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Theoretical Perspective

A History and Experimental Analysis of the Moon Illusion

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The moon illusion is one of the most ancient and persistent questions of natural philosophy. The investigation of this phenomenon has played a crucial role in the genesis and ongoing development of the field of perception, being a major point of consideration for Ptolemy, Alhazen (Ibn al-Haytham), Leonardo da Vinci, Descartes and George Berkeley. Relatively recent empirical studies have focused on explanations of the illusion created by contrast with the horizon (Ponzo illusion). However, a careful review reveals that the far more dramatic appearance of the moon illusion still remains unsolved. This paper takes a historical view of the explanations over three major paradigms: the classical, the experimental, and the modern perceptual theories. The natural tension between mathematics and observation is also a sub-plot.

Keywords: history of science, gestalt, phenomenology, perception, moon illusion, Alhazen, Leonardo da Vinci, structure of scientific revolution

Have you ever noticed how big the moon looks on the horizon on certain nights? I took a vacation to the southern tip of the Baja Peninsula in Mexico a few years back. One night the rise of the moon was beyond belief. I felt as if I could touch it. It seemed to fill half the sky. I dashed for my camera and took a photograph, eager to share the remarkable moonrise with friends. To my disappointment, the moon appeared tiny, no bigger than usual. Was I hallucinating? I could not let it go. When I explored this phenomenon further, I learned that this experience is fairly common. It refers to an optical illusion, a familiar problem, to those in the field of visual perception, commonly known as the moon illusion. Some believe there is no illusion at all, but that it can be explained by the laws of convergence. Yet a cursory examination of the anticipated size of the moon based on these laws will reveal a sharp difference between observation and theory. Others believe only a minor illusion occurs due to the contrast of the moon against the horizon. Though this may be true on some nights, the variability in the size of the illusion makes it clear that this does not explain the more remarkable experiences of an enormous moon on other nights or why it changes so drastically over the course of the seasons.

Each generation appeals to the advances it has made in the sciences to "finally" provide the accurate explanation of the moon illusion. Viewed as a history, this series of chest-pounding assertions and claims as to the "true" nature reality of reality confesses the role of imagination in scientific reasoning and the truly dynamic nature of scientific explanation. The moon illusion thus acts as a sort of Rorschach test against which the scientific projections of each age can be catalogued and observed. As a glaring anomaly of modern optical laws, it, perhaps, provides the keystone for a more complete perceptual paradigm: reflection on the daily occurrence can direct our search for a natural law which more accurately describes the phenomenon of vision and its "natural language."

Any discussion of the moon illusion needs to consider three common observations: the apparent size of the moon in relation to its distance, its brightness, and variability of its size. These rest on several seemingly puzzling physical facts: (a) though the moon always looks larger on the horizon than when at its apogee, it is actually physically closer to the earth when at the horizon (by the distance of half of the earth's rotation), (b) subjective experience of the range in size increases between twice and sometimes, even ten times as large, depending on atmosphere, location on the earth of the sighting, and quality of the light, and (c) on the evenings of the largest "moon illusions," the moon is sometimes reported to be even closer than the horizon. If you try to take a photograph, the most pronounced illusions will appear tiny in the photograph. Looking through a cardboard tube or telescope will make it look smaller, though closing one eye will not make it go away.

The moon illusion provides a good illustration of the "pendulum" theory of history (Holton, 1978; A. Blumenthal, "lecture", January 27, 2007) in that several schools have "swung" into vogue at times with similar themes being discussed in different guises. The history of the moon illusion also provides a particularly good illustration of Kuhn's paradigm-model (Laudan, 1980), in which a phenomenon is interpreted through a particular lens or "model from which spring particular coherent traditions

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of scientific research" (Kuhn,1969, p. 10), as we can trace the explanation of the moon illusion in multiple paradigms.

Though current experiments concerning the moon illusion may suggest a direction towards which future investigation may be fruitful, its current status, as still unresolved, nicely demonstrates the lack of a teleological end even for scientific history. As cultures, we simply direct attention to arbitrary locations, build a knowledge base around particular epistemologies and then move into adjacent fields of enquiry, sometimes forgetting important points and often motivated by the political and institutional aims of a given era (Franchini, 1969).

Neither science nor history is cumulative or progressive. Though it is true each age creates new knowledge, it also forgets previous knowledge and this is as much due to political discourse as a scientific one (e.g. the burning of the library at Alexandria). Our history depends upon the means by which these histories are encoded (Kuhns, 1996, p.160-167; Franchini, 1969) and the paradigms through which they are understood. To make a simple analogy from our lifetime, betamax videos can provide no history when there are no betamax players. The same goes for entire languages. I hope to demonstrate this same perceptual process occurs in scientific explanations, as in vision when describing an illusion. Each paradigm privileges certain epistemologies over others and requires a hermeneutic to unlock its interpretation.

This paper is broken into two main parts. The first part is a selective history highlighting the main philosophers and their experiments in the literature. This includes a systematic discussion of the experiments done to rule out certain answers. In the next section, an analysis is provided in which several threads for future exploration are provided for the reader. I end with my own humble opinion.

