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Emmert's Law and the moon illusion

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Abstract—A cognitive account is offered of puzzling, though well known phenomena, including increased size of afterimages with greater distance (Emmert's Law) and increased size of the moon near the horizon (the Moon Illusion). Various classical distortion illusions are explained by Size Scaling when inappropriate to distance, 'flipping' depth ambiguity being used to separate botton-up and top-down visual scaling.

Helmholtz's general Principle is discussed with simpler wording — that retinal images are *attributed* to objects — for object recognition and spatial vision.

Keywords: Size scaling; constancies; hypotheses; hardware/software; Helmholtz's principle; cognitive; isoluminous; top-down/botton-up scaling; Muller–Lyer illusion; Ponzo distortion illusion.

INTRODUCTION

Theories are suggested and tested throughout science with surprising phenomena; yet phenomena cannot speak for themselves, but must be interpreted to have a meaning. As interpretations depend on theories, there is circularity at the heart of science. Classifying phenomena can help. We will try to classify phenomena of perception — especially various kinds illusions — in terms of *kinds* and *causes*. This should at least make some confusions explicit, so they can be seen and discussed, perhaps resolved with experiments.

It may seem odd that the physical sciences demand genuine phenomena and yet studies of perception gain insights from illusions — departures from the world of objects. The point is, although illusions are false in physical terms, they are genuine phenomena of *representations* by brains and eyes and the other senses, of objects and events of the physical world.

Some illusions are due to physiological errors of signal processing, and others to misleading knowledge accepted for interpreting sensory signals. These essentially

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different, *physiological* and *cognitive* illusions correspond, at least roughly, to computer hardware and software errors. Although conceptually very different, they are easily confused in practice. Yet this kind of distinction applies to all machines, as machines have causal processes obeying physical laws, and procedures for applying these processes to serve a purpose (more or less efficiently) of some kind.

Thus a car may not arrive in time from mechanical failure; or very differently, from taking an inappropriate route, which might have been selected without human intervention by its satellite navigator. Its guidance is not only from physical laws but from knowledge, represented in its electronic map. An inaccurate map gives cognitive errors even though the mechanisms are working normally in terms of physics. Again, although billiard balls obey basic laws of physics, the game depends on its arbitrary conventional rules and how they are scored. This duality permeates biology in general and in particular how vision works.

HELMHOLTZ'S PRINCIPLE FOR SEEING OBJECTS FROM IMAGES

The central question for theories of vision to answer is how objects — solid things existing in space and time — are seen from the very different ghostly images in eyes. Explanations are at least as much in terms of cognitive procedures, as how these are carried out physiologically. This was realised by the founder of the modern science of perception, Hermann von Helmholtz (1821–1894), who contributed immensely to understanding both physiological and cognitive aspects of vision. He suggested a general principle underlying seeing objects (Helmholtz, 1866. English translation 1924):

> '*Objects are always perceived as being present in the field of vision as would have been there in order to produce the same impression on the nervous system, the eyes being used under ordinary normal conditions*'.

Helmholtz would accept that 'ordinary normal conditions' include the state of the perceiver's physiology and what is being perceived. We may take it as read that errors or illusions may occur when either is abnormal. This does not imply intelligent cognition — which may indeed adapt to avoid errors in abnormal conditions — though Helmholtz did think of perception as intelligent Unconscious Inference based on empirical probabilities.

Unfortunately, Helmholtz does not tell us what object 'would have been there', to 'produce the same impression on the nervous system'. How does recognition work when the past object was different from the present retinal image? The friend may have changed quite significantly from the present small flat photograph, or the very different lines of a cartoon, and yet be recognised. Recognising is not from matching the present image to a remembered image; but rather to a web of associations stored in memory, and these tend to be very different for people sharing the same experience, making testimony puzzling and hard to trust. (Yet oddly, perception and memory are studied separately and seldom combined theoretically.)

Rich cognitive processing fits Helmholtz's account of perception as *Unconscious Inference,* especially as inferences are from *descriptions*, and never directly from facts or phenomena. Perceptions seem, indeed, to be like hypotheses of science, being largely fictional accounts but indirectly related to objects and events. Both are predictive to many non-detected or sensed features of things, and into at least the immediate future (Gregory, 1980).

