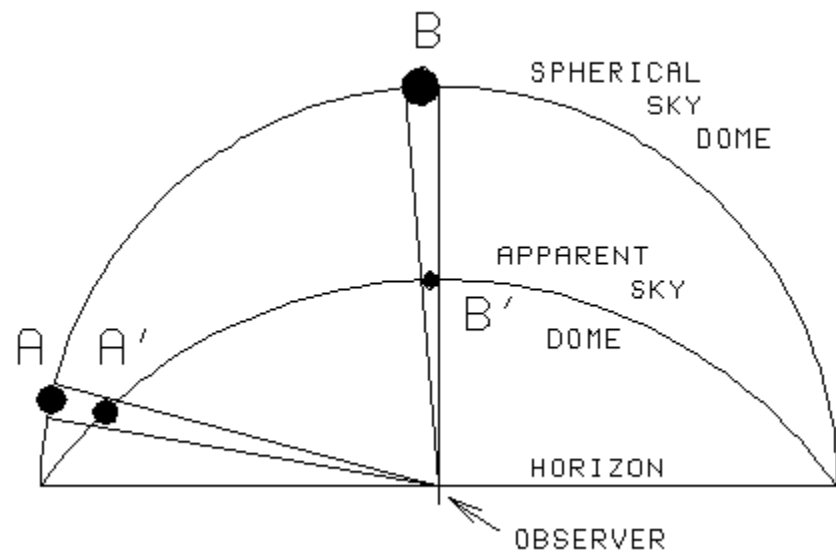
If there's a mental map or model, it need not be assumed to be located in a particular place in the brain. Very likely it is an interactive linking of specific visual functions distributed over various locations in the physical brain.  
**The mental sky-dome model.**



**The sky-dome model of the moon illusion,  
from the 1872 "Buch der Erfindungen"  
(book of inventions) vol. 2, p.239.**

This commonly seen explanation postulates that we have in our minds a mental map or model of the shape of the sky. We use this model as a real-time reference surface for objects too distant for stereoscopic distance cues, even when there are no other cues in the visual field to serve as distance benchmarks. This mental model does **not** picture the sky in the shape of a hemisphere, but is more like a relatively shallow, inverted soup-bowl. When we view something on the horizon we perceive that it's located on a portion of the sky farther away than an object of the same real angular size at the zenith.

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**This figure shows the comparison between a spherical sky dome and the shallow apparent sky bowl. When an object of constant size is seen near the horizon at A, and then near the zenith at B, we judge that both are "on" the apparent sky bowl, and therefore the object seems to be at A' and B', with A' being farther away**

**than B', and is therefore judged to be larger.**

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This diagram is the one usually seen in books that champion this hypothesis. But the diagram can be misleading. The hemispherical sky-dome in the picture is quite irrelevant, and ought to be omitted, for it falsely suggests a mental process of "projecting" the moon onto **that** dome. That's not a necessary part of the process.

The important point of the argument is that our judgment starts with the stimulus of the retinal image of the moon, which is very nearly the same size for horizon moons or overhead moons. Stated in an equivalent way: The moon has nearly the same actual (physical) angular size wherever it is in the sky. So we mentally assume that an object of this retinal size lies **on** the perceptual sky dome. That dome is perceived as more distant at the horizon than overhead.

This is the same as saying, "What is our judgment of actual size of two things at different perceived distances, even though they have the same angular size?" The answer is that the one assumed nearer is judged to be smaller. This conclusion is consistent with the mental judgment that the horizon moon is farther from us.

This process supposedly operates even (especially) in the absence of any other visual cues. But the process is confused when we have our heads in an unusual position. This may be the result of our knowledge of the orientation of our head, from visual cues, and perhaps from information from the balance-sensing mechanisms of our inner ear. When there **are** competing sensory cues, our judgment of angular size can be altered by them, which may account for the confusing results of experiments designed to show that visual cues are the sole reason for the moon effect.

Any hypothesis that depends on a mental model of the sky requires that we have some way to know, at least approximately, which direction is "up". The illusion is "anchored" on our judgment of "up" and "down".

### **What's wrong with the sky-dome model as an explanation of the moon illusion?**

One reader of the earlier version of this document mistakenly assumed I was promoting and defending the sky-dome model as an explanation of the moon illusion. That was not my intent at all, so I must increase the wordiness of this document by pointing out the obvious objection. Let me be very clear. The evidence for the illusion of the sky an inverted bowl is, in my view, abundant and undeniable, and must be dealt with if we are ever to understand the moon illusion. However, to use it as an explanation of the moon illusion is specious.

Consider an equally plausible argument using the sky-dome. We know that the full moon displays constancy of appearance (surface features) no matter where it is in the sky. It is the **same** moon wherever we see it. Few persons, when asked, would claim that the moon actually changes its physical size like a deflating balloon as it moves up in the sky. We adults agree that the moon has size constancy (children may not have formed such a conclusion). If we observe the moon in a starry sky, most persons say that the apparent distance of moon and surrounding stars is the same. There's no visual clue (such as parallax) to lead us to think otherwise. All of these "sky objects" are judged to be on this flattened "sky dome." If that is so, then the overhead moon should be judged **larger** in angular size, since it is on a portion of the sky that we judge is nearer to us.

