The Moon Illusion Explained

Finally! Why the Moon Looks Big at the Horizon and Smaller When Higher Up.

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Introduction and Summary

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[Technical Notes on the Murray, Boyaci, & Kersten (2006) experiment were added in June, 2006.]

For many centuries, scientists have been puzzled by the common illusion that the rising moon at the horizon looks considerably larger than it does later, at higher elevations toward the zenith of the sky. For at least nine centuries they have known that the angular subtense of the moon's horizontal (azimuth) diameter always measures about 0.52 degrees at an earthly observation point no matter where the moon is in the sky. In other words, there is no physical (optical) reason why the horizon moon should look larger than the zenith moon.

Because the moon's angular size remains constant, photographs of the horizon moon and zenith moon taken with the same camera settings yield images which are the same size, as represented by Figure 1.
Such pictures prove that the earth's atmosphere certainly does not "magnify" the horizon moon.

Figure 1: This sketch represents what a double-exposure photograph of the horizon moon and zenith moon looks like.
The two moon images have the same diameter on the film (and a print) because the angle the endpoints of the moon's diameter subtend at a camera lens remains the same.

Many researchers have taken such photos in order to convince themselves. They all were convinced.
You can try it yourself.

Most people are quite amazed when they first learn that fact:

They had expected, instead, that a photograph would resemble the very different sketch in Figure 2, below, with the lower circle drawn larger than the upper circle.

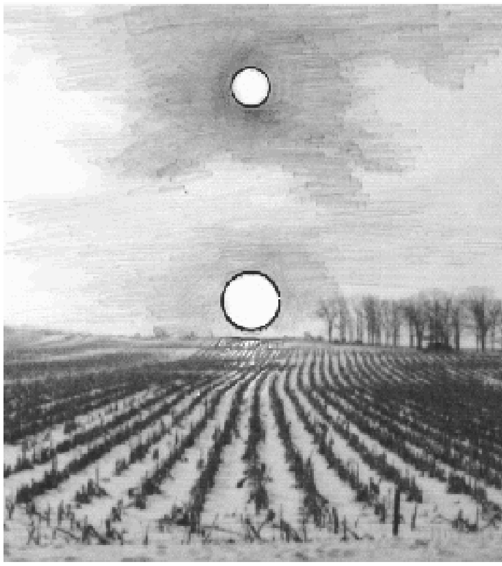


Figure 2. This sketch portrays two moon-like spheres with the lower one's diameter subtending an angle at the reader's eye 1.5 times larger than the angle subtended by the upper one's diameter.

Most people will say this Figure 2 "front view" imitates their moon illusion experience.

Many research measures of the moon illusion have been published. For some people the horizon moon's angular size can look as much as twice as large as the zenith moon's, but a value from 1.3 to 1.5 times is about average. The ratio of 1.5, illustrated by Figure 2, will be used in most of the examples in this article.

The same illusion also occurs for the sun and for the constellations as they appear to move between horizon and zenith positions. The term 'moon illusion' commonly is used for all such examples, however.

A New Theory Is Needed.

For more than 100 years, various scientists interested in visual perception (a specialty within psychology) have conducted experiments on the moon illusion and published their results in reputable scientific journals.
And, for more than 50 years the illusion has been discussed in introductory psychology textbooks that typically have offered two competing explanations: The very old*apparent distance theory*, and a *size-contrast theory* . But both are unsatisfactory, so researchers have been seeking a new theory to replace them. They are critiqued in detail in Section II, but briefly described below.

The Apparent Distance Theory Description: Popular But Inadequate.

This ancient theory is still the best-known attempt to explain the moon illusion.
According to this theory we do not perceive angular sizes: By default, that means the horizon moon and zenith moon *look* the same angular size, so the phrase "looks larger" can refer only to the moon's *linear size* in meters.

The picture at the left mimics that illusion with both moon images subtending the same angular size.

The theory proposes that, with both moons appearing the same angular size. the horizon moon looks a larger linear size than the zenith moon *because it looks farther away* than the zenith moon.

For instance let the lower disc image in that picture represent a large hot-air balloon of diameter 10 meters, tethered 100 meters away, and suppose the upper disc represents a helium-filled party balloon 1 meter in diameter floating directly above the nearby cornstalks only 10 meters away.

A person who experiences that *pictorial illusion* would say that, compared with the upper balloon, the lower one looks farther away and a larger linear diameter (and volume).

Advocates of the apparent distance theory have suggested two different reasons why the horizon moon would look farther away than the zenith moon.
The most popular version of the theory appeals to the ancient idea of a "sky dome illusion" (critiqued later).
However, at least since 1962 the "sky dome" version has been rejected and replaced by a version that assigns the main cause to changes in the patterns of *cues to distance* in the moon's vista. The extensive researches of Rock & Kaufman (1962, Kaufman & Rock, 1962, and many others) have revealed this strong association.
For instance, the horizon moon "looks larger" when the horizon vista includes many visible cues that would signal a very great distance for that moon, while the zenith moon looks smaller when its vista includes relatively few cues that would signal a far distance.
It is important to keep this well-established data in mind, because any new theory obviously must take it into account.

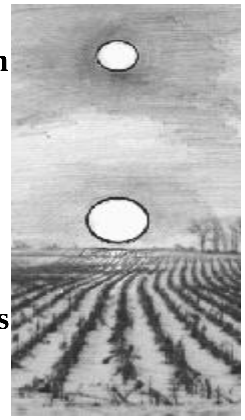
The "Size-Distance Paradox".

According to the apparent distance theory, all observers who say the horizon moon "looks larger" than the zenith moon are *required* to also say "it looks farther away." If that describes your own moon illusion, then that old explanation may fit your experience.
But you are among a very small minority.
For, as vision researchers have pointed out for at least 40 years, most people simply do not say the horizon moon looks farther away than the zenith moon (see Boring, 1962, Gregory, 1965, McCready, 1965, and many others). Instead, for most people the larger-looking horizon moon either looks about the same distance away as the zenith moon, or, more often, it *looks closer* than the zenith moon.
That complete contradiction between observers' reports and what the apparent distance theory requires is well-known among researchers: It also occurs in attempts to apply the apparent distance theory to many other classic "size" illusions: it is called the "size-distance paradox".
Yet it rarely is mentioned in popular articles about the moon illusion. For instance, a recent study by L. Kaufman and J. Kaufman (2000) that somehow became widely

publicized in the popular press, claimed to offer support for the apparent distance theory, but it did not (could not) deal with the fatal contradiction.

The solution to properly describing most peoples' moon illusion and removing the "paradox" is to realize that the phrase "looks larger" refers, first of all, to the angular size, and secondarily may also refer to the linear size, as discussed next.

An Angular Size Illusion First.



Again, the moon illusion for most people is illustrated by the picture at the right. It is *as if* the angular subtense were larger for the horizon moon than for the zenith moon.
It thus is *as if* the optical image of the moon on the retina were larger for the horizon moon than for the zenith moon. (Optical experts have argued, convincingly, that the moon's physical *retinal image* has a constant diameter of about 0.15 mm.)

That claim that the constant 1/2 degree angular size of the moon looks larger for the horizon moon than for the zenith moon (McCready 1965, 1985, 1986) now is being accepted by nearly all researchers (see Ross & Plug, 2002).

The idea also has been recognized by a version of the popular "size-contrast" theory.

The Angular Size-Contrast Theory.

The best-known alternative to the failed apparent distance theory has been a "size-contrast" theory. Of course, the word "size" is ambiguous: it could refer either to angular size or to linear size.
But, Restle (1970) properly treated the basic moon illusion as an angular size illusion by proposing that it is due to the *angular size contrast* effect found in many other classic "size" illusions.
He pointed out that the vista near the horizon moon typically includes many visible elements that subtend angles smaller than the moon's 1/2 degree, including the short angular subtense between the rising moon and the horizon line. On the other hand, the visible elements in the zenith moon's vista usually subtend angles larger than 1/2 degree, especially a large, and relatively empty, zenith sky.
The theory merely claims that those different contrasts between the moon's 1/2 degree subtense and the smaller and larger angular subtenses in its surroundings somehow make the horizon moon's 1/2 degree subtense look larger than the zenith moon's.

Baird, Wagner and Fuld (1990) recently brought that theory up to date by phrasing it in terms of the present 'new' theory (McCready 1985, 1986).

The angular size contrast theory has difficulty, however, explaining the old, well-established observation that the large-looking horizon moon will look smaller if one bends over and views it upside down (Washburn, 1894).

Moreover, this simple theory does not go far enough to explain *why* the angular size contrast effect occurs. (It is critiqued in Section II).

Another Theory Needed

Until recently, those two competing theories were the only ones vision scientists took seriously. And, because both are unsatisfactory, new theories have been published. But, the two-dozen (or so) scientists most familiar with experiments on the moon illusion still have not accepted any one theory. In 2004 the jury was still out.

New Description.

What we need is an acceptable explanation for the angular size illusion the moon illusion reveals.
Moreover, this basic angular size illusion necessarily is accompanied either by a*distance illusion* or by a *linear size illusion* or else all three illusions occur together.

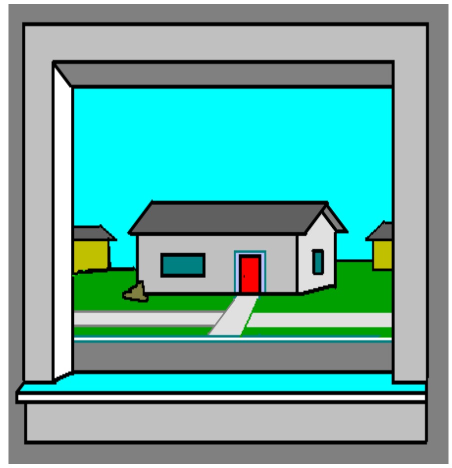
For instance the picture at the right imitates the moon illusion for most people. One common perceptual outcome is that the two moons look about the same distance away, so the horizon moon necessarily looks a larger linear size than the zenith moon because it looks angularly larger.
Or, as another common perceptual outcome, the two moons appear the same linear size (and volume) so the horizon moon necessarily looks closer than the zenith moon *because* it looks angularly larger. Those two perceptual outcomes and some others are presently discussed in detail.

A relative new explanation for such illusions (McCready 1965, 1985, 1986) is reviewed in this present article.
However, before the new theory is elaborated, it is important to clarify the distinctions between our perceptions of angular size and linear size, because popular articles typically don't make that distinction.

The Perceived Values.

Consider the simple example illustrated by the drawing below.
Suppose we are looking at a house across the street that is 30 feet wide seen entirely through a nearby window opening that is 30 inches wide:
We can say the house looks farther away than the window. Its *perceived distance* is greater: we might say the house "looks about 120 feet away" and the window "looks about 5 feet away."
We also can say the house *looks larger* than the window, meaning that our *perceived linear size* for the house's width might be "about 30 feet" and the window's width "about 30 inches".

We also can say the house *looks smaller* than the window, and that does not contradict the other statement because now we are referring to their angular subtenses, in degrees.



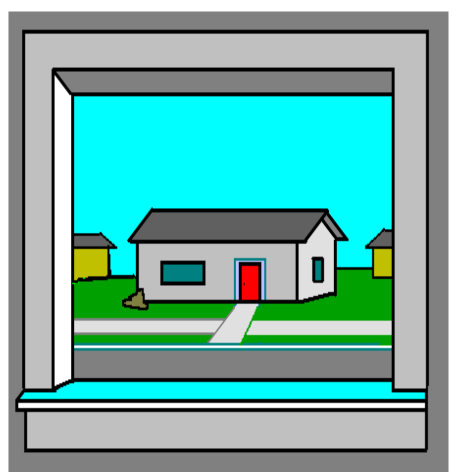
That is, we are referring to the *directions* in which the edges of the house and window appear to lie from our point of view, their *visual directions*.
For instance, the left edge of the house appears in some direction from us, which obviously differs from the *perceived direction* of the right edge.
By definition, an angle is the difference between two directions from a common point (the vertex).
Accordingly, the *difference* between the perceived directions of the outer edges of the house from our point of view is the *perceived angular size* for the house.
Let's say the perceived angular size for the house width is about half as large as the perceived angular size for the width of the window's opening.

It is important to understand that we experience *both* the linear size and the angular size comparisons (Joynson, 1949) along with seeing the distance comparison.
For a viewed object we often can state a linear size (in meters) and a distance (in meters). But we typically cannot verbally estimate an angular size (in degrees) for it. (After all, we rarely practice doing that.) Notice however that when we say one object "looks larger" than another, we most often are using the verb "looks" to describe not the perceived linear sizes, but the perceived angular sizes for them!

Obviously, whenever we say how large an object "looks" compared with another object, we should carefully specify which one of the two very different kinds of "size" experience we are comparing (Joynson, 1949).

The sketch also can be used to illustrate two important aspects of *visual processing.*

Visual Processing.



First there is *linear size constancy*. For example, the nearby window can look 1 meter tall; and the far window on the end of the house also can look 1 meter tall. If so, we say the far window looks the "same size" (linearly) as the nearby window, while at the same time it "looks smaller" (angularly) than the nearby window, and farther away.

Secondly, that example clearly illustrates the *cue to distance* textbooks call merely "relative size," an incredibly ambiguous term. This powerful distance cue properly should be called the *relative angular size*

cue to distance. **That is, if two objects look the same linear size (linear size constancy) and one looks angularly larger, it "automatically" looks closer.**

The new theory offers complete descriptions of the many ways in which the moon's angular size, linear size and distance appear to change. The theory has four main parts, outlined below.

New Theory, Four Parts.

Part 1. An Angular Size, Linear Size and Distance Illusion:

Other vision researchers who also describe the primary "size" illusion as an angular size illusion include: Acosta (2004) Baird (1970) Baird, et al. (1990) Enright (1975, 1987a, 1987b, 1989a, 1989b) Gogel & Eby (1994) Hershenson (1982, 1989) Higashiyama (1992) Higashiyama & Shimono (1994) Komoda & Ono (1974) Ono (1970) Plug & Ross (1989, 1994) Reed (1984, 1989), Reed & Krupinski (1992), Restle (1970) and Roscoe (1979, 1984, 1985, 1989). Moreover, in their recent most comprehensive book, "The Mystery of the Moon Illusion," Ross and Plug (2002) review the long history of speculation and research on the moon illusion and accept that the basic illusion is an angular size illusion.

Also, in an earlier long review, Plug and Ross (1989) concluded that the distinction emphasized by McCready (1965, 1985, 1986) between perceived linear size and perceived angular size, as well as the idea that the horizon moon has a larger perceived angular size than the zenith moon, "....might turn out to be the most important conceptual and methodological development in the history of the moon illusion since Ibn al-Haytham [Alhazen] redefined the illusion as a psychological phenomenon" (page 22).

*********** TECHNICAL NOTE Added June 7, 2006 ************
Extremely important research on visual angle illusions recently was published in*Nature Neuroscience.* The article is, “The representation of perceived angular size in human primary visual cortex,” by Murray, S. O., Boyaci, H., & Kersten, D. (2006).

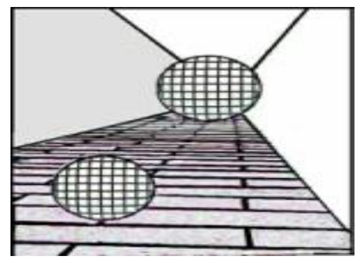
The authors measured an angular size illusion and relate it to the moon illusion. [Yet none of the moon illusion articles they cite describe it as an angular size illusion!]

This note summarizes what they found and how it fully supports the ‘new’ theoretical approach emphasized here..
[A more detailed analysis of their experiment is in Appendix B]

Their abstract is as follows..
"Two objects that project the same visual angle on the retina can appear to occupy very different proportions of the visual field if they are perceived to be at different distances. What happens to the retinotopic map in primary visual cortex (V1) during the perception of these size illusions? Here we show, using functional magnetic resonance imaging (fMRI), that the retinotopic representation of an object changes in accordance with its

perceived angular size. A distant object that appears to occupy a larger portion of the visual field activates a larger area in V1 than an object of equal angular size that is perceived to be closer and smaller. These results demonstrate that the retinal size of an object and the depth information in a scene are combined early in the human visual system.”

The study used a composite (photo-montage) of a hallway with two spheres on its floor at different distances and subtending the same angular size, but the angular size of the 'far' sphere looked at least 17% larger than the angular size of 'near' sphere, let's say it was about 20%.
That (copyrighted) picture can be seen at the following link (open it in a new window, and click on the image there to see a larger version).
faculty.washington.edu/somurray/sizedemo



The crude sketch at the right resembles their picture. But, for a detailed analysis you should use their original image.

Their picture looks like a photograph taken when one sphere was five times farther away from the camera lens than the other. Both spheres subtended the same angle at the camera lens, so the linear (metric) diameter of the far sphere had to be about five times the diameter of the near one.
In a likely pictorial (3D) illusion the perceived distance of the “far’ sphere is about five times greater than for the ‘near sphere.
And, for an example, suppose the ‘near’ sphere has a perceived linear diameter, of, say, 6 inches, so the far one looks about 30 inches in diameter.

If the spheres correctly look the same angular size, then that huge (5-times) linear size illusion for them illustrates the dominant approach to such illusions (the apparent distance theory, Emmert's law and "misapplied size-constancy scaling", see later). But that mundane, 5-times larger, linear size illusion is not the illusion that was measured.

Instead, the interesting illusion was the angular size illusion, which also occurs for the two disks on the screen which are the images of the spheres.
Those disks correctly appear at the same distance, and form equal sized images on the retina, but the perceived angular size of the disk that is the image of the ‘far sphere’ measured at least 17% larger than the perceived angular size of the disk that is the image of the ‘near sphere’.
The observers were asked to make the two disks look the same angular size, and also look the same linear size, which tasks yield the same final setting when the disks have the same perceived distance (to the screen).
Hence, the perceived linear sizes of the disks likewise differed by at least 17%.

The major new discovery was that the sizes of the activity patterns in cortical area V1 that corresponded with the equal retinal images of the two disks, were not equal, and

their measured size difference correlated almost perfectly with the perceived angular size difference (say, 17%) for the two disks (and also for the apparent "spheres").

The authors point out that those results do not support the dominant approaches to "size" illusions.

For instance, a University of Washington website offers a review of the study at,
http://www.uwnews.org/article.asp?articleID=23005
It quotes Dr. Murray as follows,
"It almost seems like a first grader could have predicted the result. But virtually no vision or neuroscientist would have. The very dominant view is that the image of an object in the primary visual cortex is just a precise reflection of the image on the retina. I'm sure if one were to poll scientists, 99 percent of them would say the 'large' moon and the 'small' moon occupy the same amount of space in the primary visual cortex , assuming they haven't read our paper!"

That comment overlooks the fact that, like first graders, but using 10th grade geometry, quite a few of us vision scientists (previously listed) have pointed out, at least since 1965, that the angular size illusion for the moon (and in other classic illusions) is *as if* the constant retinal image size changed when distance cue patterns changed.

Because that is very basic illusion, and given what has long been known about the neural projections of the retinal surface into area V1 (Brodmann area 17), it has seemed quite likely that the 'size' change would already appear that early in the brain.

After all, angular size perception is nothing more than perception of the different directions of two seen points from oneself, which perception is important for rapid orienting responses that are vital to survival.
[Indeed, in many animals' visual systems, the *superior colliculi* are very much concerned with direction perception, so one could make a wild guess and speculate that these even more primative brain loci are involved in the creation of angular size illusions.]

The Murray, et al. study directly relates to studies of the moon illusion in pictures (Enright, 1987a, 1987b, 1989a) which were not mentioned (see later here, in Section I). Also not mentioned was that the results fully support the 'newer' approaches that explicitly describe angular size illusions controlled by changes in distance cues, as advocated here.

A difficulty is that, in the article's discussion section the interpretations actually use the 'dominant approach' (the apparent distance theory) and confuse perceived angular size and perceived linear size (called 'perceived behavioral size').
For instance, it is suggested that distance cues evoke a supposed "scaling" of some entity called the viewed object's 'retinal projection" to yield a "perceived behavioral size" for the object, "whereby retinal size is progressively removed from the representation" (p.422).

That very old idea overlooks that the (flexible) perceptual correlate of the extent between two stimulated retinal points is not a perceived linear size, but the perceived angular size. And, as the authors clearly showed, the perceived angular size is more precisely a perceptual correlate of the extent of the activity in area V1.
In other words, the discussion section offers the 'dominant' interpretation which does not even describe the angular size illusion that was measured, let alone explain it.

As was easily predictable, other articles already are mis-interpreting the Murray, et al. experiment in the 'dominant' way. For instance, the results have been said to illustrate Emmert's Law and 'misapplied size-constancy scaling' which do not (cannot) apply to an angular size illusion.

The Murray, et, al. findings are mentioned again in several places here, as support for the present approach.
Also, the experiment is analyzed in Appendix B, including a section that shows how the oculomotor micropsia/macropsia formulation can fit the data.

************ End of Technical Note of June 07, 2006 ************

Part 2. Distance Cue Control:

As already noted, any explanation of the moon illusion must take into account that virtually all research has shown that the changes in the moon's perceived angular size correlate most strongly with changes in those visible patterns in the moon's vista that are known to be strong *cues to distance*.
These distance cues are the visual patterns that make objects look three-dimensional and appear at different distances from us. They are well understood by photographers and artists who use them in a flat (2D) picture to create a 3D pictorial illusion.
Concerning the moon illusion, the distant-looking moon will look angularly larger when changes in the available distance cue patterns in its vista 'signal' that it is even farther away from us: That often happens for the horizon moon. (But it typically doesn't look farther away because other cues dominate the perception.)
And, when changes in distance cues indicate a shorter distance to the moon, or else if the distance cues are greatly reduced, the moon will look angularly smaller than it did. That often happens for the zenith moon. (But it typically doesn't look closer because other cues dominate the perception.)

Consequently, the fundamental scientific task is to explain *why* changes in distance cue patterns can make the constant angular size of an object appear to change.

The present theory is one of the few that offers a plausible explanation for that association. It begins by appealing to another, more basic illusion known as *oculomotor micropsia/macropsia*.

Part 3. Oculomotor Micropsia/Macropsia:

Among the many classic "size" illusions, the largest, by far, seems to be *oculomotor micropsia/macropsia*. It was first described by the physicist, Charles Wheatstone (1852) in an article reporting observations he made using the research stereoscope he had invented earlier. For more than a century the illusion was described merely as follows: While one is looking at a fixed object that subtends a constant angular size, if one then accommodates and converges one's eyes to a distance much closer than the object's distance, the object's "apparent size" ("perceived size") decreases. Of course, those ambiguous terms could refer to the perceived angular size, or to the perceived linear size.

Since 1965, several researchers have specified that it is primarily a visual angle illusion (McCready, 1965, 1983, 1985; Ono, 1970; Komoda & Ono, 1974). And, it necessarily is accompanied, secondarily, either by a linear size illusion, or by a distance illusion, or else all three illusions occur.

Moreover, it certainly is controlled by distance cues (McCready, 1965, 1983, 1985). Although much less familiar than other illusions, oculomotor micropsia/macropsia is not only large, but also ubiquitous. Indeed, I have proposed that it is the basic angular size illusion behind many of the best-known "size" illusions (see later).

Its manifestations can be briefly described as follows:

A. It is controlled by adjustments of the eyes.

(1). As a rule, when the eyes focus and converge to a closer distance than a viewed object its angular size appears to become smaller (micropsia) than it was before the readjustment.

(2). And, when the eyes adjust to a farther distance, the angular size of a viewed object appears to become larger (macropsia) than it was before.

Most readers can conduct the following demonstration of oculomotor micropsia.

A Simple Demonstration.

The next time you look at the horizon moon, deliberately create oculomotor micropsia by strongly converging ("crossing") your eyes, say by looking at the bridge of your nose, but pay attention to the moon. That over-convergence of the eyes will create double vision of the moon and some blurring, but notice that the moon's angular size momentarily looks smaller than it did. At the same time, the moon will look either farther away than it did, or its linear size will look smaller, or else both of those secondary illusions will occur. That angular size illusion resembles what occurs during viewing of the zenith moon (except that the eyes don't have to be strongly "crossed.") However, in this demonstration the apparent decrease in angular size undoubtedly is greater than the decrease found during natural viewing of the zenith moon. [Indeed, this demonstration of micropsia even works for the zenith moon, which already looks angularly smaller than the horizon moon.]

When you then return both eyes to being aimed straight ahead (their "far," divergence position) the moon will look single again and momentarily will look angularly larger

than it just did (relative macropsia). Hence it also will look either closer than it just did, or its linear size will look larger, or else both of those secondary illusions will occur.

B. Eye adjustments are controlled by distance cues, etc.

(1). Oculomotor adjustments to "far" typically are triggered by cues to a very far distance. In turn, that induces macropsia. (And, despite the eyes' adjustment to a farther point, the now "larger-looking" object typically does not appear to move farther away, because some other cues dominate the final perception.)
Enright (1975, 1989) and Roscoe (1989) have shown that this macropsia condition usually occurs during viewing of the horizon moon.

(2). On the other hand, cues to a near distance trigger oculomotor changes to "near" which, in turn, induce micropsia. (And, despite the eyes' adjustment to a nearer point, the now "smaller-looking" object typically does not appear to move closer because some other cues to distance dominate the final percept.)

(3). During viewing of a distant object, some closer objects near the line of sight can make the eyes adjust to a short distance and induce micropsia for the distant object (and all objects). This occurs especially when one is looking through a window screen or a wet windshield (see Roscoe, 1989).

(4). Moreover, vision researchers are well aware of two natural phenomena that can induce micropsia.
***Night myopia* refers to the common result that eye adjustments to a near distance usually occur in the dark.**
And, *empty-field myopia* refers to the common result that eye adjustments to a near distance also occur when there is a relative lack of distance cues in the field of view.
Enright (1975, 1989) and Roscoe (1989) have noted that those two natural 'myopia' conditions often occur during viewing of the zenith moon, and induce micropsia.

C. Overt Muscle Activity Is Not Required.

(1) Oculomotor micropsia can occur even when the internal eye muscles responsible for accommodation (focusing) are paralyzed by eye drops (Heineman, Tulving, and Nachmias, 1959). Thus older people with presbyopia have the illusion when they merely *try* to focus closer.
That finding has made researchers understand that the muscles most responsible for the illusion are the external muscles that make the eyes converge and diverge.

(2) An important further finding has been that, to induce micropsia/macropsia, overt changes in the convergence muscles often are not necessary: There seems to be a*conditioned* relationship, by which changes in distance cues have gained the power to induce micropsia and macropsia directly (automatically) without causing the eye muscles to change.

These matters are discussed in detail in Section III.

In other words, the present theory is that the moon illusion is an example of the basic illusion of oculomotor micropsia/macropsia, induced by changes in the distance cue patterns in the moon's vista, even when the eye muscles don't change.

Part 4. A Theory of Oculomotor Micropsia/Macropsia:

To describe the basic moon illusion as an angular size illusion is itself an important 'new' idea. To propose that it is an example of a more basic angular size illusion, such as oculomotor micropsia/macropsia, only redescribes it, and does not yet fully explain it. To have a complete theory it is necessary to also explain why oculomotor micropsia/macropsia occurs.

One explanation has been shown to fit (mathematically) the published research measures of oculomotor micropsia/macropsia very much better than do any other theories (McCready, 1965, 1983, 1985, 1994; Komoda & Ono, 1974; Ono, 1970). It is reviewed in Section IV.

Briefly stated, oculomotor micropsia seems to be a normal perceptual-motor adaptation which "corrects" angular size (direction difference) perceptions in order to make them more accurate visual predictors of orienting bodily movements (such as rapid head rotations) aimed at targets that lie in different directions at different distances and that demand immediate full attention.

Enright (1989) has offered a similar perceptual-motor adaptation explanation.

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A Note. (Revised June 7, 2006)

In January, 2000, many articles in the popular media announced that a "new" theory of the moon illusion had been published by L. Kaufman and J. Kaufman (2000). However, it is simply the old apparent distance theory, advocated by L. Kaufman and I. Rock in 1962.

It explicitly rejects use of the perceived angular size concept, so it cannot possibly explain the majority moon illusion.

The article also claims that the data contradict the present oculomotor micropsia theory (McCready, 1965, 1985, 1986).

But the oculomotor micropsia theory is not properly described as an angular size illusion.

When you read the original article, if you insert the otherwise 'forbidden,' perceived angular size concept "between the lines," you can see that the data do not contradict the oculomotor micropsia theory.

The recent research by Murray, et al. (2006) (discussed above) clearly found a physical basis for angular size illusions like the moon illusion, and that completely contradicts the apparent distance theory.

How oculomotor micropsia can also apply to the Murray, et al, data will be discussed in Appendix B.

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Now consider some more detailed descriptions of the moon illusion.

Versions of the Moon Illusion.

Absolute Moon Illusions

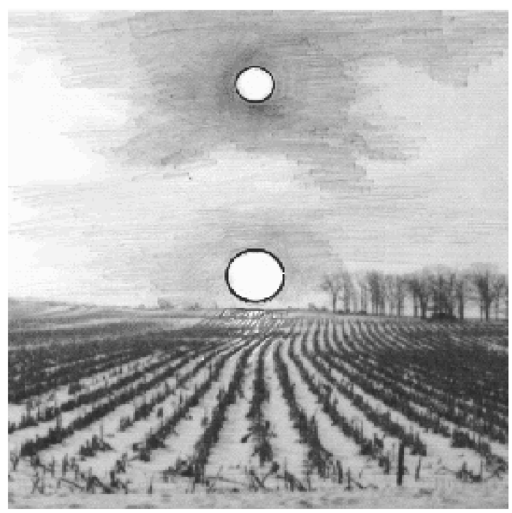
The moon's linear diameter is 2160 miles, but it obviously looks much smaller than that. Its perceived linear size (in meters) varies widely among people and even changes for one person as the viewing conditions change.

The moon's distance from us averages about 238,000 miles, but it obviously looks much closer than that. Its perceived distance (in meters) varies widely among people and even changes for one person as the viewing conditions change (such as while driving among hills or in a city).

The moon's angular subtense *measures* an essentially constant 0.52 degree. Its absolute*perceived* angular size has not yet been determined for any location, but that doesn't matter here, because scientists are most interested in the *relative illusion.* Namely, the constant angular size appears to change.

Relative Moon Illusions

The three most common versions of the moon illusion are outlined below using the picture at the right if you use your imagination.
The lower disc looks a larger angular size than the upper disc to imitate the moon illusion that most people suffer. We also must consider how far away the moon looks, and how large its linear size looks.



1. *Same Distance Outcome:* Here the portrayed horizon moon looks angularly larger than the zenith moon, and, in agreement with one's factual knowledge, they look about the same distance away. Hence the horizon moon must look a larger linear size than the zenith moon (by the same proportion that its angular size looks larger) and that contradicts one's knowledge that the moon remains the same linear size (and volume).
For an analogy, suppose the picture shows a large balloon and a smaller balloon floating directly above it.

In order to understand how this visual processing works, consider a very simple example using just the two circles in that flat picture. Various distance cues make that pattern appear to be on the same flat page (screen), so the circles correctly look the same distance from you.
Consequently, the lower circle's linear diameter (in mm) on the page correctly looks about 1.5 times larger than the upper circle's *because* its angular size (in degrees) correctly looks about 1.5 times larger.

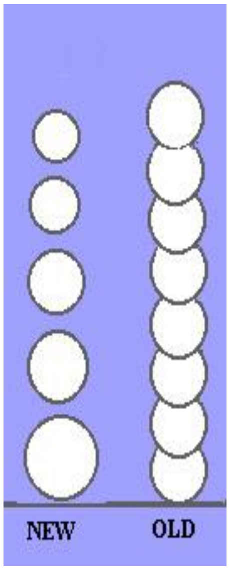
2. ***Same Linear Size Outcome:*** **Here the horizon moon again looks angularly larger than the zenith moon, but now, in agreement with one's factual knowledge, both moons look the same linear size. So, the horizon moon looks closer than the zenith moon.**
For an analogy, imagine the picture shows two balloons that are the same linear size (and volume). If so, then the lower one looks closer than the upper one *because it looks a larger angular size*.
In other words, that linear size constancy outcome sets up the powerful, relative angular size distance cue discussed earlier.

3. ***Intermediate Outcome:*** **Here all three illusions occur. Compared with the zenith moon, the horizon moon looks angularly larger and closer and a larger linear size. Now the phrase, "looks larger" refers both to the linear size and to the angular size.**
But, most people seem to be satisfied with saying merely that it "looks larger and closer" without bothering to mention that *both* the angular size and the linear size look larger. They can be more specific if they realize that there are the two different "size" experiences.
This outcome may be the most popular one.

Those three outcomes are described in much more detail in Section I using side-view diagrams.

Now compare, again, the new theory with the apparent distance theory.

A Quick Comparison Of The Two Theories:



The illustration compares the present new description with the apparent distance theory.
The stack of circles on the left illustrates the new description: The angular size of the moon appears to decrease as the moon rises toward the zenith.

The stack of equal-sized discs on the right illustrates the old description by the apparent distance theory. As the moon rises, its angular size appears to remain constant, and the basic illusion is that it appears to come closer as it approaches the zenith, so the horizon moon will look farther away than the zenith moon, hence look a larger linear size.

If that "old" sequence of circles imitates your own moon illusion, then you are among the few whose experience can be described by the apparent distance theory.

Because the conventional theory does not describe most peoples' moon illusion, it is fair to ask *why* so many readers and authors have not noticed that it fails to describe their own moon illusion.

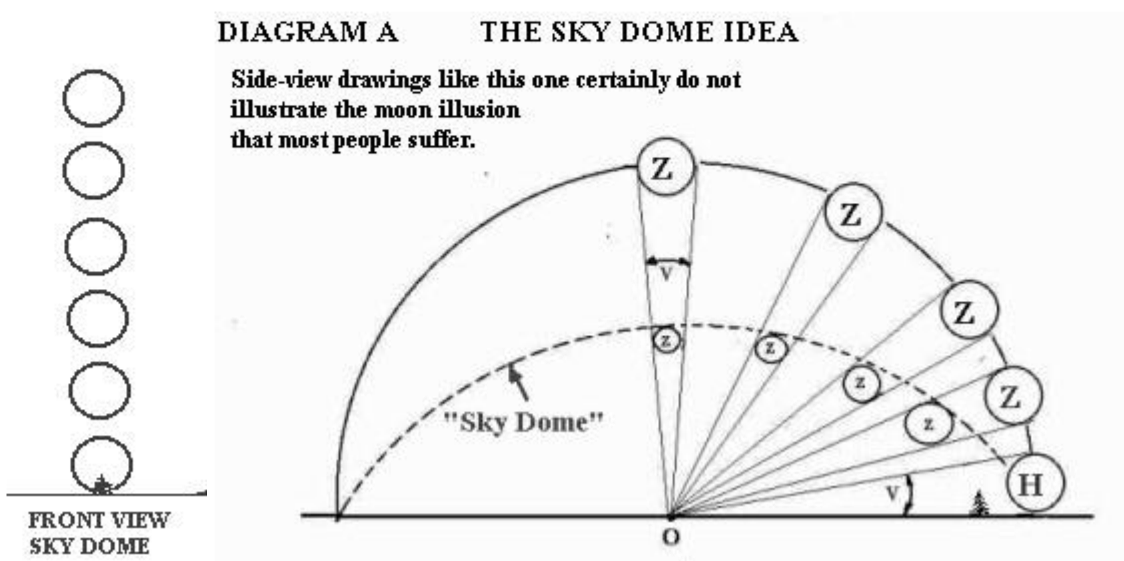
I am convinced that a major source of the problem is that virtually all articles that present the apparent distance theory do not use appropriate front views. Instead, they offer only a side-view diagram that can easily trick readers into thinking the side-view is describing their own moon illusion, but it doesn't.