History

The amount written on the moon illusion over the years is tremendous (Ross & Plug, 1989a). Every major natural philosopher seems to have at least contemplated the phenomenon though not all give an assured answer (for example, neither Newton nor J. J. Gibson venture a guess). The review of the scientific literature is organized into three major time periods: classical (Aristotle, Ptolemy, Al-Kindi, Avicenna (Ibn Sina)), experimental (Alhazen (Ibn Al-Haythm), Da Vinci, Kepler, Descartes), and the modern which includes both perceptual (Berkeley, Ponzo, James, Schur, Boring, Kaufmann and Rock) and neuropsychological (Tulving, McCready, Enright) schools.

For large stretches of time, the moon illusion is considered "solved" by a dominant paradigm yet advances in technology (i.e.,camera, space travel), knowledge in relevant fields (e.g., publication of Vesalius' *Fabrica*) and, more often, acute observations cause certain solutions to be ruled out, thus re-opening channels of discussion by scholars and scientists. Over time, the question has moved from the domain of astronomy to optics, punctuated by observations of ocular physiology, to the apparent paradoxes of visual perception. Unfortunately, each approach only sometimes includes the results of the previous perspective(s). The classical theories lay down the basic concepts and general rules of optics in dialogue with largely astronomical observation. The general conclusions of the classical theories create the boundaries through which subsequent discussion is framed for the experimental schools. However, the modern perceptual theories lack the grounding of vigorous mathematics found in earlier theories. It is interesting to note which aspects of the debate have passed onto the present schools of perception (and which ones have been forgotten).

Classical Theories

Like most thinkers, the classical philosophers produced theories in particular historical eras in which their dialogue was embedded. They used the language and assumptions of their paradigm and often defined their solution in contrast to opposing views of their time period. The classical era was marked by two main schools, most prominently defined by their epistemology, each privileging certain means of knowledge. The peripatetic schools favored natural observation. This contrasts with the schools which favored the proof of mathematical analysis and demonstration. This ongoing debate and dialogue from the classical era is often framed within the terms of the intromission and extramission debate (Lindberg, 1978).

As historians of medieval science point out (e.g., Lindberg, 1967, 1976, 1978; Sabra, 1978, 1987), historians tend to simplify this debate, often overlooking the sophistication of the arguments and the fact that, mathematically, the extramission theory allows mathematicians to predict and accurately represent experience in three dimensions under many conditions. Aristotle's critique of the Platonic perceptual position, found in De Sensu 2.438 (Lindberg, 1978, p.217), is that it is built upon a foundation that does not seem acceptable to natural observation: "It is unreasonable to suppose that seeing occurs by something issuing from the eye; that the ray of vision reaches as far as the stars, or goes to a certain point and there coalesces with the object, as some think."

Aristotle (322BC/1962) takes the position that vision occurs in the space between object and observer, through which the form of the object, or *simulacran*, is imprinted directly onto consciousness. From this theory of vision naturally flows his explanation of the moon illusion, found in his text concerning natural phenomena, *Meteriologica* (Aristotle, 322BC/1962): namely, the moon illusion is caused by the atmosphere; the moisture in the air magnifies the moon's image. Visually, Aristotle attributes the illusion to refraction of light by the atmosphere combined with the reflection of light off of the eye itself. This is the first known scientific explanation of the moon illusion (though mention of the illusion occurs in more ancient texts such as the clay tablets of Nineveh and Babylon (Ross & Plug, 2002, p.3)).

Whereas Aristotle's observation is a passing remark, a more detailed analysis and exploration of the moon illusion in ancient times comes from the Greek philosopher-astronomer-mathematician, Claudius Ptolemius (Ptolemy). Ptolemy comments on the moon illusion three times: in *The Almagest*, *Optica*, and *Planetary Hypotheses* (Sabra, 1987). The range of subjects reflects the multiple fields to which it pertains: mathematics, anatomy, and physiology, as well as astronomy and physics. Through each of these individual lenses, Ptolemy offers an explanation of some aspect of the illusion. The passage in *The Almagest* is the one most quoted as being his position (Plug 1989b), drawing on the analogy of the "apparent enlargement of objects in water, which increases with the depth of the immersion." (Ross & Plug, 2002, p.7). The best critique of this Aristotelian position comes from Ptolemy himself (Sabra,1987). In his Optica, he points out this explanation does not hold for the moon illusion as the observer would be in the denser medium of water and the moon in the lighter medium of space. If anything, the presentation of the moon should shrink.

Euclid's *Elements* predicts proportion of size to distance. Applying a particular axiom (ax. 1:2), Ptolemy develops the original law of convergence for visual perception. This law is based on a crucial assumption: the frame of reference as egocentric. That is, he calculates his theorems from the point from the eye to the object in the field. The great distance of the moon would assume a dot of light. Its huge size contradicts the prediction made by Ptolemy's (and later, Emmert's) Law of Convergence. Since the moon illusion is the most glaring anomaly and evident illustration of the weakness of his system, it plays a pivotal role. This accounts for the obsessive attention placed on the phenomenon throughout Ptolemy's career.