Helmholtz's Principle is undoubtedly important, but its expression is complicated and quite hard to understand, or remember. So perhaps we may risk an attempt to simplify it? I shall take the liberty of putting the essential point as:

> 'Objects are *attributed* to images in the eyes, from knowledge gained through past experience'.

Recognition is not from remembered retinal images; but rather from all manner of associations, depending on individual knowledge and interests. So recognition of the same object or event can be very different, for each observer or witness. This complicates the question: What past experiences contribute to present perception? In what ways must they be similar to the present to, as Helmholtz put it: 'produce the same impression on the nervous system?' Helmholtz has little or nothing to say on this, but he may well have been referring to *attributions* to images, rather than to images themselves. This at any rate is the account we shall consider here.

Helmholtz left plenty of questions for us to try to answer. His general Principle seems to be an excellent start towards an account of object perception, as no doubt was his intention, as he introduced his Principle at the beginning of a long discussion. (*Physiological Optics*, Vol. III, page 2.) Whether he would entirely accept this 'attribution' way of putting it we cannot say, but surely this is in the spirit of his thinking.

Helmholtz recognised, as we have said, that illusions occur when the physiology is malfunctioning or when knowledge from the past is inappropriate to the present; so sensory signals are misread. He saw that we can infer backwards from phenomena of illusions to discover the brain's knowledge and working rules, for creating perceptions.

We might say that perception shows its own colours and battle plan in illusions, while perceptions are not anchored to the object world. Illusions serve like chemist's test tubes-isolating phenomena from contamination by the rest of the universe — so they can be studied with simple experiments. Perceptual illusions can even escape laws of physics — so we experience paradoxes and ambiguities — even though objects themselves cannot be paradoxical or ambiguous. This may be controversial for quantum physics: Are its paradoxes and ambiguities in the physical world, or in the accounts given by physicists? These are questions beyond our scope, which is limited to discussing a few well known though puzzling phenomena.

VISUAL DISTORTIONS AND CONSTANCIES

Frequently occurring illusory phenomena are *distortions* of various kinds. Distortions of size and shape in flat figures are associated with seeing distances in three-dimensional space. A key concept for explaining many visual distortions is size Scaling, normally giving stable Constancy for seeing objects and their positions; but producing illusions of distortion, when scaling is not appropriate to physical distances (Gregory, 1963, 1997).

Visual Constancies were described by the seventeenth century French philosopher René Descartes, who wrote in *Dioptrica* (1637):

> '*I need not, in conclusion, say anything special about the way we see the size and shape of objects; it is completely determined by the way we see the distance and position of their parts. Thus, their size is judged according to our knowledge or opinion as to their distance, in conjunction with the images that they impress upon the back of the eye. It is not the absolute size of the images that counts. Clearly they are a hundred times bigger [in area] when the objects are very close to us than when they are ten times further away; but they do not make us see the objects a hundred times bigger; on the contrary, they seem almost the same size, at any rate so long as we are not deceived by (too great) a distance*'.

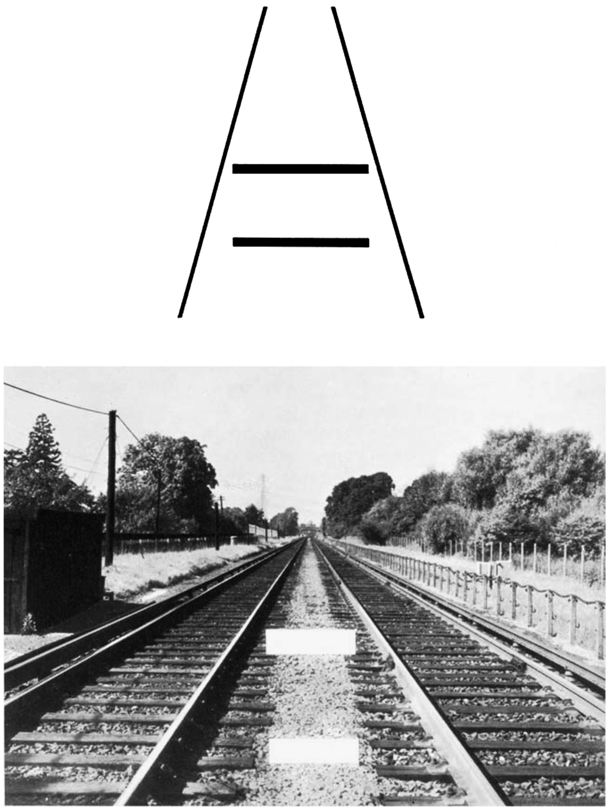
This is a clear account of what we call Size Constancy, though it can hold for unknown objects and even in unfamiliar conditions. Descartes describes what we call Shape Constancy in similar terms, being clear that vision is not slave to the eyes' images, or indeed to the world of objects.

