Clinical and Experimental Ophthalmology 2005; **33**: 571–575

Conundrum

Why is the moon white?

Sobha Sivaprasad FRCS and George M Saleh FRCS
West Kent Eye Centre, Princess Royal University Hospital, Orpington, Kent BR6 8ND, UK

Abstract

Land's Retinex theory is used to explain why we perceive the colour of the moon as white. The lightness values of coloured areas are computed and the energy at the particular area (moon) is compared with the surrounding area (space-vacuum).

Key words: colour, retinex theory, visual illusion.

Most would agree that the colour of a full moon is creamy white. However, when samples of moon rock and dust are observed close up, their colour is seen as dark grey or black. A popular explanation offered is that the moon is brilliantly lit by the sun and thus diffusely reflects all the wavelengths of the sunlight hence appearing white. But, is this explanation correct? When a piece of jet-black coal is held out in dazzling sunlight it still appears black. So why is the moon white?

The answer lies nearer than is often thought. For more than a century, the classic teaching of colour perception was based on Young-Helmolz three different photoreceptors each with differing spectral sensitivities. The combined relative stimulation of each cone results in the hue detection.[1] However, Edwin Land, in a series of experiments (Mondrian experiments) demonstrated that the cortical interpretation of colour relies not only on the absolute wavelength of the incoming light, but also on the wavelength relative to the surrounding environment. It is the product of calculations of the retina and the cortex, and the theory is called Land's Retinex theory.[2] Retinex is derived from the word 'retina' and 'cortex' and it illustrates colour constancy.[3]

This has two important implications. First, a lighting source (with its differing spectral composition) does not dramatically alter the colour that we perceive. Unlike a camera we do not have great difficulty in discriminating colour under artificial lighting conditions relative to sunlight. Second, if the relative input from around the object of interest is altered, that will in itself alter the perception of the object of regard.[4] For example, a red apple looks red on a white plate but looks even darker when placed on a blue plate. Our eyes correct for the different lighting conditions and colour. Eyes and the brain subtract the surrounding bias and help us maintain a constant impression under varying background.

How does this relate to the moon? Although the moon may be grey or black, we perceive it as white. The fact that we see the moon as white is actually a visual illusion. Referring to Land's theory, the eye computes the colour based on relative inputs. The moon, however, is not in the environment our brain and eyes are evolved to function in. The relative input of an absolute vacuum is black. The inputs from the surface of the earth are erroneous as they are not in the same environment of space. There is thus an artificial brightening of the moon relative to its surroundings and we, therefore, visualize it as white.

A major visual phenomenon is that objects with low reflectance look dark and objects with high reflectance look light. It is with reflectance that sensation of colour is strongly correlated when we view the world around us. However, colour sensation is also dependent on characteristics of the field of view. Therefore, what the eye perceives from each point is clearly the product of reflectance and the illumination. The eye can determine reflectance only if illumination is uniform. As we are all aware, the illumination from the sun is modulated by several factors and is not uniform. The Retinex theory is based on this aspect of colour invariance.[5] As long as the colour or grey scale of an object is viewed under adequate lighting, a colour patch does not change its colour even when the luminance of the scene is changed. In this case, a gradient of illumination across space does not alter the perceived colour of the moon. If the luminance level reaches a threshold, the sensation of colour vanishes. In Land's algorithm, the lightness values of coloured areas are computed and the energy at the particular area (moon) is compared with the surrounding area (space-vacuum).

This phenomenon may have implications in the future with humans frequenting space and terrains beyond. Missions to the moon and Mars are planned on the Earth with the visual perception that we have on this planet. However, the visual perception in outer space may be different and humans, being a very visually dependent species, should be aware of this aspect of visual perception.

■ *Correspondence:* Dr Sobha Sivaprasad, West Kent Eye Centre, Princess Royal University Hospital, Orpington, Kent BR6 8ND, UK. Email: senswathi@aol.com

References

1. Valberg A. Unique hues: an old problem for a new generation. *Vision Res* 2001; **41**: 1645–57.
2. Land EH, McCann JJ. Lightness and retinex theory. *J Opt Soc Am* 1971; **61**: 1–11.
3. Helson H. Some factors and implications of color constancy. *J Opt Soc Am* 1943; **33**: 555–67.
4. Blake A. Boundary conditions for lightness computation in Mondrian world. *Comput Vision Graph Image Process* 1985; **32**: 314–27.
5. Brown RO, MacLeod DIA. Colour appearance depends on the variance of surround colors. *Curr Biol* 1997; **7**: 844–9.

Constancy, illumination and the whiteness of the moon

Robert W Kentridge PhD
Department of Psychology, University of Durham, Durham, UK

Despite being made of dark rock, the moon appears white, both at night and in daylight. Explanations in terms of misapplication of absolute lightness estimation heuristics and misperception of the nature of the moon's illumination by direct, unscattered sunlight are proposed.

Sivaprasad and Saleh present us with an intriguing and thought-provoking conundrum; I fear, however, that the explanation proffered is incorrect. I am sure that the whiteness of the moon, despite the drab grey of the rocks of its surface (Fig. 1a), is indeed an illusion that depends on a failure of some perceptual constancy mechanism. I doubt, though, that the basis of this illusion is as simple as contrast-induction where the high contrast of a grey moon against the almost perfectly black surround of empty space induces the illusion that the moon is white. It is pretty easy to illustrate that this cannot be the sole cause of the moon's apparent whiteness. The moon seen against a blue daytime sky (Rayleigh-scattered sunlight) or against clouds (geometrically scattered sunlight) still appears white (Fig. 1b). The game is probably given away by the fact that, at night, the moon very often appears self-luminous (i.e. appears to be a source of light rather than simply a reflector of it, Fig. 1c). This suggests that the whiteness of the moon is not a consequence of contrast-induction but rather an error of lightness-anchoring – the heuristic selection of surfaces within a scene that are most likely to be efficient reflectors of all wavelengths of light – in other words, white. The authors are correct in noting that a key problem in visual perception is the inference of the reflectance properties of surfaces independent of their illumination – the achievement of colour-constancy.