Comparing these two hypotheses with contradictory conclusions leads us to see the inadequacy of both of them, and the emptiness of this sort of argument. It forces us to examine just what we mean by "distance", "size", and "angular size". We will return to this point later. This confusion does not invalidate the **perception** of a flattened sky dome, but does reveal the dangers in trying to use one illusion (the sky dome) to explain another (the moon illusion).

I hate to suggest this, but many of the arguments about moon and sky illusions are similarly flawed, and seem only to be playing verbal games with the reader. They "sound good" but fall apart on close examination.

## **The flattened sky-dome hypothesis examined.**

So why should we have this shallow-bowl model of the sky? Or, to put the question another way, why do we have a cognitive processing mechanism (however complex) that, in effect, gives us a perception of the sky distorted to conform to such a model? Two suggestions have been made. (1) The mechanism is hard-wired into our brains from birth. (2) The mechanism is built up through experience, by daylight sensory experiences, from a host of visual cues in everyday life.

Studies of children from age 4 to adult suggest that the moon illusion is present in children, and is stronger than it is in adults. It **decreases** in strength with age. [Liebowitz, H. and Hartman, T. "Magnitude of the Moon illusion as a Function of the Age of the Observer." *Science*, 130, 569-570.] This study was done indoors in a large darkened room (no other visual cues) with artificial moons at distances of 85 feet.

Studies with children can be confusing, for a child will often reach out to touch a distant object, like the moon on the horizon. Children haven't yet developed the same mental model of visual space that adults have. This study suggests that visual experience as one matures to adulthood modifies the illusion by improving our judgment of horizontal distances, thereby **decreasing** the illusion. This casts doubt on any explanations that assume that the moon illusion is a result of visual experience and suggests that the illusion itself may be innate and present at birth.

The hard-wired hypothesis supposes that natural selection has shaped those brain mechanisms that process and interpret sensory data, devoting more resources to those things that are important to survival. This results in brain resources being biased toward things seen in front of us, fewer resources to things overhead. Similar imbalance of perception details are present in animals.

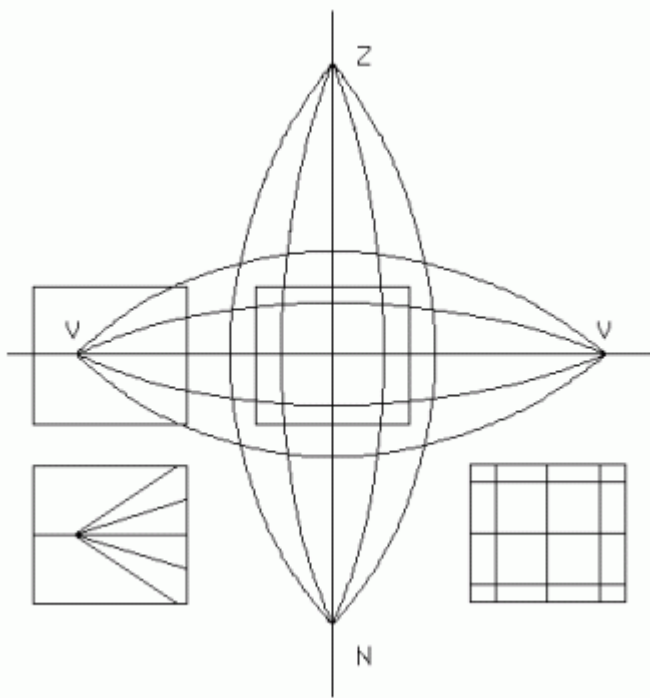
Running great risk of over-simplifying a complex problem, we might say that things seen overhead appear smaller in angular size because our brain never evolved adequate resources to interpret data we judge to be "overhead". That data was not important to our species' survival. Our visual space allocates less detail and poorer judgment of relative distances for objects at large elevations up, or down.

## **Anisotropy of visual space.**

Luneberg (1947) proposed a theory of vision that attempted to relate physical space with virtual (perceptual) space. He concluded that virtual space is non-Euclidean, that it is a Riemannian space of negative curvature: a hyperbolic space. Visual space does not have the same metric properties in all directions. (This idea is mentioned here for completeness, not to claim that Luneberg developed the idea fully and successfully, nor that he applied it to the moon illusion.)

This hypothesis is most helpful in understanding the fact that all lines of a set of physically parallel lines are also perceived as straight. Certainly they are not rendered straight on our retinas, and their curvature on the retina changes in complicated ways as we move our eyes right/left and up/down. Yet at any instant, they seem perceptually straight. Our brain is continually recalculating the data from the retinal image, to give a perception of straightness. Is our cognitive apparatus biased to render "straightness", or is this merely a by-product of cognitive processes that "correct" the "warped" retinal image to resolve visual contradictions when our eyes scan the real visual world? We live in a modern world with many straight and parallel lines: streets, walls, railroad tracks, etc. Yet the mechanism for dealing with the visual world evolved to its present form long before our ancestors ever experienced such geometric regularities. Clearly this process has more fundamental importance to our vision than rendering straight lines "correctly". I am **not** arguing that the curved retina is the **reason** for the anisotropy of visual space. I'm simply pointing out that the brain has mechanisms for dealing with the retinal shape, and the dynamically changing retinal image (as the eyes scan a scene), to produce a stable, and reasonably consistent geometry of visual space. This is what psychologists call "perceptual space".