The Misinterpretation Problem.

A terribly misleading side-view is the very popular sky dome diagram, which fails to describe or explain most peoples' moon illusion.

The Sky Dome 'Explanation'.

Diagram A illustrates the sky dome idea so often used in presentations of the apparent distance theory.
For this side-view we are looking north at a person at point O who is facing east (to the right) to see the horizon moon indicated by circle H. The moon rises into various zenith positions shown by the large Z circles all at the same radial distance from point O. According to an ancient idea the sky looks like the ceiling of a flattened dome, with the zenith sky looking closer than the horizon sky. The moon supposedly appears to sit upon that illusory sky surface and glide along it as it rises. So, the moon *appears* to take up the positions shown by the smaller, z circles drawn along the imaginary dome, so, for the person at point O. the z moon appears to come closer.
Because that distance illusion has the 'H moon' looking farther away than a 'z moon' the horizon moon necessarily must look a larger linear size than a zenith moon *in order to keep their angular sizes looking equal.*



Notice that all the angles are drawn equal, which specifies that, for the person at point O, *all the perceived zenith moons look the same angular size as the perceived horizon moon*.
For us to experience what that person is seeing, we must look, instead, at the front view at the left: Here we are looking east to see a string of rising 'moons' that all look the same angular size.
Well, if that front view happens to imitate your own moon illusion, then you are among the few for whom the apparent distance theory and sky dome idea might apply.
Obviously, the sky dome diagram fails to describe most peoples' moon illusion. So why is it so popular?

The big problem here is that for us readers the H circle in the diagram obviously looks angularly larger than each z circle. And, that happens to imitate a front view of most peoples' moon illusion. But that is not at all what the diagram is meant to show. Instead, the diagram is meant to show, as a side-view, that the observer at point O sees all those moons as having the same angular size. That is, what the person at point O is seeing is not shown to us by using unequal circles.
Yet, because those unequal-looking circles imitate most reader's moon illusion, that perception "rings true," so a reader could mistakenly think Diagram A is describing his or her own moon illusion, but it doesn't.

Don't let the sky dome illustration trick you into thinking it describes and explains your own moon illusion or the majority moon illusion.
Nowhere else have I seen a sky dome diagram accompanied by an appropriate front view like the one above.

Some other very misleading diagrams are critiqued in Section II.

Side-views for the new descriptions are presented in Section I.

Why Is The New Theory "New"?

In the long history of speculation about the moon illusion, the present description and the explanation for it are very recent developments. That happens because, first of all, this theory applies the relatively new general theory of the perception of linear size, distance, and the visual angle (McCready, 1965, 1985). This new general theory wholly replaces the most commonly used old rule known as the "size-distance invariance hypothesis" (discussed in Section II).

Theorists who accept this 'new' general theory include, Baird, Wagner, & Fuld, (1990), Enright (1989), Komodo & Ono, (1974), Gogel & Eby, (1994), Higashiyama, (1992), Higashiyama & Shimono (1994), Ono, (1970), and Reed, (1989. That is, although this present article focuses upon the moon illusion, the arguments go far beyond that illusion: They need to be taken into consideration in all discussions of visual perception of spatial relationships.

The present theory also is 'new' because its formulation has depended upon information about oculomotor micropsia published only since 1965: Likewise, it has depended upon having moon illusion research data published since about 1975 (Enright, 1975 to 1989; Iavecchia, et al, 1983; Roscoe, 1979 to 1989).

In 2002, Ross and Plug published their excellent book, "The Mystery of the Moon Illusion." It currently is the most complete source of information about the illusion. On page 195 they state: "The moon illusion is one of the few perceptual phenomena that tap a broad spectrum of sciences: astronomy, optics, physics, physiology, psychology, and philosophy. Its explanation illustrates the history of scientific explanation, and in particular the history of perceptual psychology."

Ross and Plug review the incredibly long history of speculation about the illusion, and examine in detail the published experimental research data that any theory must explain. They strongly support the idea that the moon illusion begins as an angular size illusion.

They evaluate current theories including the present "new" theory (McCready, 1965, 1985, 1986) even citing this present web article (as it was in 2001).

They also conclude, of course, that, "No single theory has emerged victorious." (p. 188).

Four Other "New" Explanations for the Moon Illusion.

Four other relatively new explanations also treat the majority moon illusion as an angular size illusion.
1. Hershenson (1982, 1989) offered a theory which appeals to a perceptual process he calls the "loom-zoom system."
2. Reed (1984, 1989) appealed to a perceptual experience he calls "terrestrial passage."
I won't try to review those two theories. They are reviewed in Ross & Plug (2002).

3. Baird, Wagner, & Fuld (1990) have offered a 'simple explanation' of the moon illusion. They have revived the "size"-contrast explanation advocated by Restle (1970), and clearly stated it in terms of the present "new" general theory. That theory is critiqued in Section II.

4. Enright (1989) has proposed that the moon illusion certainly illustrates oculomotor micropsia/macropsia: His many experiments have left little doubt about that.
The explanation he proposes for oculomotor micropsia (Enright, 1989) is similar to the perceptual adaptation explanation I have offered, but differs in some details (see Section IV).

5. Roscoe (1984, 1985, 1989) and his colleagues (Acosta, 2003, Iavecchia, et al 1983) have conducted many experiments which clearly show that the moon illusion illustrates oculomotor micropsia.

Roscoe's many publications (see Roscoe, 1979, 1989) have emphasized the largely overlooked role that oculomotor micropsia can play in some airplane crashes when, to land the airplane during bad weather, the pilot depends upon a "heads up" viewing device that shows an image of the airport's landing strip. Briefly stated, this nearby screen induces oculomotor micropsia, so the pilot "sees" the airport runway as too far away, and may land ("crash") beyond the runway (and some have).
A similar condition with the eyes unwittingly adjusting to a near distance exists for a person driving with a wet windshield, especially at night, or driving in a fog. The resulting oculomotor micropsia can make objects in the road ahead look too far away, so the driver will overestimate the safe braking distance, and may discover, too late, that an object was much closer than it appeared.
In other words, trying to understand the causes of the 'moon illusion' is more than just an idle pursuit.

Section I. New Descriptions of The Moon Illusion

**This section elaborates the new descriptions of the moon illusion.
It carefully defines the relevant perceptual dimensions, describes how they relate to each other and compares these perceptual magnitudes for the horizon moon and zenith moon.**

**It emphasizes that for most people the illusion starts with the constant angular size (visual angle) of 0.52 degrees looking larger for the horizon moon than for the zenith moon. Consequently, either the perceived linear size (in meters) or the perceived distance (in meters) also changes, or else both of those perceived metric values appear to change along with the change in the perceived angular size.
Some logical rebalancings of the perceived metric values for the moon due to the change in the perceived angular size are described and illustrated.
Many facts about the moon illusion are reviewed, especially the strong correlation between changes in the perceived angular size and changes in patterns of distance cues.
Finally, some classic flat-pattern "size" illusions are reviewed that also begin as angular size illusions controlled by distance cues.**

THE BASIC DIMENSIONS

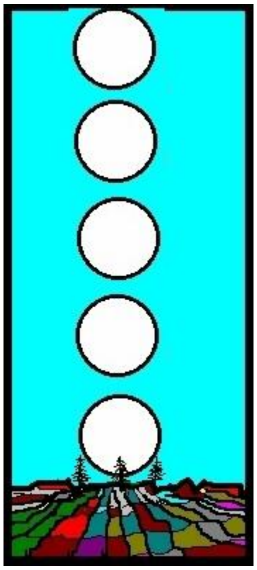
Consider first the physical measures.

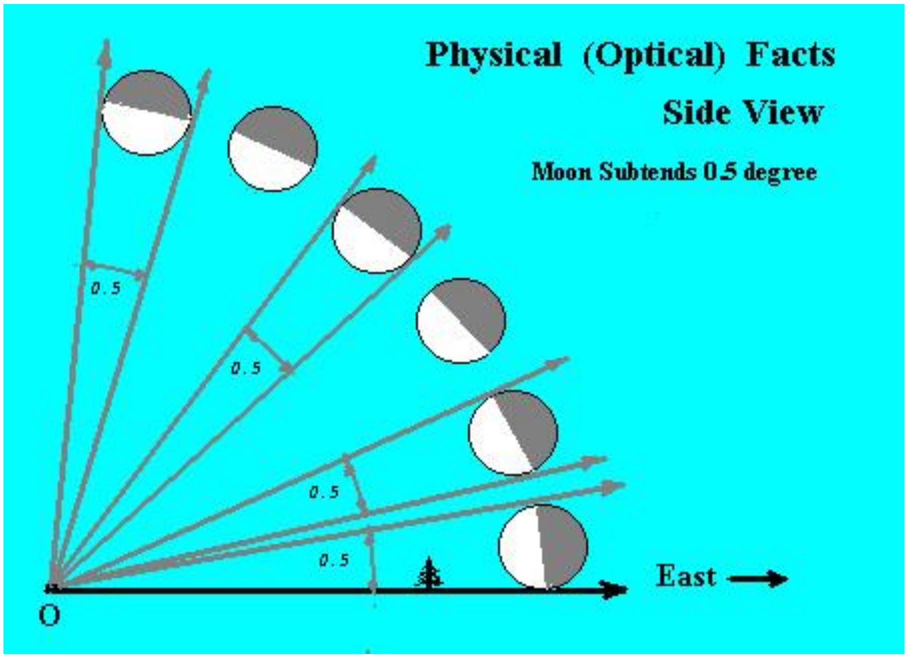
The Physical (Optical) Dimensions.

**The two drawings below represent the optical facts for the moon.
For the side-view we are looking due north at an observer at point O who is looking east (to the far right) at the extremely distant full moon at the horizon. The moon rises on a circular arc to a zenith position above the observer's head.
The dark half of each circle indicates the unseen back hemisphere of the full moon.**

**At the left is a front view that goes with that side-view. It illustrates how a camera at point O would record the rising full moon and three trees on the ground at a great distance east of the observer. In the side-view the tree image represents the third tree, which obscures the other two in this view.
Keep in mind that these diagrams do not illustrate the perceptual experience of the**

person at point O.





Linear Size and Optical Distance: **The moon's linear diameter is approximately 2160 miles and it's distance from point O averages about 238,800 miles.**
[Such diagrams rarely are drawn to exact scale, but they accurately portray the relative relationships. Also, for present purposes the diagram overlooks the fact that the horizon moon is about 2% farther away from point O than the overhead zenith moon due to the added radius of the earth, so the angular size of the horizon moon actually measures about 2% *smaller* than the overhead zenith moon's.]

Angular Size or Visual Angle: **For each 'moon' in the side-view the arrows indicate the*optical directions* of its top and bottom edges from the observer's eye at point O. The difference between those two optical directions can be measured directly using a theodolite, as the *angular size* for the moon's diameter.**
Again, at all positions in the sky, the moon subtends about 0.52 degrees.

Vision researchers prefer to call this measured angle the *visual angle*, (the more "scientific" synonym for angular size). It is a physical measure, so the adjective "visual" may be misleading. It probably should be called, instead, the "ocular angle" or the "optical angle".

Some confusion once existed in the moon illusion literature because astronomers use the term "apparent size" for this objective (physical) angle they measure for the moon's diameter. But psychologists use the adjective "apparent" (and also "perceived") only for a *subjective* value (or else for a research measure of a subjective value).

Technical Note:
The visual angle can be calculated, of course, using the simple rule, Tangent$\underline{V}$ = $\underline{S}$/$\underline{D}$, in which $\underline{S}$ is the frontal linear size and $\underline{D}$ is the distance from the eye.
So, the ratio of the moon's linear diameter (3475 km) to the viewing distance (384,400 km) equals 0.009, which is the tangent of 0.52 degrees.
In optical terms, the ray of light from a diameter's endpoint to the center of the eye pupil is the *chief ray* of the bundle of light rays that focus to a small point on the retina to form there the optical image of that diameter's endpoint. Likewise for the opposite end of that diameter.
The angle between those two chief rays is the visual angle, $\underline{V}$ deg.
The optical image of the moon formed on the retina is just like the real image formed on the film in a camera. The diameter of this *retinal image*, $\underline{R}$ millimeters, is determined directly by the angular size, $\underline{V}$ degrees, in accord with the simple rule, $\underline{R}$ =$\underline{n}$Tan $\underline{V}$ with $\underline{n}$ equal to about 17 mm. (See Figure A1 in the Appendix.) So, the diameter of the moon's circular retinal image is about 0.15 mm. [End of Technical Note.]

By the same token, the front of any object will subtend a visual angle of 0.52 degrees (so its retinal image size is 0.15 mm) whenever the distance to that frontal extent is 111 times its linear size. For example, 0.52 degrees would be the visual angle for a barn 47.5 feet wide located one mile away, for a USA penny (19 mm in diameter) held 2.1 meters from the eye, and for this printed capital letter, O, viewed from a distance 111 times its measured diameter.

In order to properly describe the moon illusion, we must use unambiguous terms for the perceptual (subjective) dimensions, so let's define the required terms by considering the *absolute* moon illusions.

Absolute Moon Illusions.

Perceived Linear Size.

The moon obviously doesn't look 2160 miles wide.
A person might say, for instance, that its width looks about 1 mile, or 100 yards, or 30 feet. [Interestingly, Ross and Plug (2002) cite many old reports that people (including some scientists) had said the moon looked only about 10 to 30 centimeters in diameter!]
A researcher would record such reports as perceived linear size values (synonym, apparent linear size).
Most people have difficulty stating how large the moon's linear size looks. But our main interest is in the *relative* comparison: And people easily can say that the horizon moon's linear size looks either larger, the same, or smaller, than the zenith moon's without having to state an absolute perceived linear size value for either moon.

Perceived Distance.

The moon obviously doesn't look 240,000 miles away.

A person might say it looks 4 miles away, or 2 kilometers away or 100 yards. Those reports would be recorded as perceived distance values (synonym, apparent distance).

Most people have difficulty stating how far away the moon looks, or even how far away a distant terrestrial object looks. For instance, even professional golfers do not always trust their expert distance perception, so they pace the remaining distance to the green or else consult their list of prior measurements.

Again our greatest interest is in the *relative* comparison. And people easily can say that the horizon moon looks either farther away, or closer or at the same distance as the zenith moon without having to state an absolute perceived distance for either moon.

Perceived Visual Angle (Perceived Angular Size).

Remember, the angular size experience has everything to do with one's perception of the directions of viewed points from oneself.
The crucial observation here is that one *sees* that the moon's left edge lies in some direction from oneself; it has a certain perceived direction. For example, let's say the direction the moon's left edge *looks* happens to be "due east" from oneself.
One also sees, of course, that the moon's right edge lies in a given direction from oneself, a direction that obviously appears to differ from the direction in which the left edge appears. Let's say the right edge looks simply "a wee bit in the southeasterly direction."
The amount by which those two perceived directions differ (in degrees) is theperceived visual angle for the moon. Unambiguous synonyms are, apparent visual angle, perceived angular size, and apparent angular size)
[An old term, "perceived extensity" (Rock & Kaufman, 1962a) was used by Plug & Ross (1989) but it lacks an angular connotation, so they switched to using the term "perceived angular size" (Plug & Ross, 1994; Ross & Plug, 2002).]

Evaluating The Perceived Visual Angle.

A well-trained observer might say, for instance, that the horizon moon looks 2 degrees wide, or 1 degree, or 3/4 degree, or 1/2 degree (no illusion). Each such report would be recorded as the perceived visual angle, in degrees.
However, most of us cannot reliably *say* how many degrees a given viewed object appears to subtend. We don't practice doing that because it usually isn't necessary. Instead, to indicate to someone else the magnitude of an angular subtense we are seeing, we often use a sweeping gesture (Ono, 1970): For instance, we point a finger in the *direction* of place 1, then at place 2, and the other person observes the change in the direction our finger is aiming: That method provides the other person with a value for the difference (angle) we are seeing between the directions those two places appear to lie from us.

Indeed, more sophisticated pointing (aiming) devices have been used to measure absolute perceived visual angles for viewed objects (Gogel & Eby, 1994; Komoda & Ono, 1974; Ono, Muter and Mitson, 1974).
A research problem, however, has been that the moon's subtended angle is too small to

obtain an objective measure of the visual angle experience for it.
For instance, we could point our nose from the moon's left edge to its right edge, and the angle our head turns through would be a measure of the perceived angular size. But that tiny rotation would move the tip of the nose only about 1.3 mm, because the head's rotation axis is about 130 mm (5 inches) behind the nose.
Besides, the important prediction is that the initial head rotation angle would be about 1.5 times greater for the horizon moon than for the zenith moon. So the difference between those two movements of the nose tip that would reveal that relative illusion would be only about 0.65 mm, much too small to measure.

No objective measures of the perceived angular size have been published for the moon.

Of course, because the perceived visual angle usually is larger for the horizon moon than for the zenith moon, there must be an *absolute angular size illusion* under some (or most) viewing conditions. [Yet, at some elevation of the moon the perceived angular size might "correctly" equal 0.52 degrees.]

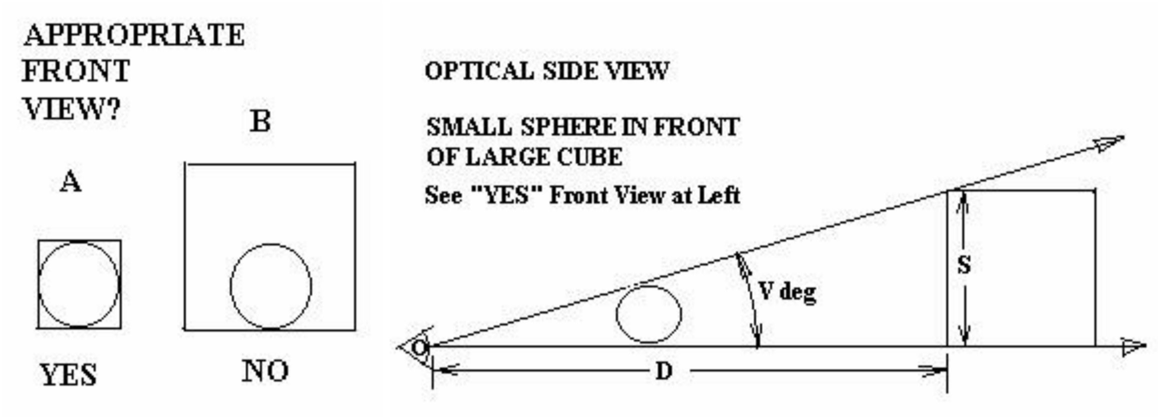
At any rate, people can compare the perceived angular sizes of the horizon and zenith moons without having to provide an absolute value for either moon. And the relative illusion can be objectively measured, as follows.
In the simplest direct experiments, observers view the natural horizon moon and compare its "size' with the "size' of a distant artificial 'moon' image located at a high "zenith" elevation. That surrogate moon's angular size then is changed until it looks the "same size" as the horizon moon. Its final "looks equal" angular subtense typically is larger than 0.52 degrees. The ratio of its angular size to the horizon moon's value of 0.52 degrees thus is an objective measure of the relative moon illusion.
Experiments like that have provided the many published ratios that range from 1.0 to over 2.0.

Side-View Descriptions.

To describe what a person perceives when looking at an object we begin with an optical diagram of the physical arrangement, and then create a diagram of the perceptual values the person is reporting.

Optical Drawing.

For example, the side-view below has an observer's eye at point O looking at a small sphere located directly in line with a larger cube that is just far enough away so that the height of the cube and the diameter of the sphere subtend the same visual angle, <u>V</u>deg, at point O.
The cube's height is its linear size, <u>S</u> meters. Its front surface is <u>D</u> meters from the eye.
The geometrical relationship is given by the simple equation, tan<u>V</u> = <u>S/D</u>.
(The dimension lines for the smaller <u>S</u> and <u>D</u> values for the sphere are not shown.)



In reverse, the upper arrow indicates the chief (central) ray of the bundle of light rays that head toward the eye from the objects' upper edges. Likewise, the lower arrow indicates, in reverse, the chief ray for each object's bottom edge. Those ray bundles eventually form the physical (optical) images of those edges on the retina, to generate the *retinal images* of the sphere and the cube face.
The diagram illustrates, as well, the optical situation for a camera with its lens at point O.

Front Views.

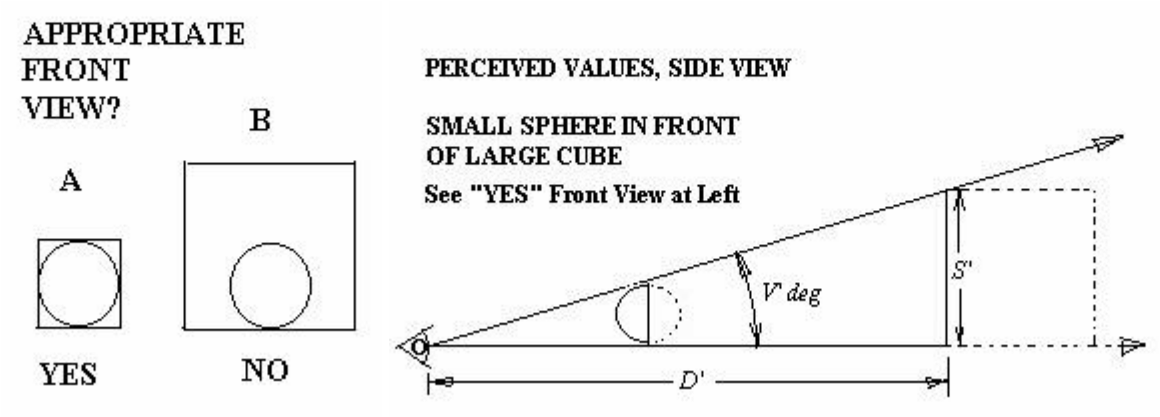
The "YES" front view is what the camera's picture would look like.
That "YES" diagram also shows what the optical images on the retina would be like.

The "NO" front view is not what the camera would record, and not what the optical images on the retina would be like.
Of course, that "NO" front view might appear on an engineer's drawing to go with the side-view. But that orthographic projection method is inappropriate for visual science.
Now consider what the person at point O may perceive.

Perceived Values Drawings.

The diagrams below illustrate an arrangement of perceptual values for the observer whose eye is at point O. For this example we'll assume the perception is correct (no illusion), so the cube looks the same angular size as the sphere, also a larger linear size and farther away.
Of course the person sees only the front surfaces of the sphere and cube, so the unseen rear portions are indicated with dotted lines in the side-view.
The arrows from the eye to the top and bottom of the perceived sphere indicate the*perceived directions* of those edges. They coincide with the perceived directions of the top and bottom edges of the perceived cube.
The difference between the two perceived directions is, *V'* deg, the perceived visual angle. It is the same for both objects here.

**The dimension, *S'* is the perceived linear size (in meters) for the cube's height.
And, *D'* is its perceived distance (in meters).
[The smaller *S'* and *D'* values for the sphere are not indicated.**



**The "YES" front view shows the reader what the person at point O is seeing.
That is, it resembles what an artist would draw to accurately portray what he or she sees when looking at the sphere and cube from point O.**

The "NO" front view certainly does not imitate what that person sees.

Notice, however, that if readers were given only that side-view, it would be easy for them to think (mistakenly) that the small circle and larger square in that side-view could imitate what the front view would be like. That is, without having the appropriate front view, a viewer might be misled into assuming that what he or she would see from point O would resemble the "NO" front view with the cube looking a larger angular size than the sphere.

As cautioned in the earlier critique of the 'sky dome' idea it is important not to misread a side-view diagram in that manner.

The Perceptual Invariance Hypothesis.

The diagram illustrates the theory that those three perceptual values relate to each other in accord with the "new" simple rule, *S'/D'* = tan *V'*. This rule (McCready, 1965, 1985) recently was dubbed the *perceptual invariance hypothesis* by Ross and Plug (2002).

Psychophysical Rule.

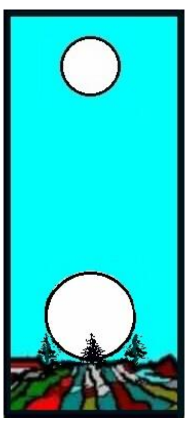
**An additional rule is needed, of course, which will relate the subjective visual angle value, *V'* deg, to the objective visual angle, <u>V</u> deg, by way of the size of the retinal image of the viewed object. That additional *psychophysical* rule is discussed later (in Section III).
However, for present purposes, it is sufficient to say merely that "certain factors" can make *V'* deg, not equal <u>V</u> deg. The moon illusion will become fully explained when all**

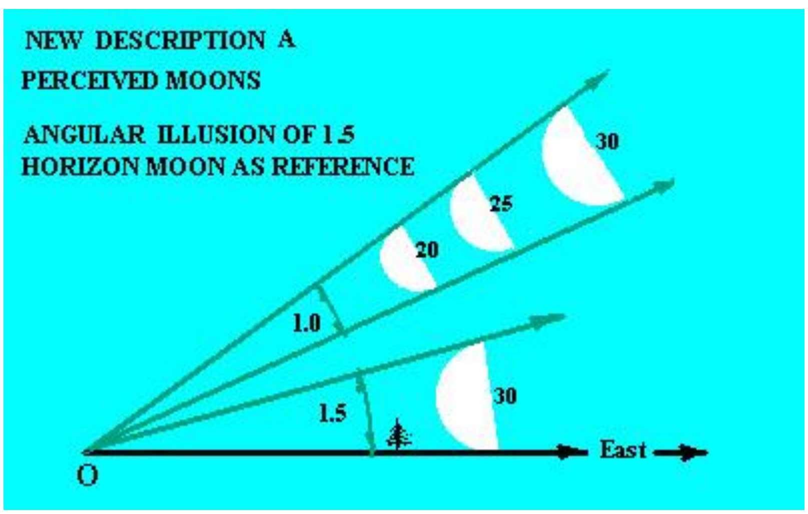
those 'certain factors' are identified and understood. As already noted, the most important "certain factors" seem to be changes in the patterns of distance cues.

The Relative Moon Illusions

How the experiences of perceived angular size, perceived linear size and perceived distance for the majority moon illusions relate to each other was described in the Introduction using a front view. They now can be described using a side-view as well.

The side-view (at the right below) portrays that we are looking north toward an observer at point O who is facing east (way off to our far right). The perceived full moons are drawn as semi-circles because a person obviously doesn't see the rear hemisphere of the moon.
[Any side-view diagram that purports to illustrate the moon illusion cannot logically use a uniformly filled circle (or full disc) to represent a perceived moon. However, virtually all the side-views in other articles on the moon illusion have used full circles. That simple mistake undoubtedly has helped side-view diagrams like the sky dome diagram fool some readers.]





The lower semi-circle represents a potential perceived horizon moon. The other three semi-circles represent potential perceived zenith moons, all at the same perceived elevation angle, but at three different perceived distances.

Side-views with the perceived angular sizes drawn *unequal*, were included in my moon illusion lectures (McCready, 1964 - 1992) but have been formally published in just a few places (McCready, 1983, 1986). So, most readers probably are seeing them for the first time.

Perceived Angular Sizes.

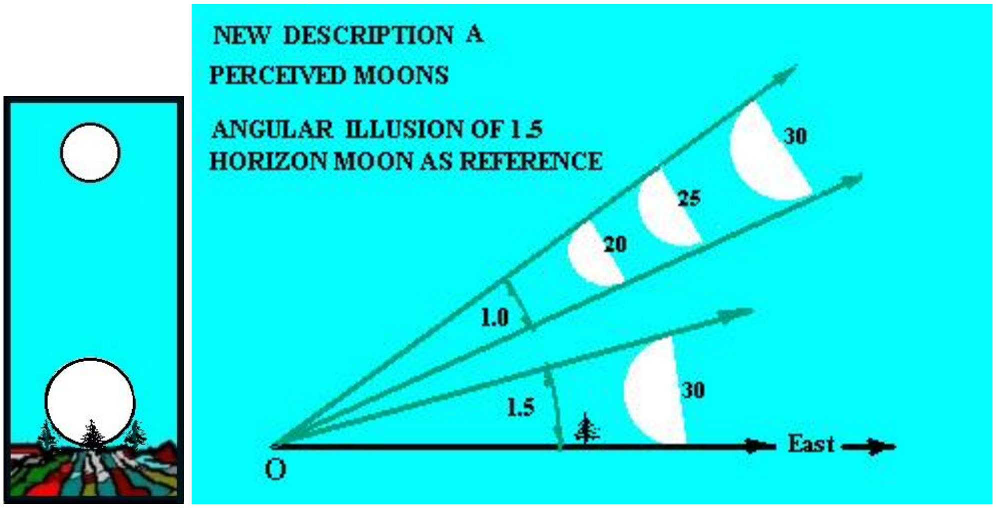
The arrows from point O through the top and bottom of each semi-circle indicate theperceived directions of the top and bottom edges of that moon. For this example the perceived angular size for the horizon moon is assigned, arbitrarily, a value of 1.5

angular units simply to illustrate an illusion with it looking 1.5 times angularly larger than the zenith moon's perceived angular size of 1.0 unit.

The front-view (at the left) portrays what the person at point O is seeing. For this front view we are looking east and see a portrayed 'horizon' moon whose angular size looks about 1.5 times larger than the 'zenith' moon's. Our angular size experience for those two circles thus imitates *all* of the angular size experiences the side-view diagram is describing for the person at O.
That is, for *every* outcome illustrated by the side-view, the person at O says "the horizon moon looks angularly larger than the zenith moon."

Perceived Linear Sizes.

The number 30 next to the perceived horizon moon represents the *perceived linear size*in some unit of linear measure. For instance, the person at point O might have said the horizon moon's diameter looks about 30 cm, or 30 in., or 30 ft., or 30 yards, or 30 meters, or 30 stories tall.



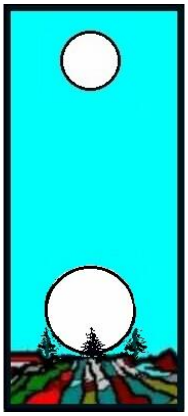
The numbers beside the perceived zenith moons (20, 25, 30) indicate their perceived linear sizes, for comparison with the horizon moon's perceived linear size of 30.

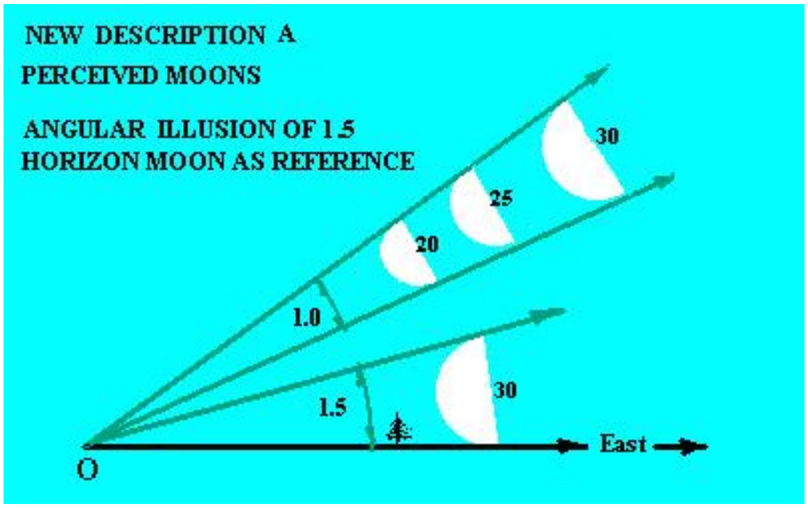
Perceived Distances.

In the side-view the distance of each semi-circle from point O represents the perceived distance of that apparent moon.
Some observers report that the just rising horizon moon looks only slightly beyond the most remote looking horizon objects (Hershenson, 1982). The three trees represent such perceived horizon objects, and tree on the right is pictured in the side view, where it obscures the other two perceived trees.

Some Common Outcomes.

As previously discussed, the most popular versions of the moon illusion seem to be a*same-distance outcome,* a *same-linear size outcome* and an *intermediate outcome*. Those outcomes and some others are described below.





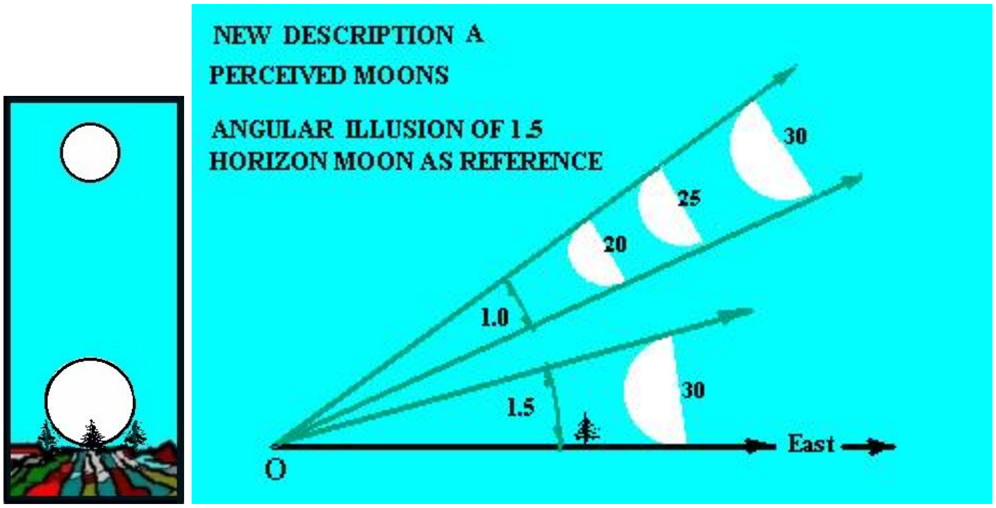
The Same Distance Outcome:

This outcome is illustrated by 'horizon moon'-30 and 'zenith moon'-20. Both moons look about the same radial distance away, so the horizon moon's linear size (30) necessarily looks larger than the zenith moon's (20) by the same proportion that its angular size looks larger. The person's typically abbreviated report is that the horizon moon "looks larger and about the same distance away" as the zenith moon.

Accordingly, if the moon looks like a sphere, the horizon moon appears to have a greater volume than the zenith moon despite one's knowledge that the moon's volume remains constant. That is, the moon looks somewhat like a round balloon that becomes deflated as it rises.
Factors that can lead to a 'same-distance' perception include the so-called "equidistance tendency" (Gogel, 1965) or an "equal-distance assumption" (McCready, 1965, 1985) which could be due simply to one's knowledge that the distance to the moon remains essentially the same.

The Same Linear Size Outcome:

This outcome is illustrated by 'horizon moon'-30 and 'zenith moon'-30 which necessarily appears 1.5 times farther from point O than the 'horizon moon' does. The horizon moon's angular size again looks larger than the zenith moon's. But the moon appears to remain the same linear size of 30 units, so that makes the horizon moon look closer than the zenith moon *because* it looks angularly larger.