> '*Again, our judgments of shape clearly come from our knowledge, or opinion, as to the position of the various parts of the objects and not in accordance with the pictures in the eye; for these pictures normally contain ovals and diamonds when they cause us to see circles and squares*'.

Many experiments have been carried out since, on the Constancies, especially by Thouless (1931, 1932), Holway and Boring (1941) and Ittelson (1951). It turns out that Constancy is not perfect or complete, and is affected by conditions such as available distance clues, and also by knowledge of sizes and shapes of objects.

It has been suggested that Constancies are given by active scaling processes, that may be set quite directly *bottom-up* from depth clues, such as perspective; or very differently *top-down* from the 'Perceptual Hypotheses' of depth as seen (Gregory, 1962, 1968, 1980, 2001). The quite generally accepted suggestion is that many distortion illusions are due to inappropriate size Scaling by a variety of clues (Gillam, 1998).

It is found that inappropriate Scaling can occur even when depth is not seen, especially when countered by surface texture of the illusion figure (see Fig. 1), so it appears flat in spite of quite strong depth clues (see Note 1). A few of many



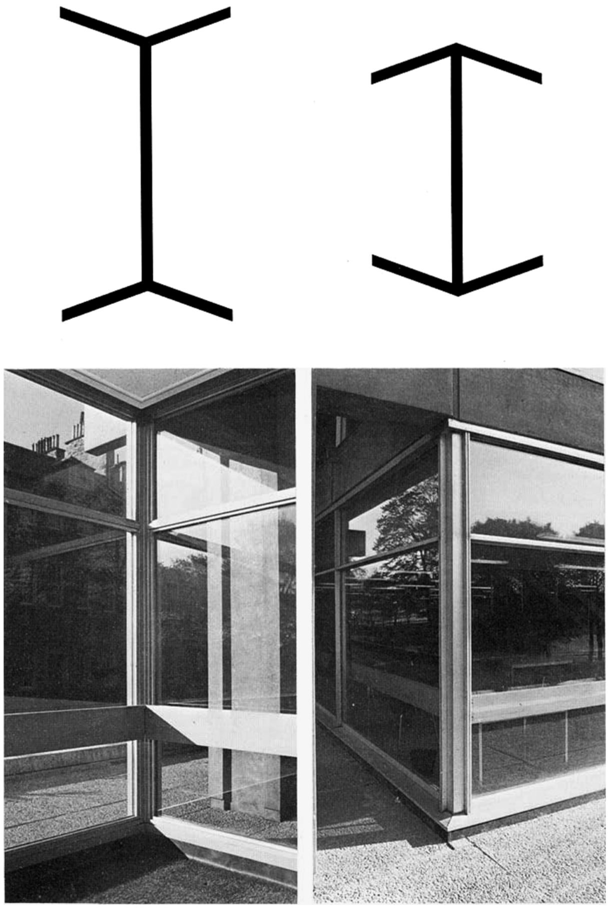
(a)

Figure 1. (a) Ponzo illusion, with a typical perspective context. Expansion occurs with *represented* distance, here convergence of parallel lines as of a railway. The distortion occurs even when the figure appears flat, locked to its textured picture-surface.

familiar examples will serve to illustrate the principle with perspective in pictures, of mis-setting Scaling to produce distortions.

It has been found that, when these illusion figures are presented in appropriate depth, as with stereoscopic projection or anaglyphs, the distortions are lost (Gregory and Harris, 1975). This is shown with anaglyphs in Gregory (1997). Loss of distortion by appropriate Scaling is to be expected, when Scaling is appropriate to distance. This loss of distortions does not seem to fit any other suggested theory, so is good evidence for the notion of inappropriate Scaling as the cause of these distortions.

Evidence that size Scaling can be set either 'upwards' by depth clues or 'downwards' from perceived depth, comes from the curious phenomena of ambiguous 'flipping' depth, when perception changes though the image in the eye is unchanged (Gregory, 1963, 1980). The best-known example of flipping depth ambiguity is the Necker Cube drawing of a wire cube without perspective (Fig. 2(a)).