Only when we scan our eyes around this geometric world, consciously trying to get the "bigger picture", do we become aware how our eye/brain mechanism handles this problem. Try this experiment. Look at a long straight wall. The wall seems to have straight and parallel lines when our line of sight is perpendicular to the wall. But when looking parallel to the wall, those same lines appear to be straight lines converging to a "vanishing point" on the horizon. Shifting our gaze from one end of the wall to the other we integrate all of these views and finally perceive that those parallel lines appear as curved lines diverging from a point at the horizon, becoming nearly parallel, then converging to a point at the other horizon. This is the geometric world of our wider visual field, one of curved lines, a "Remannian" space. But when we fix our gaze in one direction, our brain straightens out those curves, producing a result like the "Euclidean" space of an artist's strict perspective rendering.



**The larger visual space.**  
**Spherical perspective of parallel lines**  
**perceived from wide-ranging sweeping of the eyes**  
**over more than a whole hemisphere.**  
**This is similar to a fish-eye lens photograph.**  
**Z (zenith), N (nadir), V (left and right vanishing points).**  
**The insets show how parallel lines are**  
**rectified as straight in the smaller visual field.**

This process does not, however, consistently "correct" angles between lines. Right angles in a perspective drawing are usually not right angles on the paper or canvass. Nor are angles correctly perceived by the eye when the plane of the angle is tilted with respect to our line of sight.



Once we recognize that visual space may not be anisotropic, and that it is a somewhat consistent distortion of real space, we have a new way of thinking about the moon illusion and related sky illusions.

Anyone can appreciate the character of this anisotropy by looking at the daylight cloud-covered sky in relatively flat terrain. Physically the cloud canopy is nearly a flat plane, as is the earth under our feet, because the radius of their curvature is so large compared the distance to the visual horizon. Think of observing the sky from a ship in the middle of an ocean. The ocean does appear nearly flat, but the cloud cover appears as an inverted shallow bowl. This shape can be appreciated even better if the observer slowly moves his eyes to scan around the horizon and up from horizon to zenith, with conscious intent to get a feeling for the shape of things in this larger visual space. Some people even perceive that the ocean curves somewhat upward toward the distant horizon just as the cloud cover curves downward. In any case, most people judge the sky at the horizon to be the same distance as the horizon.

How does this impression square with the situation in real (physical) space? The physical distance to the most distant object one can see on the horizon depends on the elevation of the observer's eye above the water. One can derive the formula for it, in terms of the earth's radius. For an eye elevation of six feet, the things we see on the horizon are actually about 3 miles away. Alto-cumulous clouds are about 2 to 3.5 miles overhead. So, physically, the distances are nearly the same, yet the overhead clouds **seem** much closer to most people than those near the horizon. This calculation may not seem quite fair, for we can see clouds that are physically well beyond the surface horizon, around 100 miles away, due to their height above the earth surface. But can any reader and observer honestly claim that the clouds at the horizon **seem** farther away than the water at the horizon? I've never found anyone who would make that claim?

Since the clouds at the horizon are about 100 miles away, the physical dome of a cloud-covered sky is a **very** flattened bowl (or saucer), 100 miles in radius and only a few miles high. Yet when this calculation is done, even the most seasoned mathematician or physicist must admit "I don't **see** it that way!" Need we further belabor the point that the

geometry of our visual space of such distant things is severely warped compared to physical space?

We have a strong impression that the cloud cover "joins" the horizon. Can this simply be that there's absolutely no visual cue to suggest that they are at different distances? Our brain may be making the simplest reconciliation of the situation.

Why does the cloud cover appear to curve downward at all? This is seen even when there are individual clouds with cues of shape, size, and shadowing. Beyond a certain distance, a distance set by other visual cues, our brain refuses to place objects at a greater apparent distance, especially if there are no **local** cues indicating objects between the horizon and the cloud cover. By "local" I mean, visually contiguous objects near the horizon line. Our cognitive mechanism seems to prioritize decisions, favoring reconciliation of "adjacent" cues at the expense of those displaced from one another by larger visual angles.

These facts illustrate that when we are dealing with these great distances, our usual geometric **logic** about distances is essentially useless to describe what we **perceive**. Once this fact of perception is realized, one also realizes that many of the experiments and theories of the moon and sky illusions and many of the published papers on the subject of visual illusions are simply irrelevant our judgments of very distant objects.

Why is visual space anisotropic? Specifically how does the anisotropy work? Why does the "metric" of this anisotropy shift in response to visual cues, such as objects at various distances in the field of view, and even on past visual experience? And why does some anisotropy remain even if nearly all visual distance cues are absent? Those are questions that need to be addressed. Little progress has been made in that direction. But we can't solve the moon and sky illusions until we deal with those questions.