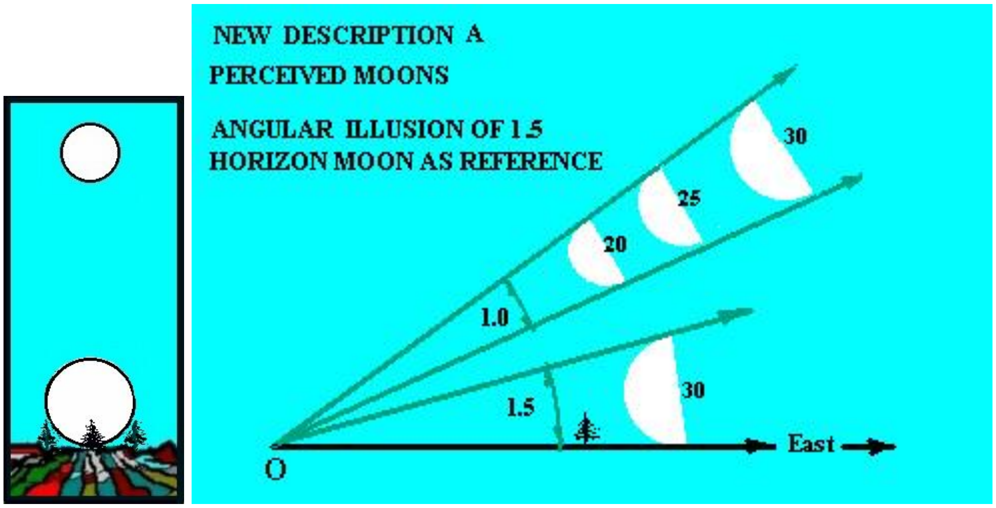
Most observers who experience this outcome seem content to say merely that the horizon moon "looks larger and closer" than the zenith moon, without mentioning that the linear sizes appear equal.

That outcome illustrates *linear size constancy*. Factors that can lead to it include an "equal linear size assumption" (McCready 1965, 1985) which can be due simply to one's knowledge that the moon remains the *same* moon (identity constancy) so its physical size would not appear to change.

The "looks closer" illusion here illustrates the powerful, 'relative perceived visual angle cue to distance'.
It also illustrates that the distance-cue patterns responsible for increasing the perceived visual angle for the horizon moon are being overruled by that other cue. (See a later discussion of this *cue conflict*.)

Apparent Initial Retreat.

In this linear size constancy outcome, the rising moon logically would at first appear to move *farther away*, retreating to the east before it appears to move overhead toward the zenith.



An Intermediate Outcome:

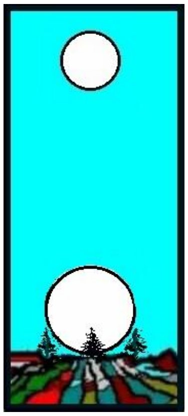
Sometimes, all three relative illusions occur at the same time, as shown by 'horizon moon'-30 and 'zenith moon'-25.
The observer's full report is that, compared with the zenith moon, "the horizon moon looks angularly larger, linearly larger and closer."

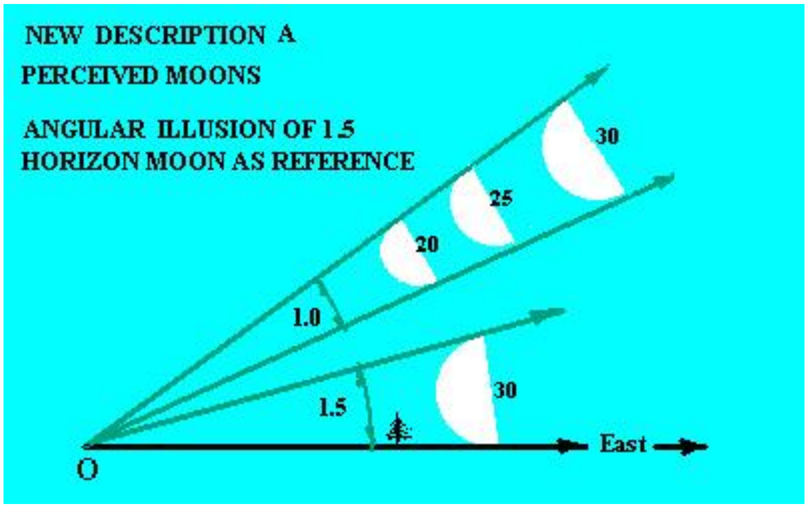
The common abbreviated report, "looks larger and closer" thus is ambiguous. It could refer either to the same linear size outcome or to an intermediate outcome.

Vertical Ascent.

Notice that in this intermediate outcome, 'zenith moon'-25 appears almost directly above the 'horizon moon'. Indeed, a characteristic of most intermediate outcomes is that the rising moon first appears to move away (a bit more eastward) and then almost straight up before it appears to come forward to start its long trip overhead toward the zenith. That logical result of the new description presently is illustrated much better in Figure 6.

It is important to point out, again, how a side-view diagram can mislead hasty readers.





Potential Misreadings.

One possible misreading of the side-view concerns the three upper 'zenith moon' semi-circles. For the reader they correctly appear to have different angular sizes, but what they clearly illustrate is that, for the person at point O, all three zenith moons have the same perceived angular size, as illustrated by the front view at the left.

Also, the reader correctly sees that the 'horizon' semi-circle-30 and the 'zenith' semi-circle-30 subtend the same visual angle, but what those two illustrate, of course, is that the person at O is seeing a horizon moon that looks 1.5 times angularly larger than that zenith moon, as shown by the front view.
A reader who doesn't take those facts into account will miss a main point of the diagrams.

Survey Data.

Many anecdotal reports published over the last 100 years have indicated that a majority of people say simply that the horizon moon either "looks larger and closer" than the zenith moon, or "looks larger and at the same distance."
That also has been the finding of many published 'moon illusion' experiments in which participants were asked for a distance comparison.

Some surveys indicate that the three outcomes described above account for the moon illusions of at least 90% of the population.
For instance, at least annually, from 1964 to 1992, just before beginning my lecture on the moon illusion (McCready, 1964-1982), and without giving hints about what I expected, I asked the class (or audience) to recall their usual distance comparison for the horizon moon versus the zenith moon, and "vote" for either "farther" or "same distance" or "closer" on a 'ballot' I provided. Then they "voted" for their usual 'size' comparison ("larger" or "same size" or "smaller").
Each person exchanged ballots with a nearby person who then reported that other person's set of choices in the show of hands that provided the totals I wrote on the blackboard

Over those 28 years, more than 800 participants took part.
In a large audience, at least 75% (and often 90%) chose both "larger" and "closer."
About 5% to 15% chose both "larger" and "same distance."
Only about 5% chose both "larger" and "farther" (McCready, 1983, 1986).
It must be noted that some people report no relative "size" illusion for the moon.

Hershenson (1989) has reported similar survey results.

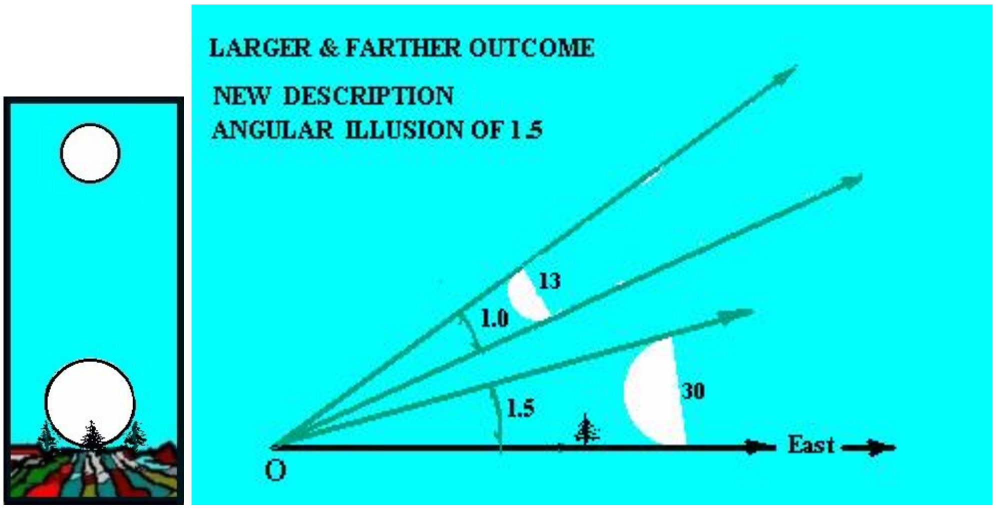
Of course, reports about memories are not reliable evidence, but those numbers do not disagree with published results from experiments.

Notice that the most popular simple report, "looks larger and closer," is incomplete, hence ambiguous. It can refer to either a same linear size outcome or an intermediate outcome. In order to obtain a full report an experimenter must explain to the observer the distinction between the linear size and the angular size, which is not easy to do.
At any rate, after my lectures, many people said they know the moon remains the same physical size, but the horizon moon usually appears a larger physical size (and volume) than the zenith moon, as well as closer. That may indicate that the intermediate outcome is the most common one.

A fourth possible outcome needs to be described.

A Larger and Farther Outcome:

For the relatively few observers who say the horizon moon "looks larger and farther away" than the zenith moon, it could be that for some of them, "looks larger" refers both to the angular size and to the linear size.
That perception is shown in the different side-view below.



Here the 'horizon moon' looks 1.5 times angularly larger than the 'zenith moon' and farther away, so its perceived linear size of 30 units looks more than twice as large as the 'zenith moon's' of 13 units.

The report, "looks farther away," at least partially agrees with the distance-cue patterns responsible for the illusory increase in the perceived angular size

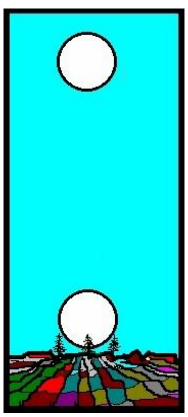
Two more possible outcomes are illustrated below.

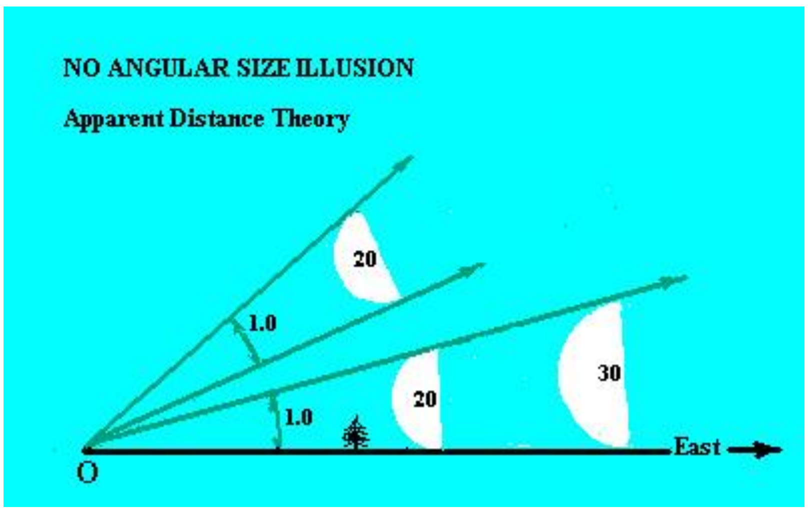
Two Outcomes With No Angular Size Illusion:

If the moon appears to remain the same angular size, there are two likely outcomes.

1. No Moon Illusion:

"Horizon moon'-20 and 'zenith moon'-20, indicate the result for those few people who have no relative moon illusion. Both moons have the same perceived visual angle, the same perceived linear size and the same perceived distance.





2. The Apparent Distance Theory Description.

Among the approximately 5% of people who say the horizon moon "looks larger and farther away" than the zenith moon, it could be that for some of them the ambiguous phrase "looks larger" refers only to the perceived linear size, while the angular sizes look equal.
That outcome is illustrated by 'horizon moon-30' and 'zenith moon-20'.
This is the only moon illusion the apparent distance theory can describe.
It proposes that the horizon moon and zenith moon look the same angular size (as shown by the front view), so if the horizon moon "looks larger" it is because it looks farther away than the zenith moon.
That also is the only illusion the sky dome diagram illustrates.

Again, don't let the fact that 'horizon' semi-circle 30 looks angularly larger than 'zenith' semi-circle 20 mislead you. The diagram clearly is constructed to show that the observer at point O sees all the moons as having the same angular size.

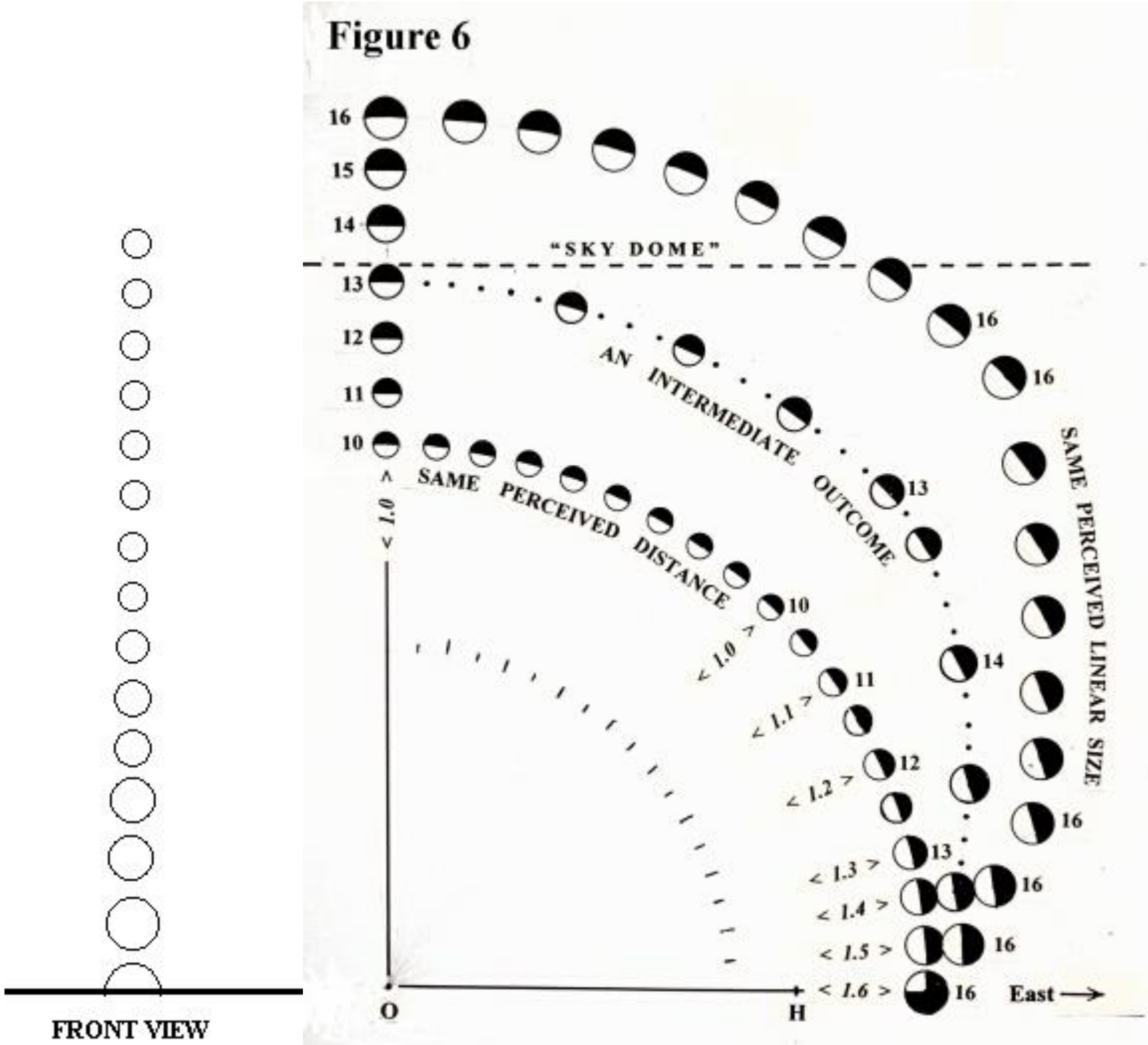
Previously published articles (McCready, 1983, 1986) included a more elaborate side-view diagram of the new descriptions. Ross and Plug (2002) recently republished it as their Figure 10.8. A similar version is Figure 6, below.

A More Complete Side-View: Figure 6.

Many of the anecdotal reports in the scientific literature seemed "strange" because they contradicted the dominant, apparent distance theory (creating the unresolved size-distance paradox). However, most of those reports now can be seen to be not paradoxical but quite sensible. And they can be used to help construct Figure 6.

For the Figure 6 side-view the observer at point O is looking eastward at the horizon moon and watching it rise to the zenith. The distance from point O to each perceived moon represents its perceived distance. The 'horizon moon' appears just beyond point H, where the most-distant terrestrial object appears to be.

The number to the right of an ascending 'moon' specifies its perceived linear size in some arbitrary metric unit. For the 'horizon moon' it is 16 units.



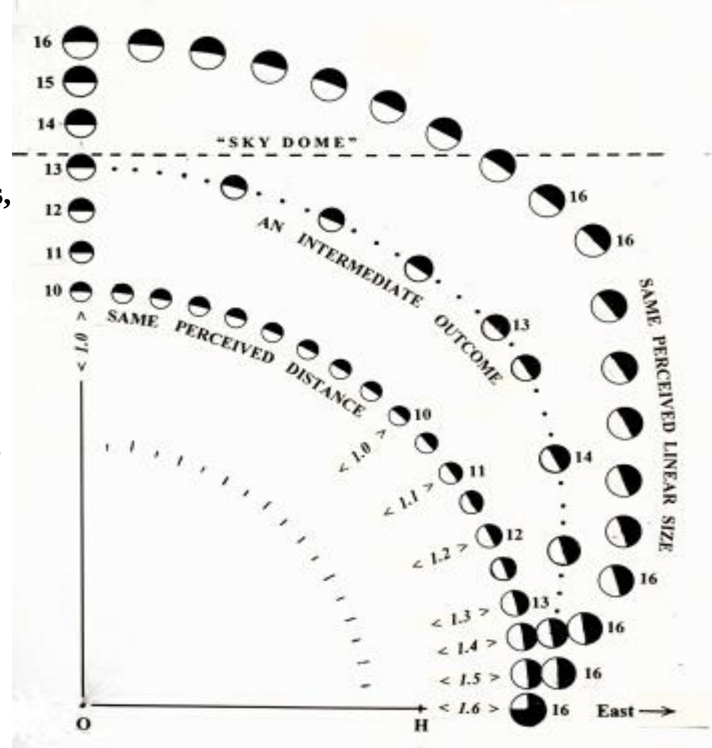
The 'moons' along the arc at the same perceived distance from point O are drawn at elevation intervals of five degrees. The number to the left of each 'moon' on that arc (such as < 1.6 > for the horizon moon) refers to the perceived visual angle for that moon and for the other 'moons' at that same elevation angle.

The front view approximates, in part, what the observer at point O is seeing.

How fast the perceived visual angle decreases while the moon's elevation steadily increases, evidently varies among observers. Figure 6 makes use of several published reports which indicate that the visual angle appears to decrease more rapidly during the first part of the moon's upward journey than it does later. For this example, the perceived visual angles begin with a value of *1.6* for the horizon moon, and decrease in an irregular manner up to *1.0* for the zenith moon at an elevation of about 45 degrees, after which point the perceived visual angle remains *1.0* up to the 90-degree zenith pole.

Figure 6 is a carefully scaled drawing: Each 'moon' is drawn at the distance from point O specified by the chosen perceived visual angle and perceived linear size values for it. Accordingly, for each type of outcome the diagram accurately predicts the path the rising moon would appear to take as it climbs into the zenith sky. The three most common outcomes are described again with each description now specifying the distinctive route the moon would appear to take as it rises.

Figure 6



The same perceived distance outcome is represented by the 'moons' strung along the circular arc at the same radial distance from point O. Accordingly, while the perceived visual angle decreases from *1.6* units to *1.0*units, the perceived linear size decreases from 16 to 10 units.

The same perceived linear size outcome is represented by the outermost arc of 'moons'. They have the same perceived linear size of 16 units while their perceived visual angles decrease from *1.6* units to *1.0* unit.

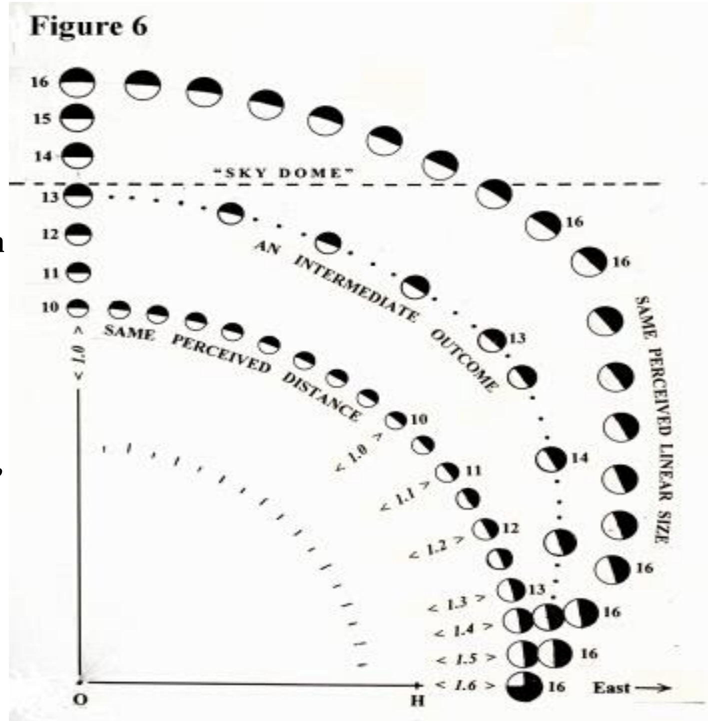
This linear size constancy outcome is especially noteworthy because the geometry specifies that the horizon moon initially appear to rapidly retreat eastward and then appear to ascend in an almost vertical path, as if it were a balloon rising straight up.

An intermediate outcome example is illustrated by 'moons' drawn along a path of dots between the other two outcomes. It includes a slight "bulge" to the east followed by an almost vertical apparent ascension during the first part of the path. The path ends in the overhead zenith moon of perceived linear size, 13 units. Countless other intermediate outcome paths obviously are possible.

That Initial Upward Path and the "Bulge".

In the linear size constancy and intermediate outcomes, that "bulging" path the geometry requires was a very pleasant surprise when it first showed up (in 1981) in the first carefully scaled diagram made for a moon illusion article (McCready, 1983).

In the first place, that predicted apparent movement of the moon to a greater distance just after it rises, followed by the almost vertical ascension, agrees with my own moon illusion experience. Many students (like me in 1949) have found that textbooks do not describe their moon illusion.



Secondly, that "bulge" became mentioned in the literature by Hershenson (1982, p. 438) for the setting sun. Specifically, as the sun appears to drop down in the west, its perceived visual angle typically enlarges, and some people say it appears to come forward (toward them) in the moments just before it slips from view below the horizon.

Likely Zenith Paths.

The route the moon appears to follow through the higher elevations seems to vary greatly among observers. Researchers have not yet agreed upon any particular description of the path through the upper sky. Consider, however, some likely paths Figure 6 can predict.

The zenith path for the same perceived distance outcome follows the circular arc to the 90-degree zenith pole.

The zenith path for the same linear size outcome is shown by the string of 'moons' of perceived linear size 16. The ones higher than an elevation of 45 degrees are arbitrarily on a circular arc at a perceived distance 1.6 times greater than those on the arc for the same perceived distance outcome.

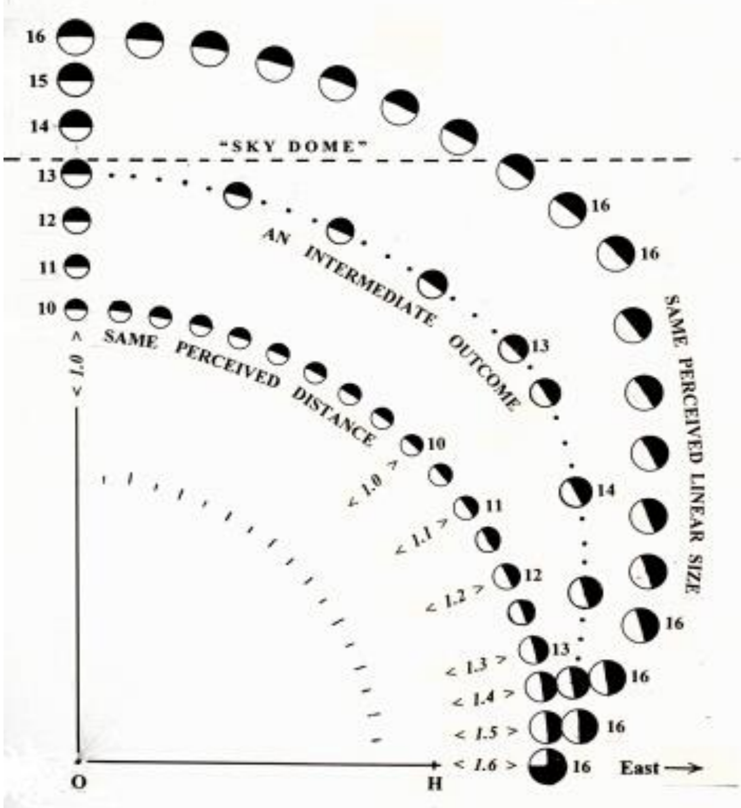
The zenith path for an intermediate outcome arbitrarily is drawn as the string of dots about halfway between those two other paths: It ends with circle 13 at the 90-degree elevation.

The Sky Dome, Perhaps.

Those three paths from horizon to zenith obviously differ greatly from the traditional "sky dome" description. For instance, for many people that hypothetical sky surface at the horizon is far beyond the apparent horizon moon.

Yet part of a sky dome illusion could be appealed to for higher elevations, as indicated in Figure 6 by the dashed horizontal line at the altitude of the perceived 'zenith moon'-13.

Figure 6



Indeed, Gilinsky (1980) proposed a compromise version, in which the horizon moon looks considerably in front of the sky, but rises to eventually meet the sky dome at a higher elevation. For example, as Figure 6 can suggest, the rising moon might appear to ascend along the equal-perceived-linear size path until it reaches the sky dome and then it could appear to follow that more-or-less flat path to the zenith pole, and through it.

In reverse, that predicts a perceived path for the sun moving from zenith to the western horizon.

Established Facts About the Moon Illusion.

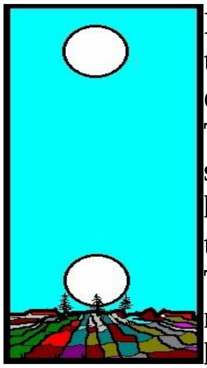
The publications mentioned so far, along with many others, have provided information that any theory of the moon illusion must explain. The essential facts are reviewed below.

Fact 1: It Is A General Illusion.

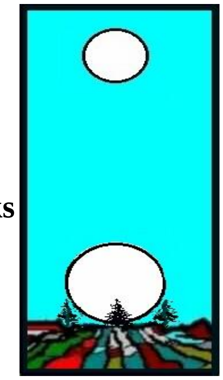
The 'moon' illusion is not limited to celestial bodies.

The apparent angular magnification and minification controlled by distance cues exists for other objects, as well.

For terrestrial objects this is a logical result illustrated by the diagrams below.



In each diagram, the two outer trees subtend at your eye the same angular subtense as the horizon moon's diameter.
The diagram at the left can mimic what a person would see if there were no moon illusion: The horizon moon looks a particular angular size, and the zenith moon looks the same angular size.
The diagram at the right can mimic the most common moon illusion. When compared with the diagram on the left it shows the horizon moon's visual angle looking 1.5 times larger than it would if there were no illusory magnification. The main point being made here is that the angular separation between the two outer trees also looks 1.5 times larger than it would if there were no illusion.



That has to be true, because those two outer trees logically must appear to bracket the just risen moon, no matter what size it looks.
In other words, as a general rule, the apparent enlargement of visual angles applies to distant terrestrial objects (and their separations) that appear far away near a distant horizon, such as trees, barns, and hills (Higashiyama, 1992, Higashiyama & Shimono, 1994, Roscoe, 1989)

For instance, one old 'explanation' was that the horizon moon looks big because it looks as big as, say, a huge barn seen near it. Well, if that barn were magically hoisted up to a high elevation while being kept at the same viewing distance, it would "look smaller," just as the zenith moon does.

This same generic "moon illusion" also occurs for objects indoors. Therefore, investigators have measured it using surrogate 'moons' objects (such as golf balls) presented in viewing conditions that simulate horizon and zenith vistas.

Fact 2: Distance-Cues Control The Illusion.

Long ago, the experiments by Rock & Kaufman (1962a, Kaufman & Rock, 1962a 1962b) convincingly showed that the changes in the moon's perceived angular size correlate most strongly with changes in distance-cue patterns in the moon's vista. Recently, Kaufman and Rock (1989) reviewed their research as well as the abundant research of others who demonstrated that role of distance-cues.

How far away an object looks from oneself is determined almost entirely by distance-cues. For example, binocular cues include stereoscopic depth perception, the most accurate source of 3D perception for distances up to, say, 100 meters. Convergence of the eyes also is listed. Movement parallax is extremely accurate.
Monocular distance-cues include linear perspective and texture gradients, often responsible for the depth illusions in pictures.

Both are combinations of the basic distance cue of 'relative angular size' combined with linear size constancy.

For instance, a pictorial illusion for the picture at the left includes some trees and a horizon moon that look much farther away than the clipped cornstalks in the foreground.

A texture gradient is illustrated by the individual images of the short stalks whose angular sizes appear to decrease toward the middle of the picture: If the stalks realistically look about the same linear size (in inches) they appear to be in a snowy plane tilted toward a distant horizon.

Linear perspective is illustrated by the converging rows of cornstalk images. If the lateral separations (in inches) between those pictured rows appear to be the same linear size, so they look linearly parallel, those rows appear to recede toward the distant pictorial horizon *because* their angular separations appear to progressively decrease from the bottom to the middle of the picture.

Regarding the moon illusion:
The horizon moon looks its largest when distance-cue patterns in its vista are indicating that terrestrial objects, such as the trees, hills, or buildings which appear on or near the horizon moon, are very much farther away than nearby objects.
That is, the distance-cue patterns are indicating large *perceived depths.* [Perceived depth is the perceived distance between a near object and a farther object. And, for an object, perceived depth is the perceived distance from a front edge to a back edge.]

When changes in the available distance cue patterns in the moon's vista 'signal' that it is even farther away from us, the distant-looking moon will look angularly larger. Such cue patterns often exist for the horizon moon. (And as already noted, the now "larger-looking" horizon moon typically does not appear to move farther away because some other distance cues dominate the final outcome.)

Evidence.
If available distance cues are artificially reduced for a large-looking moon it will look smaller. For instance, one can hide the distance cues in the terrain under the horizon moon by using one's hand, or by looking at the horizon moon through a small tube. [A complication here is that looking through a tube is known to induce oculomotor micropsia.]
Another way is to reduce the effectiveness of the distance-cue patterns for great depth. For instance, if one bends over and looks at the horizon scene with the head upside-down, the horizon moon looks much smaller than it did before the inversion (Washburn, 1894).

On the other hand, when a change in distance-cues indicates that the moon has moved to a shorter distance, or else when there are very few distance cues, the moon's constant angular size appears to decrease (minify). This latter condition typically

occurs for the zenith moon, especially when there is a large empty sky, a vista that lacks many distance-cue patterns which would create a great perceived depth between nearby viewed objects and far ones

Fact 3: Flat Pictures Offer Angular Size Illusions Due To Distance Cues.

A picture rich in distance cues can create an angular size illusion.

For instance, in the picture below, the three circles are the same size.
Observers typically say the middle one looks larger than the lower one. But, there are two quite different linear size illusions here.

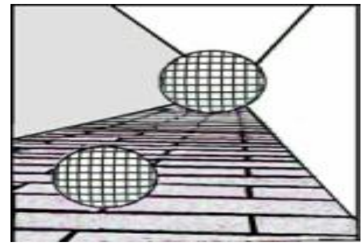
First there is a pictorial outcome: A horizon sphere' looks much farther away than a lower 'sphere' sitting between the cornrows, so it looks a much larger linear size (and volume) than the lower one. [As with any picture, viewing it with one eye, especially through a tiny hole (pinhole) can enhance the illusion.]
That illusion illustrates the apparent distance theory if the two 'spheres' look the same angular size.

The other linear size illusion here concerns the circles themselves: They correctly appear on the same page, so they have the same perceived distance, and the middle circle looks slightly larger, in millimeters, than the lower circle, let's say 5% larger.
This linear size illusion occurs, of course, because the perceived visual angle is slightly larger for the middle circle than for the lower one.
This small visual angle illusion is the most interesting one, because it cannot be described or explained by the apparent distance theory.

Going back to the pictorial illusion, the far-looking horizon sphere also looks, say, about 5% larger angularly larger than the nearby 'cornrow' sphere in addition to looking a very much larger linear size.

Now compare the upper and middle circles. They also can illustrate a small visual angle illusion, which partially mimics the moon illusion: The 'horizon moon' looks, say, about 5% angularly larger than the 'zenith moon'.
Indeed, researchers have used pictures like that and measured that small 'moon illusion' (Enright, 1987a, 1987b). Others, however, have reported their results only in millimeters, and, guided by the apparent distance theory, did not mentioned the visual angle illusion that lies behind that linear size illusion (see Coren & Aks, 1990). Yet, that angular size illusion is precisely the one that needs to be explained.

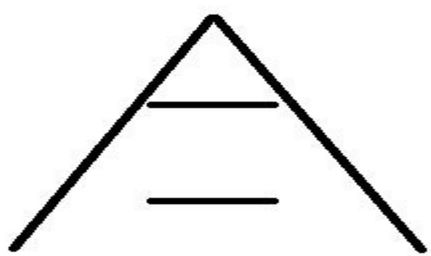
Even in very realistic pictures the angular size illusions are much smaller than the natural moon illusion, but the distance-cue patterns for the real moon are, of course, more complex.



********* NOTE Added June 19, 2006 **********
The crude sketch at the right slightly resembles the much more realistic picture used in the experiment by Murray, et al. (2006) previously discussed in the Introduction and Summary Section.
As they point out, it was in the same category as the Ponzo illusion (below).
And, of course, that category includes Figures like those described above and the ones used in Enright's studies of the moon illusion in pictures.
Again, the Murray, et al. discovery was that the sizes of the activity patterns in cortical area V1 that corresponded with the equal retinal images of the two disks , were not equal; and the measured size difference there correlated almost perfectly with the measured perceived visual angle difference for the two disks (which was at least a 17% V-illusion for their very realistic picture).
Thus, as noted earlier, it seems that in all such 'classic' flat pattern 'size" illusions, the distance cue patterns are having their influence before the neural activity in the retina reaches Area V1.
(The Murray, et al. results are analyzed in Appendix B.)
***************End of June 19 Note ********

Fact 4. Very Simple Patterns Also Illustrate Angular Size Illusions.

The Ponzo Illusion.

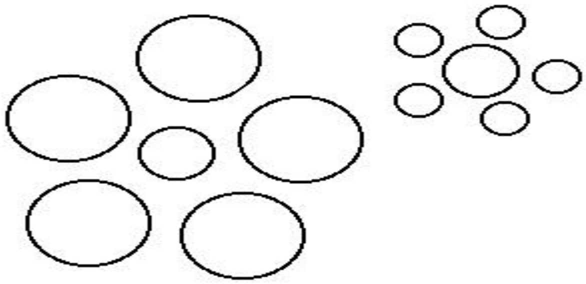


The two horizontal lines are the same linear size, so they subtend the same angular size at the reader's eye.

Popular descriptions emphasize the pictorial illusion that the two converging lines can appear to portray the edges of a road going into the distance. In that linear perspective outcome, the upper line can appear to portray a 'bar' lying on the road about twice as far away as the 'bar' the lower line portrays; thus the farther-looking 'bar' looks about twice as long (its length in meters) than the closer-looking 'bar'.
Some articles suggest that the moon illusion is "merely the Ponzo illusion upside down."
But, again, the report here that one object "looks larger and farther away" than the other does not describe the majority moon illusion.

On the other hand there is the only 'Ponzo illusion' that has seriously interested researchers. Namely, all the lines appear on the page, at the same perceived distance, and the upper horizontal line looks a slightly larger linear size (say about 5% larger)

than the lower one *because* it looks a slightly larger angular size. (A more detailed version is in Section II).