Ptolemy returns to this subject in his *Optica*. Here, Ptolemy articulates what is known today as the size-distance invariance principle. It is worth looking at the translation directly as it articulates the main points that will be later tested experimentally (transl., Sabra):

1. For, generally, just as the visual ray, when it strikes visible objects in other than what is natural and familiar to it, sense all the differences less, so also its sensation of the distances it perceives is less
2. And this is seen to be the reason why, of the celestial objects that subtend equal angles between the visual rays, those near the point above our head look smaller, whereas those near the horizon are seen in a different manner and in accordance with what is customary.
3. But objects high are seen as small because of the extraordinary circumstances and the difficulty in the act of seeing.

So here, Ptolemy explains the three basic conditions of the size-distance paradox:
(a) perception of distance is dependent upon boundary conditions, (b) the angle at which we view objects plays a confounding role with brightness and distance, especially in regard to celestial viewing, and (c) the human act of vision plays a role.

In yet a later book concerning astronomy, *Planetary Hypotheses*, Ptolemy comes to the conclusion that the moon illusion is "an error that occurs to sight on account of the difference in perspective (unique) to large distance" (Sabra, 1987, p.160). This time Ptolemy notes the moon illusion as a problem of perception in a particular case: large distance beyond the normal range of convergence. It is interesting to note that he has abandoned his earlier theories of the confound between angle, brightness and distance. Most likely, he simply cannot enable them to work mathematically. So from an original view, grounded in Aristotelian physics, he moves to an optical one and finally to one based on human perception. Of course, as Ptolemy is assuming a geo-centric view of the world, increasing anomalies and mathematical difficulties with his view of extramissive light may have been confounded by his astronomical assumptions. Yet this trajectory from a confident physical position to a description of a physiological mechanism to simply calling it an error is common to many natural philosophers.

The debate among various other philosophers centers around the basic Aristotle-Ptolemy split. In the Islamic world, scientists mirror this same back-and-forth, though the arguments and mathematics become more sophisticated, both adding strength to each position and also exposing more fallacies in the opposing theory. Al-Kindi "solves" the illusion with mathematical proof. Ibn Sina defends and strengthens Aristotle's position. I'd like to highlight Lindberg's (1978) point that these philosophic differences naturally grew out of their individual epistemologies: one was based on mathematical predictability while the other on natural observation. In a good illustration of a field in a crisis (Kuhn, pp.66-76): both intromissionists and extramissionists privilege specific knowledge which best matches their interpretations. The moon illusion again plays a crucial role as it becomes the strongest evidence for natural observation and the main obstacle to a mathematical claim on reality.

Alhazen (Ibn al-Haytham) reconciles these two schools. Alhazen begins with an assumption of allocentric space: the purpose of visual perception is to receive light. This is the cornerstone of his *Optics* (Transl. Sabra). He ridicules the idea of light consciously moving from the eye to the object, abandons the idea of simulacran through which forms are imprinted in the mind and, instead, takes the position of punctiform analysis of individual rays of light reflecting off all of the points in a surface, arriving perpendicular to the eye.

It is important to realize that Alhazen's insights grew out of a criticism of the dominant paradigm. He draws attention to the contradictions in Ptolemy's positions, highlighting the shortcomings of the application of Ptolemaic *Optics* (Sabra, 1966). He also makes a clear distinction as to what his claim is: he is seeking to understand direct vision. The role of vision in constructing space is excluded in this text. In a beautiful microcosm of his larger optical theory, Alhazen provides an excellent commentary on Ptolemy's positions. He accommodates Aristotle's observations and maintains the integrity of Ptolemy's mathematics while expanding its application by an algebraic order.

Alhazen's first comment on the moon illusion appears in his *Commentary on the Almagest* (Sabra, 1987). Here he attempts to provide the geometric proof through which size of the moon could be magnified by refraction. Thus, he protects Aristotle's thesis. The moon's light, when refracted by the atmosphere, could be made to look much larger. He demonstrates this through mathematical proof. Alhazen's next comment on Ptolemy's version of the moon illusion is to be found in *Solution of Difficulties in the Almagest Which a Certain Scholar has Raised* (Sabra, 1987). As his knowledge of optics grows, we see Alhazen wrestling with the reconciliation of Ptolemaic and Aristotelian orthodoxy. He abandons his own earlier position.

In a clean, observant, and erudite style, Alhazen provides his most complete statement on the moon illusion in Book III (On the Errors of Direct Vision), Chapter VII (Errors of sight in inference when the illumination in the visible object falls outside the moderate range) of his *Optics* (Sabra, 1989). He begins by explaining the conditions under which sight perceives size: "sight perceives size from the magnitude of the angles subtended at the center of the eye and from the magnitudes of the distances of the visible objects and from comparing the magnitudes of the angles to distance." (Sabra,1987, p. 237).

The moon illusion obviously does not meet the conditions set by other perceptions of depth. It could be said that Alhazen provides an intervening objects-aerial perspective hypothesis: that is, we consider figure in relation to ground cues. Since the horizon moon finds itself in a terrestrial frame of reference, the moon, based on its brightness, is placed in relation to other objects. Just as in aerial perspective when a brighter object appears farther, the mind makes an unconscious inference against a flat sky. Alhazen's insistence that the size of the moon is perceived rather than actual remains a central tenet for explanations moving forward.