### **Space-filling**

The research clearly indicates that nearby objects in the field of view do influence our judgment of the distance and size of more distant objects. In a general way, it seems that

- Objects in the visual field that are contiguous to the distant objects have the greatest effect on size judgments.
- When there are many objects in the field of view for which we can readily and unambiguously assign sizes and distances, this can give a strong impression of greater distance for those objects "beyond" the others.
- When there are few contiguous objects and few strongly located nearer objects in the field of view, distant objects appear nearer.
- We tend to perceive an object with fewer distance cues to be "just beyond" the farthest object for which we have mentally assigned a concrete "distance".
- Easily recognized objects, and those for which distance cues are strong, are probably processed by the brain first, leaving more ambiguous objects for later processing. Of course the whole process is so rapid we think that the judgments are instantaneous.

It's as if our visual space becomes "filled" with objects for which our brain can readily assign distances, leaving those with fewer (or ambiguous) distance cues to occupy the "more distant" space, located just beyond the more confidently located objects.

Even within the visual space of relatively unambiguous distances and sizes, our brain has placed objects in this space by resolving visual conflicts and by using some visual cues to modify and reinforce other cues.

### **Trehub's retinoid model.**

Arnold Trehub, in his book *The Cognitive Brain* (MIT Press, 1991) proposed a comprehensive theoretical model of cognition, postulating neuronal mechanisms and systems that are responsible for cognition. He hypothesizes a neuronal structure that acts as a dynamic buffer for processing information from the retina, which he calls a *retinoid*. This retinoid performs many functions, some of which determine how visual sensory information is interpreted, before it is passed on to higher levels of visual processing. The retinoid organizes and integrates visual information into a unified model of visual space. Trehub calls it a "visual scratch pad" that stores spatially organized information as short-term memory.

One need not delve into the details of how this might work on the cellular level in order to recognize the importance of this general idea to the study of perception and to illusions of perception.

The visual process begins with sensory data, primarily from the retina. The retinal images represent a crude map (in two dimensions) of the real space of luminous points. The cognitive processes synthesize this data, reconciling ambiguities, correcting for deficiencies of the eyes themselves and creating a final "veridical" image that we perceive as the space we are looking at. Past experience plays a role, when we observe familiar objects.

For example, we see three faces of a cube, but our experience with cubes generates a veridical judgment that the cube has six faces, including the ones that produce no retinal sensation until we rotate the cube. Our brains have established sub-processing systems for cubes, spheres, trees, and other familiar objects, treating them as entire objects even when we see them only partially.

The veridical image is in some ways better than the retinal images at any instant. Yet it can also have features that simply aren't an accurate representation of real space, as demonstrated by the many visual illusions studied by psychologists. Many such illusions have contradictory visual cues, and the brain does the best it can at reconciling those contradictions.

This cognitive bias of veridical space depends upon our prior cognitive judgment of up and down. We have a sub-processing brain mechanism for the space surrounding us. But the data funneled into this system has already subconsciously been realigned at an earlier stage of cognitive processing that made a judgment about up and down. Various cues, including our vestibular balance mechanism tell us at all times how our head is oriented. Then the rest of the cognitive apparatus further interprets visual cues based on this judgment of "up". [The older "sky dome" hypothesis depends upon this up/down judgment also.] Tilt of the head can slightly alter this judgment, but if there are enough cues, it won't destroy the sky and moon illusions. However, hanging by one's heels or looking at the sky with head inverted greatly reduces the illusion for many people. But this orientation also confuses one's interpretation of many visual spatial relationships. It's worth noting that the quality of many visual judgments is much reduced when viewing the world from this unusual position, even when viewing a picture or

photograph that is **also** inverted. Things don't seem quite right. The quality of cognitive processing is severely degraded.

The moon illusion is consistent with what would be expected from evolutionary considerations. We have evolved cognitive processes that provide high quality visual information from nearby things, and things on our level that we can walk to and experience from various angles. These are all important to survival. Things seen high above, in the sky, or even those seen below, as when looking over the edge of a cliff, are less important. Therefore distance discrimination and detailed judgment of other visual properties of overhead objects is compromised.

### **The size-distance paradox.**

Most people have a cognitive model that relates angular size to distance. This is called the "size-distance invariance law". When one observes two persons, one subtending a small angle, one a larger angle, one judges the person subtending the small angle to be more distant. This works for objects that we know or have already judged (from memory and other cues) to be "really" about the same size.

As usually seen, the sky-dome model "explains" the moon illusion in this manner: The retina receives a certain size stimulus, the same angular size for horizon or overhead moons. The brain has a model of the sky that causes us to judge that the overhead moon is the nearer one. Therefore since the two moon images have the same retinal size (stimulus), we judge the overhead moon to have smaller actual size. As indicated earlier, this over-simplified "explanation" seems to me empty and misleading.

Some who object to the "sky-dome" model in any of its variants point out that when subjects are asked which moon is larger, they answer "The horizon moon." When asked which moon is nearer, most will say "The horizon moon." This, critics say, contradicts the simple sky-dome explanation, and therefore invalidates it. They call this the "size-distance paradox". This objection, in my opinion, carries no weight.

In these discussions we must distinguish three levels of sensory processing that play a role in the final judgment.