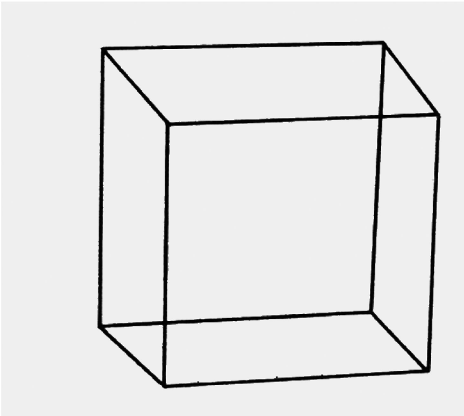


(b)

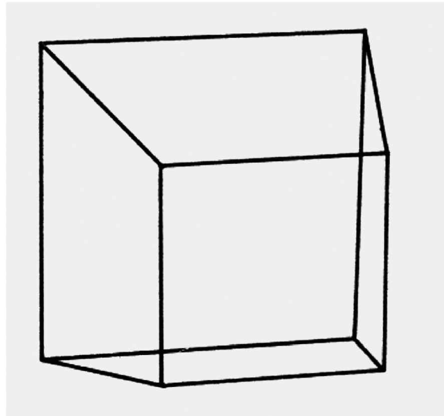
Figure 1. (Continued). (b) Muller–Lyer 'corner' illusion. The line represented as *further* by perspective of an inside corner is visually *expanded* — normally compensating shrinking of the image with distance, but producing corresponding illusory expansion in flat figures, as there is no true distance to compensate.

Because of the texture of its flat surface, it appears in paradoxical or one might say *pseudo* depth. The 'pseudo' depth of pictures makes them very different from normal objects, and pictures are extraordinary as they represent other objects, lying in a different space and time, to have unique multiple realities. This drawing of a truncated pyramid is the shape the true cube *appears* when flipped in depth, the larger face being the apparent back of the depth-reversed cube.

A wire cube will reverse in visual space even when it is held in the hand — so vision and touch separate (Shopland and Gregory, 1964). This is dramatic with rotation, for the visually reversed cube will rotate oppositely to the cube experienced by touch. For the drawing, either of the flipping perceptions may be true, or false; but here touch tells the truth, though does not reliably inform vision.



(a)



(b)

Figure 2. Necker cube. (a) Drawing of a wire cube without perspective. With a textured background (as here), it 'flips' in paradoxical *pseudo* depth. A truly three-dimensional wire cube flips in depth without paradox, with associated dramatic phenomena described in the text. (b) Drawing of a pyramidal perspective cube. As a wire model — when viewed from a critical distance, with the smaller face nearer — the front and back faces can give the same-sized retinal images; so Scaling effects can be observed. When flipped perceptually in depth, they appear very different sizes, as described in the text.

A reversed wire cube is wonderful to behold. According to its orientation, it may suddenly stand up on one corner and pirouette with a wild dance, dictated by each movement of the observer.

When the wire cube flips in depth it *changes shape.* When *not* reversed, it looks like a true cube; though the near face gives a larger retinal image, so Constancy must be operating appropriately. But when flipped in depth the now apparently further (actually the nearer) face looks much larger. It looks like a truncated pyramid, with the apparently back face larger than the front. Though visually surprising this is to be expected; for when near and far are interchanged, the apparently further face will give a larger retinal image, as it is truly nearer. Is this all there is to it?

We can make the retinal images of the near and far faces equal — by making the nearer face slightly smaller and viewing from the distance that gives the same sized images in the eye (see Note 2). Any apparent size changes of the faces when it flips in depth are noted, with changes of shape of the wire model. The further face looks somewhat larger when it is, or is not, depth-reversed though the images are the same size. The implication is that constancy Scaling is set 'downwards' from seen distance, so follows depth-reversal.

There are bizarre visual-motion effects whenever the observer moves. The wire cube will rotate *against* the observer's movements when not depth-reversed (as for normal objects), and *with* the observer's movements when reversed in visual depth.

This is the same as the movement of a flat anaglyph picture, seen in un-reversed depth, but at twice the speed. A slight movement of the head will immediate show whether it is, or is not, reversed from the direction it appears to rotate with each small movement.