He recognizes, however, that he has not explained certain aspects of the moon's appearance. His theorems of subtended angle, though could account for stars, do not match the apparent size of the moon at its known distance. He, like Ptolemy, does adjust for variation from atmospheric refraction. He states that it is a tertiary factor accounting for the variation in the size. Much like Ptolemy before him, Alhazen, in the end, defines the moon illusion as a psychological problem (Hershenson, 1989, p. 22), though still maintaining a possible physical cause: he classifies the moon illusion as an error of illumination.

Alhazen's achievement can hardly be overstated: he provides a new theory of light, an applied mathematics, and replicable model. A case can be made to date the Scientific Revolution from the publication of his *Optics*. His explanation of the moon illusion is an exquisite piece of natural philosophy, specifically accounting for aspects of perception and light within his broader system of cognition. His application of logic bound by phenomenal experience is remarkable, making subtle and insightful distinctions in the categorization of sensation from inference. Furthermore, Alhazen introduces a new methodology to the study of the moon illusion: an experiment with a verifiable hypothesis based on a mathematical model. He makes predictions of celestial events based on this model and the reflection of rectilinear lines. In Europe, Roger Bacon, Johannes Kepler, Leonardo da Vinci, and Descartes are among those who follow his lead (Lindberg, 1967). Copernicus is able to establish his proof of a heliocentric universe using theorems derived from Alhazen such as 'Urdi's Lemma and Ibn al-Shatir's model for the motion of the moon (Saliba, 1999).

Alhazen's *Optics* marks the end of the classical era and invites a new one: one of experimental method based on quantifiable mathematical analysis. Future studies build on his basic paradigm: one which accounts for the process of vision (rather than 'seeing') within allocentric space while making subtle, clean, and exact distinctions between sensation, perception, and cognition. Alhazen's intervening objects hypothesis becomes the most cited explanation for the moon illusion not only for his age but up to the present day.

Experimental Constructs

The experimental era is marked by the introduction of Alhazen's thought, extended by the innovations in anatomy being made in Europe, especially by the publication of the *Fabricus* by Vesalius. Alhazen's *Optics* suggests its own questions: limited by the anatomy of Galen, it cannot provide a full anatomical explanation of the physiological mechanism. Alhazen is puzzled as to how the eye is able to receive rectilinear light while excluding refracted light without sending the visual system into confusion. Concerning the moon illusion, nearly every major thinker during this age follows Alhazen's intervening objects theory with minor observations. The next major innovation in this scientific discourse is provided by the curious Italian, Leonardo da Vinci.

In the early historical texts of perspective of the thirteenth century written by Bacon, Peccham, and Witelo, all three authors follow Alhazen and present an intervening objects theory as to the cause of the moon illusion (Lindberg, 1967). One of the most striking examples of the European conversion to Alhazen's optics is demonstrated dramatically in the notebooks of Leonardo da Vinci (Pedretti, 1977). Da Vinci is noteworthy because he introduces a new variable: the construction of space. He moves beyond the assumption of flat space into a more nuanced theory of curvilinear space (Pedretti, 1963).

Originally a student of Alberti (Kemp, 1977, p.130), da Vinci falls out of favor with the visual pyramid principles of perspective. This parallels a change in his general attitude found only in his later notebooks (1508) in which "he attempts, far more consciously and rigorously that in his early science, to make the tightest possible correlation between natural structure and natural law" (Kemp, 1977, p.138). In his attempt to achieve this correlation, he abandons faithful obedience to the thinkers of antiquity and, instead, following Alhazen, adopts a position of experimentation. An early suggestion by da Vinci is that the pupil must be a certain size to witness the moon illusion: that an increased aperture lets in more light which, in turn, creates a larger array. According to da Vinci, if we are to account for the curve of the horizon, the illusion can, in part be due to the angle of difference between object and ground based on gradual movement. This observation flows naturally from an allocentric understanding of light (and is not explained by Alberti or Ptolemy). In an example (that looks much like the later Gibson cylinders), da Vinci explains lateral foreshortening in terms of spheres in relationship to curvature of the eye. Building on the previous observation of the curved horizon, the illusion of the moon can be understood as being due to spherical aberration based on contrast of spheres over curved horizon. Da Vinci builds on this again more intricately in the *Codex Leicester* in which he names the secondary light source reflecting off of the surface of the earth as the confounding variable which causes the unexplained magnitude of the moon illusion (Richter, 1970).

The next major advance during this era comes from Johannes Kepler who extends Alhazen's optical presentation of perpendicular light to the reddish concave surface of the retina (Lindberg, 1976, p. 178-202). This is the same Kepler who has already perfected the Copernican view through his calculation of elliptical orbits. While observing the lunar eclipse in 1600 as the assistant to Tycho Brahe, he notices that the moon's diameter shrinks (ibid). How could this be? When he discovers that this was predicted by Alhazen, he immediately shifts his focus from astronomy to vision and immerses himself in Alhazen's *Optics*.