1. The sensation itself. In this case, the diameter of the image on the retina, stimulating light receptors there. All commentators agree that the moon illusion does not occur on this level.
2. The unconscious judgment of some "physical" property, such as brightness, angular size, color. This may be influenced by past experience, or by quirks of innate cognitive functioning, but is done without us consciously "thinking about the matter" or deliberately "analyzing" something.
3. The reasoned consideration of the sensation, by questioning and by conscious analysis. Example: "Those two bars seem connected, but that can't be so, for it violates some laws of math or physics." On this level, judgments may be expected to be quite different for untrained and trained observers, and also different for those unschooled in math and physics compared to those who are. The moon illusion literature is largely silent on these possible differences of interpretation.

Mixing these levels has confused many discussions of the moon effect.

**What is the meaning of 'size'?** When dealing with physical measuring instruments such as cameras and telescopes, the relations between angular size, linear size and distance is a straightforward application of trigonometry.

$$\tan(\text{angular size}) = (\text{linear size})/(\text{distance})$$

Or  $\tan(\alpha) = S/D$

But visual judgments of linear size and distance are clearly confounded by visual illusion effects of various kinds. So "apparent linear size" and "apparent distance" were introduced, and the size-distance-invariance hypothesis was written:

$$\tan(\text{angular size}) = (\text{apparent linear size})/(\text{apparent distance})$$

Or  $\tan(\alpha) = S'/D'$

On this view, if distance cues predominate, altering D to D', then the apparent size S' will be "computed" by the brain as necessary to interpret the angular size A of the image on the retina. But if size cues predominate (as when you are looking at a person whose size is familiar from long experience), the apparent distance D' will be computed by the brain.

This hypothesis has an underlying assumption. That the angular size of importance is simply the physical size of the retinal image, the visual stimulus. But is it possible that perceived angular size is also subject to illusory effects? If so we should write:

$$\tan(\alpha') = S'/D'$$

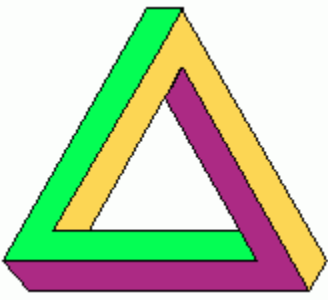
This view, and this equation, were first proposed by Don McCready [1965]. He developed this more fully in his [1985] paper, and applied it to the moon illusion [1986]. His website provides a very thorough presentation of these ideas.

This raises the question: What are we doing when we judge the "size" or "distance" of something (like the moon) for which we've had no experience close-up, and whose physical linear size and distance are too large to perceptually comprehend anyway? When we say a moon is "larger", are we talking about angular size or linear size?

Some argue that the basic moon illusion is one of angular size. Certainly all the experiments that ask subjects to compare the moon's image (or a simulated moon) with a physical object (or a simulated physical object) are asking for a comparison of perceived angular size. Also, the interpretation of experimental studies may be confounded by ambiguity of the meaning of the word "size", as understood by the subjects and by the experimenters. Even if the experimenter carefully explains to naive subjects the difference between angular size and linear size, and between "real" size and "perceived size", a subject may be incapable of making those distinctions when describing an observed object.

I will not belabor the three size equations given above, for they may not even be relevant to the question of the moon illusion. The moon illusion operates at real distances essentially infinite, and real sizes beyond direct apprehension. The only relevant variables are angular size, real and apparent. However we must admit that experimental studies of illusions seen in nearby space may help us understand the cognitive mechanisms that may also apply to the moon illusion.

Some studies have asked subjects "which moon seems nearer", which seems an unfair question, but still one cannot deny that we have mental processes that produce at least an approximate subconscious judgment of "near and far" for things in the sky, and this is certainly relevant to the



sky illusions. The cognitive judgment of apparent angular size is made at a very early level of cognitive processing, without "thinking about it" consciously (deliberately). When asked which moon is larger, we then must consciously process this question (without being consciously aware of our previous unconscious determination of its apparent angular size).

Suppose an observer has subconsciously determined that the horizon moon has larger angular size than the zenith moon. This is the "perceived" angular size,  $\mathbf{A}'$ . When asked which moon is nearer, the observer may consciously reason that the horizon moon must therefore be nearer. Never in this process is this observer aware of the *unconscious* process by which his brain already concluded that the horizon moon had larger angular size. No contradiction or paradox is present here, for these two levels of mental processing are not simultaneous. The contradiction comes only when we think about what we said.

Most visual illusions contain similar judgment contradictions. When the Penrose impossible tribar is seen, a subject may judge that the right side is more distant than the left, based on the way they connect at the top vertex. But then, looking at the constant angular width of the lower horizontal bar, the subject is forced to conclude that the two bottom corners are the same distance away. Contradiction. Yet each individual judgment seems "right" and is based on habitual visual associations of everyday experience. This is what makes illusions tantalizing.

Observers schooled in physics and math, physicists, astronomers, and amateur sky-gazers, have learned somewhat different conscious models. When asked "Which moon is nearer" they may respond "That's an unfair question; it's still the same moon, and in both cases the distance and size are too great to make a distance judgment." If a follow-up question is asked, "Which one **seems** nearer?" the answer is often "Well, you can't trust your eyes in such matters." Many scientists have learned (by their mistakes) not to trust their eyes in certain kinds of informal observations. As Helmholtz said, "I would never believe anything solely on the evidence of my eyes." Unlike Helmholtz, most physical scientists do not inquire into the reasons behind visual deceptions, they simply try to stick to observations and instruments that can be **shown** to produce reliable and observer-independent results.