PICTURE DEPTH

Depth as seen in pictures is often curiously paradoxical. One is not quite fooled into touching the object in the picture; yet it may look almost 'real'. An impressive perspective picture has only what we may call *pseudo depth,* being trapped by its surface, though 3-D anaglyphs (such as Julesz's dot stereograms) escape from their backgrounds. This can happen with *trompe l'oeil* pictures, as their monocular depth clues are so powerful; yet perhaps surprisingly, even the most technically perfect photographs seldom have the 'reality' of *trompe l'oeil* paintings.

The picture surface may be minimised or made invisible in various ways: high-contrast bright lines on black paper; back-lit transparency; most effectively 3-D stereo anaglyphs. Curious phenomena occur when the observer moves — broadly opposite to the phenomena of truly three-dimensional wire cubes. When not depth-reversed, it rotates *against* the observer's movements. When depth-reversed it will rotates *with* the observer's movements. Although the physics is unchanged, perceived motion parallax reverses when near and far switch visual depth.

A pictured object, such as of a wire cube (Fig. 1(a)), is essentially different from a true wire cube because the picture has no parallax, as it is physically flat. Yet a flat but visually depthy picture, will appear to rotate with observer motion. A 3-D anaglyph rotates or moves in remarkable ways, as we have said, which need explaining as there are no physical or optical changes of parallax (see Note 3). The viewer has to know he is moving. If he is moved passively on wheels, the picture will not rotate, unless evidence of movement is provided — and of course *this* might be illusory!

DOES HELMHOLTZ'S PRINCIPLE EXPLAIN ROTATION OF 3-D PICTURES WITH OBSERVER MOTION?

In our words: Is motion *attributed* to stationary retinal images, when the observer moves? To see whether this follows from Helmholtz's Principle we should ask: in what common situations do we see objects moving, though their retinal images are unchanging?

This happens when we are following a moving object, such as a person running ahead or a car in front, by walking or driving at the same speed. It happens also with rotation. One's partner in a waltz spins around while continually facing one. Reading a book as one turns around, the book must be rotated for the page to remain visible. Such a rotation is common for near objects to be seen while moving, though may not be noticed.

The moon and the stars seem to follow one's movements on Earth. This is particularly clear, when driving in an open car at night. It is as though strings attach the moon and stars to the moving car. The moon and stars are so far away there is no significant change in their positions, as we move around on Earth (see Note 4). For nearby objects this can only happen for things moving or rotating with one, keeping the eyes' images unchanging. So, we attribute ego-based movement to the distant moon and stars, and rotation to near-by pictures and anaglyphs seen in depth though they are flat. For they give the same image while we move, which normally happens with motion or rotation of objects, linked to the observer's movements. Helmholtz's Principle applies to these curious phenomena, of flat pictures appearing in depth, as movement is attributed to unchanging retinal images when the observer moves, as the seen object is normally in corresponding motion then retinal images are unchanging.

EMMERT'S LAW

After-images are useful for experiments on these issues as the image is unchanging and exactly fixed to the retina, though the eyes move. It was known in antiquity that after-images look larger when seen as more distant. Their retinal origin was not, however, appreciated until the seventeenth century. Emmert (1891) found a linear relation of distance and size of an after-image seen on a moving screen — now named Emmert's Law — that after-images are seen to double in size with each doubling of seen distance. The after-image changes size on a moving screen, and has a fixed size for any constant distance, over a very wide range.

It might be thought that this changing size of an after-image is due to changing relative areas of background texture lying within or outside the after-image. But it changes size when viewed in complete darkness, with no textured screen, when the observer moves, though not so lawfully as with a visible screen (Gregory *et al.*, 1959). Emmert's Law is not limited to after-images; microscopic structures of the retina are seen as large objects on a distant screen, when revealed by a small moving light as an entoptic phenomenon, obeying Emmert's Law, as for after-images (see Note 5).

Although after-images are useful for experiments, they fade quite rapidly. It is quite easy to provide unchanging optical images, by projecting a spot of light or a picture on a screen, and viewing with the eyes at the same distance as the projector. Or, a point source of light casting a shadow on a screen may be used, with the eyes close to the point-source. In either case the picture or shadow on the screen will double in size with each doubling of distance and yet, like an after-image, remain the same size in the eye. A small modification — viewing from in front of or behind the projector — allows Constancy measurements to be made, by setting the resulting optical change to cancel or null deviations from Emmert's Law (Anstis *et al.*, 1961). This method is not suitable for moving observers, though (an electronically generated) display may be expanded or shrunk with an observer's backwards or forwards movements to measure Constancy similarly by nulling (Gregory and Ross, 1964a, 1964b).