Building on the ocular studies of Vesalius's *Fabrica* and Maurolico, who illustrate the influence of the lens, Kepler extends the insights of anatomy to the study of optics. Starting with the outer eye, Maurolico points out that the human eye has two lenses which can become either concave or convex. While Maurolico uses his insight to create eyeglasses to correct vision, Kepler is the first to recognize its importance to completing Alhazen's mathematical optics (Lindberg, 1976, p.108). Kepler also uses da Vinci's analogy of the camera to describe the process of vision, though with more detail through the aperture of the pupil and lens in focusing perpendicular rectilinear rays. The two lenses play a major factor in this theory as it solves one of Alhazen's problems—how can we see particular forms if light is reflected off of all surfaces in every direction? The answer is that we focus through the bending of two lenses within the locus of attention. As a natural extension of his logic, the moon illusion occurs due to the increased proportion of space of the moon projected onto the retina when one lens is concave and the other convex in both eyes. However, Kepler realizes the moon illusion cannot be predicted on the basis of retinal image alone and holds to the position of Alhazen: sensory information of the retina is being influenced by the context (Plug and Ross, 2002, p.176). More importantly, Kepler is able to rule out certain suggestions. Kepler rules out the moon illusion as an astronomical event. And he also dismisses the angle of regard as he determines both the horizon and zenith moon subtend the same angle on the retina (Egan, 1998, p.605).

Descartes discusses the moon illusion in the sixth book of his *Optics* (Descartes, 1985[Trans. Cottingham, J., Stoothoff, R., and Murdoch, D.]). Descartes' studies in convergence and accommodation extend Kepler's retinal image into binocular focus and extends the process of vision farther into the brain, into the Cartesian "theater" where these retinal images are combined. Just as Alhazen is limited by the medical knowledge of his time, so, too, was Descartes able to speak only speculatively about how mental processes occur. Descartes assumes a model in which the brain makes internal calculations based on distal cues to determine distance (TAD Model) (Egan, 1998). He also supports the intervening objects theory, yet using the analogy of a computing machine, claims this experience is based on an exact, internal mathematical calculation taken from each eye individually. His mathematics highlight the contribution of each eye, making a distinction in Kepler's perceptual theory and providing an explanation of Panum's area – the overlapping area of the two fields of vision which creates the impression of depth.

The intervening objects theory (usually with some variation of the flat sky or aerial perspective) is supported by many others throughout this era: Huygens, Helmholtz, Wundt (Plug, 1989b). Using an opthalmometer of his own making, Helmholtz (1877) provides an interesting explanation of the size-contrast illusion (of which the Ponzo illusion is a type). He notes that humans automatically compare two frames of reference: a horizontal view and a vertical one that each survey a vast difference in degree. He also highlights the role of color in the interpretation of proximity.

Following Alhazen, most scientists come to understand the moon illusion as an error of sight. It is tabled and categorized as an anomaly and pushed into the column of unsolved problems. Aside from da Vinci's interlude on space and secondary light sources and Helmholtz's color theory, very little deviation from the standard suggestions emerge.

Modern Era

For Berkeley, the moon illusion is a perfect illustration of his theory of vision (Berman, 1985). Berkeley discusses the illusion extensively in *An Essay Toward a New Theory of Vision*, sections 67-78. George Berkeley points out under what narrow circumstances explanations are valid and posits the first modern perceptual account of the moon illusion. Berkeley believes the moon illusion is caused by some relationship between the angle of our eyes, the vestibular system, and cognition (Berman, 1985). Berkeley is a modern paradigm creator, drawing attention to anomalies of mathematical application and highlighting human perceptual apparatus.

Berkeley makes a devastating critique on optics: their laws are no laws at all. They cannot account for the illusion. In its place, he points to the role of learned cues: we associate closer distances based on our tactile experience; larger ones with our auditory experience. Perception is not a camera. He makes some interesting claims: the moon illusion is caused by an interaction of the vestibular system and angle of regard that somehow causes us to perceive it as larger. It follows from his theory that size is a learned cue from our experience in relation to objects we know. Yet he dismisses the intervening objects theory by saying the moon is just as large when objects are blocked by a wall or seen over an ocean. Berkeley claims our experience of the atmosphere provides the main distal cue (Berkeley, 1995; Berman, 1985).

In the rise of the Berkleyan perspective, we see another era beginning in the study of the moon illusion. Theories become more focused on the individual brain and how it interprets experience. Whereas optics (and its corresponding physiology) becomes a mature science in both mathematics and medicine, the focus of perceptual studies becomes increasingly narrow. Perception emerges as the resistance to the field of materialist optics. The interaction of space and experience of luminance largely disappears from optics but re-appears in the neuropsychological literature. Perceptual studies favor different epistemologies which, in turn, privileges different data.

The heirs of the modern era are no longer bound by the geometric axioms and mathematical precision of the behavior of light upon which the theories of Ptolemy, Alhazen, Kepler, and Descartes are based. Subjective experience takes full stage in the modern, Anglo-American study of the moon illusion.

The questions of astronomy and optics are largely dismissed by Berkeley and later scholars in lieu of a more focused research tradition that goes back to direct observation. and the reproduction of the illusion in experimental settings. The continued increase of medical knowledge concerning vision and the brain also pushes perceptual researches to seek exact physiological mechanisms in individual brains.