The Classic Ebbinghaus illusion (Titchner's circles).

In the patterns at the left, the two central circles are the same size, but their linear sizes *on the page* look unequal, *because* the angular size for the circle surrounded by smaller circles looks slightly larger (say about 10% larger) than the angular size for the circle surrounded by larger circles (McCready, 1985).

The Angular Size Contrast Theory.

Again, because the apparent distance theory cannot explain these classic flat pattern illusions, the best-known alternative has been the angular size contrast theory.

It proposes that an observer is comparing each target image's angular size to the average angular size for the images in its immediate context, which images subtend larger or smaller visual angles than the target. And that somehow makes each target's angular size look even smaller or larger than its actual visual angle.

The theory uses the fact that for many of these illusions (including the moon illusion) those changes in the visual angle subtenses of context images for the targets happen to be the bases of linear perspective and texture gradients, the distance-cue patterns so often correlated with visual angle illusions.
Some explanations for this well-known contrast effect are discussed in detail in Section II.
But, again, researchers have not yet accepted any one explanation.

Any theory of 'size' perception that applies to the moon illusion must deal with all the facts listed above.

The Two "Sizes" Controversy.

A few researchers still question how the perceived visual angle concept differs from the perceived linear size.
The distinction between these qualitatively different "sizes" was pointed out long ago by R. B. Joynson (1949; Joynson & Kirk, 1960). But, until recently, few researchers have used Joynson's revelation. Recognizing the distinction is crucial to understanding the new theory (McCready, 1965, 1985, 1986).

The "Perceived Size" Problem.

A major impediment to recognizing the distinction has been the common use of just*one* "size" concept called simply "perceived size" or "apparent size".
In some articles it consistently refers only to the perceived linear size. But some other

articles use the amazing idea that the "perceived size" sometimes correlates with an object's linear size in meters, and sometimes correlates with the object's angular subtense in degrees! The reader often must try to figure out which concept the ambiguous "size" term refers to at the moment!

Some of the most confusing treatments of illusions invoke the concepts ambiguously called "size constancy" and "size constancy scaling" (Gregory, 1963. 1965, 1970, 1998). The concept properly refers to constancy of the perceived linear size. But in many discussions, "size constancy" is defined as if it were not constancy of perceived linear size, but constancy of perceived angular size, which, in the present view, doesn't make sense and would be quite maladaptive.
This "size-constancy" problem is discussed near the end of Section II.

Ross & Plug (2002) accept the concept of perceived angular size, but question how it differs from the perceived linear size. They evidently are reluctant to abandon the most influential *general* theory of human spatial perception that uses only one "perceived size" (or "apparent size") concept (Gregory, 1963, 1965, 1966, 1968, 1970, 1998).

Moreover, a few researchers, notably Kaufman, L. & Kaufman, J. (2000) still do not accept that a person can have an angular size experience along with the linear size experience!

The Main Task.

The angular size illusion, however, is the basic "size" illusion in many classic illusions, and precisely the one that has defied explanation for so long.
In order to move toward an explanation for it, it is crucial to keep in mind that it is controlled by changes in distance-cue patterns.

Once that angular size illusion is explained, it becomes relatively easy to explain the linear size illusions and distance illusions that accompany it.

That task is addressed in Section III, after the critique of conventional theories in Section II.

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Section II. Conventional Descriptions.

As already noted, the most popular explanation for the moon illusion is the apparent distance theory which does not (cannot) describe the basic angular size illusion that most people suffer. It is critiqued after the following review of the angular size contrast theory that can describe the basic angular size illusion.

Visual Angle Contrast Theory.

A "size contrast" theory long has been the major replacement for the apparent distance theory. Of course, the term "size" is ambiguous: There is a *linear size contrast*effect, described later. The *angular size contrast* effect is more appropriate for the moon illusion. For instance, Restle (1970) used degrees of arc as the relevant unit of measure for his "size-contrast" theory of the moon illusion. Recently, Baird, Wagner & Fuld (1990) advanced that explanation by explicitly describing it as visual angle contrast illusion and by stating it in terms of the new general theory (McCready, 1965, 1985. 1986).

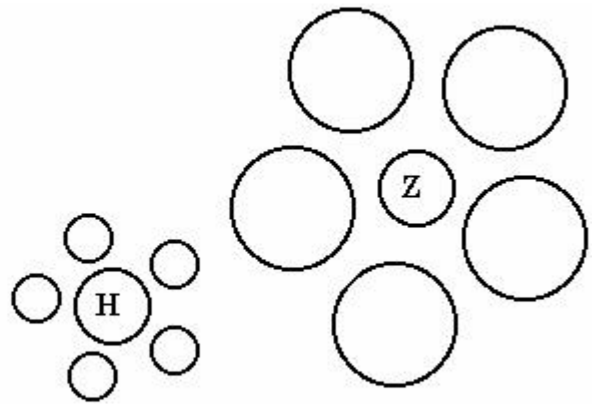
Angular Comparisons.

The theory emphasizes that many of the visible details in the horizon scene near the rising moon subtend visual angles smaller than 0.52 degrees, for instance, objects that subtend tiny angles, the small separations between objects, and the small separation between the just risen moon and the horizon itself.
It thus can be said that the horizon moon looks angularly larger than those selected details.
Next, it is noted that many visible details in the zenith moon's vista subtend visual angles larger than 0.52 degrees, such as large clouds, and the large separations between them, especially a huge expanse of empty zenith sky.
It thus can be said that the zenith moon looks angularly smaller than those selected extents.
So far so good.
But then it is said that the horizon moon looks angularly larger than the zenith moon*because* of those two independent comparisons. This third statement, however, takes a leap of logic that creates a serious problem.

A Problem.

The difficulty can be illustrated using the Ebbinghaus illusion arranged to slightly imitate the moon illusion.

The center circles are the same size, H = Z.
However, H looks larger than Z
The context circles for H have an average size, Ah, smaller than H.
The context circles for Z have an average size, Az, larger than Z.
We can say,
1. "H looks larger than Ah."
2. "Z looks smaller than Az."
But we cannot logically conclude,
3. "therefore, H looks larger than Z."



After all, facts 1 and 2 remain true no matter if H looks equal to Z, or even if H happened to look smaller than Z.

The trouble is that, for an uncritical reader the sequence of sentences, 1, 2, 3, could "sound" logical and create the impression that it 'explains' the contrast effect; but it doesn't.

To approach the problem another way, consider the moon illusion again.
To say the horizon moon's visual angle of 0.52 degrees looks larger than the visual angles of smaller extents near it doesn't say it looks larger than 0.52 deg.
No *absolute* visual angle illusion is being described.

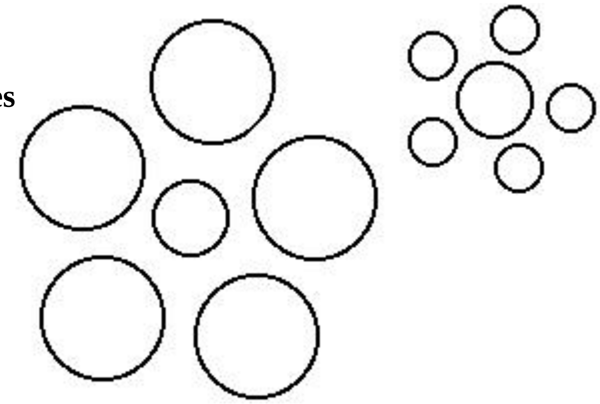
Likewise, to say the zenith moon's visual angle of 0.52 deg looks smaller than the visual angles of larger extents near it doesn't say that it looks smaller than 0.52 deg. Again, no *absolute* visual angle illusion is being described.

However, at least one of those absolute illusions obviously exists behind the relative illusion, and must be explained. Yet, popular discussions of the angular size contrast theory of the moon illusion don't describe or explain an absolute visual angle illusion.

Yet, a few theories have been offered for other classic "size" illusions that reveal the contrast effect.

Explaining Visual Angle Contrast. .

In the Ebbinghaus pattern, for instance, the two central circles subtend the same visual angle but the one surrounded by smaller circles looks a slightly larger angular size (say about 10% larger) than the circle surrounded by larger circles.
Obviously, either the center circle at the left looks smaller than its actual size, or the center circle at the right looks larger than its actual size, or else both of those absolute illusions are occurring.



Attempts to explain at least one of those absolute illusions emphasize that the illusion is*as if* the equal retinal images of the center circles were unequal: Therefore, it seems clear that at some neurological level in the visual system beyond the retina the patterns of nerve cell activity that normally correlate with 'retinal image size' must be unequal for those two target images.
Accordingly, some theorists, notably Oyama (1977) have proposed that these distortions occur at some brain level and are due to electrochemical interactions among neighboring neural cells there.
Of course, the pattern of activity of these presumed neural structures would be the physical (biological) precursor of the magnitude of the subjective, perceived visual angle.

*********** NOTE Added June 20, 2006 ************

As previously noted, the experimental results of Murray, et al. (2006) indicate that the "neurological level" mentioned above is reached in Area V1, (or perhaps in an even earlier level).

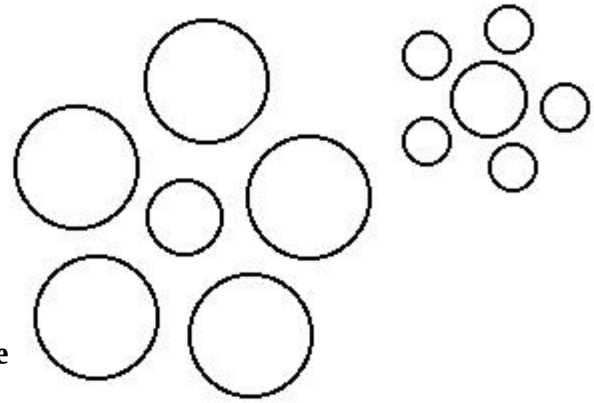
****************End of June 20 Note *********

Researchers have not yet accepted any particular explanation for the angular size contrast effect. But consider the following.

The Distance-Cue Connection.

The visual angle contrast theory can use the fact that for many of these classic illusions (including the moon illusion) the changes in the visual angle subtenses of the context images happen to also be distance-cue patterns.

For example, a possible pictorial illusion with the Ebbinghaus pattern is that the ten context circles portray discs of the same linear size (linear size constancy), so the five portrayed discs at the upper right look farther away than the five at the lower left, *because* they look angularly smaller (thus illustrating the perceived angular size cue to distance). Therefore, it can be argued that these context patterns act as distance-cue patterns that educe the relative visual angle illusion, providing a small imitation of the moon illusion (McCready, 1985.



Moreover, this distance-cue connection allows the oculomotor micropsia/macropsia theory to be proposed as an explanation for that angular size contrast effect (McCready, 1985), and as discussed in detail later, in Section III.

*********** NOTE Added June 20, 2006 ************
Again, the experimental results of Murray, et al. (2006) indicate that in all such 'classic' flat pattern 'size" illusions, the distance cue patterns are having their influence before the neural activity from the retina reaches cortical Area V1.
(The Murray, et al. results are discussed in Appendix B.)
*****************End of June 20 Note **********

Inverted Viewing.

Regarding the moon illusion, the most common criticism of the visual angle-contrast theory has been that if one bends over and views the entire scene upside-down, the horizon moon and all the terrestrial extents seen near it will look much smaller (angularly) than they do when they are seen right-side up (Washburn, 1894).
Consequently, various researchers have noted that this inversion of the entire horizon scene obviously does not change the "size"-contrast relationship between the horizon moon and the smaller extents seen near it; therefore, the proposed "size"-contrast effect evidently does not contribute very much to making the horizon moon look larger than the zenith moon (Boring, 1962; Rock & Kaufman, 1962a).

Technical Note (in 2001): Successive Visual Angle Contrast.
A slightly different contrast effect is that the perceived visual angle for a target may be made smaller by viewing it after staring for a while at a pattern consisting of elements that subtend visual angles much larger than the target.
Conversely, the target's constant angular size looks larger after one has stared at a pattern of elements that subtend much smaller visual angles.
To explain this successive contrast effect, theorists have suggested it illustrates an "adaptation" of hypothetical neurological entities in the visual system. Some theorists refer to them as "spatial frequency detectors," which also can be called "visual angle detectors." Other theorists refer to them as "size channels," an ambiguous term that properly should

be "visual angle channels," in order to avoid suggesting there might be such peculiar things as "linear size channels." End of technical note.

*********** NOTE Added June 20, 2006 ************
The results of the Murray, et al. (2006) experiment support an 'old' view used here, and by Oyama (1977), McCready (1965, 1985), and a few others.
This view is that the physical precursor of the perceived visual angle, V' deg, is not some hypothetical "channel" or "spatial frequency detector," but the physical extent, say a 'brain size', *B* mm, between activated cells in a layer of brain cells (probably in Brodmann area 17. And, this extent, *B* mm, is a (flexible) isomorph of the extent, R mm, between the activated cells in the retinal layer that are stimulated by the optical images of two viewed points that subtend a visual angle, V deg.
The Murray, et al. results suggest that *B* mm, is in the 'layer' of cortical Area V1.
So, the successive contrast effects undoubtedly occur before the retinal neural activity pattern reaches Area V1.

*****************End of June 20 Note **********

It may be useful, in passing, to differentiate between angular size contrast and *linear size contrast.*

Linear Size Contrast.

Consider a simple example of linear size contrast:
You are watching a volleyball game and looking down onto the distant court at a woman who is 5 feet, 8 inches tall standing in the middle of a group of players all taller than 6 feet. And, as a linear size illusion, that woman might look, say, only 5 ft, 5 in. tall.
That could happen because, although the surrounding players offer an average physical "linear size context" taller than 6 ft, their heights *appear* to average, instead, a height closer to what you personally may have learned as an average for "tall women," let's say about 5 ft, 9 in. So, because the woman looks about 4 inches shorter than that (mistaken) perceived average of 5 ft. 9 in. for the players, she looks shorter than her true height, to illustrate a linear size contrast illusion.

A linear size contrast effect may or may not be accompanied by a visual angle contrast effect.

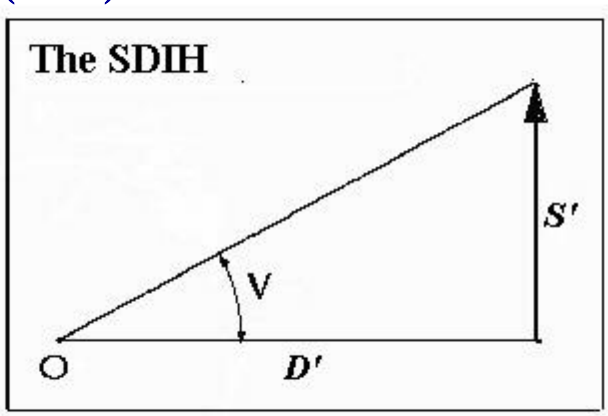
Conclusion:
If the visual angle contrast theory explains a small portion of the moon illusion, it can be said to *supplement* the oculomotor micropsia theory that provides a more complete explanation of the large visual angle illusion for the moon.

The Apparent Distance Theory.

The basic reason the apparent distance theory cannot describe the majority moon illusions that begin as visual angle illusions is because it uses only one "perceived size" concept (also called "apparent size) which must be the perceived linear size. That limitation is imposed by the standard logic (geometry) the theory uses, as described below.

The Size-Distance Invariance Hypothesis (SDIH).

Readers familiar with the literature on "size and distance" perception will recognize that traditional theories have used the rule called the, *size-distance invariance hypothesis* or SDIH, diagrammed at the right.
The perceived object (arrow) has a perceived linear size of *S'* meters at a perceived distance of *D'* meters. The angle, V degrees, is the *physical visual angle* .



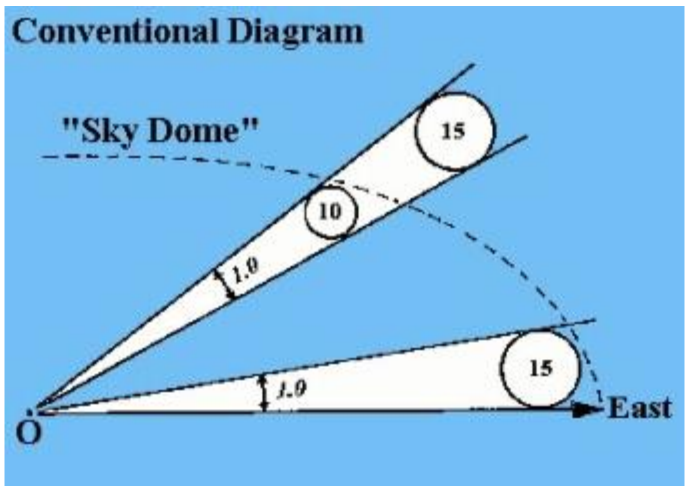
The SDIH equation thus is, $S'/D' = \tan \underline{V}$.
The SDIH obviously omits the perceived visual angle concept, *V'* deg.

The theory's assumption that the moon *looks* the same angular size from moonrise to dawn is rarely stated explicitly. But it clearly is revealed by side-view illustrations used in presentations of the theory.

Conventional Side-View.

Conventional diagrams like the one below illustrate that an observer at point O sees all moons as having the same angular size.

The 'horizon moon' here has a perceived linear size of 15 metric units.
The only moon illusion the SDIH describes is illustrated, for example, by 'zenith moon'-10. And to have a perceived linear size of 10 units it must be at a distance from point O equal to 2/3rds the distance of 'horizon moon'-15. in order to subtend the same the perceived visual angle (of 1.0 unit).
(Published side-views often include the 'Sky Dome' idea.)



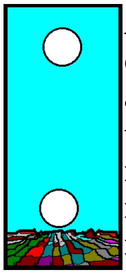
The observer at point O would say the horizon moon looks the same angular size, farther away, and a larger linear size than the

zenith moon.

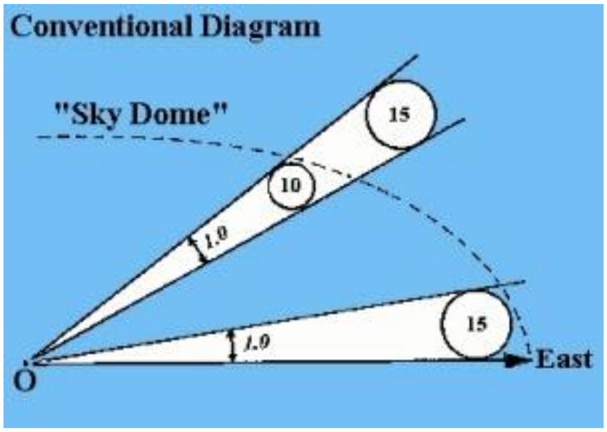
That experience can be imitated for us (again) by the front view at the right.
Suppose the lower circle portrays a huge hot air balloon tethered to the ground far away, at about the distance of the tall trees.
And suppose the upper circle is a picture of a small toy balloon floating directly above the corn stalks in the foreground.
Compared with the 'zenith' balloon, the 'horizon' balloon thus looks the same angular size, looks much farther away, and looks a much larger linear diameter, in feet.
That pictorial illusion mimics the experience the conventional side-view is illustrating for the observer at O. It also illustrates the apparent distance theory of the moon illusion, if the 'balloons' look the same angular size.

Again, Side-View Diagrams Can Fool Readers.

Conventional side-views invariably use filled circles. But only a front view logically can use filled circles. The front view at the left goes with that side-view

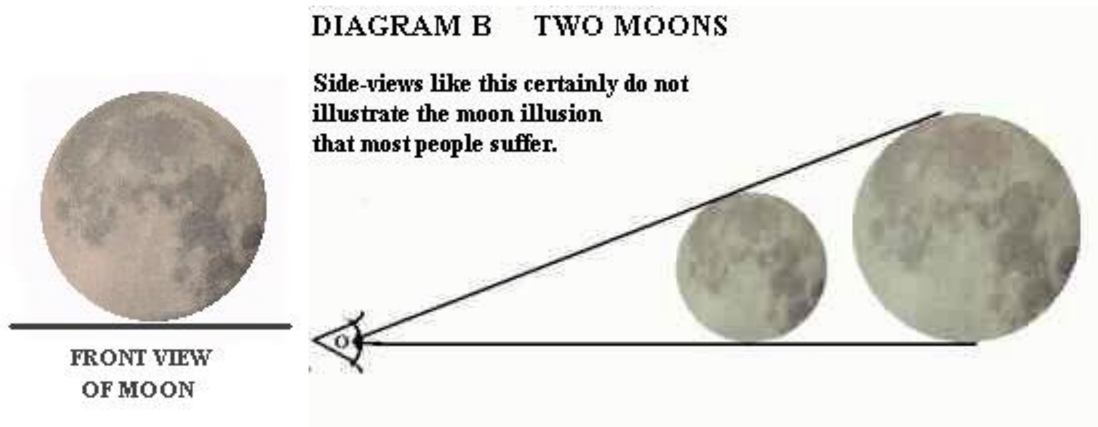


Again, in the side view, 'horizon' circle-15 correctly looks a larger angular size than 'zenith' circle-10, so that imitates the visual angle illusion most people suffer. Consequently, if not given an appropriate front view, readers who merely glance at the side-view without analyzing what it is showing could mistakenly think it describes and explains their own moon illusion.



A Silly Diagram.

Diagram B resembles some diagrams meant to illustrate the apparent distance theory.
Of course, it is absurd to use a front view of the moon in a side-view, but that is the least problem with Diagram B.
The biggest problem is that it does not describe most peoples' moon illusion.



After all, Diagram B purposely shows that the person at point O is seeing two 'moons' that look the same angular size.
The front view shows us what that person is seeing. It has to be a single full moon image because the first 'moon' in diagram B exactly occludes the rear 'moon.'
The two moon images in Diagram B correctly look different angular sizes, so they imitate the moon illusion of most readers, consequently, some readers can be misled into thinking the side-view describes the majority moon illusion.

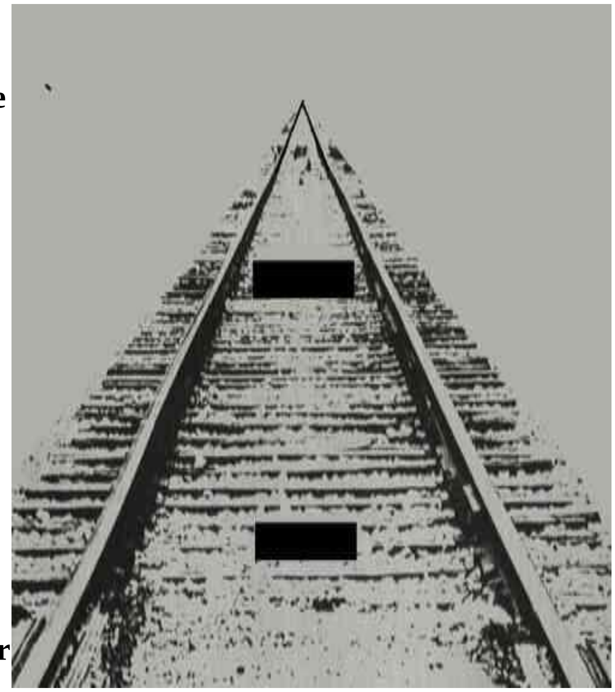
This easy misinterpretation of side-view drawings evidently occurs quite often, and it undoubtedly is responsible for much of the confusion in the moon illusion literature. Authors who publish those diagrams either have misread them, or else their own personal moon illusion happens to be the rare outcome that the moon looks the same angular size at the horizon and zenith.

Two Other Inappropriate Analogies.

Moon illusion articles often mention two other examples that are wrong and misleading; the "railroad track" illusion and the behavior of afterimages.

The 'Railroad Track' Illusion:

In this popular version of the Ponzo illusion, the dark rectangles are the same linear size on the page, so they subtend the same angular size at the reader's eye. Most people say the upper one "looks larger" than the lower one



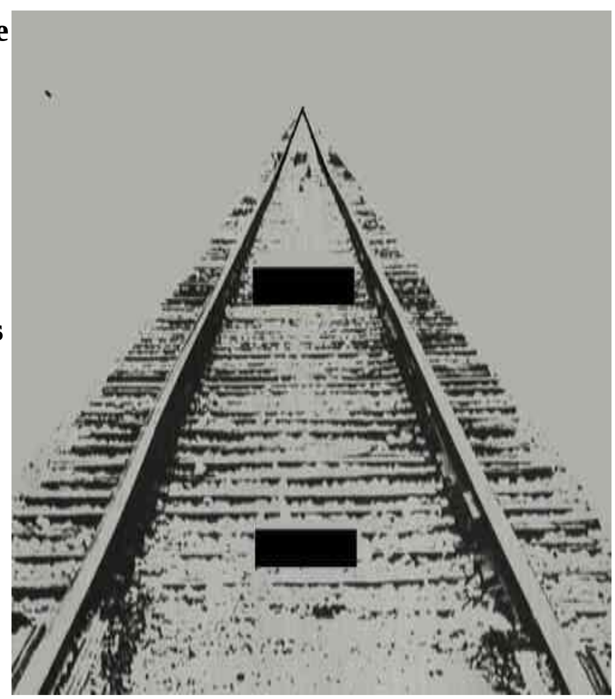
The Pictorial Illusion

Some moon illusion articles repeat the apparent distance theory from beginning psychology texts (for instance, Wenning, 1985) and suggest that the moon illusion is "merely the railroad track illusion upside down." But that analogy fails because it uses only the pictorial illusion of tracks going into the distance, with the rectangles portraying perceived *objects* lying on the roadbed. [To enhance the illusion, view it with one eye.]

For instance, the object portrayed by the upper rectangle can appear to be about three times farther away than the object the lower rectangle portrays. The viewer says, "the upper object looks about three times farther away and about three times as long (in feet) as the lower object." That rather large linear size illusion illustrates the SDIH and the apparent distance theory.

But, even upside down, the appearance that one object looks farther away and a larger linear size than the other object which subtends the same angular size does not imitate the majority moon illusion.

At any rate, that pictorial illusion is not the one that has interested scientists.



The 'Paradoxical' Ponzo Illusion.

The quite different illusion yielded by the Ponzo picture is that the two equal rectangles can correctly look like flat bars printed on the same flat page, so they correctly appear at the same viewing distance, but the upper bar looks a slightly bigger linear size (in millimeters) on the page than the lower bar does, let's say about 10% longer.

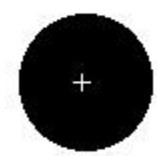
This linear size illusion clearly illustrates an underlying *angular size illusion;* the upper bar appears to subtend an angular size about 10% larger than the lower bar does.

This very small, combined angular size and

linear size illusion has interested researchers much more than the mundane pictorial illusion, for several reasons:
1. It cannot be described or explained by the apparent distance theory and SDIH.
2. It illustrates an angular size illusion induced by changes in distance-cues, so, to a small degree it imitates the angular size illusion for the moon .
3. The linear perspective and texture gradient cues here are the changes in the visual angles of the context images for the bars. So, the angular size contrast theory can be applied to this illusion.
4. This illusion also can be explained as yet another example of oculomotor micropsia/macropsia (as discussed in Section III).

Afterimages and Emmert's law.

Another analogy, offered by King, & Gruber, (1962) concerns the "size" an afterimage looks when it is "projected' to different distances.



For instance, you could stare for about 15 seconds at the center of the black disc from a distance of, say, 20 inches, and then look at another place on this screen, where you will see a bright white afterimage that properly appears the same linear size and at the same distance as the black disc. But if you move back from this screen to, say, 40 inches, that afterimage on the screen now will look twice as far away as it did and twice the linear diameter.
That happens because the afterimage has, in effect, the same angular size the black disc had when you stared at it; therefore, in accord with the SDIH, as $S'/D' = \tan V$, the afterimage's perceived linear size will increase by the same proportion that its perceived distance ("projected distance") increases.
Psychologists call that important rule, *Emmert's law.*

Some currently popular "moon illusion explanations" (e.g., Wenning, 1985) merely repeat the analogy (without attribution) that an afterimage of a small disc projected onto the horizon surface of the illusory sky dome would look farther away, hence look a larger linear size than when projected on the sky dome's apparently closer zenith surface.
But, once again, the analogy fails because hardly anyone says the horizon moon "looks larger and farther away" than the zenith moon.

Although the apparent distance theory of the majority moon illusion can be rejected its two main versions are reviewed next. One appeals to a supposed illusion that the sky appears like a surface: The other appeals to changes in distance-cues.

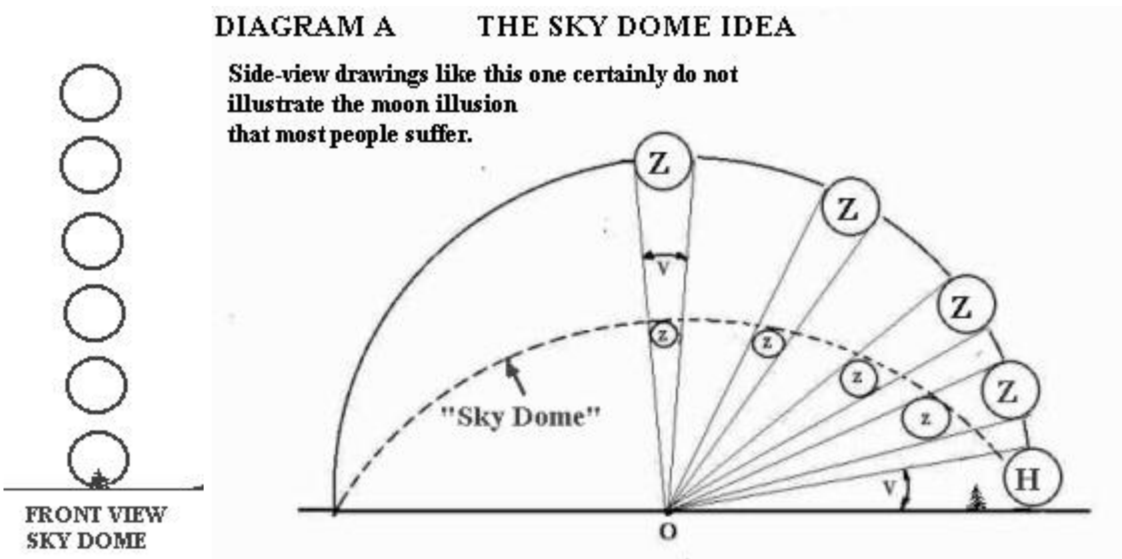
Alhazen's Ceiling and the Sky Dome.

According to Plug & Ross (1989; Ross & Plug, 2002) the first scientist to clearly recognize that there is no physical basis for the moon illusion was Ibn al-Haytham, the 11th-century astronomer known to us as Alhazen. That is, he observed that the moon's angular size remained constant. (So, the atmosphere does not somehow create the illusion.)

He then proposed that the sky looks like the flat ceiling of an enormous room, and the rising moon appears to move along it in a more or less flat trajectory, so the moon would look closer at the zenith thus it would look a smaller linear size than it did at the horizon.

The Sky Dome Again.

A similar old idea was the sky dome illusion, described in the Introduction, and repeated below using Dagram A. The rising moon supposedly appears to glide along this illusory sky surface. For the person at point O, the 'H moon' thus looks farther away than a 'z moon', therefore it must look a larger linear size than a z moon in order to keep their angular sizes equal.



The angle, V deg, is the same for all 'moons' because in standard discussions it starts out being the constant physical value (0.52 deg). However, the moment a discussion turns to describing how the person at point O *perceives* the moons, all those equal angles become, by default, perceived angular size values, (*V'* deg). In other words, for the person at point O, *all the perceived zenith moons look the same angular size as the perceived horizon moon*. The sky dome diagram obviously fails to describe most peoples' moon illusion.

Once again, filled circle H in the diagram correctly looks angularly larger than each z circle. That imitates the majority moon illusion, but does not imitate what the diagram is illustrating for the person at point O. For us to experience what that person is seeing, we must look at the front view at the left.

Other Problems.

For many people the horizon sky appears to extend far beyond the horizon moon (see Gilinsky, 1980).

Another difficulty is that research studies of the apparent shape of the sky do not confirm the flattened dome model for all observers (Baird & Wagner, 1982).
Similar disconfirming data is reviewed by Ross & Plug (2002).

Finally, even researchers who still advocate the apparent-distant theory have pointed out that one does not need to appeal to a sky surface illusion in order to 'explain' why the horizon moon would look farther away than the zenith moon (Rock & Kaufman, 1962a, Kaufman & Rock, 1989, Kaufman & Kaufman, 2000)
They appeal, instead, to the changes in distance-cue patterns.
In a sense, the sky dome theory is obsolete.

The Size-Distance Paradox.

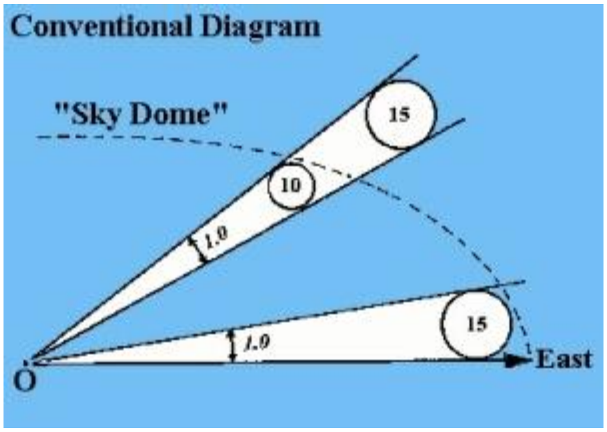
Some researchers long ago pointed out that the size-distance paradox which results from trying to apply the SDIH and apparent distance theory to various illusions cannot be resolved. (Boring, 1962).
But, what rarely has been pointed out is that the 'paradox' completely vanishes when one uses the perceived angular size concept in addition to perceived linear size (McCready, 1965, 1985).

Nevertheless, there have been two major attempts to resolve the 'paradox' while still clinging to the SDIH and using a single 'size' concept called merely "perceived size" or "apparent size." One attempt uses a hypothetical "registered distance" concept.
The other refers to two hypothetical levels of "size" scaling.
However, as shown below, both attempts are illogical.

The Registered Distance Idea.

The registered distance proposal invents a three-Stage perceptual process (Kaufman and Rock, 1962, 1989; Kaufman L. & Kaufman, J. 2000).
In Stage 1, certain factors, such as distance-cues, establish a greater "registered distance" for the horizon moon than for the zenith moon. But this registered distance remains out of consciousness.

In Stage 2, the increased 'registered distance' operates at an "unconscious level" to make the conscious "perceived size" greater for the horizon moon, in accord with the SDIH (stated by, $S'/D' = \tan V$). This "size" is, of course, the perceived *linear* size. The logic of this second stage is illustrated in the conventional diagram by the two 'moons' of perceived linear sizes, 15 units and 10 units.



Next is stage 3, which is described with a statement such as, "because the horizon moon now looks larger than the zenith moon, it looks closer."
Notice, however,this proposed stage 3 is*impossible* according to the very logic (the SDIH) being used,
As the diagram illustrates, when the moon's perceived visual angle remains the same, if the moon's perceived linear size is increased from 10 units to 15 units, the geometry *requires* that

the moon then look about 1.5 times *farther away* than it did. The increase in perceived linear size cannot result in a decrease in perceived distance.
The registered distance idea does not resolve the 'paradox'.

The difficulty here, of course, is that every reader clearly understands the phrase "it looks larger, so it looks closer," which is how Stage 3 is worded. This phrase describes our many everyday experiences for objects whose *visual angle* increases, usually because the objects come closer to the eyes. It also describes our common experience that the *object* we 'see' in a movie appears to approach us when its image on the screen enlarges (zooms) to create the perceptual event called "looming," a popular term for a large increase in the perceived visual angle.