Since distances are not seen directly but by various depth-clues, which may be misinterpreted, Emmert's Law must follow *apparent* rather than physical distance. So it should not be surprising if Emmert's Law follows *illusory* distances, as of a wall of an Ames Room. This has been found by Boerse *et al.* (1992) and by Dwyer *et al.* (1990). An after-image looks larger on an apparently though not physically further wall of the Ames Room, and it changes shape with an apparent tilt (see Note 6).

Emmert's Law size changes should follow apparent changes of distance of the faces of a 'flipping' ambiguous object such as a wire cube. This does seem to be so, but the observation is not easy to make and should be confirmed. That Emmert's Law follows *apparent* distance as of the illusory wall of an Ames Room, and probably a flipping wire cube, shows that it can work from top-down perceived distance quite apart from depth clues, as these are two very different ways of seeing depth — 'upwards' from clues and 'downwards' from 'perceptual 'hypotheses' of distances — which can take off from physical distances as dramatic illusions.

Is Emmert's Law due to size Scaling, associated with Constancy? It works over a huge range of distance, though Scaling (as seen in distortion illusions) gives only small changes, limited to perhaps 1:3 and generally far less. The range of Emmert's Law seems to extend over the whole range of seen distance (see Note 7). This points to Helmholtz's principle operating: An object in external space is attributed to the after-image, its size being set by the size an object giving the image would have at the distance it is seen.

On this account Emmert's Law could hardly be represented at early stages of visual processing. But it has recently been found, with functional magnetic resonance scanning (fMRI), that distortion of the Ponzo illusion is related to change of size of corresponding activity in the primary visual area V1 (Murray *et al.*, 2006). This correlate with bottom-up scaling is of great interest: Is it related to Emmert's Law?

While the screen moves further away the after-image is seen expanding, as it is attributed to a receding object expanding to give the same-sized image. This does not require or involve Scaling. We would not expect to find Emmert's Law size change in V1, unless V1 simply represents size whatever the processes involved, which seems unlikely. Meanwhile this qualified prediction remains to be tested, which should be an interesting fMRI experiment.

THE HARVEST MOON ILLUSION

The full moon always looks the same size when high in the sky; but when low on the horizon it may appear huge, almost twice as large, though its image in the eye is the same. There have been many theories over the last two millennia attempting to explain the Harvest Moon illusion (Ross and Plug, 2002) (see Note 8).

An explanation was offered in the 2nd Century BC by the astronomer Ptolemy (Claudius Ptolemaeus). In his book on optics Ptolemy realised that the moon

Illusion is not an optical phenomenon, but is 'psychological'. He knew that the angle the moon subtends to the eye is the same whether it is low on the horizon or high in the sky. Ptolemy suggested, as a psychological cause, that when near the horizon, it appears to be *further* away and so *larger*. This is invoking what we call Emmert's Law. But generally, people report seeing the moon appearing *nearer* when it is seen as larger, near the horizon — so violating Emmert's Law.

A small coin held at arm's length covers the moon. So the moon could be the size of a coin; yet we see it as about the size of an orange. On a clear night over the ocean, it appears considerably larger and somewhat nearer than the horizon. One *sees* it at this sort of distance though one *knows* it is almost a quarter of a million miles away. Here as so often, perceptual experience and conceptual knowledge disagree.

It has been suggested that the inclination of the eyes is important for the Moon Illusion (Holway and Boring, 1941). But the illusion is present, to much the same extent, when the moon is high in the sky but close to a mountain. Most important — the low apparently large moon looks small when viewed through a tube, cutting out the surroundings. This may easily be checked by the reader. Evidently the change of size is related to features of the surrounding scene, the moon appearing larger when there are rich depth-clues (see Note 9). When low on the horizon (or near the side of a mountain) there are surrounding texture and perspective depth clues which scale up the size of the moon, as in the Ponzo illusion (Fig. 1(a)).