### **Oculomotor micropsia and macropsia**

Don McCready's web documents emphasize the importance of angular size illusions. He also proposes an explanation of the moon illusion based on angular size illusions due to oculomotor micropsia, an illusion that accompanies the accommodation of the eye lens and the convergence of the two eyes. Oculomotor micropsia has been known since it was discovered by Charles Wheatstone (1852), and has been amply demonstrated experimentally for nearby objects, those for which convergence and accommodation play a dominant role in perception of distance. McCready's detailed website document describes this effect quite well.

Briefly oculomotor micropsia is this: Normally, if there's only one object, or a dominant object, in the field of view, our eyes try to converge and accommodate to its distance. The muscles that control convergence and accommodation send signals to our brain, which are important distance cues. But when one's eyes converge and accommodate on a distance nearer than that of the object, that object appears to subtend a smaller angle than if one's eyes were converged and accommodated upon it. Micropsia means "appearing small", and here refers to the visual angle subtended by an object. The reverse effect, macropsia, occurs when the eyes converge or accommodate at a distance greater than the object being judged.

Why would the eyes converge or accommodate at distances different than the object of interest in the field of view? Several reasons. A very large number of nearby objects spread over the field of view may bias the brain towards convergence at their distance. For most people, the functions of convergence (aiming the eyes to a common point) and accommodation (focus setting of the eye's lenses) are "locked together" so if one converges to nearby objects, the accommodation adjusts to that distance also, and vice-versa.

Proponents of this hypothesis as explanation of the moon illusion argue that if there are a number of distant objects in the field of view, as there would be when observing the rising or setting full moon, the brain adjusts accommodation and convergence to them. But when viewing the full moon directly overhead, in a clear sky, there are no other distance cues, and the eye adjusts to its **resting focus** a distance of 1 or 2 meters. This makes the perceived angular size of the overhead moon seem smaller. Further support of this hypothesis is the effect of dark surroundings, which bias the eyes to adjust to the **dark focus** distance of about 1 meter.

But, these micropsia and macropsia illusions cause angular size differences of less than 10%, nowhere near large enough to account for the moon illusion seen by most persons.

Also, if accommodation were involved in the moon illusion, you'd think that elderly people who have lost nearly all accommodation should not perceive the illusion. Yet they do. Persons with eye lens implants have no accommodation, and they do perceive the moon illusion. Covering one eye removes convergence from consideration, but that doesn't make the moon illusion go away.

As usual in these matters it's not so simple. Experiments have shown that even when one eye is covered, or blind, the muscles and the eye lens still accommodate to the distance perceived by visual information supplied by the other eye. Also when the eye lens muscle is paralyzed in both eyes by use of atropine drops, micropsia still occurs. It seems that micropsia and macropsia are not the result of physical changes in the eyes, but are caused by processes occurring in the brain, the same processes that control the muscles of the eyes and the ciliary body that adjusts the focus of the eye lens.

### ***The planetarium sky.***

Does the same thing happen in a planetarium? No! This is why the planetarium is a poor simulation of what we see in the night sky. All real-sky effects are beyond the range where our stereoscopic vision (due to eye convergence) works (about 50 to 100 feet), so our eyes can't triangulate objects in the sky. The planetarium, with, say a 50 foot diameter dome, has all star images just within the range of stereoscopic vision, and this fact dominates our judgment, minimizing other psychological effects. Also, as we walk into a planetarium we have a visual and rather direct feeling for its size that persists even after the lights are turned off.

Have you noticed that the moon, projected onto a planetarium dome with exactly the correct angular size, seems the same apparent size wherever it is located on the dome, and therefore appears "too small" when on the horizon, compared to our memory of the setting or rising moon in the real sky?

I've been informed (Jan 2000) that some researchers claim that the threshold for detecting depth due to retinal disparity is 1 arc second, so persons with normal vision can detect distance differences between the moon and objects up to at least 100 meters away. Such experiments are done under "ideal conditions" and

usually involve judging whether two points of light are equally far away. My comments about the planetarium sky do not depend on the correctness of this figure, since the planetarium dome is clearly well within the range of stereoscopic vision, whichever figure you accept for the maximum distance for stereo vision.

The hypothesis of the importance of eye-convergence (stereoscopic vision) in the moon illusion can be tested. Suppose we suppress stereoscopic cues in the planetarium by covering one eye. Experiments related to the moon illusion, especially those where nearby objects (nearer than about 50 feet) are in the field of view, should also be done with one-eyed viewing to suppress stereoscopic cues. This has not always been recognized as an important visual cue in these experiments. However, I think they play little role in the moon illusion itself, or any related illusion related to objects beyond the range of stereoscopic vision, except to establish the distance of nearby reference objects in the field of vision.

This illustrates why experimental psychology can be every bit as difficult as physics. As McCready says (August 1999): "Clearly, no theory has been fully accepted by the experts yet."