In other words, the "size" we invariably are referring to when we say an object "looks larger and closer" is not the object's linear size, but the visual angle it subtends. The object's linear size typically appears to remain the same (linear size constancy). Indeed, this linear size constancy must occur in order for the increase in the perceived visual angle to yield the shorter perceived distance as an example of the relative angular size cue to distance.

Because the sentence that describes the illogical Stage 3 "sounds" good it creates a false impression that the paradox has been resolved.

Two "Size" Scalings Proposal.

A slightly different attempt to resolve the size distance paradox proposes that the scaling (valuation) of "perceived size" and distance occurs at two different perceptual levels (Gregory (1963, 1965, 1966, 1968, 1970, 1998).
The proposal uses the logic of the SDIH and apparent distance theory, so the scaled "perceived size" has to be only the perceived linear size, in meters.
Applied to the moon illusion, the proposal is that the distance-cues for a greater distance cause a *primary scaling* of the horizon moon's 'perceived size' larger than the 'perceived size' for the zenith moon (which is yielded by the primary size scaling for it).

Then a *secondary scaling* occurs, described only by a phrase such as "the horizon moon's larger 'perceived size' makes it look closer than the zenith moon."
Again, that sentence is illogical according to the very logic (the SDIH) the proposal uses.

Other difficulties abound in moon illusion discussions that use a "size-constancy" concept.

The Flawed, Size-Constancy" Approach

The opening sentences in 'size-constancy' discussions point out that it refers to the very common observation that an object's 'perceived size' (*S'*) appears to stay the same when, for example, an increase in the object's distance from the eye decreases the angular size (V deg) the object subtends, hence the size of the object's retinal image decreases.
Other sentences point out that, when *S'* remains constant, the object's perceived distance (*D'* meters) must increase: That is, in accord with the SDIH equation rearranged as, *S'* = *D'* tanV, when V decreases, *S'*, will remain the same only if *D'*increases in inverse

proportion to the decrease in V deg.
Because the SDIH equation specifies that *S'* is the perceived linear size, in meters, that perceptual constancy must be more precisely called, linear size constancy.

Much confusion arises in 'size-constancy' discussions whenever the term 'perceived size' is used in a manner which makes it refer not to the perceived linear size, *S'* m, but also to the perceived visual angle, *V'* deg, which the SDIH doesn't include.
In other words, many sentences unwittingly fail to distinguish between *S'* m and *V'*deg, so from one phrase to another the term 'perceived size' can change from referring to *S'* meters to referring to *V'* degrees.

Consequently, many discussions of "size" constancy end up defining it as constancy of the perceived visual angle, *V'* deg, when the visual angle, V deg , changes!
For instance, Trehub's (1991) theory of the moon illusion uses a single "perceived size" concept and the SDIH, to propose a hypothetical model of brain processes that might underlie 'size constancy' and Emmert's law. But, the proposal ends up treating 'size constancy' as constancy of perceived angular size instead!

*********** NOTE Added June 20, 2006 **************
As already noted, Murray, et al. (2006) explicitly state that they measured the perceived angular size illusion.
So, the results do not (cannot) support the standard, SDIH, approaches.
However, in the article's discussion section, the interpretations of those results often use the SDIH logic, and confuse perceived visual angle (V' deg) and perceived linear size, S' cm, (called 'perceived behavioral size').

For instance, it is suggested that, for a viewed target that has a constant retinal image size, R mm, an increase in the target's perceived distance, D' cm, elicits a supposed "scaling" of some entity called the viewed object's 'retinal projection" to yield a larger "perceived behavioral size" for the object, "whereby retinal size is progressively removed from the representation" (p.422).
But that suggestion states the SDIH logic used by Emmert's Law, by "misapplied size-constancy scaling," by the apparent distance theory, and by the "registered distance" argument.
So, it cannot apply to the visual angle illusion that was measured!
It actually suggests that the (flexible) perceptual correlate of the extent. R mm, between two stimulated retinal points is the perceived linear size, S' cm, rather than the perceived visual angle, V' deg.
It also implies that 'size constancy' is a constancy of the perceived angular size, V' deg, which would be terribly maladaptive.

As was easily predictable, other articles already are mis-interpreting the Murray, et al. experiment in that same manner.
*****************End of June 20 Note **********

That common mistake generally has gone unrecognized.
It is discussed in detail at the end of Appendix A.

Obviously, many 'size' illusions have made it necessary to reject the SDIH and apparent distance theory.
Also, the visual angle contrast theory doesn't go far enough to explain the moon illusion.
The oculomotor micropsia theory offers another alternative, discussed in Section III.

Section III. Explaining the Moon Illusion, and Evidence For The Visual Angle Illusion

The new theory first describes the basic relative visual angle illusion that characterizes the moon illusion suffered by at least 90% of the population. It then explains why changes in the moon's perceived visual angle correlate with changes in distance-cues, by proposing that the illusion is an example of oculomotor micropsia/macropsia.

Oculomotor micropsia described briefly.

Oculomotor micropsia is a visual angle illusion caused by changes in the activity of eye muscles. The muscles most involved in the illusion are the external ones that turn the eyes to aim both of them onto the same viewed point (the process called convergencefor a point close to the face, and divergence for a very distant point). Also involved might be the muscle inside each eye which changes the shape of the lens in order to sharply focus the optical images on the retina (the process called accommodation). Since 1965, some researchers have claimed that the "size" illusion caused by changes in convergence and accommodation is primarily a visual angle illusion (McCready, 1965, 1983, 1985; Ono, 1970; Komoda & Ono, 1974). This visual angle illusion necessarily is accompanied, secondarily, either by a linear size illusion, or by a distance illusion, or else by both.

The illusion is described as follows:

Micropsia.

While looking at a fixed object which subtends a constant visual angle, if one focuses and converges one's eyes to a distance closer than the object, the visual angle of that object looks smaller than it did, as micropsia. Four outcomes commonly have been found for the accompanying linear size and distance perceptions.

1. The object appears at about the same distance as before (an equidistance outcome) in which case its linear size necessarily looks smaller than it did (off-size).

2. The object's linear size continues to appear the same (linear size constancy) in which case the object necessarily looks farther away than it did (the relative perceived angular size cue to distance).

3. The object looks both linearly smaller and farther away than it did (an intermediate outcome).

4. The object appears closer than it did (in agreement with the oculomotor change) so its linear size necessarily looks very much smaller than it did (off-size).

Historically, the simple term micropsia ("looking small") has had two quite different meanings, and that has created much confusion. To avoid confusion, I use the term*micropsia* only for a visual angle illusion, and the term, off-size, for the linear size illusion.

All the outcomes listed above have been found among observers in experiments on oculomotor micropsia, but the 4th outcome has been found less often that the others (Komoda & Ono, 1974; Ono, Muter, & Mitson, 1974).

Tech Note: Because of the oculomotor micropsia data (and much other evidence) vision scientists have known for a long time that neurological afferent "feedback" from contractions of the eye muscles involved in accommodation and convergence does not provide a strong cue to *perceived distance*. Instead, the 'distance-cue' that controls micropsia seems to be the neurological brain activity (the efferent "motor command") being sent to (or about to be sent to) the muscles in order to make the eyes move (whether or not those muscles contract). End of Tech Note.]

Macropsia.

The converse of oculomotor micropsia is *oculomotor macropsia.* It can be witnessed when one shifts the focus and convergence of one's eyes from a nearby viewed object to a much greater distance. In that case, the viewed object's visual angle looks larger than it did, and the object looks either a larger linear size (off-size) or closer, or else both of those secondary illusions accompany the macropsia. (I'll use the term, oculomotor micropsia, as a general term both for micropsia and for macropsia, unless otherwise specified.)

Oculomotor micropsia is perhaps the largest visual angle illusion, and it occurs during everyday viewing whenever convergence and accommodation change, which, of course, is quite often. Amazingly, this omnipresent illusion is rarely mentioned in conventional discussions of "size" illusions.

Although oculomotor micropsia is a very dramatic illusion, it is limited: For instance, in micropsia the visual angle for an object rarely looks smaller than half its true value. And, in macropsia the object's visual angle rarely looks larger than twice its true value. Those limits are sufficiently broad, however, to encompass the small visual angle illusions that are the basic illusions in many of the best-known "size" illusions. Why oculomotor micropsia occurs is explained in Section IV. How it becomes the basis of the moon illusion is discussed below.

Eye Adjustments in the Moon Illusion.

When one is looking toward the horizon moon, the distance-cue patterns in the typical horizon vista usually make one's eyes adjust, as expected, for "very far" (optical infinity). Consequently, to illustrate oculomotor macropsia, the horizon moon's visual angle looks large. But how large? At this time no measures of the perceived visual angle for the horizon moon have been published. (As previously noted, it would be extremely difficult to measure perceived visual angles as small as one or two degrees.) The best guess is merely that for most observers the perceived visual angle for the horizon moon is greater than 0.52 degrees.

On the other hand, the zenith moon's visible context typically has few distance-cues that indicate great depth: And, as vision researchers found long ago, when there are

few distance-cues the eyes tend to adjust to a resting focus position about 1 or 2 meters from the face. A closely related phenomenon is that in relatively dark surroundings, the eyes tend to adjust to a nearby dark focus position, also about 1 meter from the eyes. Indeed, many of us become slightly nearsighted in relative darkness, a phenomenon known as *night myopia.*

These eye adjustments to "near" typically occur while one is viewing the zenith moon, therefore they can induce micropsia, and the zenith moon looks angularly small. But how small? One guess is that its perceived visual angle is less than 0.52 degrees. [However, evidence from some other illusions indicates that the perceived visual angle may equal the visual angle when the eyes are adjusted to the resting focus position; therefore, the perceived visual angle for the zenith moon might equal 1/2 degree.]

It should be noted that, although the eyes' adjustments to a relatively near position during natural viewing of the zenith moon undoubtedly would create imperfect optical imagery, the viewer usually is unaware of these "faulty" adjustments because they are involuntary and not quite large enough to cause double-vision or obvious blurring. Likewise, it has been shown that when people look to a very far distance the eyes often will focus *beyond* optical infinity, and the resulting blurring is not noticed.

Evidence.

Enright (1975, 1987a, 1987b, 1989a, 1989b) and Roscoe (1979, 1984, 1985, 1989) have published evidence for all of the above descriptions. They also measured the changes in eye adjustments while observers viewed artificial, surrogate 'moons' at different distances, and also measured the accompanying changes in the perceived visual angle for those 'moons' when they were optically placed in horizon and zenith settings. Those measured changes in the perceived visual angle that accompanied a given change in eye adjustments, turned out to be about the same magnitude as the relative changes commonly found in laboratory studies of oculomotor micropsia. Essentially the same results have been obtained for objects and images in other laboratory setups that imitated viewing of the moon

The experiments by Enright and by Roscoe have provided the most significant data on the moon illusion offered since the researches of Rock & Kaufman (1962a, Kaufman & Rock, 1962a) revealed the major role of distance-cues.

The oculomotor micropsia illusion thus can explain why changes in distance cues induce the moon illusion. However, while you were reading the new descriptions of the moon illusion presented so far, you undoubtedly noticed that the distance-cues which initiate the magnification of the horizon moon's perceived visual angle typically do not make the horizon moon *look* farther away than the zenith moon.
After all, the many details in the landscape or cityscape extending toward the horizon moon form the distance-cue patterns which indicate that terrestrial objects near the horizon are much farther away than nearby objects. Those distance-cues for great depth are the ones that make the eyes adjust for "very far," and that evokes the macropsia illusion. Those distance-cues certainly could also establish a greater

perceived distance for the horizon moon than for the zenith moon, but they usually don't. Why they don't is examined next.

Seeming Contradictions and Cue Conflicts.

The horizon moon most often looks either about the same distance away as the zenith moon or *closer.* These results are not paradoxes because they do not require a revision of the new theory. Instead, they merely reveal that the viewing conditions include several different sets of distance-cues that compete with each other for determination of the relative perceived distance for the moon.

Reviewed below are the two determiners of perceived distance that most often conflict with the changes in the vista distance-cues, and with the changes in eye adjustments.

The Equidistance Tendency.

Suppose this pair of letters, O o, is a picture of two spheres. One easy perception is to see them as pictured spheres at the same distance from the eye. In that case, the sphere that looks angularly larger also looks linearly larger. Let's say they look like a pictured baseball and a pictured golf ball at the same distance from you. That percept can be attributed to an *equidistance tendency* (Gogel, 1965) or an *equidistance assumption*(McCready, 1965).

By analogy, for people who say that the horizon moon "looks larger and about the same distance away" as the zenith moon, the equidistance tendency has won the competition between the different determiners of the moon's apparent distance. Factors that can establish equal perceived distances for the two moons include one's*knowledge* that the moon's distance from the earth remains essentially constant from dusk to daybreak.

The Relative Perceived Visual Angle Cue to Distance.

For most people, the larger perceived visual angle for the horizon moon than for the zenith moon makes the horizon moon look closer than the zenith moon. This relative perceived visual angle cue to distance is one of the strongest monocular cues, and here it overrules the equidistance tendency, overrules the patterns of distance-cues which are evoking the changes in eye adjustments, and overrules the eye adjustments themselves as distance-cues. This strong distance-cue logically depends upon the occurrence of *linear size constancy*.

Linear size constancy.

At base, linear size constancy refers to the tendency for an object to look the same linear size from one moment to the next when other things change. It certainly dominates everyday viewing of objects; especially those we *know* don't change their size arbitrarily. That is, linear size constancy is an aspect of *identity constancy*, our tendency to assume that an object remains the same object from one moment to the next (Piaget, 1954).

Linear size constancy also refers to a perception that two viewed objects look the same linear size (or nearly so). For example, let this pair of letters, O o, again be a picture of two spheres: Another easy perception is to see two pictured spheres which are the

same linear size (say two baseballs): And in this case the one that looks angularly larger necessarily looks closer. That example illustrates the relative perceived visual angle distance-cue.

Relative perceived visual angle distance-cue.

As discussed earlier, the relative perceived visual angle distance-cue is the basic element in *linear perspective* and *texture gradients,* two powerful distance-cue patterns. For instance, as illustrated again by the picture of a cropped cornfield, both of those cue patterns offer objects of similar shapes arranged in a series in which the objects appear to subtend decreasing visual angles: therefore, if those objects appear to be about the same linear size (linear size constancy) they necessarily appear to recede from the viewer as their perceived visual angles decrease.

As Gibson (1979) emphasized, this perception of increasing distance with decreasing perceived visual angles has become a more-or-less automatic response in most adults. It is a response to the overall *pattern* of changing visual angles (the ecological display), which pattern is a texture gradient and a linear perspective pattern. In other words, the resulting perception of increasing distance with decreasing perceived visual angles for similar-shaped objects does not necessarily require adults to first consciously perceive equal linear sizes for those objects.

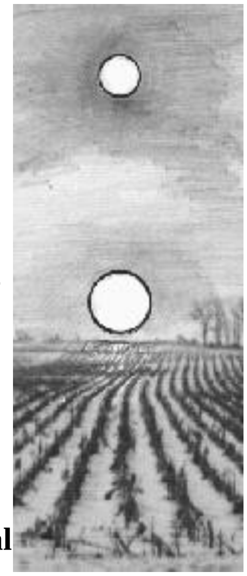
Getting back to the moon illusion, consider that in the typical vista for the horizon moon, the linear perspective and texture gradient patterns formed by the terrain are the distance-cues primarily responsible for making the eyes adjust for "very far." Therefore, the fact that most people say the horizon moon "looks larger and *closer*" than the zenith moon clearly means that the larger perceived visual angle for the horizon moon is a distance-cue strong enough to prevail over the other potential determiners of its perceived distance.

Ubiquitous 'Moon Illusion.'

The term 'moon illusion' has become a generic term. The same illusion occurs for the sun and for the constellations when they are seen in a horizon position compared with a zenith position.
And, again, the 'moon illusion' occurs for objects other than just celestial bodies. So, many researchers have measured the 'moon illusion' in experiments conducted indoors, as well as outdoors, using spheres (including golf balls) or other kinds of target objects presented in fabricated displays which offer distance-cue patterns that are changed in order to imitate the changes typically found between horizon moon viewing and zenith moon viewing. The "size" and distance perceptions obtained with

these surrogate moons have been essentially the same as those obtained for the real moon.

Evidence That The Moon Illusion Begins As A Visual Angle Illusion.



One obvious indication that the visual angle looks larger for the horizon moon than for the zenith moon is, again, that people initially expect a photo of the two moons would look something like the picture at the right.

Another indication is that some people initially believe the horizon moon is closer to the earth than is the zenith moon, which, if true, would make the visual angle larger for the horizon moon than for the zenith moon. Actually, during the same evening the visual angle for the horizon moon is about 2 percent *smaller* than that for the zenith moon, because the distance to the moon from one's observation point is greater for the horizon moon than for the zenith moon by almost the distance of the earth's radius.

Another indication is the very popular initial belief that some physical phenomenon (say atmospheric refraction) is optically magnifying the horizon moon (that is, increasing its visual angle). But, no such magnification occurs. Instead, refraction by the atmosphere temporarily*reduces* the visual angle of the vertical diameter of the just rising full horizon moon, which makes it look a bit "squashed down," like an oval. The setting sun likewise appears that oval shape.

Retinal Image Size Constant.
When people first realize the moon's visual angle remains constant, some may think the cause of the illusion lies in the optical system of the eye. After all, the illusion certainly is *as if* the horizon moon's retinal image were larger than the zenith moon's. So, some people initially suppose that there probably are changes in the lens or in the size of the pupil opening which make the retinal image larger for the horizon moon than for the zenith moon. However, experts on the eye's optics agree that, when the moon's retinal image is sharply focused, it is an illuminated disk about 0.15 mm in diameter, and, although changes typically do occur in the lens and in the pupil size during normal viewing of the rising moon, such changes either would not change the retinal image's size or would change it so little that such a change certainly could not be responsible for an illusion ratio as large as 1.5, or even 1.1. Besides, older adults with presbyopia (whose lens cannot change) experience the moon illusion in full.

A related analogy, of course, is that the illusions of oculomotor micropsia occur in full while the lens and the iris muscles are temporarily paralyzed (by eye drops) and in that condition the retinal image cannot change size (Heinemann, Tulving & Nachmias,

1959). Therefore, it seems certain that the moon illusion also would occur in full under that paralysis condition which deliberately keeps the retinal image size constant.

Additional evidence that the moon illusion begins as a relative visual angle illusion for most people derives from the methods used to measure it.

Perceived Visual Angle for the Moon.

As discussed in Section I, if one pointed one's nose from one edge of the moon to the opposite edge, the angle of the head rotation would be an appropriate measure of the perceived visual angle, *V' deg*: But it would be too small to measure reliably. Even smaller would be the angle of an eye rotation when one looked from edge to edge. So, no measures of the absolute perceived visual angle have been published for the moon.

Instead, researchers have measured only how the perceived visual angles compare for the horizon moon and the zenith moon. A popular method for making those relative measures is discussed next.

Surrogate Moon Method.

Nearly all measures of the moon illusion have been made using comparison methods that resemble the following example. These methods provide further evidence that the moon illusion is basically a visual angle illusion.

An observer views the full moon, just risen above the horizon, and also looks upward into the zenith sky at an optical image of an illuminated disk (a virtual image) seen there by means of a special optical apparatus. (See Kaufman & Rock, 1962a, 1962b.) That disk image serves as a surrogate zenith moon, and when it subtends 0.52 degrees, it typically looks smaller than the horizon moon: So, the disk's visual angle is increased until the observer says it looks the same as the horizon moon's. In general, among a large group of observers many different disk sizes would be chosen, and if the average of those choices happened to be a disk subtending 0.78 degree, it would illustrate a moon illusion with an average magnitude of 1.5.

Without doubt, when comparison methods like that are used, the "size" the observers are matching is the perceived visual angle. Recent measures obtained using a similar technique have been published by Reed & Krupinski (1992).

That concludes the presentation of the new theory except for an explanation of oculomotor micropsia. So, let's summarize what has been discussed so far.

Summary of the New Theory.

The 'moon illusion' in all its forms clearly illustrates the following:

When a pattern of distance-cues indicates a much greater distance for a viewed object than for nearby objects, one's eyes adjust to a far position when one views that far object, and, in turn, that makes its visual angle look slightly larger than its true value,

to illustrate oculomotor macropsia. That describes the condition typically found during viewing of the horizon moon. It also is the condition found for all the other objects on or near the horizon seen over an extended terrain pattern that offers abundant distance-cues to great depths

On the other hand, a relative absence of distance-cue patterns which would indicate great distances (depth) between the nearest and farthest viewed objects typically makes the eyes adjust to a relatively near, resting focus position; so a viewed object's visual angle looks slightly smaller than its actual value, to illustrate oculomotor micropsia. That situation exists for a relatively "empty" field of view and also in dim light. It typically occurs during viewing of the zenith moon.

Of course, the 'moon illusion' in all its forms clearly illustrates that the truly ubiquitous illusion is oculomotor micropsia. So, to claim that the moon illusion is merely an example of the less famous illusion of oculomotor micropsia only partly explains it. In order to complete the theory it is necessary to explain (in Section IV) why oculomotor micropsia occurs.

Section IV. Explaining Oculomotor Micropsia

Describing Oculomotor Micropsia Again

While one is looking at an object that subtends a constant visual angle, V deg, if one then accommodates and converges one's eyes to a distance much closer than the object's distance, the object's perceived visual angle, *V'* , decreases. As described earlier, this micropsia typically is accompanied by one of three outcomes: In a same distance and off-size outcome, the object's perceived linear size, *S'* decreases in proportion to the decrease in *V'*: In a same linear size and increased distance outcome, the perceived distance *D'* increases in inverse proportion to the decrease in *V'*. In anintermediate outcome, *D'* increases and *S'* decreases, as *V'* decreases.
In a less common, decreased distance, off-size outcome, the object looks closer than it did (in at least partial agreement with change in accommodation and convergence) so*S'* looks considerably smaller than it did (very much off-size).

All those outcomes have been found in micropsia experiments (Komoda & Ono, 1974; Ono, Muter, and Mitson, 1974).

A macropsia illusion ("looks angularly larger") is obtained by shifting accommodation and convergence to a distance beyond the viewed object.

Explanations for the illusion can be divided into the "old" and the "new," as follows.

Old Explanations

Some researchers long ago recognized that oculomotor micropsia is *as if* the viewed object's retinal image size, R mm, had decreased, so they sought reasons why that physical change might actually happen, even though optical calculations predicted that a change in accommodation or pupil size would not change R for a constant visual angle V deg. But, Heinemann, Tulving, & Nachmias (1959) showed that the illusion occurs in full with accommodation and the pupil paralyzed by atropine drops.
And, Smith, Meehan & Day, (1992) recently confirmed that, as predicted, R remains constant for a constant visual angle, V, when accommodation changes.
So there is no optical basis for that visual angle illusion.

Apparent Distance Theory Unsatisfactory

In 1960 the apparent distance theory was the most popular explanation.
It proposed that accommodation and convergence to a closer distance act as distance-cues that make the object look closer than it did, so it must look a smaller linear size (off-size) in order to keep the visual angle the same. But very few people say the object "looks smaller and *closer.* " This unresolved "size-distance paradox" led most researchers to reject the apparent-distance theory.

Three New Theories

Since 1965, three "new" theories have been proposed.
The first (McCready, 1965; Ono, 1970) was based upon an analysis in terms of

subjective experiences: The second, (McCready, 1983, 1985, 1994) is based upon an analysis in terms of the orienting reflex. It is the theory emphasized here. The third theory (Enright, 1989) is based upon an analysis in terms of a quite different reflex called the *vestibular oculomotor reflex.*

Observation 1.

The visual angle illusion of oculomotor micropsia is controlled by activity somewhere in the eye muscle systems responsible for routinely focusing and converging the eyes to the changing distances of objects.

Observation 2.

Abundant data from laboratory studies of oculomotor micropsia clearly indicate that the change in the perceived visual angle for an object away from the visual angle for it also occurs during normal everyday viewing whenever the eye adjustments change. The crucial question thus becomes, why would one's perception of directions, a vitally important visual function, become routinely distorted in this manner?

Observation 3.

All three theories propose that the continual adjustments and readjustments of visual angle perception during everyday viewing must be serving a useful purpose: They must be part of some kind of *normal* perceptual-motor adaptation. More specifically, it is proposed that these alterations of visually perceived directions serve the purpose of preventing or "correcting" errors in bodily responses that are guided by the directions in which objects appear.

Observation 4.

All three theories propose that the most likely reason why errors of that kind would occur is related to the fact that the eyes lie about 10 cm (four inches) in front of the center of the head. The three theories differ only in the choice of the visually guided response that would be affected by that displacement of 10 cm. In other words, each theory offers a different answer to the question, what bodily response, when guided by visually perceived directions, would become more accurate as a result of the direction illusions of oculomotor micropsia?
Consider how the first two theories answer that question.

First Theory: a Subjective Analysis.

The initial theory (McCready, 1965) was based upon an analysis of how one's visual perceptions of the angular size, distance and linear size for an object would relate to one's tangible (touch) perceptions (haptic perceptions) of the angular size, distance and linear size for the object when one looks at it while holding it. Without going into detail here, the analysis began with an assumption that the vertex of the perceived visual angle is the *visual egocenter* (or *center of visual directions)* a subjective locus which, according to some investigators, lies at about the center of one's body image of one's head, thus, in effect, about 10 cm behind the eyes.

Working from that assumption, it was shown that, if the perceived visual angle equaled the visual angle for an object being held as it approaches the eyes, the linear size and distance the object looked would begin to progressively disagree with how its linear size and distance felt. Then it was shown that this disagreement could be avoided if the perceived visual angle for the object (let's say one's own hand) equaled not the visual angle, but equaled, instead, the smaller angle the object subtended at about the center of the head. Accordingly, if that particular "correction" of visual angle perception occurred, and if it were appropriately linked to the distance to which the eyes are accommodated and converged, that would explain oculomotor micropsia.

A significant result of that analysis was a simple equation (see later) that specifies the amount by which the perceived visual angle should become less than the visual angle in order to bring about the appropriate correction for each viewing distance for an object. The equation furnishes numerical predictions that were shown to match, almost perfectly, the data of oculomotor micropsia published up until 1963. No other theory had come close to explaining the data that well.

Indeed, in 1970, Melvin Komoda and Hiroshi Ono ran experiments to test that theory and its equation. (Komoda & Ono, 1974; Ono, Muter, & Mitson, 1974). They concluded that it was the only available theory of oculomotor micropsia that could account for their numerical results and, as well, the published results of other investigators.

Second Theory: the Orienting Reflex Analysis.

Later, the theory was improved (McCready, 1983, 1985) by using a more behavioral analysis that restates the "correction" in terms of the head rotation component of theorienting reflex. Simply put, the theory proposes that the alterations of visual angle perception that show up as oculomotor micropsia improve the speed and accuracy with which one can turn one's head toward a nearby object that demands attention. This theory furnishes the same equation provided by the first theory.

The privately published article, "Toward the Distance Cue Theory of Visual Angle Illusions" (McCready, 1994a) elaborated the theory and showed how well the simple equation also fits micropsia data published after 1963. The following review begins by describing the orienting reflex.

Orienting reflex.

If an object suddenly captures or demands one's attention, one's head and eyes usually turn quickly, and more or less automatically, in the direction of that object. These involuntary movements are part of the well-known orienting reflex.

For instance, when one is looking at a given object, and a "new" object suddenly appears at a different place in the field of view, one's head usually will turn toward the "new" object: A successful rotation of the head aims the face directly toward the attention-grabbing object. This outcome thus places both ears and both eyes squarely into their "straight ahead" position, a position that can improve one's ability to assess,

binocularly and binaurally, any threat the "new" object might introduce. The angle the head will rotate through is gauged by the difference one sees between the old object's direction and the direction of the new object. In other words, the visual perception that predicts the angle of the initial head rotation from one seen object to the other is the perceived angular separation between them.

If the head's initial ballistic turn toward the "new" object misses the mark, a corrective rotation occurs, but only after a brief delay. In order to enhance one's safety, it thus would seem quite important to correctly see the angular separation (the visual angle) between the objects, so that the perceived visual angle can predict and gauge an accurate initial turn of the head. Therefore, a visual angle illusion, such as oculomotor micropsia, would seem to be maladaptive. However, as explained below, it isn't that simple: The illusions of oculomotor micropsia actually can be quite adaptive for objects near the face. To illustrate that idea, let's consider how head rotation angles relate to visual angles.

Angles.

Horizontal (side to side) rotations of the head take place around a vertical axis, here called the Y-axis. It is located behind the eyes by a distance that averages about 10 cm in adults. That displacement of 10 cm would be expected to create some errors in visually initiated orientations of the head, as illustrated by the following example.

An Example.

Suppose, first of all, that two viewed objects are at a very great distance and separated, left to right, by a visual angle of 18 degrees. Because they are very far away, the angle they subtend at the head's Y-axis also essentially equals 18 degrees. So, the angle of an accurate rotation of the head, to aim the face from one object to the other, would equal the visual angle. Thus, it would be most appropriate to have the perceived visual angle equal the visual angle, which for this example is 18 degrees.

For two nearby viewed objects, however, it is quite a different story.

For instance, to pick an extreme example, suppose two objects are only 10 cm (4 inches) from the eye, and separated, left to right, by a visual angle of 18 degrees: They thus are about 20 cm from the head's Y-axis, so the angle they subtend there is only 9 degrees. Accordingly, the angle of an appropriate head orienting response aimed from one to the other would be *half* the value of the visual angle. In this example, if the initial turn of the head from one object to the other equaled the visual angle of 18 degrees, the head would dramatically overshoot its mark. Therefore, that initial turn would be more accurate if the angular separation of the two nearby objects *looked* half of the visual angle they subtend. Of course, having the perceived visual angle equal to half of the visual angle is a very dramatic illusion, but in this case it would serve a useful purpose for objects sitting 10 cm from the eyes.

The correction also would improve non-emergency, "voluntary" rotations of the head intended merely to aim one's eyes and ears and critical attention from one viewed object to another.

What the theory proposes, of course, is that this useful modification of visual direction perception occurs as a normal perceptual adaptation during everyday viewing. And, in order to be appropriate, the magnitude of the corrective change in the perceived visual angle away from the visual angle value must somehow be linked to the distance of the objects from the eyes. As discussed next, that necessary connection undoubtedly is mediated by eye muscle factors.

Micropsia Controlled By Eye Muscle Factors..

The corrective changes in perceived visual angles are linked to the viewing distance primarily by means of the activity in the neurological system that controls the muscles responsible for changing accommodation and convergence. That is, the distance to which the eyes have just been adjusted, or are about to be adjusted, determines the magnitude of the correction of a perceived visual angle value.

Efference Readiness.

Without going into detail here, it turns out that the key factor is not an overt adjustment of the eyes, but the covert brain activity that is the precursor to such muscle activity. Such physiological activity aimed at moving the eye(s) has been called "motor efference readiness." Loosely speaking, one's mere "intention" to move one's eye alters one's perception of the *direction* of a viewed object. This concept has a long history in visual science [See the review and experiments by Festinger, Burnham, Ono, & Bamber (1967)].

For micropsia, the present proposal is that the intention (readiness) to converge and focus the eyes to some given distance is what "signals" or "controls" the change in the perceived visual angle appropriate for objects at that distance, whether or not that efference readiness leads to actual motor efference activity that changes the eyes' adjustments, see Enright (1989).
Foley (1980) refers to this particular factor as the *egocentric distance signal*.

An Equation for Oculomotor Micropsia.

The orienting reflex theory leads to the following general equation, which specifies by how much the perceived visual angle, *V'*, should change away from the target extent's visual angle, V, in order to yield the appropriate 'correction' for a given target distance.

$$V' / V = D_c / (D_c + T)$$

D_c is the *convergence distance*. It theoretically would equal the distance being signaled by the efference readiness for the viewed target, which currently can't be measured. So, D_c nominally can be, instead, the distance to which the eyes are accommodated and converged. And, lacking that measure, one has to let D_c equal the target extent's

distance, D, from the eye pupil, and *assume* that the eyes were appropriately adjusted (which can be a mistake).

T **is the *turn correction factor* . It nominally equals the distance from the center of the eye pupil back to the Y-axis for rotations of the head, about 10 cm in adults. However, for body rotations, bending over, and other such large orienting movements, *T* could be much greater than 10 cm.**

Again, predictions made by that equation fit the early published data on micropsia almost perfectly (McCready, 1965) and also fit the data published after 1963 quite well (McCready, 1994a). As may be expected, however, the results for a few observers in some viewing conditions in some studies are not fit well by the equation. But, as yet, no other theory can explain the micropsia data that well.

Moreover, the equation *perfectly* fits published data for some other visual angle illusions that previous theories could not fully explain, but which now can be explained as examples of oculomotor micropsia (McCready, 1994b) especially the classic illusion of curvature of the *apparent fronto-parallel plane* (McCready, 1995).

[How well the equation, and the concept of efference readiness fit many classic flat-pattern illusions and the data of Murray, et al. is shown in Appendix B.]

Micropsia for objects.

The proposed correction alters, of course, the perceived visual angle (*V'*) for a viewed object's frontal width (or height or diameter). As a rule, the closer a viewed object is to the face, the more *V'* becomes less than V deg, if the eyes properly focus and converge upon the object as it moves closer.

What may seem confusing here is the fact that, as an object of fixed linear size approaches the eye, the V for it increases, so *V'* also increases. The effect of the micropsia correction is merely that the increase in *V'* does not quite keep up with the increase in V deg. Again, even for an object very close to the eyes, *V'* rarely becomes less than half of V deg.
It is important to point out that the correction *never* keeps the perceived visual angle "constant" when V deg (hence the retinal image size, R mm) changes, as is unwittingly suggested by the popular (and illogical) definitions of "size constancy."

As discussed next, some obvious revisions of the theory are needed in order to describe macropsia illusions.

Macropsia.

As it stands, the orienting reflex theory describes only micropsia: It does not describemacropsia, with *V'* deg greater than V deg. Yet, as indicated earlier, macropsia seems to be a common outcome for objects at great distances in complex

landscapes or other scenes rich in distance-cues that indicate great depth between the nearest and farthest objects (see Higashiyama, 1992; Higashiyama & Shimono, 1994).

Indeed, macropsia for distant objects was revealed by the moon illusion researches of Roscoe and his colleagues (Roscoe, 1985, 1989) and also by Enright (1975, 1989a). A significant finding has been that the perceived visual angle usually equals the visual angle not when the eyes are adjusted to a great distance, but when they are adjusted, instead, to their resting focus (dark focus) position, let's say at a distance of about 1 meter.

For instance, recall that inverted viewing of objects seen near the horizon, including the moon, causes their visual angles to appear to shrink: That viewing condition reduces the efficacy of distance-cues to a great depth, so, like the viewing condition for the zenith moon, it apparently makes the eyes adjust to a resting focus position. What the data indicate is that, for this resting focus condition, the "smaller" perceived visual angles for objects actually may equal their visual angles. If so, then "true" micropsia (the perceived visual angle less than the visual angle) would occur when the eyes are adjusted to a distance closer than, say, 1 meter.

Micropsia versus Macropsia.

It therefore seems that, during everyday viewing when the eyes accommodate and converge upon objects at various distances, there is a general macropsia illusion when one views objects farther away than a meter, and a general micropsia illusion when one views objects less than a meter away.
In terms of the proposed orienting reflex "correction," it thus seems that *V '* deg is kept "correct" for objects just beyond reach, while micropsia corrects for closer objects that might pose a threat, and the macropsia found for distant objects, although it is an illusion, does not create a safety problem because distant objects don't pose a threat as immediate as those within one meter of the face.