The full answer seems to be that the moon is scaled up in size by surrounding depth clues, as for the Ponzo and many other 'perspective' illusion figures; but this increase in size makes the moon appear *nearer* because, unlike a picture or illusion figure, the sky is not a textured surface, fixing its distance. It is like a Ponzo illusion drawn with luminous paint and viewed in the dark.

The Moon Illusion is seen with a cloudy sky. Presumably the cloud — which must of course be transparent for the moon behind it to be visible — is not seen as a surface trapping it. Unlike a picture or illusion figure on a textured surface, we see the moon through the cloud and not trapped to a surface, so its increased size makes it appear nearer.

SUMMARY

When the corresponding illusion figures are presented on a textured surface, they do not look nearer as they are locked by texture to the surface. But if the background is made invisible (drawn in luminous paint and viewed in darkness and preferably with one eye), then like the moon, the illusory expansion makes it *larger* and *nearer*. Emmert's Law is violated, as the apparently larger object looks nearer; but there is a good reason for this — bottom-up Scaling by depth clues giving an effectively larger image, which by Helmholtz's principle looks nearer.

This leaves a question: Why does the moon look the same size each time it is seen when high in the sky? Here there are no depth-clues, for scaling its size or distance.

We may introduce the concept of *default* sizes and distances. The notion of setting by defaults is familiar in computers and word processors, adopting typical settings in the absence of data or instructions. A default from earthly experience could scale the moon, though what these experiences are, we do not know. Prior probabilities are very important for visual perception, especially when available data are weak or absent. The moon is so strange, so different from objects on Earth, it is hard to guess which familiar objects are accepted as references for seeing the moon. Helmholtz has little or nothing to say on what objects from the past serve as references for present perception, and we cannot add much more today. Perspectives of parallel lines and corners evoking distortions, such as the Zöllner and Muller-Lyer illusions, are rare examples of identified visual references from past experience, recognised as they produce striking phenomena of illusion. Do babies see the moon and its illusions as we do? Are clues to distance and references for size, seen with knowledge inherited from the ancestral past, represented in the genetic code?

The full moon appearing ever the same size while high in the sky, is a more important and less understood phenomenon than its dramatic expansion, as a Harvest Moon descended from the heavens to our horizon on Earth.

NOTES

1. Countering texture can be removed, as by painting in luminous paint on a black background and viewing in the dark, with one eye to prevent stereopsis. Pictures rich in monocular clues may then appear in realistic depth. It is possible to measure the depth, as seen by optically introducing a small marker light, which may be placed in any position in three dimensions, and viewed with both eyes to give vergence information of its distance from the eyes. By placing the marker close to depicted features, their position can be measured and plotted in visual space. The trick is to introduce a small moveable marker light into the picture optically. This does however take some skill (Gregory, 1969).
2. The wire cube should be painted matt black to avoid occlusion clues. The critical distance for the pyramidal cube can be found from the near face exactly hiding the further face. A small cube should be viewed with one eye, from a position where all its faces are visible.
3. This works well with the random dot anaglyphs in Bela Julesz's (1971) book *Foundations of Cyclopean Perception*, now re-printed.
4. For high speed flying this is somewhat different, as the Earth is curved. Also there is lack of reference as, generally, Earth objects are not seen at the same time as the stars, except when for example when we are looking up through trees.
5. As well known, moving a small torch or flash light held in gentle contact with the closed eye, some way to the side, reveals the 'Purkinje Tree' of blood vessels, and also nerve fibres, essentially as the moving shadows on the underlying

receptors. Selective adaptation normally hides them (Wade and Brozek, 2001). These are microscopic structures, yet seen as huge distant objects.

6. We have confirmed this in the Ames Room that used to be in the Techniquest Science Centre in Cardiff, now unfortunately removed.
7. I have found that after-images of the setting sun obey Emmert's Law over distances of several miles.
8. The history of the Harvest Moon illusion is discussed fully by Helen Ross and Cornelis Plug (2002), *The Mystery of the Moon Illusion*. They leave the cause an open question, but their discussion is interesting and useful.
9. This is the basis of the well-known account given by Lloyd Kaufman and the late Irvin Rock (1962). But this account makes the wrong prediction, saying the moon looks *further* on the horizon, though it is reported as looking *nearer*. My view is that it is scaled bottom-up by perspective and texture gradients to make it look larger and so nearer, contrary to Emmert's Law. Lloyd Kaufman told me quite recently that he now accepts this interpretation.

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