### ***What's the bottom line?***

In summary, it seems to me that:

1. The class of size illusions that includes the moon illusion affect primarily objects at distances beyond those where stereoscopic and other strong distance cues are operative. We therefore should not expect that the size-distance invariance laws for near objects are even relevant to the moon illusion.
2. The sky illusion (sky-dome as a shallow inverted bowl) should not be ignored, for it is nearly universally observed. Both it and the moon illusion may arise from the same cause. Understanding the sky illusion may be the key to understanding the moon illusion, but to merely invoke the sky illusion as the **cause** of the moon illusion evades the fundamental issues, and is empty of content.
3. The sky illusion represents a warping of visual space for objects so distant that other everyday cues to distance and size are inoperative.
4. The sky illusion depends greatly on one important cue: our sense of what direction is **up**. Cognitive processing of visual space may be linked to our knowledge of the tilt of the head, from visual cues relating to up/down and the vestibular balance mechanism in the inner ear. Therefore we know the position of our head and eyes relative to "up"

- and "down". However, some studies show that head tilt alone plays only a small role in angular size determination of isolated objects in an indoor laboratory environment, in the absence of other stimuli.
5. Other objects seen in the visual field while viewing the moon can further modify our judgment of distance and size, confusing some of the experiments that have been done.
  6. Spatial relations that are familiar, unambiguous, and easily "computed" are processed promptly, and perceived objects are mentally assigned sizes, distances and locations in visual space. Ambiguous objects, and those with no strong distance cues are processed after the near visual space has been "filled" and are assigned to distances just beyond the "filled" space, if that can be done without cognitive conflict.
  7. Trehub postulates that we are born with a subconscious cognitive processing mechanism that is innate. It is a result of evolutionary necessity for devoting more visual processing resources to nearby space, and space at eye level, but fewer resources to things seen at higher elevation. Therefore the angular size of objects at eye level is perceived as greater than the angular size of the same objects seen when looking upward. This model does not rule out the possibility that such perceptions can be modified through experience and by particular sets of visual cues. Such cognitive models may serve as a guideline for experimental investigations, but direct experimental confirmation of all of a model's details is necessary before it can be considered a physically and biologically correct explanation.
  8. We have many descriptive models of cognition that certainly are better than nothing, but do not adequately and fully represent what goes on in the brain. Their power to correctly predict how we perceive particular new situations is not impressive. These are very much like a flow chart of a computer program, which doesn't give us a clue about what goes on at the bit and byte level when the program is run on a particular computer.
  9. The final word has not yet been written on this subject.

— Donald Simanek

### ***AN INCOMPLETE BIBLIOGRAPHY***

The literature on the moon illusion is vast, indicating an obsession with the problem that borders on lunacy. I'm in no position to compile a complete and definitive bibliography. I do not have easy access to the relevant journals, especially the older ones. Fortunately Hershenson's book includes many literature references, as do the web sites listed here. I have not consulted all of

these. Some were recommended by others. I welcome suggestions for making this bibliography more useful.

In this document I have not attempted to give a complete history of ideas about the moon illusion, nor have I tried to indicate in every case who first proposed a hypothesis or who did the experimental studies, or when, for I had no intention to write a definitive history of the subject. Besides, it's often impossible to know who **first** had a particular idea, as distinct from who was first to publish it. Bart Borghuis' web document may be consulted for such details, and the anthology by Herschenson [1989] contains detailed review and bibliography of the literature of the subject.

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## SOME INTERNET SITES

Listing these sites here does not constitute endorsement of the validity of their content. I, personally, have reservations about many of them.

1. [The Moon Illusion, A literature thesis](#) by Bart Borghuis. A very extensive review of the published research, and the theories of the moon illusion.
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4. [The Moon Illusion](#) by Carl J. Wenning.
5. [The Moon Illusion](#), by Hendrik Ball.
6. [The Moon Illusion Explained](#), by Don McCready.
7. [Sensation & Perception; Ponzo Illusion](#).

Input and suggestions are welcome at the address shown to the right. When commenting on a specific document, please reference it by name or content.

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**FEATURE**

**Summer Moon Illusion**

**06.20.05**

**The lowest-hanging full moon in 18 years is going to play tricks on you this week.**

Sometimes you can't believe your eyes. This week is one of those times.

Step outside any evening at sunset and look around. You'll see a giant moon rising in the east. It looks like Earth's moon, round and cratered; the Man in the Moon is in his usual place. But something's wrong. This full moon is strangely inflated. It's huge!

You've just experienced the Moon Illusion.

Sky watchers have known this for thousands of years: moons hanging low in the sky look unnaturally big. Cameras don't see it, but our eyes do. It's a real illusion.



**Above:** A time-lapse sequence of the moon rising over Seattle. To the camera, the moon appears to be the same size no matter what its location on the sky. Credit and copyright: Shay Stephens. [\[More\]](#)

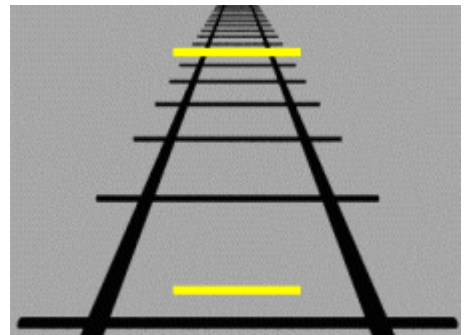
This week's full moon hangs lower in the sky than any full moon since June 1987, so the Moon Illusion is going to be extra strong.