One line of speculation, however, has been that the macropsia illusion for objects seen near a distant horizon might be adaptive if it were equivalent to having a "built-in" telescope that slightly magnifies distant terrestrial objects (Higashiyama, 1992). Indeed, there is evidence that visual acuity is slightly better for distant targets than for near ones, and also slightly better for a target when it is undergoing oculomotor macropsia (McCready, 1963). Those two phenomena might be related to each other, but that is not certain.

The simple equation obviously must be rewritten in order to describe both micropsia and macropsia. In its present form it does not predict a visual angle illusion as large as the moon illusion. However, that problem with the simple equation does not mean that the moon illusion is not an example of oculomotor micropsia/macropsia.

Half-Angle of the Sky Illusion.

Macropsia for distant horizon objects also seems to be revealed by the illusion known as the half-angle of the sky. For instance, while observers are viewing an "empty" sky

and asked to indicate the point which looks halfway between the horizon and the zenith pole (at 90 deg elevation) they typically indicate a place only about 30 deg above the horizon. In other words, the direction difference (visual angle) from the horizon up to 30 degrees appears to be about 45 degrees, for a macropsia illusion of magnitude about 1.5. An explanation for that absolute visual angle illusion could go a long way toward explaining why the horizon moon's small visual angle would look 1.5 times larger than 0.52 deg. The present 'new' theory for oculomotor micropsia can explain a macropsia magnitude as large as 1.5 for a small visual angle, but it cannot easily account for an absolute visual angle illusion as large as 1.5 for a target subtending 30 degrees.

This brief review now must mention some other puzzling "size" and distance illusions that also can be explained as examples of oculomotor micropsia.

Oculomotor Micropsia for Flat Patterns.

During everyday viewing, the shifts of accommodation and convergence among viewed objects invariably are a response to the distance-cues in the viewing situation that specify the distances of the objects from the eyes. The role of changes in distance-cues in the moon illusion, in all its forms, was discussed earlier.

An additional fact is that distance-cue patterns in flat pictures also can evoke slight changes in accommodation and convergence, which, of course, create micropsia.

To understand how flat patterns induce oculomotor micropsia, consider what happens when one views pictures like the one below (discussed earlier). The texture gradient and linear perspective distance-cues create the pictorial illusion of a winter cornfield extending toward a very distant horizon.

Visual Angle Illusion

Consider first just the middle and lower circles. As previously noted, observers can say both circles correctly appear on the same page, so they have the same perceived distance, and the middle circle looks slightly larger than the lower circle, let's say 10% larger, to reveal the underlying visual angle illusion that has been of greatest interest.

Again, the apparent distance theory cannot explain that small visual angle illusion for the two equal circles on the page.

How the angular size contrast theory may explain it was discussed in the earlier analysis of the 'paradoxical' Ponzo illusion.

How the oculomotor micropsia/macropsia theory can explain it is discussed below.

Perspective Vergence

Many researchers have clearly shown that this kind of "size" illusion in flat pictures is controlled by changes in the monocular distance-cue patterns: Indeed, the more effective the distance-cue patterns are in creating a great pictorial depth illusion, the greater is the "size" illusion (Kilbride & Leibowitz, 1972; Rock, Shallo, & Schwartz, 1978).

Moreover, researchers found, long ago, that when one views the image of a 'far' object in a flat picture, the eyes tend to converge and focus to a farther distance than they do when one views the image on the page of a 'nearby' object. This common effect is called *perspective vergence* (for recent reviews see Enright, 1987a, 1987b, 1989).

Of course, for a flat picture held perpendicular to the line of sight, the viewing distance is essentially the same for all the images, therefore those changes in eye adjustments caused by changes in distance-cues are optically inappropriate: However, they usually are small enough to prevent double vision and noticeable blurring. Nevertheless, they are large enough to induce a slight degree of oculomotor micropsia: Therefore, in response to the change in distance-cues in the flat pattern above, when the lower "near" circle and "far" middle circle are viewed successively, the eye adjustments change, and the perceived visual angle becomes slightly larger for the middle one than for the lower one. (Why it also occurs for simultaneous viewing is presently discussed.)

'Moon Illusion' In Pictures

Enright (1987a, 1987b, 1989) measured the small visual angle illusion obtained using pictures similar to the picture above (without the lowest circle). The "horizon" circle typically looks slightly larger than the equal "zenith circle" because the eyes adjust for a farther distance for the horizon one than for the zenith one.
That result thus imitates the moon illusion in a small way. (Also, the crude picture used here may not yield as large an illusion as those used in research studies.)
Similar measures of that "moon illusion in pictures" were made by Coren & Ax (1990) but they did not distinguish between the linear size illusion (which they measured) and the underlying visual angle illusion.

In general, the oculomotor micropsia explanation outlined above applies to *all* the flat pattern illusions to which researchers previously have applied the apparent-distance theory without success. Well-known examples discussed earlier are the Ponzo illusion and Ebbinghaus Illusion (McCready, 1983, 1985). It seems clear that the very famous Mueller-Lyer illusion also can be explained that way.

In short, many of the classic flat-pattern illusions that have defied explanation now can be explained as visual angle illusions that illustrate oculomotor micropsia induced by changes in monocular distance-cues in the flat pattern.

These illusions for flat patterns are more complicated than that, however, because the relative visual angle illusion also may exist even when the eyes are fixed upon one place in the pattern and not shifting their focus or convergence. In order to explain how

changes in distance-cues induce these *simultaneous* relative visual angle illusions, the theory of oculomotor micropsia must be taken a step beyond what has been described so far, as follows.

Conditioned Micropsia.

Changes in distance-cue patterns evidently have acquired the power to induce a visual angle illusion more or less directly, without first causing a change in the eye muscle adjustments as an intermediate event. It is *as if* the changes in distance-cues anticipate the adaptive corrections of oculomotor micropsia.
After all, oculomotor micropsia constantly occurs during everyday viewing, and the changes in oculomotor adjustments that induce these changes in perceived visual angles away from the visual angle values typically are caused by changes in distance-cues. So, it seems reasonable to suggest that, due to this constant association, those changes in perceived visual angles have become conditioned to the distance-cue changes. Consequently, when similar changes in distance-cues occur, even in flat patterns, they can evoke illusory changes in perceived visual angles directly (McCready, 1985, 1986, 1994a).

As discussed in Appendix B, the present idea is that cues to distance establish the efference readiness, expressed by Dc in the equation, which controls the micropsia (McCready, 1994a). This proposal is discussed more fully in Appendix B.

For that reason it also is possible for the moon illusion to occur as a direct response to distance-cue patterns without necessarily involving overt eye muscle changes.

Before closing, it is necessary to mention the third "new" theory of oculomotor micropsia.

Theory 3: Enright's VOR Theory.

Enright (1989) also considers oculomotor micropsia to be a normal perceptual adaptation that "corrects" for problems that would arise because head rotation centers lie about 10 cm posterior to the eyes. But he has proposed a different explanation for it. His theory appeals not to the orienting reflex, but to a quite different 'normal' physiological reflex known as the *vestibular oculomotor reflex*, or VOR.
My review of that VOR theory (in McCready, 1994a) indicates that it might provide an equation identical to the one provided by the orienting reflex analysis. However, I'm not certain about that, because it is not yet clear how the VOR reflex would apply to perceived visual angles. The needed clarification undoubtedly will be offered by Enright.

Conclusion.

Oculomotor micropsia is a ubiquitous illusion.
It provides an explanation for the moon illusion in all its forms.
It also can explain many other "size" and distance illusions to which researchers have

applied the apparent-distance theory, without success. In short, the new theory wholly replaces the apparent-distance theory of illusions.

How oculomotor micropsia can explain many of the best known flat pattern "size" illusions is shown in Appendix B.

The new theory is supplemented by the "size"-contrast theory that obviously is an angular size-contrast theory. However, for the moon illusion, this angular size-contrast seems to add very little to the overall illusion.

A promising explanation for oculomotor micropsia is the present theory based upon the orienting reflex. As shown elsewhere (McCready, 1965, 1994a, 1995) it offers numerical predictions that match published measurements of micropsia amazingly well.

The key to understanding the new theory is to understand the distinction between visual angle perception and linear size perception, and to accept the idea that both "sizes" are perceived at the same time. That idea is unconventional, so it is reviewed in more detail in Appendix A.

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1945 U.S. Army, field artillery specialist training, instrument & survey.
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Research and Teaching

1949-52 University of Michigan, Vision Research Lab, Research Assistant.
1952 Bausch & Lomb Optical Co., Rochester, NY. Scientific Bureau, Engineer.
1953-54 University of Michigan, Vision Research Lab, Research Assistant.
1954-58 Argus Camera Co., Mathematical Design Group, Engineer.
Lens design, image evaluation.
1958-63 University of Michigan, Department of Ophthalmology, Vision Research Lab,
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1962 taught grad courses in visual psychophysiology.
1962-63, joint appointment, Department of Psychology, Lecturer,

1963-65 University of Chicago, Ophthalmology, Eye Research Labs,
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Appendix A (Revised November 09, 2004)

The (New) Theory of Size, Distance and Visual Angle Perception.

The new theory of visual perception of linear size, distance, and the visual angle (McCready, 1965, 1983, 1985, 1986) still is controversial because it conflicts with well-entrenched basic assumptions of conventional theories of "size" and distance perception. For instance, the theory that dominates the literature (the SDIH) does not include the idea that we perceive the visual angle. A few writers even state that the visual angle is not perceived.
In order to counteract those traditional assumptions, details of the new theory are presented here.

New Logical Rule.

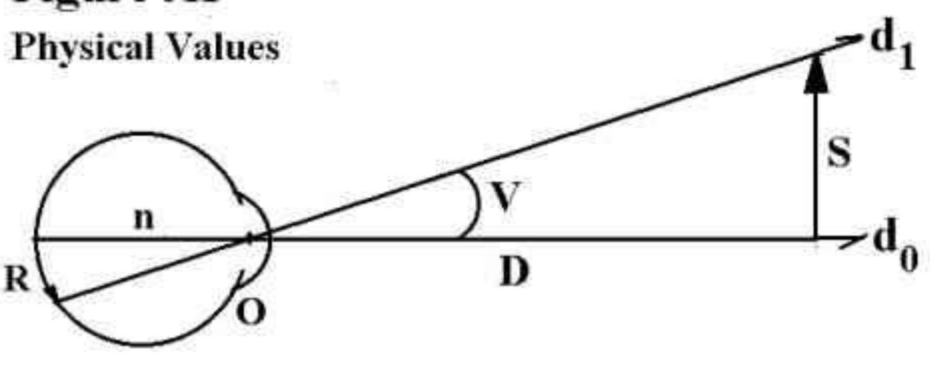
Consider the relationships of the objective (physical) values for a viewed frontal extent (Figure A1) and the subjective (perceived) values for it (Figure A2).

Physical Values: Figure A1

An observer whose eye is at point O is looking at the base of a frontal extent (the vertical arrow, the "distal stimulus". It has a frontal linear size, S meters and is D meters from point O, the center of the eye's entrance pupil.
The direction of the extent's base from point O is, d_0 , let's say "straight ahead" or "eye level to the horizon". The direction of the extent's upper end from point O is, d_1 , toward some specific elevation.
Each of those direction lines in Figure A1 also indicates (in reverse) the path of a ray of light from an object's endpoint to and through eye point O. Each such ray is known as the *chief ray* in the center of the large bundle of the light rays from the object point which pass through the cornea, pupil and lens to focus as the optical image of the extent's endpoint on the retina.
The angular difference between the two chief rays indicated in Figure A1 is the visual angle, V degrees. Thus, the visual angle, V degrees, also is the difference ($d_1 - d_0$) between the directions of the extent's endpoints from point O.

Figure A1

Physical Values



Equation A1 states the relationship between those external (distal stimulus) measures.

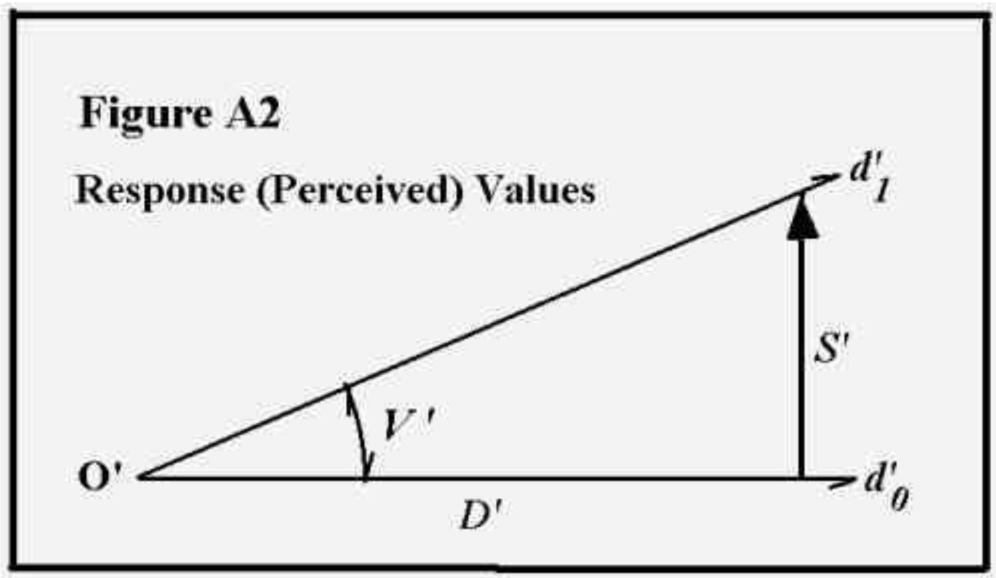
tanV = S/D (Equation A1)

An inverted real image of the object is formed on the retina. This retinal image (proximal stimulus) has a linear size, R millimeters given by the equation, R/n = tanV , in which n is the *nodal distance*, approximately 17 mm.
Consider next the response measures commonly referred to as the "perceived values."

Perceived Values: Figure A2

The subjective perceived frontal extent has a perceived linear size, *S'* meters.
Its perceived distance, is *D'* meters.
Point O' is an objectively measured point that researchers refer to as the effective locus of the subjective cyclopean eye: For present purposes, point O' may be considered to coincide with point O in Figure A1.

The two perceived directions from point O' are, d_0' and d_1'.
For instance, the object's base appears, let's say, "straight ahead" or "toward the horizon", and the tip appears toward "a higher elevation."
Those perceived directions differ by the perceived visual angle, *V'*, degrees.



According to the new theory, the three perceived values relate to each other as stated by Equation A2.

$S'/D' = \tan V'$ **(Equation A2, the perceptual invariance hypothesis)**

Ross & Plug (2002) recently dubbed that equation (McCready, 1965, 1985) the *Perceptual Invariance Hypothesis*.

An additional equation is needed to relate the perceived angular size, *V'* deg, to the physical angle, V deg, and that relationship must involve the retinal image size, R mm.

Retinal Size and Perceived Angular Size

All modern researchers agree that we do not perceive or "sense" the retinal image (a proximal stimulus) or its properties, as such: Instead, perception is "distally focused." That is, we have (we create) visual images only of external objects and their properties. There certainly is no "sensation" which could be called the "perceived retinal image size", *R'* mm.

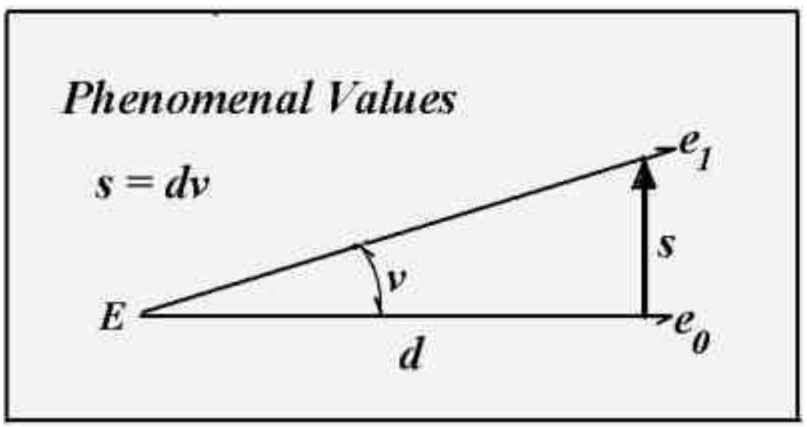
One reason why some researchers did not use the concept of the perceived visual angle, *V'*deg is because they felt that to use *V'* deg was tantamount to accepting the ancient, obsolete idea that a person somehow "senses" the retinal image's size.

However, in terms of the present theory, *V'* deg does not concern a linear size value in meters, it concerns, instead, one's perception of directions. For instance, many theorists, notably Helmholtz (1962/1910) and Hering (1942/1879) have argued, convincingly, that the*visual direction* of a viewed point (its subjective egocentric direction) is determined by a combination of factors, with its final value due to a process that necessarily combines the position of the point's image on the retina with information about the position of the eye with respect to the head (and body). And, the final perceived direction, *d*, for an object predicts the direction the eye should turn to in order to focus directly upon it:

Also, *d* predicts the direction the head or body should be aimed in order to let the person examine the object more closely or to reach toward it.

For two points which have different egocentric directions, the person obviously is seeing the*difference* between those visual directions, and the magnitude by which they differ correlates primarily with the distance, R mm, between the points' retinal images. That perceived difference between two subjective directions defines the perceived visual angle, *V'* deg, for their separation. Therefore, *V'* deg essentially is the perceptual (subjective) correlate of the "size" of the retinal separation, R mm, between the optical images of the points.

Technical Note: *The Subjective (Mental) Dimensions:*
Initial presentations of the 'new' theory (McCready, 1965, 1983, 1985) carefully differentiated between the private, subjective (mental) dimensions and the public, objective response measures of those mental entities. That is, the values, *V'* deg, *S'* meters and *D'*meters which a researcher obtains and writes down as the "perceived" values are physical behavioral response measures of the observer's subjective entities, *v* , *s*, and *d*. The present*theory* is that those (private) mental dimensions relate as illustrated below.



Point *E* represents the *visual egocenter*, the place in one's (subjective) body image of one's head from which one feels one is viewing the world. *E* also could represent the (subjective)*cyclopean eye*.
The subjective directions from *E*to the phenomenal object's endpoints are the *visual egocentric directions*, e_0 and e_1
The phenomenal visual angle, *v*, is the difference ($e_1 - e_0$) between the directions.
Those phenomenal directions may or may not agree with the actual directions from the face, thus *v* may or may not agree with the actual visual angle.
The *phenomenal linear size*, is *s*.
The *phenomenal distance*, is *d*.
(Please overlook this very temporary re-use of the small case symbol, d.)
The proposed rule is that, $s/d = v$.
From that *theory* is derived the testable *perceptual invariance hypothesis*, $S' / D' = \tan V'$, which proposes how the response measures of the subjective values would be expected to relate.

However, the custom in the literature has been to let the term "perceived value" (also "apparent value") stand for *both* the subjective value and an objective response measure of it.

Accordingly, I have been following that traditional practice in this article.
(End of Technical Note.)

New Psychophysical Relationship

Next we need to express the *psychophysical* relationship between the perceived value *V'* deg and the physical value , V deg, as mediated by R mm. Any such rule must express the flexible relationship between *V'* deg and V deg which shows up in visual angle illusions. For the moment, it is sufficient to say first that, in general, *V'* deg is a function (*F*) of R mm and *'other factors'*. So, we can write,

$V' = F$ (R, and *'other factors'*)

And, because R mm is directly valuated by V deg (in accord with, R/n = tanV), we can express the relationship between *V'* and V as,

$V' = F$ (V, and *'other factors'*)

Consequently, to arrive at a complete explanation of visual angle illusions, including the moon illusion, researchers will have to fully identify and quantify those 'other factors' and write psychophysical equations much more detailed than those above. Indeed, quite a few equations have been published which use very complex mathematics (see recent textbooks on cognitive psychology, and, for instance, Indow, 1991).

Brain Models: **Moreover, recent texts often offer complex models of (hypothetical) brain activities: Each model describes neurophysiological mechanisms invented to explain *why* the particular psychophysical equation the author is using fits published data. But, a problem with some of those complex models (e.g., Trehub, 1991) is that the equations they are trying to explain are based upon a logic (usually the SDIH) which does not differentiate between perceived visual angle, *V'* deg and perceived linear size, *S'* meters: Such models confuse those two qualitatively different concepts, and thus are very confusing.**

Those '*Other Factors*'.

As already noted, one set of 'other factors' that can change *V'* away from V deg, includes changes in the state of the oculomotor system. For instance, oculomotor micropsia illustrates that *V'* will become slightly less than V deg, when the oculomotor system adjusts to a closer distance. Some theories of that adjustment refer to hypothetical brain mechanisms (Enright, 1989).
A second set of 'other factors' includes changes in distance cues (which may or may not alter the oculomotor state). For instance, as the moon illusion illustrates, with V deg constant for a viewed object, there usually will be a slight increase in *V'* when major distance cue patterns signal an increase in the object's distance.

Visual Angle Contrast Theories as Evidence.

A third well-known set of '*other factors*' includes changes in the size of the visual angles subtended by extents which appear close to the target object (simultaneous contrast), or

changes in extents that are intently stared at before the target is viewed (successive contrast).
For instance, as previously discussed, the "size contrast" theory of the moon illusion (Baird, Wagner & Fuld, 1990; Restle, 1970) clearly addresses it as a visual angle-contrast illusion

Other theories of "size"-contrast illusions appeal to hypothetical interactions among nerve cells in the visual system beyond the retina, which supposed activities relate directly to the size of the retinal image, R mm: So, those activities are considered to be the biological precursors to *V′* deg (Oyama, 1977).
Yet other theories refer, instead, to changes among "spatial frequency detectors," and some others refer to an *adaptation* of "size channels" (best called, "angular size channels"). Both of those terms refer to hypothetical nerve cell structures in the brain whose activities are directly related to R mm. Therefore, they logically relate to the perceptual angular size dimension, *V′* degrees, rather than to the perceptual linear size dimension, *S′* meters.
The writers of those theories obviously accept that the perceptual correlate of R mm is not *S′*meters, but *V′* degrees.

Additional evidence that the visual angle is perceived can be found in discussions of visual acuity.

Visual Acuity.

One's basic skill of perceiving the different directions of two viewed points from oneself is presumed in all discussions of visual acuity: It refers to the accuracy with which one can distinguish the direction of one viewed point from the direction of another.
For, example, minimum separable visual acuity can be measured using a series of two small black bars printed on a bright white paper, like those below.

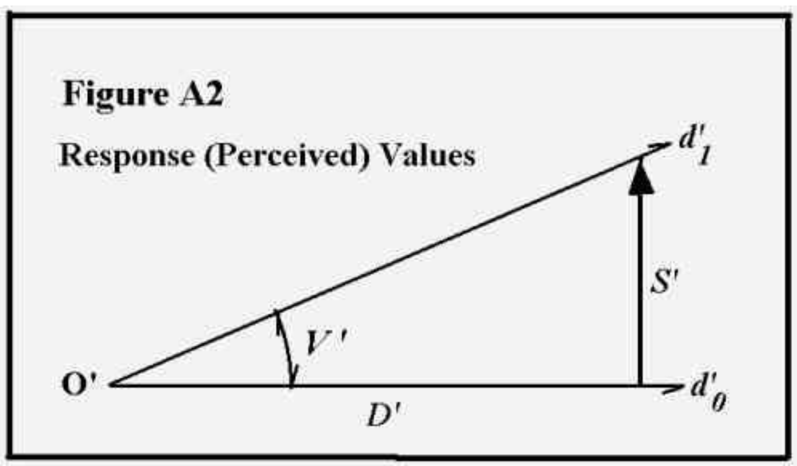
Typically, a person views such patterns from a distance of 20 feet, and notices which patterns have bars so small that they don't look like two bars, but like just dark blobs. The ability called "20/20 vision" means that the person is able to see two bars separated by a visual angle of one minute of arc, but cannot see as two bars the pairs separated by less than 1 minute.

Perception textbooks invariably describe visual acuity in their discussions of the optics of the eye, so those discussions obviously reveal that people perceive the visual angle. Yet, in later chapters the discussions of "size" perception and "size" illusions, rarely discuss direction perception and our perception of the difference between two directions (the visual angle and angular size perception) even though the most puzzling "size" illusions begin as visual angle illusions.

How the new theory describes valuations of the perceived values has been published in detail elsewhere (McCready, 1965 and 1985, especially pp. 333-334). This *visual processing* model is reviewed below.

Visual Processing: A Modified, Unconscious Inference Model.

To describe how the perceived metric values (*S'* and *D'*) are valuated it is convenient to use a modified version of the *unconscious inference* model attributed to Helmholtz (1962/1910) and used by most theorists who have used the standard approach, especially Rock (1977, 1983). The present model differs from the standard model by including both the perceived visual angle, *V'* deg and the perceived linear size, *S'* meters.



The model uses Figure A2 and Equation A3 (below), which is a simpler version of Equation A2 obtained by using the small angle rule that, tan*V'* = *V'* radians.

S'/D' = *V'* rad (Eqn. A3)

The model proposes that, for a viewed object, an initial activity (a *pre-processing* event) provides a specific perceived visual angle value, *V'* rad, as determined by the retinal image size, R mm, and 'other factors'. The values of *S'* meters and *D'* meters are obtained in a manner that is *as if* two "processing steps" had occurred almost simultaneously to furnish values which will agree with Equation A3 for the given value of *V'*.

Those processing activities occur outside conscious awareness. Modern theorists accept that such valuations are the result of visual system activities which furnish the physiological precursors (brain correlates) of the final subjective conscious qualities for the perceived object. So, as noted earlier, many different models of brain events have been published. None has been accepted yet.

Describing The Visual Processing of *S'* and *D'*

In processing Step 1, either *S'* meters or *D'* meters becomes *scaled* (valuated) directly.

In Step 2, the other metric value becomes valuated indirectly, as if it had been *computed* to conform with the rule, *S'/D'* = *V'*, for the value of *V'*, (as given by *V'* = *F*(R and 'other factors').

The term "unconscious inference" refers to Step 2. Step 2 also has been called a "taking-into-account" process (Epstein, 1973).

The initial scaling of *S'* or *D'* can occur by *cuing* or by *hypothesizing*.

Scaling of *D'*

D' m may be scaled by *absolute cues to distance*.

For instance, if we are touching an object, we feel how far it is from our face, and this

perceived "haptic distance," can directly scale the visual *D′* for it.
And, as discussed earlier, the physiological brain activity pattern which correlates with the "effort" we are about to expend to focus and converge (binocularly) upon a target may directly valuate *D′*. For instance, Foley, (1980) called it the *egocentric distance signal*.

Or, *D′* can be hypothesized, a form of visual imagery in which the target appears at an assumed, presumed or suggested distance (Gibson, 1950).

Once *D′* is scaled, *S′* becomes 'computed' (as Step 2) so the results agree with the rule, $S' = V'D'$ meters.

Scaling of *S′*

The perceived linear size, *S′* , may be scaled by *cues to linear size*.
For instance, if we are holding an object, we feel a "haptic size" for it (in inches) which can directly scale the visual *S′* for it.
Also, S’ m for an object can be scaled directly by a cognitive linear size for it which illustrates the "familiar size" (or "known size") cue to linear size (Bolles & Bailey, 1956; Ono, 1969).

After all, our current visual percept of an object predicts what we would find upon closer inspection of it, and that prediction is based upon what we already have learned about such an object when we previously perceived it in sufficient detail to allow us to have learned most of its properties.
Those properties include such things as how large it feels (its haptic linear size), its volume, its weight, its hardness, its colors, its temperature, its smell, its taste, the sounds it emits when tapped, etc., etc. All those perceptual properties collectively make up the object’s cognitive *identity*. And, most objects have a name which by itself can call up the appropriate perceived linear size, *S′* for the object.

S′ also can be scaled by hypothesizing, in which the target appears an assumed, presumed or suggested linear size (Coltheart, 1970; Hastorf, 1950).

Once *S′* is scaled, *D′* becomes 'computed' (as Step 2) in accord with, $D' = S' / V'$ meters.

Balancings

Although *D′* or *S′* could be scaled to be almost any reasonable value, the computing step (or its logical equivalent) prevents any conflicting independent scalings of *D′* and *S′* from producing a *ratio*, S' / D' , that would be inconsistent with *V′* rad.
As discussed earlier, there may be conflicting distance cues for an object, and the final *D′*value for it may be a compromise among several potential values.

For this review I won't focus upon the differences between Steps 1 and 2, except to show that some of the traditional 'cues to distance' actually involve not cuing of *D′* , but a 'computation' of *D′* after *S′* has been scaled.

Two Targets

Consider next the processing steps when two (or more) targets are compared. Several likely types of outcomes were described earlier for the moon illusion. Two are reviewed below using a front view picture of two men.

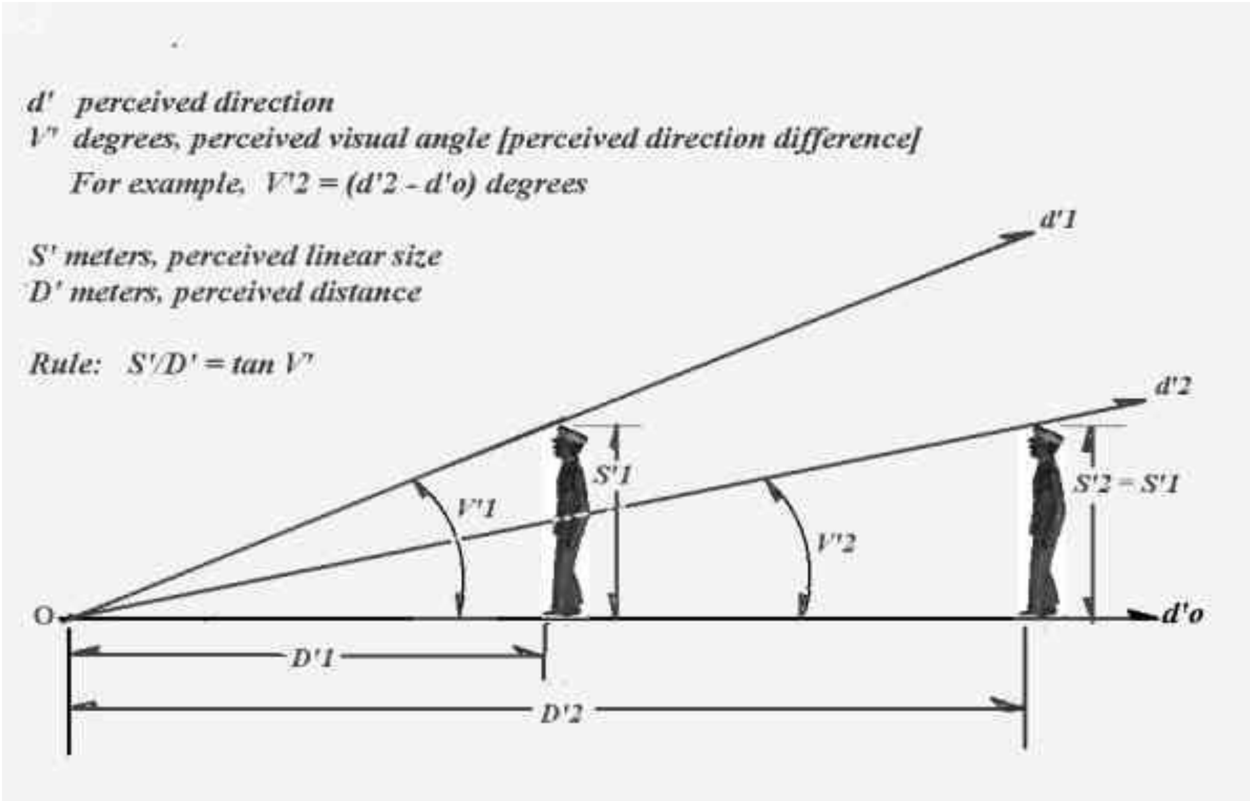
An Equidistance outcome.

The picture easily leads to a percept of two men at the same perceived distance.
As Step 1, this *equal distance scaling* could result from a (cognitive) "equidistance assumption" (McCready, 1965, 1985) or an "equidistance tendency" (Gogel, 1965).
(Also, there might be pictorial details which act as cues to signal an equal perceived distance scaling.)

If so, in Step 2, the perceived linear height (S' m) of the man on the left becomes twice that of the man on the right because his perceived angular subtense (V' deg.) is twice as large.

An Equal Linear Size Outcome.

Now consider an example in which the two men in the picture were the same height and the one on the right was twice as far from the eye as the other. A side view of that arrangement appears below.
The front view (above) as seen by the person whose eye is at point O, is repeated below.



For the man on the left (in both pictures) the perceived values relate as stated by the equation, $S_1' / D_1' = \tan V_1'$
For the man on the right, the perceived values relate as stated by the equation, $S_2' / D_2' = \tan V_2'$

Now let scaling (Step 1) make the men's linear sizes look equal.
That could happen if the observer *knows* their heights, so the *S'* values could be scaled equal by the (cognitive) familiar size cue to linear size.
Or, if the men are unfamiliar, that scaling could occur due to an "equal linear size assumption " (McCready, 1965, 1985). Indeed, looking at that front view you can see both men as being the same height (and at different distances).

Thus. given $S_2' = S_1'$, Step 2 computing makes the ratio of the perceived distances equal to the inverse ratio of the perceived visual angles, as stated by $D_2' / D_1' = V_1' / V_2'$.
As illustrated in the side view, the man on the left thereby looks half as far away as the other one.
That particular computation illustrates, of course, the *relative angular size "cue" to distance*.

***Identity Constancy*: The above diagrams and equations also can describe the simpler case in which a single viewed object is compared at time 1 and time 2, after the object's distance and visual angle have changed. Equal linear size scaling for many objects can be attributed**

quite simply to *identity constancy*. After all, we adults assume that most objects stay the same object from moment to moment when other things change, which illustrates *identity constancy* (see Piaget, 1954). Obviously, if one accepts that an object is the same *unchanging*object from time 1 to time 2, its perceived linear size, S', remains the same, hence, if its perceived visual angle changes, its perceived distance also must change.

That equisize scaling illustrates *linear size constancy*.

Linear Size Constancy.

An object typically appears to stay about the same linear size when its visual angle and retinal image size change as a result of a change in the object's distance from the eye. That illustrates linear size constancy.

Two Objects: **Linear size constancy also refers to having two objects of the same linear size look the same linear size when they are at different distances. For instance, reconsider the example illustrated above, with the two men looking the same height, as illustrated in the side view.**
Equations that describe the outcome are as follows:

Again we can use the small angle approximation, tan $V' = V'$ rad, and substitute V' for tanV'. Putting the two previous equations together thus yields,

$(S_1' / S_2') / (D_1' / D_2') = V_1' / V_2'$ **which rearranges to:**

$S_1' / S_2' = (D_1' / D_2')(V_1' / V_2')$ **Equation B1**

For this example, $V_1' = 2V_2'$, so the equation becomes,

$S_1' / S_2' = 2D_1' / D_2'$ **Equation B2**

Equal perceived linear size scaling here furnishes $S_1' = S_2'$, so Equation B2 becomes, $D_2' = 2D_1'$, Thus, $D_1' = D_2' / 2$, which means the man on the left looks half as far away as the man on the right, (and, again, that 'computing step' illustrates the relative perceived visual angle cue to distance).

Linear Size Constancy By Computing.

An alternative process is that, as Step 1, some distance cues could scale both perceived distances correctly, so the man on the left looks half as far away ($D_1' = D_2 / 2$). Thus Equation B2 becomes $S_1' / S_2' = 1$. In this case, the linear size constancy outcome is the result of computing (Step 2).