Two experiments in the first quarter of the century are particularly striking. In line with Berkeley's emphasis on the more dramatic presentations of the moon illusion, Hans Hinner (1919) takes eyewitness accounts from an observatory in the Black Forest at which location the illusion occurs dramatically. His observation is worth noting because it does not seem to have an answer in terms of optical theory: "It is downright astonishing when, in the light of the setting sun, we suddenly see clearly houses and trees at a distance of 50 km, which shortly before, and with more intense illumination of the sun, we could not even see with fieldglasses" (Ross & Plug, 2002, p.84).

William James describes his brief field experiment with the moon illusion in *Principles of Psychology* (p.92-93). If, as Molreaux claims, the moon illusion disappears when seen through a tube, it follows that the illusion is caused by some faculty of binocular vision. If this is the case, would the cause of error also magnify if we were to watch the illusion with binoculars? James' reports that the moon does not look bigger but that it does appear closer. He introduces *extensity*—the experience of varying proximity of an object under static conditions of its size in the visual field--as a separate distinction in the perception of a distant object. He is unable to name the factor in the environment or internally, however, which causes variability in extensity.

Another interesting field experiment worth noting is that of Lohman (1920). Lohman watches the moon rise from the bottom of a hill until the illusion disappears. He then climbs the hill and the illusion re-appears. He takes his results to mean the illusion is caused by proximity of the moon to the horizon (Ross and Plug, 2002, p.118). This could be considered an experiment in the tradition of figure-and-ground as relational cues for perception.

Ponzo (1913) provides a greater level of detail to this explanation: what he calls 'angular contrast'. The basic idea is that the visual system determines size by looking at objects in the environment in relation to each other. The gestalt movement, along the same philosophic lines, makes several insights which pertain to the illusion. Erna Schur, working with Kohler (Koffka, 1935), provides the central experimental study. She is able to produce both the illusion of increased size and some degree of extensity. Schur's experiments are interpreted by Koffka as providing "substance to our radical rejection of (size constancy)" (Koffka, 1935, p.95). Schur produces the illusion in which "most people judge the horizon moon to be closer than the zenith moon" (Egan, 1998, p.609).

Here we are beginning to move from Alhazen's flat sky to half-hemisphere assumptions of concave space. Relevant to this line of thinking is Kohler's (1967) ping-pong glasses' experiment: in which spatial depth radical changes by looking through a white, convex filter.

Over the course of four years, Boring (1940a, 1940b, 1940c, 1943) publishes four papers, testing for change in angle from the eye and head, angle of elevation, and binocular vision. Boring uses mirrors to see if the illusion will change in relation to the angle at which it is seen, since the mirror rather than the head can be adjusted. The use of mirrors to explore the moon illusion can be dated to Theon the Younger and the School of Catatropics centered in Alexandria in ancient times (Thorndike, 1923). Boring comes to two conclusions: the illusion is caused by eye elevation (not vestibular position) and that binocular vision plays a major role. He discounts the intervening objects hypothesis since he is able to produce the illusion both with and without intervening objects.

Boring's research is strongly challenged by Kaufman and Rock (1962; 1992). Kaufman and Rock (1962) conduct a simple yet powerful demonstration in which they project a moon and terrain onto a screen, wait one minute and then remove the terrain. As they repeat this demonstration, the illusion increases and decreases. Thus, it may not be the intervening objects that create the distal cue but the ground. The strongest critique probably comes from Frances Egan (1998) who observes the lack of distinction between definitions of registered and perceived distance. Kaufman and Rock explain (Egan, 1998, p. 617): "The term *registered distance* . . . was meant to imply that the perceptual system automatically takes sensory information correlated with distance into account when computing distance." Egan points out that Kaufman and Rock cannot define what they mean by the term "sensory information". Yet the fact that they maintain its openness, in part, is perhaps due to a rule out of all the variables they did account for. Kaufman and Rock (1989) also note that though they were able to create the illusion from angular contrast, they were unable to reproduce Schur's findings concerning the closeness of the moon. Since this study controlled for all but one variable, they highlight that variable: stray light.

The ongoing discussion strangely echoes the intromission-extramission debate. Ptolemaic views again come into vogue. For example, in a contemporary study, Kaufman and Kaufman (2000) provide equations based on distance "from eye to object" (p. 503). Kaufman and Kaufman continue to apply Euclid in a Ptolemiac manner-- using the same axiom (1:2) that Alberti did in his laws of perspective. Their mathematics do not use the allocentric proofs created by Kepler and Descartes based on Alhazen's general principles. Kaufman and Kaufman say: "Because gradients in angular size give rise to perceptions of distance, perspective is described as a Euclidean cue" (p. 505). At this distance, though, perspective of distance is caused by cues of illumination (if we follow Alhazen). Light from the object and its angle (not distance from us) determines size and form.

In a more recent article Kaufman and Kaufman (2000) produced a very good stereogram of the moon illusion. This would suggest that binocular vision within Panum's area may play some role in the perception of the illusion (reversing a previous position by Kaufman and Rock) and backing the suggestion offered by Descartes and James. Dali (1977) produces this same effect with paint. A good model does not necessarily offer a valid proof.