What makes the moon so low? It's summer. Remember, the sun and the full Moon are on opposite sides of the sky. During summer the sun is high, which means the full moon must be low. This week's full moon occurs on June 22nd, barely a day after the summer solstice on June 21st--perfect timing for the Moon Illusion.

When you look at the moon, rays of moonlight converge and form an image about 0.15 mm wide in the back of your eye. High moons and low moons make the same sized spot. So why does your brain think one is bigger than the other? After all these years, scientists still aren't sure why.

A similar illusion was discovered in 1913 by Mario Ponzo, who drew two identical bars across a pair of converging lines, like the railroad tracks pictured left. The upper yellow bar looks wider because it spans a greater apparent distance between the rails. This is the "Ponzo Illusion."

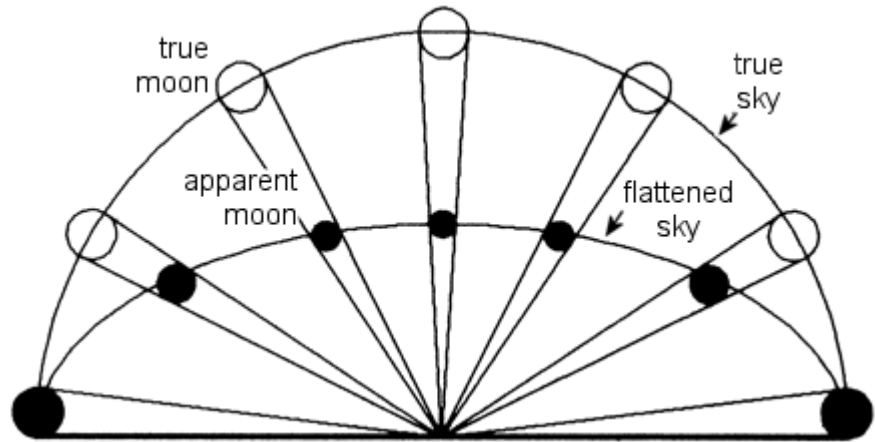
**Right:** The Ponzo Illusion. Image credit: Dr. Tony Phillips. [\[More\]](#)



Some researchers believe that the Moon Illusion *is* Ponzo's Illusion, with trees and houses playing the role of Ponzo's converging lines. Foreground objects trick your brain into thinking the moon is bigger than it really is.

But there's a problem. Airline pilots flying at very high altitudes sometimes experience the Moon Illusion without any objects in the foreground. What tricks their eyes?

Maybe it's the shape of the sky. Humans perceive the sky as a flattened dome, with the zenith nearby and the horizon far away. It makes sense: Birds flying overhead are closer than birds on the horizon. When the moon is near the horizon, your brain, trained by watching birds, miscalculates the moon's true distance and size.



Above: The 'flattened sky' model for the Moon Illusion. [\[More\]](#)

There are other explanations, too. It doesn't matter which is correct, though, if all you want to do is see a big beautiful moon. The best time to look is around moonrise, when the moon is peeking through trees and houses or over mountain ridges, doing its best to trick you. The table below (scroll down) lists moonrise times for selected US cities.

A fun activity: Look at the moon directly and then through a narrow opening of some kind. For example, 'pinch' the moon between your thumb and forefinger or view it through a cardboard tube, which hides the foreground terrain. Can you make the optical illusion vanish?

Stop that! You won't want to miss the Moon Illusion.

## Moonrise over Selected US Cities

City	Time Zone	June 20	June 21	June 22
New York, NY	EDT	7:25 p.m.	8:39 p.m.	9:43 p.m.
San Diego, CA	PDT	6:58 p.m.	8:09 p.m.	9:14 p.m.
Washington, DC	EDT	7:31 p.m.	8:44 p.m.	9:49 p.m.
Honolulu, HI	HST	6:17 p.m.	7:26 p.m.	8:31 p.m.
Chicago, IL	CDT	7:28 p.m.	8:42 p.m.	9:46 p.m.
Houston, TX	CDT	7:18 p.m.	8:28 p.m.	9:34 p.m.
Denver, CO	MDT	7:32 p.m.	8:45 p.m.	9:48 p.m.
Miami, FL	EDT	7:03 p.m.	8:13 p.m.	9:19 p.m.
Seattle, WA	PDT	8:22 p.m.	9:38 p.m.	10:39 p.m.

Above: If your city does not appear in this list [click here](#) for more data from the US Naval Observatory.

#### More Information

[The Moon Illusion Explained](#) -- According to Don McCready, a Professor Emeritus of Psychology at the University of Wisconsin, the Moon Illusion is caused by *oculomotor micropsia/macropsia*.

[The Moon Illusion: An Unsolved Mystery](#) -- a nice overview of the Moon Illusion and its possible causes.

[New Thoughts on Understanding the Moon Illusion](#) -- from Carl J. Wenning, Physics Department, Illinois State University

[Experiment in Perception: The Ponzo Illusion and the Moon](#)

[Explaining the Moon Illusion](#) -- from the Proceedings of the National Academy of Sciences

[NASA's Vision for Space Exploration](#) -- See the Moon? NASA plans to send astronauts there, again, before the year 2020.

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