A jargon problem. is that the (ambiguous) term "size constancy scaling" (Gregory, 1963...1998) often refers not to a scaling step but to that *computing step* described by the general Equation B1.
A more serious jargon problem concerns both "cuing" and "relative size."

The So-Called "Relative Size Cue To Distance."

The ambiguous term "relative size" could refer either to a comparison of S' values or to a comparison of V' values.
And, of course, as a Step 1 scaling operation, cuing should not be confused with a Step 2

computing process.
Consequently, the common use of the term "relative size cue to distance" creates a problem.
As illustrated above, the processing steps being referred to yield a D' ratio, are described by Equation B1 rearranged as, $D_1'/D_2' = (S_1'/S_2')/(V_1'/V_2')$,
and that equation rearranges into Equation B3.

$$D_1'/D_2' = (V_2'/V_1')(S_1'/S_2') \quad \text{Equation B3}$$

The desired ratio of perceived distances is obtained by the 'computing' step after the linear sizes have been scaled equal (linear size constancy), which makes the equation,

$$D_1'/D_2' = V_2'/V_1'$$

Accordingly, the "relative size" relationship actually involved in this process is the ratio of the perceived visual angles. It certainly cannot be the ratio of the perceived linear sizes because, of course, they are equal (that is, S_2' is neither larger nor smaller, "relative to" S_1')
Conventional discussions, however, do not knowingly use the perceived visual angle concept! Therefore, those discussions of the "relative size cue to distance" cannot openly refer to the comparison of two perceived visual angles. So, their term "relative size" would have to refer to the linear size ratio, but that makes no sense because that S' ratio must be about 1.0 (linear size constancy) in order to have the desired perceived distance outcome occur.
In other words, standard discussions often unwittingly let the term "size" refer to the perceived visual angle, V' deg, although those same discussions use the SDIH which ignores the concept, V' deg.

The Distinction Is Not New, Just Neglected..

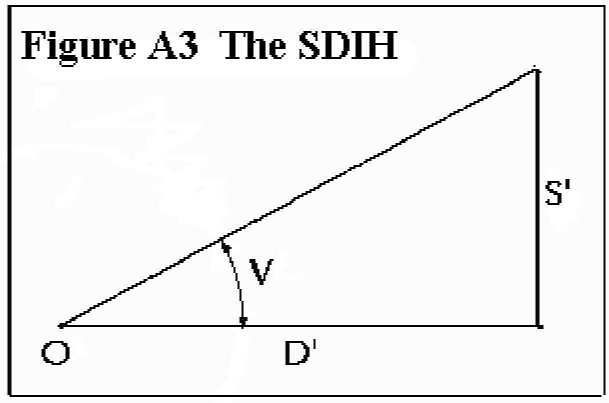
Perhaps the first clear discussion of the distinction between the perceived visual angle, V'deg and the perceived linear size S' m was published long ago by Joynson (1949; Joynson & Kirk, 1960).
The idea that we perceive the visual angle has been strongly advocated by Baird (1970; Baird, Wagner & Fuld, 1990).
In addition to McCready (1965, 1985, 1986), other articles which explicitly accept that we perceive both the visual angle and linear size for an object have been published by Rock & McDermott (1964), Ono (1970), and Komoda & Ono (1974). More recent supporting articles include Enright (1989); Reed, (1989); Higashiyama (1992) Higashiyama & Shimono, (1994) and Gogel & Eby, (1997).

The logic of new theory wholly replaces that of standard treatments, reviewed below.

Old Logic: The SDIH.

Traditional theories use the very different logical rule called the size-distance invariance

hypothesis (SDIH) illustrated by Figure A3. The geometry the SDIH uses is stated by the equation,



S'/D' = tan V (The SDIH)

Here V deg is the *physical* visual angle.
***D'* is the perceived distance, in meters.**
In SDIH sentences, *S'* is called simply the "apparent size" or "perceived size."
But notice that Figure A3 and the equation require that the measuring unit for *S'* must be the same unit used for *D'* , say meters: So, *S'* clearly has to be the *perceived linear size*, in meters.

Discussions based upon the SDIH (virtually all popular and textbook discussions) do not knowingly use the concept of the perceived visual angle, *V'* deg, and remain silent concerning the perception of directions.
Thus, by default, use of the SDIH logic implicitly suggests that the visual angle always will*look* equal to its actual value.
Consequently, the SDIH cannot logically be used to describe, predict, or explain a visual angle illusion, in which *V'* deg disagrees with the visual angle, V deg. That explains why conventional descriptions of "size" illusions that begin as visual angle illusions have been so puzzling and paradoxical.

More Jargon Problems: Much confusion in the perception literature is due to uncritical use of the ambiguous terms, "apparent size" and "perceived size." which could refer either to the perceived linear size, *S'* meters, or to the perceived visual angle, *V'* deg. When one reads standard discussions of "size" perception and "size" illusions one often cannot tell what the terms "apparent size" and "perceived size" refer to.

A very confused old suggestion was that the "apparent size" (or "perceived size") for a viewed object sometimes is valuated by factors directly related to its linear size, S meters, and sometimes valuated, instead, by factors directly related to its angular size, the subtended visual angle, V deg.
But the magnitude of that peculiar kind of "apparent size" would have to magically switch back and forth from being a certain number of meters to being a certain number of degrees, a clearly impossible transition.

The misuse of SDIH jargon occurs often in standard discussions of visual processing, as follows.

The SDIH Psychophysical Relationship.
Standard descriptions of visual processing have been using the SDIH equation as the basic psychophysical equation.
Many descriptions use it in its rearranged form as,

$S' = D'$ tanV. SDIH Rule A.

Such descriptions can be proper only if *S'* clearly is the perceived linear size.

But, in some SDIH-based sentences the term "perceived size" (or "apparent size") unwittingly refers to the perceived visual angle, *V'* deg, which is not used as such. Those sentences thus actually imply that the SDIH psychophysical equation is, illogically,
$V' = D'$ tanV deg.
Such sentences suggest that an increase in perceived distance, *D'* , "magnifies" *V'* deg for a constant V deg!
That unintentional mistaken interpretation of SDIH Rule A is as close as standard discussions get to describing a visual angle illusion controlled by distance cues (such as the moon illusion). Of course, their logic (geometry) is wrong, and the magnitudes of the "magnification" they imply are far too large.
If the writers had *properly interpreted* the diagrams which illustrate the geometry (logic) they were trying to use, they would not have written those illogical sentences.

Retinal Size: Other discussions of visual processing use the SDIH restated in terms of the proximal stimulus value, the retinal image size, R mm. For instance, they use the rule, R/n = tan V, to write the SDIH as,

$S' = D'$ R/n SDIH Rule B.

Processing sentences that use Rule B can be logical only if 'perceived size' clearly is the perceived linear size [because that rule also is, $S' = D'$ (S/D) meters].
But some sentences are based, in effect, upon a mistaken logic expressed by a version of Rule B in which the constant, n, (the nodal distance of about 17 millimeters) is omitted, as follows:
$S' = D'$ R.
Those sentences thus imply that the perceptual correlate of the retinal image size would be expected to be S' meters, and that a visual processing step provides the 'perceived size' for an object by having the perceived distance for it somehow "expand" or "magnify" the tiny retinal size, R mm, up to the much larger "size" the object looks! That very ancient idea is illogical but still appears in some articles (see below).

All the illogical sentences discussed above are responsible for the incredibly misleading 'textbook' descriptions of size constancy, which were critiqued in Section II and are discussed in more detail below.

The Size Constancy Pseudoproblem.

Nearly all published definitions of size-constancy begin by posing a ‘problem’ which does not exist. This *size constancy pseudoproblem* is created by comparing two facts about "size" perception in a way that makes them appear to contradict each other, but they really don't. And, in one way or another, this (artificial) contradiction is said to be 'resolved" by the

activity of a 'size constancy' mechanism, often described in terms of hypothetical brain activities.

In accord with the previous discussion of linear size constancy, the two facts are as follows:

Fact 1: When an object of constant size (S meters) recedes from the eye, its distance ((D meters) increases, so its angular size (V degrees) decreases, hence the size (R mm) of its retinal image decreases.

Fact 2: The perceived linear size (S' m) for the object almost always remains constant.

Additional facts are, of course, the perceived visual angle (V' deg) decreases, and the perceived distance (D' m) increases while (S' m) remains constant, as shown, for example, by the side-view diagram of the two perceived men.

The pseudoproblem is created by defining 'size constancy' with phrases that use the ambiguous terms 'perceived size' and 'apparent size' , and merge Facts 1 and 2 in illogical ways which, unfortunately, *sound* reasonable to an uncritical reader.

For instance, a short example of the illogical combination of Facts 1 and 2 would be: "The retinal size decreases, *but* the 'perceived size' usually remains constant (size constancy)."
The linking word, "but", obviously implies that an object's 'perceived size' normally would be a direct perceptual correlate of the object's retinal image size, R mm, *however*, a 'size constancy' process often keeps it constant when R changes.

A correct replacement for that illogical sentence is: "The retinal size decreases, *and* the perceived linear size (S' meters) usually remains constant (linear size constancy) while the perceived angular size (V' deg) decreases, and the perceived distance (D') increases." That proper description does not suggest any problem that needs to be solved by a 'size constancy' mechanism'.

Some published sentences which can fairly represent virtually all "textbook" definitions of 'size constancy' are quoted below. (I have emphasized the words that create the illogical link between Facts 1 and 2.)

Some Influential Quotations.
"There is a well-known set of phenomena which certainly does involve perceptual modification of retinal images ---size constancy. This is the tendency for objects to appear much the same size over a wide range of distance *in spite of* the changes of the retinal images associated with the distance of the object. We may refer to the processes involved as constancy scaling." (Gregory, 1963, p. 2).

"*Although* all objects give smaller retinal images as they recede from the eye, this geometrical shrinking is generally *compensated* by the brain, to give 'size constancy'." (Gregory, 1965b, p. 17)

"It is a well-known fact that the apparent size of an object depends not only on the size of the retinal image or visual angle but on the distance as well. Within certain limits, objects do not appear to vary substantially in size when viewed from varying distances, *despite* the fact that the size of the optical image varies inversely with distance. This phenomenon is known as size constancy. It is as if the observer took the distance into account in perceiving the size of the object. " (Kaufman & Rock, 1962a, p.953.)
"In line with this same reasoning, where the visual angle remains constant but where the distances are registered as different, the apparent size will change. In the case of an afterimage projected on surfaces at different distances, the apparent size is a direct function of the distance of the surface, a relation known as Emmert's law. The moon illusion can be considered a special manifestation of Emmert's law..." (Kaufman & Rock, 1962a.)

Notice that all such definitions implicitly *assume* an object's 'perceived size' *would be expected* to get smaller when its retinal image size (R mm) and angular size (V deg) decrease,*except that* a 'size constancy' process 'corrects' it in a manner that is *as if* V deg and R mm had been expanded (magnified).

The previous discussion of linear size constancy, however, clearly shows that the equal linear size outcomes for the perceived linear size, *S'* meters, certainly do not involve a 'correction' of the perceived visual angle, *V'* deg: Therefore, the decrease in V deg and R mm with the increased distance of an object does not create a "perceptual size" problem that needs to be solved.

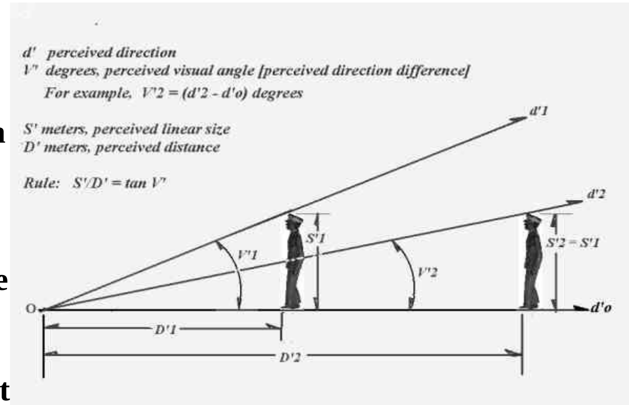
Consider next how those standard descriptions create the pseudoproblem.

An Analysis.
Keep in mind that virtually all the standard definitions of 'size constancy' (and certainly those quoted above) are using the logic of the SDIH, stated by S'/D' = R/n. And, as shown below, they are illogical no matter what the term 'perceived size' (S') actually refers to.

Is *S'* the perceived linear size? **Suppose, first, that 'perceived size' means 'perceived linear size', and the intention is to (correctly) define 'size constancy' as linear size constancy. In that case, in order to see what the SDIH suggests is the perceptual correlate of R mm, we can rearrange the equation to become, nS'/D' = R mm.**

So, according to the conventional logic, the direct perceptual correlate of R mm is the *ratio*of the perceived linear size to the perceived distance, multiplied by the nodal distance, n. In other words, according to the logic those definitions are using, the perceived linear size, *S'* ,*cannot* be the direct perceptual correlate of R. That is, when R decreases, *S'* meters can remain constant without requiring any correction that would have the same effect as 'magnifying' R mm.

That pseudoproblem also is revealed by consulting the diagram repeated at the right.



It shows that , for the observer at O, the men look equally tall, let's say 6 feet. That equal linear size perception certainly is not *as if* a retinal image had changed size.
Indeed, if the proposed 'magnification' of the retinal size' for the more distant man had occurred (to yield the same value for both men) then the picture of the man on the right would have to be drawn twice as tall as it now is, which would indicate that the observer at O would be seeing him as about 12 feet tall. And, of course, that would destroy the linear size constancy (rather than creating it).

Is *S'* , instead, the perceived angular size? **Now suppose the term 'perceived size' in the above definitions stands for the perceived visual angle, *V'* deg (even though this concept is not supposed to be used explicitly in discussions based upon the SDIH).**

When reworded using *V' deg*, the quoted definitions would imply that the perceptual correlate of R mm is *V'* deg, and, of course, that agrees with the present 'new' theory. Those reworded definitions thus would begin by correctly implying that *V'* deg will decrease when R mm decreases, due an increase in D meters. But, unfortunately, the linked phrases then convert that perfectly normal result into a "problem" (a pseudoproblem) which supposedly must be solved in order to have the 'perceived size' (*V'* deg) remain constant when R mm decreases. Hence the proposed 'size constancy' process would have the same effect as would a magnification of the visual angle and retinal image.

Those reworded sentences obviously would be defining 'size constancy' as an "angular size constancy", in which an object's visual angle almost always appeared to remain the same when the object's distance from the eye changed! That absurd idea suggests that we usually do not *see* the different directions of two fixed objects become less different when our distance from them increases. Such an outcome certainly would be maladaptive.

How illogical that idea is can easily be seen if you re-consult the diagram above.
Again, an author who uses properly interpreted diagrams, or equations with appropriate units of measure, can avoid writing those illogical verbal descriptions which can badly mislead an uncritical reader.

The conclusion is that the widespread standard definitions of 'size constancy' do not make sense, no matter what the ambiguous terms 'perceived size' and 'apparent size' refer to.

Those flawed definitions of 'size constancy', and the flawed descriptions of projected afterimages and Emmert's Law lie behind the standard, 'apparent distance' theories of the moon illusion (Gregory, 1963--1998; Kaufman & Rock, 1962a, 1962b; Kaufman &

Kaufman, 2000). That familiar "textbook" approach also was used in a moon illusion explanation offered by Trehub (1991) discussed next.

Trehub's Model

In the book, "The Cognitive Brain", Trehub (1991) constructed a complex theoretical model of brain processes that might be involved in human cognition and perception. Part of his model is devoted to hypothetical brain structures and processes involved in visual spatial perception.
In a short section (p. 242-247) he describes how those supposed neural activities might explain the moon illusion. Ross and Plug (2002) offer a brief review of the brain structures and activities Trehub posits, but in order to understand the details one must study Trehub's book.

Of course, many models of presumed brain functions which might underlie visual space perception have been proposed (see recent texts on Cognitive Psychology). Some describe complex physiological mechanisms, and some are complex mathematical models (see Indow, 1991). Each model has taken into account, of course, what was known about brain physiology at the time the model was invented. And, published research on the physiology of the visual system is adding new knowledge so fast that one must be a specialist in the area just to keep up. Only those specialists can vote on the validity of a given model.

I do not know enough to usefully comment on the details of any of those many models. However, I sometimes can judge the validity of the description being offered for the visual phenomena (usually a 'size' illusion) the model was designed to explain.

So, although not fully understanding the intricate neural structures in Trehub's model, I can, nevertheless, examine (below) his definition of the moon illusion, and the logic he used to explain it.

Analysis of Trehub's Model

Trehub (1991) did not use both *S'* meters and *V'* degrees, and did not explicitly specify what the term 'perceived size' refers to. He did not explicitly refer to the SDIH or to the apparent distance theory, but, as shown below, he offered the same 'size constancy' and projected afterimage, and Emmert's Law descriptions critiqued above.

For instance, on page 92 the changes in the 'perceived size' of an afterimage projected to different distances are described. This use of Emmert's law (also specifically referred to on page 245) clearly indicates use of the SDIH logic stated by, $S' = D'$ tanV, and $S' = D'$ R/n.

The following quotations deal with the portion of the proposed model which would do the visual processing that results in 'size constancy' and Emmert's law. (Again I have emphasized the 'linking' words that create the pseudoproblem.)

Some Trehub Quotes

"The perceived constancy in the size of an object over a range of observer-object distance*despite* large variations in the retinal size of the object .... does not seem to depend

on a process of iterative size adjustment like that performed by the size transformer. .... Thus, retinal images that become smaller as a function of increasing object distance are magnified in compensatory fashion as they are mapped onto the space represented by the mosaic cell array." (Trehub, 1991, p. 89.)

And elsewhere, "This provides a neuronal circuit for magnifying (or reducing images in rough *compensation* for the change in retinal size at different viewing distances." (Trehub, 1991, p.244).

Moreover, some 'moon illusion' articles and newsgroup discussions on the internet include comments Trehub sent to them about his book. Those messages point out that what the proposed mechanism keeps constant is the "perceived intrinsic size of an object *despite*changes in its projected retinal size as the distance between the object and the observer changes (size constancy)".

Some of those messages also mention that the book offers the details of "... an innate neuronal system that maintains size constancy by automatically expanding or contracting the brain's representation of the changing retinal image *in compensatory fashion* as an object's egocentric distance increases or decreases.

All those sentences are just as illogical as the others quoted and critiqued above. However, if Trehub's confused 'size constancy' idea were ignored, his model could be interpreted to describe the moon illusion as part of the more general visual angle illusion in which distant objects in the horizon direction look a larger angular size than objects of the same angular size located in an elevated position, as reported by Higashiyama (1992; Higashiyama & Shimono, 1994).
That is, Trehub's model might be describing some hypothetical brain activities that would yield a modification of *V′* deg away from V deg (and, of course, away from R mm) as a function of factors related to global egocentric distances and directions. If so, that revised model would apply to the moon illusion, which cannot be explained by his model based upon the logic of Emmert's law and 'size constancy scaling'. That is, if changes in *V′* deg away from V is what Trehub meant to describe, then he defeated his argument by using the SDIH logic of Emmert's law and the flawed 'size constancy' approach, both of which do not refer to or use the concept of *V′* deg.

If Trehub's specific hypothetical mechanisms were redescribed in terms of perceived visual angles (rather than perceived linear sizes), they could apply to oculomotor micropsia/macropsia, for which some general models of brain mechanisms have already been proposed (Enright, 1989; Foley, 1980).

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Section II. Conventional Versus New Descriptions
Section III. Explaining the Moon Illusion

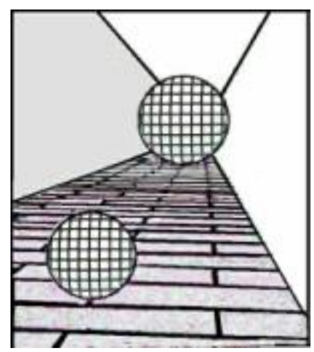
Appendix B (Posted February 05, 2007)

An Analysis of the Experiment by Murray, S. O., Boyaci, H., & Kersten, D. (2006). "The representation of perceived angular size in human primary visual cortex."

[All of the information in this Appendix B was mailed to Dr. Murray, Dr. Boyaci, Dr. Kersten and other relevant researchers in April 2006.

The experimenters measured the angular size (visual angle) illusion obtained with a flat, photo-montage that resembles a photograph of an imaginary hallway with two spheres on its brick floor at different distances with their diameters subtending the same angular size (optical angle) at the camera lens

The picture used in the study can be seen at the following link (you might open it in a new window, and click on the image there to see a larger version). http://faculty.washington.edu/somurray/sizedemo.html



The crude sketch at the right imitates the copyrighted pattern they used. (However, for the detailed analyses here, it is best to view their original picture.)
The two disks (sphere images) on the flat screen (or page) are the same linear size so they subtend the same visual angle (V deg) at an observer's eye, which, for the study was 6.5 degrees.
Therefore the retinal images of the disks are the same size.

(Some media reports of the experiment have mistakenly stated that the observers viewed a real hallway with real spheres!)

All 5 observers suffered the basic illusion that the upper disk's diameter looks a larger angular size (in degrees) than the lower disk's, so it also looks a larger linear size (in inches) on the page.

***Task.* The observer's task was to change the linear size of the lower disk until both disks looked the same angular size, and thus the same linear size on the screen. That also would make the two 'spheres' look the same angular size.**

***Results.* The observers made the lower disk from about 15% larger to 20% larger than the upper disk.**
In other words, for a useful example here, the perceived visual angle (V' deg) for the upper disk (and 'sphere') initially was, say, 17% larger than V' deg for the lower disk (and 'sphere').
Also, the perceived linear size (S' in) for the upper disk was 17% larger than for the lower

disk, while both disks had the same perceived distance (D' in).
That is, a lower disk with a visual angle, of 7.6 deg looked the same angular size and linear size as the upper disk that subtended 6.5 deg.

Of course, most observers easily could have the "3D" pictorial illusion and perceive the flat pattern as a picture of two 'spheres' with the upper 'sphere' looking farther away and a larger linear size (behavioral size, metric size) than the lower 'sphere'.
Moreover, a simple analysis (see later) of the brick pattern in the original picture indicates that, if it had been a photo of real set-up, the far sphere would have been 5 times farther from the camera lens and 5 times the linear diameter of the near sphere (in order to yield the equal optical angles at the lens).

So, to assign some approximate perceptual values to the original pictorial (3D) illusion, we can suggest, temporarily, that the 'far-looking sphere' would look 5 times farther from the viewer's eye, and 5 times the linear diameter (in inches) than the 'near-looking sphere'. (Let's say, the near one looks like a 6 inch diameter ball and the far one a 30 inch diameter ball.)
However, that very large, 500% linear size illusion was not measured, mostly because it isn't interesting. The 17% visual angle illusion is the one that has puzzled scientists for such a long time.

The authors mention that their findings relate to other flat pattern illusions such as the Ponzo illusion. The list can also include the classic Ebbinghaus illusion, and Mueller-Lyer illusion (discussed again later).
The authors also mention that their findings relate to the moon illusion (although none of the moon illusion studies they cite treated it as an angular size illusion).

Indeed, their illusion pattern is somewhat like the lower half of the figure at the right, which was discussed in Section I to illustrate that "Flat Pictures Offer Angular Size Illusions Due To Distance Cues," and also discussed in Section IV to illustrate the "moon illusion in pictures," as researched especially by Enright (1987a, 1987b, 1989).

Interpretation. **The authors' interpretation of their results used the conventional (most popular) theoretical approach that includes the apparent distance theory, Emmert's law, "misapplied size-constancy scaling," and a so-called, "scaling of retinal size." The logic (geometry) of those approaches is the size-distance invariance hypothesis stated by, S'/D' = tanV, which excludes a perceived visual angle concept, V' deg. Therefore, those approaches can neither describe nor explain the angular size illusion that Murray et al. measured.**

This Appendix B shows in detail how the 'new' general approach to size, distance and visual angle perception (McCready, 1965, 1985), (as presented in the main body of this article) describes the results of the Murray et al. experiment more fully and more

accurately than do other approaches. The logic of this approach is the perceptual invariance hypothesis, stated by S'/D' = tan V', which includes V' deg.
It describes how and when the perceived visual angle, V' deg, for a target changes away from its constant visual angle V deg (and constant retinal image size).

The major challenge is to explain why those V-illusions occur.
To that end, it will be shown in detail later how the oculomotor micropsia explanation of angular size illusions can fit the illusion measured by Murray et al, and also fit other flat pattern illusions, including the moon illusion in pictures.

***New Finding.* The major new discovery by Murray et al, was obtained using an fMRI machine to examine and measure the activity patterns in the primary visual cortex, area V1 (Brodmann area 17) while the observer viewed the picture.**
For these fMRI measures the supine observer's head was inside the magnet's core, so a mirror above the head was used to provide a view of a flat screen on which the picture was rear-projected.

Although the retinal images of the disks in the picture are the same size, the neural activity patterns which those equal-sized retinal images eventually generated in Area V1 were not the same size. The activity pattern for the upper disk was larger than that for the lower disk by an amount that was shown to be equivalent to the magnitude by which the perceived visual angles differed.
In other words, the perceptual magnitude, V' deg, correlated not with the given retinal image size, but with the changed physical extent of the activity pattern in cortical area VI that corresponded with the retinal image.

The authors point out that their fMRI results do not support the currently "most popular theories" about the brain activities involved in 'size' illusions.
After all, those theories are based upon an assumption that the activity pattern in Area V1 that corresponds to a constant retinal image size would remain the same size when distance cues and the perceived distance for the viewed target changed.

The 'new' general theory advocated here makes no such assumption. Indeed, it has always been stated that a relative, visual angle illusion is *as if* the equal retinal images were not the same size, and that obviously implies that those equal images would generate "unequal" activity patterns at an early stage in the visual system. Indeed at a stage *before* the stages where brain activity patterns occur that correspond with the perceived linear values, S' in. and D' in.
The Murray et al. fMRI results fully support the 'new' theory

The present analysis has three parts.
Part 1 describes the Murray et al, method and results in detail using the 'new' general theory.
Part 2 offers detailed interpretations of the results.
Part 3 suggests how the oculomotor micropsia explanation (especially 'conditioned

micropsia') can fit the Murray, et al. illusion, and other flat-pattern illusions . Detailed numerical examples are offered.

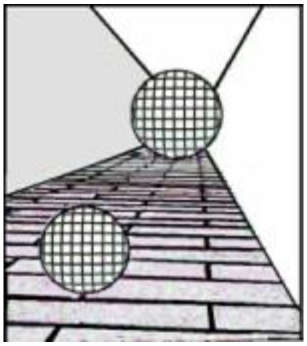
PART 1. DESCRIBING THE ILLUSION

The entire article by Murray, Boyaci, & Kersten (2006) can be found at the website,

http://www.ski.org/Visproc/pdf/Murray-Boyaci-Kersten-2006.pdf

METHOD.

Consider first the stimulus relationships.
The two disks had the same linear size (S in) on the screen (which was not reported), so their diameters subtended the same visual angle, which was, V= 6.5 deg, or V = 0.114 radian, and Tan V = 0.113.
Therefore, the retinal images of the disks had the same diameter (about 1.9 mm).
The viewing distance (D in) to the screen was not reported, but you can approximate the viewing condition if you measure the diameter (S in) of the disk on your screen and view the picture from a distance that is 8.85 times S [because, D = S/tanV]



OBSERVER INSTRUCTIONS.

The instructions to the observers were phrased in two ways.
They were asked "to adjust the size of the front sphere until its angular size matched that of the back sphere."
That sounds like the well-known, 'analytic instructions' that foster a perceived visual angle (V' deg) match of two viewed targets.
Then, because that instruction can be confusing, the observers also were "told to adjust the size so that the two images of the spheres [the disks] would perfectly overlap if moved to the same location on the screen."
That illustrates the well-known 'objective instructions' that would foster a perceived linear size (S' in) match of the two disks.

Of course, because the disks on the screen have the same perceived distance, D', those two quite different instructions will yield the same "size" match.

The following numerical analyses consider three different kinds of illusion that are likely to occur for the Murray et al. picture, Percepts A, B, and C.

Percept A is a simple pictorial (3D) illusion with no visual angle illusion. The perceived spheres look the same angular size and much different linear sizes and distances. No observer had that illusion.

Percept B is a complex pictorial (3D) illusion that adds into Percept A a 17% larger perceived visual angle for the 'far-looking sphere' than for the 'near-looking sphere'. The observers had this type of illusion, which was measured indirectly.

Percept C is the perception of the flat (2D) pattern. The disks appear at the same

distance (on the same page) and the upper disk looks 17% larger than the lower disk both in angular size and in linear size.
All observers had this type of illusion. It is the illusion that was directly measured.

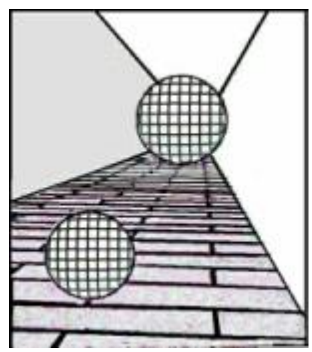
Now for some details.

PERCEPT A

A Simple Pictorial Illusion with No V-Illusion.
As mentioned earlier, if the picture had been a photograph of a real set-up, the upper sphere would have been 5.0 times farther from the camera lens than the lower sphere, so its linear diameter would have been 5.0.times larger than the lower sphere's.

That is easily determined by assuming that in the supposed 'real' set-up, the bricks on the floor would have been the same linear size, and by noticing that a brick image on the original screen (page) under the lower disk is 5 times longer than a brick image under the upper disk,. Therefore the lower 'sphere' would have been at one-fifth the distance of the upper 'sphere'.

For the present example of a simple pictorial illusion with no V-illusions, let the perceived ratios be the same as those for the supposed real set-up.
That is, let the perceived distance, D' in, for the far sphere' be 5.0 times D' for the 'near sphere'.
Hence, the perceived linear diameter, S' in, of the 'far sphere' is 5.0 times S' cm for 'near sphere'.



For the present example, let's choose some specific perceived values for the 'near sphere' as follows,
Perceived angular size, V' = 6.5 deg.
Perceived linear size, S' = 6 inches, which makes the,
Perceived distance, D' = 53 inches from the viewers eye.

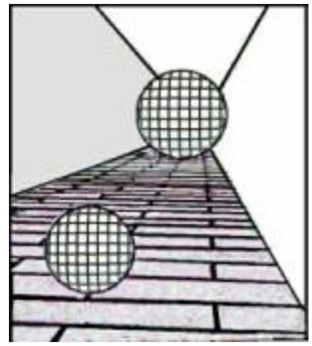
For the 'far sphere' it follows that,
Its perceived angular size also is V' = 6.5 (the same as for the 'near sphere').
Its perceived linear size is, S' = 30 inches.
Its perceived distance is, D' = 265 inches.

How those values were obtained is described below.
First, suppose those unusual floor bricks look 16 inches long (S' = 16 in). (Which can illustrate the "familar size" or "known size" cue to linear size.)
And notice that, in the picture used , the diameter of the lower disk measures (and looks) 3/8 of the brick length where that disk sits.
So let the perceived linear size of the "near sphere' be, S' = 6.0 inches.

The possible perceptual outcomes should conform to the equation, S'/D' = tan V'
We let the perceived visual angles (V' deg) equal the visual angles of 6.5 deg.
So tanV' = 0.113, hence S' = 0.113 D'

And, with S' for the 'near sphere' already scaled as 6 inches, its perceived distance becomes 'calculated' as, D' = 53.1 inches from the viewer's eye.

For the 'far sphere', with V' also 6.5 deg, the linear values (S' and D') are 5.0 times greater than for 'near sphere', so, to a first approximation, S' = 30 inches, and D' = 265 inches. That can be approximately how the 3D result looks to us.



HOW WOULD A "PERCEPT A" OBSERVER RESPOND?
Remember that the observers were not asked to make the perceived 'spheres' look the same linear diameter (the same 'behavioral size'), which would create a linear size constancy outcome.
After all, to do that, they would have to make the 'near sphere' look 30 inches wide, by making the lower disk's diameter about 5 times larger, but that huge lower disk would fill up most of the picture.
If one wanted to obtain a linear size-constancy outcome, one could make the 'far sphere' look about 6 inches in diameter by making its image (the upper disk) about 1/5th its size.

The instructions were to to adjust the size of the lower disk until both disks appeared the same angular size and same linear size on the screen.
For an observer who might have Percept A, (no angular size illusion, in agreement with 'popular theories') the two equal disks would already look the same angular size and the same linear size, so the size of the lower disk would not need to be changed.

[Notice that, for a viewing distance of D = 21.0 inches, each disk's linear diameter on the screen would be, S = 2.37 inches. (Because S = 0.113D)]

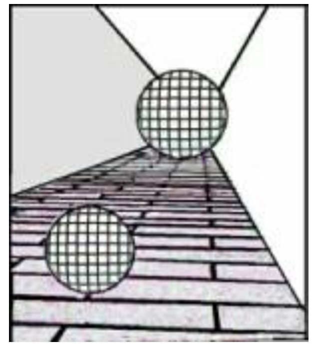
But, all observers increased the size of the lower disk. That is, all observers had a relative visual angle illusion, as illustrated next by Percepts B and C.

PERCEPT B.

Now let's add a 17% relative V-illusion into the 3D example of Percept A.

For this Percept B example let the perceived values for the 'near sphere' be the same as those for Percept A. So,
Its perceived angular size is V' = 6.5 deg.
Its perceived linear size is, S' = 6 inches.
Its perceived distance is, D' = 53 inches.

For the 'far sphere' the new values become,
Its perceived angular size is V' = 7.6 deg (17% larger than 6.5 deg).
Thus tanV' = 0.132. And the rule becomes S'/D' = 0.132.

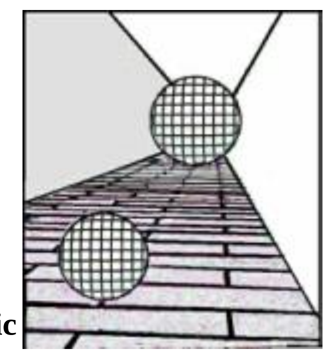


Its perceived linear size is, S' = 30 inches. (The same as in Percept A.)
Thus, D' = 227 inches. (It looks 38 inches closer than it would in Percept A.)

The present example makes use of the fact that the 17% larger perceived angular size is occurring not just for the 'far sphere' but also for the 'bricks' on which it appears to sit.
So, the ratio of V' deg for the 'far brick' to V' deg for the 'near brick' is not 5.0, but (5.0)/(1.17) = 4.27.
Therefore, because those 'bricks' look the same linear size (S' = 16 inches) to illustrate linear size constancy, the perceived distance of the 'far brick' becomes 4.27 times D' for the 'near brick', so D' for the 'far sphere' is 227 inches (rather than 265 inches).
It follows that the 'calculated' perceived linear diameter for the 'far sphere' is 30 inches , in accord with, S' = 0.132D', and also because it still looks 1-7/8 times the perceived length (16 inches) for the far brick.

In order to make the 'near sphere' look the same angular size as the 'far sphere', an observer who suffered this particular illusion would adjust the lower disk until it subtended an angular size of 7.6 deg, and the linear diameter of that lower disk on the screen would become 2.77 inches (17% larger than 2.37).
That type of pictorial (3D) illusion was measured indirectly.

Now consider how the 'near sphere' will look when its 'new' perceived angular size is V' = 7.6 deg.
Its linear diameter now will look, S' = 7 inches (17% greater than 6 inches) because it looks 17% larger than 3/8 of the 'near brick' length (16 inches) where it sits. (The 'near brick' has not been changed.)



Other starting values for S' and/or D' for the near sphere obviously are possible, depending upon the observer. Thus, many other specific outcomes can exist that satisfy the rule, S'/D' = tanV'.
At any rate, the much more interesting illusion is the flat pattern illusion.