Berman (1985), in defense of Berkeley, notes with the same disdain the English Berkeley had for the Frenchman Descartes, that Kaufman and Rock's experiments are looking only at the most minimal of illusions along a fronto-parallel plane. What about the illusion that occurs 7-10 times as large? Kaufman and Rock, like Descartes, highlight the size-distance paradox. The Boring-Berkleyan camp privileges the angle of regard. It is interesting to note that both of these positions are those articulated by Ptolemy.

In another epistemological approach, we see the continuation of the understanding of vision moving deeper into the brain. In the earliest neuropsychological explanations, Tulving et. al. (1959) explains the moon illusion in terms of oculomotor or divergence micropsia (the experience of patients with a lesion in the occipital lobe of the right hemisphere who suddenly experience objects suddenly larger or farther than others). McCready (1985; 1985b) presents what Ross & Plug (2002) call the "most important distinction on the moon illusion made since Alhazen" (p.168), which is "perceived extensity". However, McCready does not give a systematic explanation of the process, articulate a specific mechanism or name the distal cue accounting for the variability.

Enright (1989) reintroduces the angle of regard theory, though it has now been changed to look for the effect of oculomotion via the third cranial nerve as a cue for the perception. He makes a big step in terms of explanation: he begins to connect motor and sensory information within a single neuropsychological gestalt.

In other experiments during the 1980s, astronauts ruled out the role of the atmosphere in the variation of the moon's size, due to the reported presence of an earth illusion from the surface of the moon despite the lack of an atmosphere (Ross & Plug, 2002, p.7). Yet no other explanation has yet to describe the variation in other terms. Does the presence of the "earth illusion" (the apparent magnification of the earth when observing from the moon) rule out the role of atmosphere completely? If the cause in extensity is due to a condition of luminance, could the variation in the illusion be due to the inhibitory impact of the atmosphere?

Summary and Classification of Theories

Is it possible to come to a greater understanding of the moon illusion through historical analysis of the experiments, ruling out certain suggestions, while directing our attention to the places where some concordance can arise? How can we come to organize this body of literature when it extends over several thousand years, between sharply differing cultures, and several overlapping (but not necessarily congruent) scientific paradigms? Is one suggestion better than the others?

We can organize the analysis in three steps: 1) qualify the phenomenological states, 2) identify errors, and 3) discuss the implications of a view that analyzes the phenomenon in terms of neurology.

The Three Moon Illusions

An important distinction to be made in an analysis of the experiments is that these experiments attempt to describe three qualitatively different moon illusions: the everyday illusion created by angular contrast and potentially intervening objects, the "harvest moon", sometimes reddish-orange and nearly 10 times as large and the occasionally reported "floating moon" in which the horizon is interpolated. This is a point Berman (1985) makes in his defense of Berkeley's position though he does not mention the third illusion, only the first two. The first one seems to be demonstrated by the Kaufmann and Rock experiments with sudden terrain projection and angular contrast as illustrated by Ponzo and explained by Helmholtz. But what about the enormous moon that so fascinated Berkeley? How to account for the size? How come no one can replicate it? The neuropsychological parallel to optical macropsia is intriguing. It identifies a place in the right hemisphere which is being activated (or disinhibited) in those with lesions yet what in the environment is causing this in normals? It is unlikely the entire population is reducing blood flow to that exact area simultaneously.

Then there is the qualitatively different third illusion – the "floating moon" version marked by interpolation of the horizon. All mention of it in the literature is anecdotal.

The Problem of Egocentric Vision

Egocentric vision certainly acts according to the laws of convergence under certain environmental conditions yet direct vision needs to take greater account of the construction of space within which its representation lies.

In Descartes' model of binocular vision, he changes the frame of reference. Descartes builds upon Kepler's mathematical model, and improves its ability to make prediction by accounting for the role of each eye, thus explaining phenomenon such as binocular overlap. However, he also calculates from the individual outward, as in Alberti's technique for perspective. In a way, it is a natural error that emerges from his *cogito*, as he privileges human thinking over the conditions of the environment. The question truly is: how to reconcile Descartes' mathematics with a Keplerian allocentric frame of reference that also remains loyal to the natural observation of perceptual illusion? Kepler had pointed in the right direction when he rules out the moon illusion as an astronomical event and, instead directs attention to the reddish surface of the retina as part of a color processing interpretation.

Roger Bacon's single caveat upon accepting Alhazen's theory of perception was a quotation from Aristotle (Lindberg, 1967). He asks: If vision is created by rays of light reflecting off of every point in the phenomenal field, then shouldn't light also reflect off the eyes? This question may be the key to re-conceptualizing convergence. Whereas direct vision requires a focused and accommodative lens, spatial vision does not. It is created outside the locus of attention.

Naturally, the vestibular system also provides feedback to the visual to create this sense of a unified self, organized centrally along several planes of axis. Are the "binocular cells" in the cortex recording multiple frames of reference or only their difference? How are our multiple frames of reference - horizontal, vertical, and diagonal - reconciled?

Egocentric vision only makes sense when we realize that all vision is fundamentally motion-centric. Without changes in the environment, there exists no vision. Stationary objects in "veridical, consensual reality" are the true illusion. Synchronous change creates the impression of stillness. Nystagmus artificially creates this.

Emmert's Law describes one aspect of vision: that is, direct vision of rectilinear rays perpendicular to the pupil with no interference and under certain conditions of illumination. These "laws" need to be bracketed. Temporal fusion (Sherrington, 1918) also needs to be re-considered more carefully.

We need to radically re-think our model of convergence with greater emphasis on the impact of ambient light, secondary light cues, and construction of space. We need to start doing visual perception experiments at dawn. Perception is a dynamic organic process, not a static one: it is ultimately Heraclitus and not Aristotle who accurately discerns reality.

Gestalt of Sensorimotor Laterality

Alhazen's basic assumption is correct: the moon illusion is some combination of sensation and perception: yet what is the gestalt by which sensation maps to perception? If it is a cognition, which cognition? If it is psychophysical, how can we identify changes in the body?

The final category of the most recent wave of theories is grounded in neuropsychological research. In this framework, specific sensory cues are mapped with specific motor efferent activity. By observing what each hemisphere is doing independently during this phenomenon and mapping it to a particular neurological condition, perhaps researchers can illuminate a greater understanding of its mechanics. The sensory-motor interaction seems to be the basic gestalt for experience – a single, synchronous moment across hemispheres.

These studies (Tulving, 1959; McCready 1985; Enright 1989) suggest a separate neuropsychological function found in the right occipital lobe (V1) that "layers" a construct of curved spatial perception. Figure is processed in the left hemisphere as part of the attentional processes. In the study of extensity, a new aspect of vision – the space within which the object is embedded – provides an unconsidered variable in the construction of background. The use of this perceptually distinct aspect of vision is easily demonstrated by the Necker cube: the inside-out effect is not caused by any change in the relationship to figure and ground but the space in which the figure is embedded. As Kaufman and Kaufman (2000) point out, neuropsychological explanations need to provide experimental demonstration.

Assuming a flat sky allows Alhazen to predict the behavior of rectilinear light accurately. As a default position, the fronto-parallel plane is a reasonable premise. However, Alhazen sets the description of direct vision and considers all others to be errors: more detailed analysis of these errors may reveal a particular pattern in which vision operates differently under differing distances and conditions. 'Error' is the wrong word: we should create boundary conditions in the hope of understanding errors within relationship to other parameters.

My Opinion

I think the best suggestion comes from Leonardo da Vinci's *Codex Leicester* (American Museum of Natural History, n.d.). Da Vinci seems to be the only thinker who truly grasps Alhazen's critique of Ptolemy. Da Vinci suggests that the moon illusion comes from two sources of light producing two images: the first is the light of the sun reflecting off the surface of the moon that we see every day; the second is the less intense light of the sun reflecting off the surface of the earth and then the moon. As proof, da Vinci cites the second, more subtle image of the full moon "within the crescent" during the occasional waning or waxing crescent phase.

This second image is slightly displaced. It also moves the image towards the color of orange. These images are fused in Panum's Area, as two spheres along a curved trajectory. This explains why the contours of the moon's surface shifts slightly through the course of the evening – and why a moon close to the horizon will appear full even a couple days after it begins to wane (since the shaded sliver is compensated by the displaced image). This combination of images from primary and secondary light sources contributes to the sfumato effect on certain nights. The specific displacement occurs due to our unique position in between the light reflecting off the convex surfaces of the earth and the moon.

The earth's rotation varies in an annual cycle through which the angle of the secondary image reflects on varying levels of water and earth - the greater the percentage of water and degree of angle on the carom, the deeper the shade of orange. This image, in turn, can be altered by the terrestrial atmosphere, inhibiting the degree to which the amplified illusion presents. The interpolation of an object in the visual field by the moon may be due to multiple points of reference on the horizon in a geographic location particularly close to the secondary source of light or at a unique and specific angle.

If we take the cases of the moon illusion disappearing when looking through a telescope as true, then the secondary source of light (and color) is due to some process of peripheral vision.

Closing Comments

This paper is an inquiry more than a review or history. In the style of Herodotus, the intention is to note the way cultures explain the mysterious. There is a crucial place for natural observation in knowing our world. Da vinci demonstrates that this is true, as do most great scientists and artists. However, as Claude Bernard states, "gaining experience and relying on observations is different from making experiments and making observations" (Schwartz & Bishop, 1958, p.68). A good experimental demonstration would have to control for the multiple sources of light, their specific angles of reflection and the corresponding changes in size and color of the image reflected and displaced. The gold standard experiment will not only reproduce it mechanically or prove it mathematically but also match the qualities of the evenings on which the moon illusion actually happens.

Let us pay closer attention to our everyday nighttime sky and discover the relationships which create this "illusion." Let us reveal our perceptual idiosyncrasies. And let us re-calibrate our theories to our experience.

The question as to the moon illusion's cause remains unanswered. an ancient and puzzling riddle of natural philosophy whose solution has eluded our greatest geniuses. It is only for us to gaze and wonder.

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