PERCEPT C.

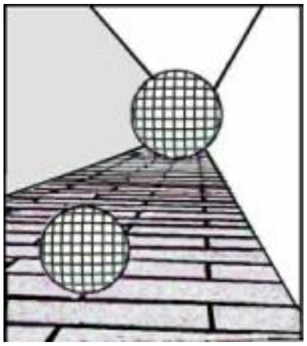
The Flat Pattern, 17% V-Illusion for the Disks.
For a convenient example let the viewing distance again be, D = 21 inches, so the disks's diameters will be S = 2.37 inches (in accord with the rule, S/D = tanV = 0.113).

For this example, let the perceived values for the lower disk momentarily be accurate.
So, its perceived angular size is V' = 6.5 deg (this will be modified later, in Part III).

Its perceived distance is, D' = 21 inches.
And, its perceived linear size is, S' = 2.37 inches.

For the upper disk, the values become,
Its perceived angular size is V' = 7.6 deg, (17% larger than 6.5 deg, so tanV' = 0.132.)
Its perceived distance also is, D' = 21 inches (it looks at the same distance as the lower disk).
So, its perceived linear size is, S' = 2.77 inches (because, S' = 0.132D').

Therefore, an observer who has this particular V-illusion would adjust the lower disk until it was 2.77 inches in diameter (and thus subtend 7.6 deg).
That is the type of illuson that was directly measured.



This 17% relative visual angle illusion for the disks on the page is the primary 'size' illusion that most needs to be explained.
As already noted, it occurs as well for the illusory 'spheres' in the complex pictorial illusion (Percept B).

PART 2. INTERPRETATIONS

To begin to interpret the results, consider first the abstract for the Murray et al. (2006) experiment, as follows.
"Two objects that project the same visual angle on the retina can appear to occupy very different proportions of the visual field if they are perceived to be at different distances. What happens to the retinotopic map in primary visual cortex (V1) during the perception of these size illusions? Here we show, using functional magnetic resonance imaging (fMRI), that the retinotopic representation of an object changes in accordance with its perceived angular size. A distant object that appears to occupy a larger portion of the visual field activates a larger area in V1 than an object of equal angular size that is perceived to be closer and smaller. These results demonstrate that the retinal size of an object and the depth information in a scene are combined early in the human visual system."

MODIFYING THE ABSTRACT.

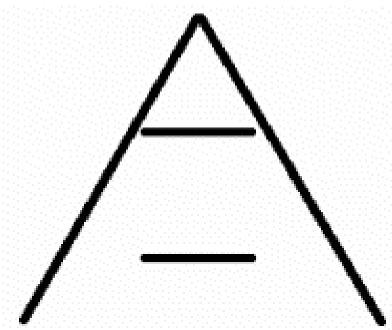
The opening sentence is, "Two objects that project the same visual angle on the retina can appear to occupy very different proportions of the visual field if they are perceived to be at different distances."
That sentence wholly supports the idea that there are visual angle illusions.
It also describes the normal condition while one views objects in the world (including the illusions of oculomotor micropsia/macropsia).

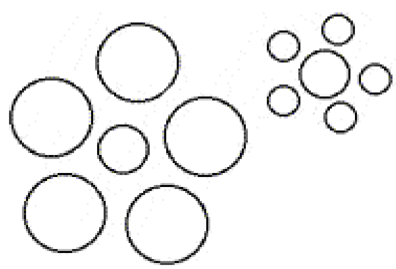
A later sentence is, "A distant object that appears to occupy a larger portion of the visual field activates a larger area in V1 than an object of equal angular size that is perceived to be closer and smaller."
[This change in area V1 undoubtedly applies, as well, in oculomotor micropsia/macropsia.]

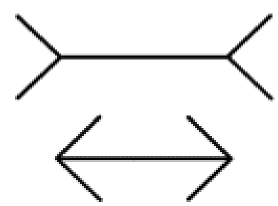
Those sentences are true for normal viewing. However, for the experiment, the two "objects" those sentences refer to are not objects. They are the illusory 'spheres' in the pictorial outcome, as in the Percept B example used above.

Instead, the *real* objects that were compared in the experiment, were, of course, the two disks on the screen (page) . And they are not perceived to be at different distances! That is, the V-illusion does not *require* that the objects be perceived at different distances. Therefore, another sentence could be added to the abstract to point out that the angular size illusion and the changes in area V1 also existed for two objects (the disks) of equal angular size that were perceived to be *at the same distance from the eyes!*.

As pointed out in Section I of this present article, that is precisely the same problem presented by many classic flat pattern "size" illusions that have resisted explanation for such a long time. The authors mention the Ponzo illusion. There also are, for example, the Ebbinghaus illusion (Titchner's circles), and the Mueller-Lyer illusion, all three illustrated below.







For such illusions, the crucial targets subtend the same visual angle, V deg, but the perceived visual angle , V' deg, is slightly larger for the target that lies within a pattern that could indicate (cue) a greater perceived distance for it than for the other target, while both targets appear at the same distance (on the same frontal page).

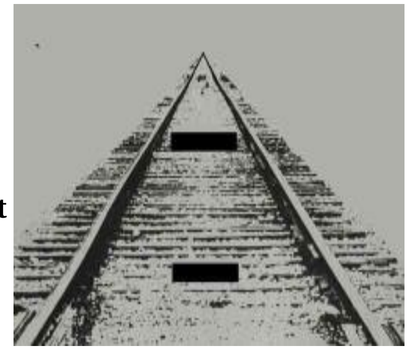
POTENTIAL PICTORIAL ILLUSION NEEDED.

It is important to keep in mind that the magnitude of the visual angle illusion for the two equal targets on the page depends upon how big the difference would be between the perceived distances of the illusory 'objects' which the flat targets might portray in a pictorial depth (3D) illusion that the pictorial distance cues could generate for the given observer.

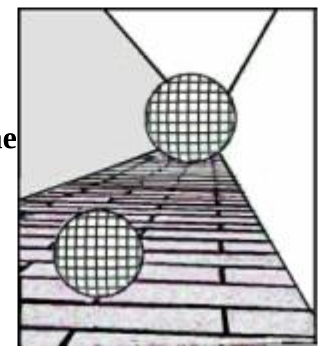
That is, the size of the V-illusion for a particular 2D flat pattern depends upon the observer's "ability" to convert some of the monocular distance cues into a pictorial (3D) illusion that can provide different perceived distances for the illusory 'objects' the flat targets may be the 'images' of.

For example, as discussed earlier in this present article, the Ponzo 'railroad track' illusion (as at the right) is easily suffered by those of us who have seen such tracks, or who, at the least, have learned to use the many linear perspective cues in our 'carpentered' environment filled with rectangular objects (e.g., windows, doors, walls) seen at a tilt, and

including the parallel edges of objects like roads, seen on the ground receding from us.



Recall that Kilbride & Leibowitz (1972) found that the Ponzo illusion was *not* suffered by people who lived in an environment that had no tracks or roads or other rectanglar objects.
Likewise, Rock, Shallo & Schwartz (1974) found that, the more an observer recognizes, interprets and accepts that a flat pattern indicates large depth (3D) values (large distance differences), the more V'deg increases for a target of constant V deg located at a nominally "far" place in the visual world (although they did not use the concept, V' deg).
Also remember that, for us, such illusions usually are weakened by inverting them, which can reduce the efficacy of the distance cues (especially "height in the plane").



Cue conflict.
In other words, the Murray et al. illusion is caused by some of the monocular distance cues in the flat 'picture' while other distance cues are making the targets correctly appear on the page (at the same distance).
For instance binocular cues, some monocular cues, and also one's knowledge that one is looking at a flat picture, all indicate that the two disks have the same perceived distance, D' cm.
Yet, 'pictorial' distance cues (mostly linear pespective for the brick images) are creating the V-illusion.

Given the general descriptions and examples above, the main task is to explain *why*changes in distance cue patterns can alter the relationship between the visual angle, V deg, and the perceived visual angle, V' deg, which is the subjective change that Murray, et al. showed was a result of a change in the neurological relationship between a given retinal size, R mm, and its representation in cortical Area V1.
That task was addressed in the body of the present article. It will be dealt with later here, in part 3.

THE POPULAR APPROACH.
A difficulty appears in the Murray et al. discussion section.
The 'explanations' of the illusion use the 'popular approach', whose logic is the size-distance invariance hypothesis (S'/D' = tanV) which omits V' deg.
Consequently, there is much confusion between the perceived angular size (V' deg) and the perceived linear size, (S' inches), which is called a 'perceived behavioral size'.
As a result, the discussion section does not *explain* the illusion that was measured.

For instance, it was suggested that distance cues evoke a supposed "scaling" of some entity called the viewed object's 'retinal projection" to yield a "perceived behavioral size" for the object, "whereby retinal size is progressively removed from the representation" (p. 422).
That very old idea overlooks that the perceptual correlate of the extent between two

stimulated retinal points is not a perceived linear size (S' cm) that somehow has been "scaled" up.
For instance, the lower disk's retinal image size, R = 1.9 mm, does not have to be magically magnified to become either 2.37 inches for the disk, or 6 inches for the illusory sphere!

Instead, the *flexible* perceptual correlate of the extent between two stimulated retinal points is the perceived visual angle, V' deg.
And this angular size perception is simply the perception of the different directions of two seen points from oneself. And that perceived direction difference (V' deg) certainly is not "removed from the representation."

And, as the authors clearly showed, V' deg is a perceptual correlate of the extent of the activity in area V1.

As easily predicted, other published articles already are mis-interpreting the Murray, et al. experiment in the 'popular' way.
For instance, some articles say the results illustrate Emmert's Law, stated by S'cm = D'tanV.
And, some articles suggest that the results illustrate "misapplied size constancy scaling", an old idea in which with the term "size constancy" refers to some sort of "scaling of the retinal size" by perceived distance.
But, as discussed in Appendix A, those conventional ideas fail to explain V-illusions and confuse linear size constancy with a supposed "visual angle constancy."

REGARDING THE CHANGES IN CORTICAL AREA V1.

Murray et al, point out that their fMRI results do not support 'dominant' theories about the probable neural activities in the brain involved in "size" illusions.
For instance, a University of Washington website offers a review of the study at,

http://uwnews.washington.edu/ni/article.asp?articleID=23005

It quotes Dr. Murray as follows (who refers to the moon illusion).
"It almost seems like a first grader could have predicted the result. But virtually no vision or neuroscientist would have. The very dominant view is that the image of an object in the primary visual cortex is just a precise reflection of the image on the retina. I'm sure if one were to poll scientists, 99 percent of them would say the 'large' moon and the 'small' moon occupy the same amount of space in the primary visual cortex , assuming they haven't read our paper!"

That comment overlooks the writings of about two dozen reputable vision scientists who, at least since 1965, have pointed out that the angular size (visual angle) illusion for the moon, and for many classic flat-pattern illusions, is *as if* the moon's constant retinal image size changed when distance cue patterns changed.
And, because that is very basic illusion, and given what has long been known about the spatially isomorphic neural projections of the retinal surface into Brodmann area 17 (now called area V1) it has seemed quite likely that the 'size' change would already appear that

early in the brain.
That is, the V' deg experience (perceived visual angle) clearly must be related to a more basic (primitive) place in the visual system than the places that relate to the coexisting, and qualitatively much different, S' cm experience (perceived linear size, or "apparent behavioral size").
As discussed in Section IV of the main text, this primacy of V' deg makes sense because the angle V' deg is the difference between the perceived directions of objects from oneself, and it thereby guides rapid orienting responses from one object to the next.
In all animals those orienting responses are critically important for survival.
[Indeed, in many animals' visual systems, the superior colliculi are very much concerned with direction perception, so one could make a wild guess and speculate that these even more primitive brain loci are involved in the creation of angular size illusions.]

Measuring Micropsia with fMRI.
Obviously, the changes in Area V1 found by Murray et al. also would be obtained for the much larger visual angle illusion of oculomotor micropsia/macropsia, by having the observer change from strong convergence to divergence.
That easily can be done using base-out, then base-in prisms.
The magnitude of that V-illusion should be as large as 2 to 1, for small targets. It will be interesting to see how far that micropsia can be pushed for large targets.
Also, micropsia would be obtained if the observer "voluntarily" over-converged while fusing a repetitive pattern, as in the Meyer Wallpaper Illusion.

Spiral Illusion Aftereffects.
After viewing a rotating spiral that appears to be contracting, if one looks at a fixed target, its angular size looks very much larger than it does without that aftereffect. Conversely, that target's angular size looks considerably smaller after one views a rotating spiral that appears to be expanding.
Those large visual angle illusions likewise should show up in Area V1.

But, back to the flat patterns.
Currently, the best-known alternatives to the deficient "popular" explanations for the classic, flat pattern V-illusions are the visual angle contrast theory (critiqued in Section II) and the oculomotor micropsia theory (detailed in Section IV) which is applied to the Murray et al, experiment in Part 3 below.

PART 3. THE OCULOMOTOR MICROPSIA EXPLANATION (posted April 29, 2007)

Here it will be shown that the visual angle illusion measured by Murray et al. could be due to oculomotor micropsia in large part, if not entirely.
How the oculomotor micropsia theory may apply to flat pattern illusions has been described in general terms elsewhere (McCready, 1965, 1983, 1985, 1986) and is briefly described in Section IV of this present article.
The argument offered below gives details and examples to clarify that proposal.
It applies the simple equation for oculomotor micropsia (McCready, 1965, 1985, 1994a,

1994b, 1995), Ono (1970), Komodo & Ono (1974), Ono, Muter, & Mitson (1974) mentioned in Section IV.

Some examples for the Murray et al. picture furnish relative V-illusion values ranging from 10% up to 26% . So they fit the obtained data very well.
This analysis also provides a model of how the oculomotor micropsia explanation can apply to many other flat pattern illusions, such as the classic Ponzo illusion, Ebbinghaus Illusion, Mueller-Lyer Illusion and the moon illusion in pictures.

THE GENERAL IDEA AND A QUICK EXAMPLE.

The analysis begins by noting, again, that, for most people, oculomotor micropsia is a natural perceptual adaptation that occurs during normal everyday viewing.
In general, the closer an object is to the eyes, the more its perceived visual angle (V' deg) becomes less than its subtended visual angle (V deg).
This angular size illusion tied to object distance undoubtedly serves some "purpose."

The present assumption is that the "purpose" of the illusion is to enhance the speed of body orienting responses to viewed objects, especially the quick "emergency" rotations and other movements of the head (see Section IV again).
That assumption led to the simple equation for the amount by which this *natural micropsia* is expected to change the perceived visual angle (V') for a target subtending the visual angle, V deg.

$$V'/V = Dc/(Dc + Tk).$$

Here the variable Dc, is the target's *cued distance* established by some or all cues for the target's distance.
In natural everyday viewing, Dc often equals the actual target distance (D).
It also may equal the target's perceived distance (D') .
But, as is especially true for classic "size and distance " illusions, Dc may not equal either D or D'.
Indeed, in a flat picture that can create a 3D pictorial illusion, values of Dc can equal the different distances being 'signaled' for targets by the monocular pictorial distance cues, even when the targets correctly appear at the distance of the page.

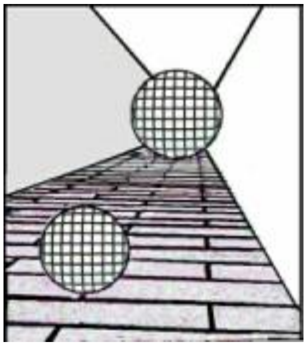
The variable Tk, is the *turn correction factor* , in inches.
Theoretically, Tk is the distance from an eye rotation center to a pivot point for a head movement.
I have analyzed (McCready, 1965, 1994a, 1994b, 1995) published experiments that directly measured oculomotor micropsia, and several other experiments that indirectly revealed oculomotor micropsia, and found that, among observers, Tk ranges from zero (no micropsia) up to at least 6 inches (15 cm) and for horizontal head rotations Tk averages about 4 inches (10 cm).

Applying the Equation.

The first example applies the equation to the original Murray et al picture (imitated by the

sketch here) and yields a 17% relative illusion by using a viewing distance of 20 inches and a Tk value of 4.5 inches. Other examples follow, and then more details of the calculations are given.

The task is to explain why the upper disk, that subtends 6.5 deg looks angularly larger than the lower one that subtends 6.5 deg, while both disks have the same perceived distance. Keep in mind that this illusion evidently will not exist (or will be very weak) for any observer who is unable to "convert" the monocular cue patterns into a 3D, pictorial illusion of a 'receding floor" with an upper 'sphere' that looks, say, 5 times farther away than a lower, nearby 'sphere'.



So, the disk illusion is linked to the 'sphere' illusion.

To begin, it is expected that natural micropsia will occur for the target extents on the flat page (screen) at its viewing distance.

Again, in order calculate this natural micropsia, the equation is,

V'/V = Dc/(Dc + Tk).

Suppose the viewing distance is 20 inches, and suppose the screen correctly looks 20 inches away, "because" the binocular cues and some monocular cues "assign" a cued distance of , Dc = 20 in.
With Tk = 4.5 inches and Dc = 20 inches the equation predicts a natural micropsia of, V'/V = 20/24.5 = 0.833.
That is, natural micropsia would be expected to make the perceived visual angles of extents on the screen. 22% less than their subtended visual angles.

Next, for these examples, let the lower disk be the standard.
So in the present example its perceived visual angle would be, V' = (6.5 x 0.833) = 5.3 deg, an absolute V-illusion of 22%.
That also would be the first prediction for the upper disk, of course.
However, V' for it is larger than V' for the lower disk while they have the same perceived distance (D' = 20 in).
In order to explain that relative V-illusion, the analysis uses the concept of *conditioned micropsia* .

CONDITIONED MICROPSIA (see Section IV again)
In the Murray et al. pattern the pictorial distance cues (especially linear perspective for the floor bricks) can create the 3D illusion that the upper sphere and the brick under it are about 5 times farther away than the lower sphere and its brick.
In Part 1, examples were given for Percepts A and B in which the *pictured* 'near sphere' looks 53 inches away when it looks 6 inches in diameter.
However, binocular cues, some monocular cues and the observer's knowledge are specifying that the screen and that target are at 20 in.
So, for the present example, assume that, as far as the visual system is concerned, the real

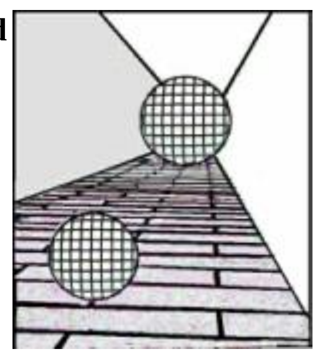
'near sphere' image is in the plane of the screen at 20 inches, so Dc for it is 20 in. And, for the 'far sphere' the pictorial cues now are signaling, "100 inches away", so Dc = 100 in. for it.

For the observer in this example, oculomotor micropsia during everyday viewing often has occurred for targets at 100 inches for which Dc = 100 in, so for such a target the equation predicts that, V'/V = 100/104.5 = 0.957, a small absolute illusion of 4.5 %.
The proposal is, of course, that the monocular distance cue patterns that have been associated with a target distance of 100 in. have acquired the ability to generate micropsia appropriate for that distance when those cues appear again, even as the simple monocular pictorial cues in a flat pattern. That result would illustrate*conditioned* oculomotor micropsia

So, for this specific example the suggestion is that the pictorial cues are treating the 'upper sphere' *as if* it were 100 inches beyond the screen, so Dc = 100. This conditioned micropsia for the 'upper sphere' thus would yield for it a perceived visual angle of, V' = (6.5 x 0.957) = 6.22 deg.
Therefore, the illusory ratio of the perceived visual angle for the 'far sphere"to that for the "near sphere' is, (6.22/5.3) = 1.17.

This predicted 17% relative angular size illusion agrees well with what Murray et al found both for the 'spheres' and the disks.
So, consider next the disks.

The Previously "Paradoxical" V-Illusion, and S-illusion for the Flat Disks.
The perceived linear size, S' inches, of the lower disk on the page is larger than S' for the upper one, and they also have the same perceived distance, D' inches.
That universal finding for classic flat-pattern "size" illusions often has been referred to as the "size-distance paradox" because it cannot be explained using the dominant theory, the old apparent distance theory, stated by, S'/D' = Tan V, (known as the size-distance invariance hypothesis) which omits V' deg.



As can be seen, the old theory requires that, when both disks subtend the same visual angle, V deg, and D' is the same for both, the S' values must be equal (they cannot differ).
That "paradox" vanishes, of course, when one recognizes that the perceived visual angles differ.
So, for the present example, the reason the perceived linear size, S' in, for the upper disk on the screen becomes 17% larger than S' for the lower disk is *because of* the more basic"size" illusion that V' deg for the upper disk is 17% larger than V' for the lower one.
To explain that V-illusion for the disks, it is suggested that, as far as the visual system is concerned, with Dc = 20 inches for the screen and lower disk, the monocular pictorial cues "signal" that Dc for the upper disk is 5 times greater, so Dc =100 inches, for that disk *even though* it correctly appears at 20 inches.
Here are more examples for the Murray et al flat pattern, using Tk values from 4 to 7

inches.

Calculations For a Viewing Distance of, D = 20 inches to the Murray et al. Pattern.

For Tk = 4.0 in. the predicted relative V-illusion is 15% .
For Tk = 5.0 in. the predicted relative V-illusion is 22%
For Tk = 6.0 in. the predicted relative V-illusion is 22%
For Tk = 7.0 in, the predicted relative V-illusion is 26%

Why the larger Tk values?

For horizontal (side to side) orientating responses of the head, the expected Tk values are about 4 inches.
For small vertical head movements (simple elevations and depressions) the pivot point for such extensions is the atlanto-occipital joint.
Diagrams that locate that joint provide an estimate of at least 6 inches for the distance, Tk, between it and the eye(s).
Moreover, Tk clearly must be even larger than 6 in. for large orienting movements that quickly aim one's head up or down, so that one can better see (and hear) objects that demand attention from above or below the "straight ahead" horizontal direction of the erect head. For these head orientations the neck bends, so the effective pivot point is farther down the vertebral column than the C1 vertebrate.
Therefore, it seems appropriate to use even larger Tk values, say 7 inches, for illusions in which the targets lie one above and other, and the dominant pictorial distance cues are organized mostly vertically in the field of view, for instance, as in the "hallway floor" or the Ponzo "railroad tracks", or a "landscape" picture.
Don't forget that "height in the plane" is a well-known distance cue.
And, inverting an illusion like those mentioned above weakens the relative V-illusion.

Calculations For a Greater Viewing Distance of D = 30 inches.

The viewing distances used by Murray et al., were not specified, and might have been greater than 20 in.
So consider next a distance of D = 30 inches, so Dc = 30 in. for the lower disk, and Dc = 150 in. for the upper disk. The predicted relative illusion would be less than for 20 inches.
For instance,
For Tk = 4 in. a relative V-illusion of 10%
For Tk = 5 in. a relative V-illusion of 13%
For Tk = 6 in, a relative V-illusion of 15%
For Tk = 7 in., a relative V--illusion of 18%.

The Mandelbaum Effect (See articles by Roscoe).

During the Murray et al. fMRI measures, the mirror between the observer's eyes and the target screen would tend to make the eyes focus and converge a bit closer than the target screen. Therefore, Dc for the lower disk would be less than the target's distance, so a slightly greater relative V'-illusion would be predicted.

Actual Accommodation and Vergence Responses.

Another likely contributor to the relative V-illusion is perspective vergence (see Enright

(1987a, 1987b, 1989a) previously discussed in Section IV.
For the flat picture used by Murray et al, it would be expected that one's accommodation and vergence responses would change slightly when one shifts fixation (or attention) between the 'near sphere' and 'far sphere'.
These oculomotor changes, stimulated by the distance cue patterns, typically are larger than would be expect for 'perfect vision" of the images on the flat page (or screen), and would induce changes in V'/V in the direction of the obtained relative illusion.
Of course, these overt changes result only when one successively views the target objects. Murray et al., mention that such changes would have only a small effect for their picture.
At any rate, these flat pattern V'-illusions do not require overt differences in the accommodation and/or vergence responses to the two targets (disks) on the page. After all, such illusions persists with accommodation paralyzed, and with binocular viewing which (as Murrray et al note) allow only very small differences in the vergence responses for the two targets.

Conditioned Micropsia and Efference Readiness .

Changes in distance cues normally cause the brain to send neural impulses in the oculomotor nerves to the eye muscles in order to change accommodation and convergence.
At least since Helmholtz (1910, 1962) it has been known that various illusions of visual direction perception occur in special situations where this "motor command" or*efference* has been sent out, but does not make the muscles contract to move the eyes, say because the muscles are paralyzed.
Thus, as Helmholtz noted long ago, accurate perception of directions is controlled not by a supposed "feedback" from one's eye muscles, but by what the eyes have been "told to do" by the efference.

As noted earlier, this efference also has been shown to control the visual direction illusions of micropsia and macropsia.
Better yet, it turns out that the crucial factor is not the efference but the neurological "preparation" to send efference, which Festinger et al, called *'efference readiness'*(Festinger, Burnham, Ono & Bamber, 1967. Festinger, White, & Allyn, 1968).
The evidence for that includes flat pattern illusions for which a change in a monocular distance cue stimulus pattern evokes a change in micropsia without eliciting overt oculomotor changes.

Thus it can be said that an 'efference readiness' is established by distance cues, and it alters the relationship between V' deg and V deg.
In turn that means that what Murray et al. showed was that the cue-established neurological activity, 'efference readiness', somehow modifies the afferent neural activity between the retina and area V1, such that the isomorphic representation of retinal image size (R mm) in area V1 is changed .
Moreover, it seems clear that the 'magnitude' of that 'efference readiness' is such that, if it actually were sent to the muscles as motor efference, it would adjust the eyes to the distance being cued for a given target by the relevant cues.
It is fair to suggest that this distance is what I have called the target's cued distance, Dc cm.

That is, Dc cm is, in effect, a measure of the 'efference readiness.'

The Moon Illusion In Pictures (see Section I and Section IV again) .

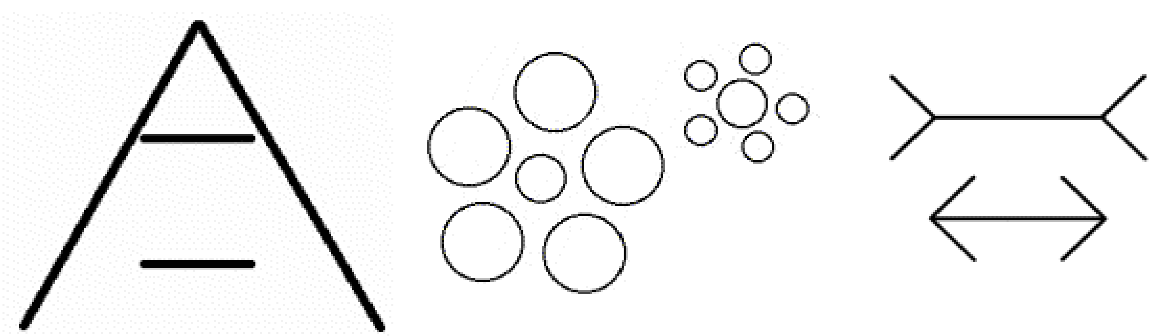
Studies of the moon illusion in pictures typically have used two disks that serve as moon images in a pattern that provides monocular distance cues that are expected to generate a pictorial illusion with a much greater D' for the portrayed 'horizon moon' than for the portrayed 'zenith moon'.
The 'horizon' disk on the page typically looks larger, both angularly and linearly, than the 'zenith' disk.

Enright (1987a, 1987b) experimented with such pictures.
Later, he reviewed such experiments (Enright, 1989a) and noted that they illustrate a visual angle illusion due to the less well-known V'-illusion of oculomotor micropsia/macropsia (as did McCready, 1965, 1983, 1985, 1986).

Enright (1989) also offered an explanation for oculomotor micropsia/macropsia that treats it as a normal perceptual adaptation for the fact that the eyes' rotation centers lie quite a bit anterior to head rotation centers.
He offered a model of the brain systems that would yield that effect.
His rational for that adaptation refers to the VOR reflex, so it differs from mine (the orienting response).

CLASSIC FLAT PATTERN ILLUSIONS.

The oculomotor micropsia explanation offered above obviously can be applied to many other flat pattern illusions that have remained unexplained, such as the Ponzo illusion, the Ebbinghaus Illusion (Titchner's circles) and the Mueller-Lyer Illusion, as shown in the diagram below.



For many decades researchers have pointed out that the context patterns for the two equal targets in each illusion happen to be distance cues that can create a 3D pictorial illusion, with one pictured object looking farther away and a larger linear size than the other one.
So far, so good.
But the nearly universal explanation has used the apparent distance theory which , as noted earlier, *requires* that the targets appear the *same angular size* and at different distances so that they will look different linear sizes.
So, it does not (cannot) even describe the more interesting visual angle illusions.

The present approach to those visual angle illusions can apply the simple equation.
[The illusions above have been arranged to let "height in plane" be an additional cue.]

For instance, for the Ponzo illusion, it is easy to see that Dc for the upper line would be about twice Dc for the lower line.
At a viewing distance of 20 in, with Tk = 4 in. that predicts a relative illusion of 9%.
And, with Tk = 6 in, an illusion of 13%.

For the Ebbinghaus illusion, Dc for the upper ("farther") circle also might be twice Dc for the lower ("closer') circle (because the large context circles are twice as large as the small ones).
The predictions thus are about the same as above.

For the Mueller-Lyer illusion, one analogy is that the upper figure resembles an open book we are looking into, and the lower figure resembles an open book, but we are looking at its outer spine.
Those cues somehow can make the spine look closer than the interior edge, and that would create the relative micropsia V-illusion .
[An unpublished equation that can evaluate Dc values for that pattern is too cumbersome to derive and use here.]

CONCLUSIONS.

The Murray et al experiments fully support the proposal that many major classic flat pattern illusions start as visual angle illusions controlled by distance cue patterns that are able to create a 3D pictorial illusion for most observers.
Likewise for the classic moon illusion.
The task is to explain the V-illusions.

Murray et al showed that the angular size illusions result from some sort of activity that intercedes in the neural pathways from retina to cortical area V1 (Brodmann area 17) to alter the neural representation of retinal image size in Area V1.
That means it alters the perceived visual angle, V' deg, value for an otherwise constant value of V deg..
My proposal (McCready, 1965, 1983, 1985, 1986) has been that the relevant distance cues establish different efference readiness values that somehow alter the relationship between V' and V.
An explanation for such illusions is that they are examples of the more basic and ubiquitous illusion of oculomotor micropsia/macropsia.
And, an explanation for oculomotor micropsia/macropsia is that it serves a useful purpose by altering the perception of direction differences (V deg) to make them more accurate predictors of rapid orienting responses, especially of the head.

The simple equation that describes the amount by which such "corrections" of V' deg should be made, has been shown to fit the data from many published experiments very well.
That equation is shown here to fit the Murray et al. data very well.

Therefore, it can be said that the illusion that Murray et al. measured is due to oculomotor micropsia..
This present analysis can be applied to other flat pattern illusions and usually fits them quite well.

At this time (May 2007) no other published theory of such illusions can explain them satisfactorily.

NOTE.
The simple equation for micropsia used here, V'/V = Dc/(Dc + Tk) , describes only micropsia (V' less than V) for all distances.
It needs to be modified so that it will also describe macropsia (V' greater than V) for large cued distances (see the research of Higashiyama).
For instance, some published data indicate that V' may equal V deg (no V-illusion) for objects at the resting focus distance of 1 or 2 meters.
And, V' becomes smaller than V' for closer targets but larger than V deg for targets beyond that distance.

THE MOON ILLUSION EXPLAINED

Finally! Why the Moon Looks Big at the Horizon and Smaller When Higher Up

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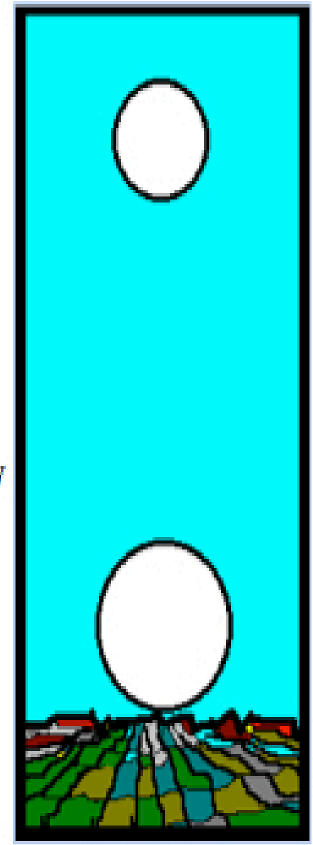
Revised November 10, 2004.



Nearly all people will agree that the picture at the right represents approximately how the horizon moon's size looks when compared with how it looks later, with the moon higher up in the sky.

If that picture resembles what you usually see, and you wonder why this famous *moon illusion* occurs, you should read the following article; for, as all illusion researchers know, a new explanation is needed:.

The picture mimics an angular size illusion; the horizon moon looks a larger angular size than the zenith moon. Most moon illusion researchers now accept that the illusion begins as an angular size illusion. However, that idea has not yet reached the general public.

Instead, the explanations commonly found in textbooks and the popular media, including virtually all "moon illusion" discussions on the internet, do not mention the basic angular size illusion. Such articles repeat the ancient idea that the horizon moon looks the same angular size as the zenith moon, but looks farther away so it logically looks a larger physical size. It often is said to look farther away due to a "flattened sky dome" illusion or due to changes in 'cues to distance' as illustrated by the "Ponzo Illusion." These explanations require that the horizon moon must first look farther away. But, all researchers know that very few people see it that way. That minority moon illusion is not mimicked by the picture above.

The picture mimics, instead, the angular size illusion that nearly all people have.
For most people, the horizon moon looks a larger angular size than the zenith moon, and the horizon moon "looks closer" than the zenith moon, because it correctly looks about the same physical size (it appears to be the same moon).
For most of the rest, the horizon moon correctly looks about the same distance away as the zenith moon, so because it looks a larger angular size it also looks a larger physical size than the zenith moon.

The scientific challenge has been to explain why those equal angular sizes look unequal.

This article is long for three reasons.
1. It advances the relatively new idea (1965, 1970, 1985, 1986) that, for most people, the moon illusion begins as an angular size illusion which has several possible outcomes.

2. It reviews in detail the very few explanations of the illusion that vision scientists are paying the most attention to (and still researching). These theories are not simple.

3. It reviews in detail the latest theory (1985, 1986, 1989) that the moon illusion is an example of the less familiar, but ubiquitous, "size" illusion known as oculomotor micropsia/macropsia. Explanations for oculomotor micropsia then are reviewed.
For the moment, it seems to be the most satisfactory explanation.

The initial version of this article was placed on this web site in May, 1999 .
Major revisions were made in December 2002.
This entire article was revised on November 10, 2004.

Then, extremely important research on visual angle illusions was published in March 2006 in *Nature Neuroscience*. The article is, "The representation of perceived angular size in human primary visual cortex," by Murray, S. O., Boyaci, H., & Kersten, D. (2006).
It fully supports the approach advocated here, so it is reviewed in the "Technical Note added June 7, 2006., in the Introduction and Summary Section,

It is analyzed in detail in Appendix B (posted February 5, 2007).

Advanced students also should consult the excellent book, "The Mystery of the Moon Illusion," by Helen Ross and Cornelis Plug, published in September 2002. It offers the most complete and up-to-date review of research and speculation on the moon illusion. They strongly advocate that the moon illusion begins as an angular size illusion.
This present article is the only website they refer to (as it was in 2001).