There are two approaches to tackling this problem, retinex-like contrast-based mechanisms and direct illumination estimation; apparently both are used by the visual system.[1] The first class of constancy mechanism involves estimating the absolute colour and brightness of a surface in a scene and inferring the colours of all other surfaces under the same illuminant relative to this (as we will see in a moment, the assumption that the surfaces being compared share the same source of illumination is critical). The second approach, directly estimating the colour of the illuminant light, involves using direct cues such as specular reflections[2] from glossy objects, or indirect statistical ones such as intensity-chromaticity correlations[3] within the scene to estimate the colour of the illuminant light. This can then be taken into account when inferring the colour of an object's surface from the light it reflects into the eyes. Even this second class of mechanism, however, still requires heuristic estimation of intensity – highlights or image statistics can provide information about the likely colour of illuminant light, but not its intensity. A great deal of experimental work has been carried out in an effort to understand the heuristics that we use in lightness-anchoring, much of it by Alan Gilchrist.[4] Here, from his website (http://psychology.rutgers.edu/~alan), is Gilchrist's summary of one rule that he has discovered: 'In a simple display, when the darker of the two regions has the greater relative area, as the darker region grows in area, its lightness value goes up in direct proportion'. At the same time the brighter region first appears white, then a fluorent white and finally, self-luminous. This is consistent with the self-luminous appearance of the moon at night. It is, however, not the complete story. A second problem is that the illumination of the moon is unusual. It is lit by direct sunlight, unscattered by the atmosphere (although reflected back to us through it). During the day the moon rarely appears self-luminous, but it does still appear white. There are, however, few, if any, cues that the moon is illuminated in a different manner to its apparent surroundings (e.g. clouds in the sky or objects such as mountains, building or trees, on the horizon). It is most likely seen as white because it is mistakenly perceived as being lit by the same illuminant as its surroundings when, in fact, its direct unscattered illumination is far more intense than the scattered illumination of its apparent surroundings. The basic phenomenon that dark surfaces can look bright under isolated illumination was first demonstrated by Adhémar Gelb in 1929.[5] The same mechanism may also contribute to the moon's appearance at night. A piece of moon rock seen on earth appears dark because there is no confusion about its illumination.

The implication of the explanation proposed here is that the moon itself should look grey when it is seen in the context of other objects unambiguously under the same

■ *Correspondence:* Dr Robert W Kentridge, Department of Psychology, University of Durham, South Road, Durham DH1 3LE, UK. Email: robert.kentridge@durham.ac.uk

Figure 1. (**a**) Apollo 17 lunar rock sample. Image courtesy of NASA. (**b**) The moon and clouds over Mosaic Canyon, Death Valley, CA, USA. Image courtesy of Dr David Dupplaw, Department of Electronics and Computer Science, University of Southampton, UK. (**c**) The moon appearing so bright as to be self-luminous. Image courtesy of NASA. (**d**) Astronaut Eugene Cernan jump-salutes the US flag during the Apollo 17 moon-landing. The rock sample in this figure was collected close to the lunar module seen behind the flag. Image courtesy of NASA.

direct illumination. This appears more or less confirmed in photographs (e.g. Fig. 1d); I have not, however, made this observation directly myself.

REFERENCES

1. Rutherford MD, Brainard DH. Lightness constancy: a direct test of the illumination-estimation hypothesis. *Psychol Sci* 2002; **13**: 142–9.
2. Yang JN, Shevell SK. Surface color perception under two illuminants: the second illuminant reduces color constancy. *J Vis* 2003; **3**: 369–79.
3. Golz J, MacLeod DIA. Influence of scene statistics on colour constancy. *Nature* 2002; **415**: 637–40.
4. Gilchrist AL. *Lightness, Brightness, and Transparency*. Hillsdale: Lawrence Erlbaum Associates, 1994.
5. Gelb A. Die 'Farbenkonstanz' der Sehdinge. In: Von Bethe WA, ed. *Handbuch der Normal und Pathologische Psychologie*, **Vol. 12**. Berlin: Springer, 1929; 594–678.

The dark shade of the moon

Paola Bressan PhD
Dipartimento di Psicologia Generale, Università di Padova, Italy

Sivaprasad and Saleh seem to suggest that we misperceive the moon as white because contemplation of the skies is not what we evolved for. The latter claim is true, of course. For example, the sun and the moon look much the same size to us; yet the sun is 400 times as far away and 400 times as large as the moon, and by the rules of size constancy should appear as such. The reason why it does not is that we have no way to judge the relative distances of celestial bodies: it was earthly, not astronomical lengths that shaped our visual system.

This argument has no bearing on the perceived colour of the moon, though, as proven by an experiment conducted nearly 80 years ago.[1] In 1929, Adhémar Gelb suspended a disc of black paper in a darkened room, and illuminated it with a projector (a 'sun'). Exactly as the moon in nighttime, the disc appeared white. The fact that it was actually black became evident only when a larger surface of higher luminance, such as a sheet of white paper, was brought into the beam of light and placed behind the black disc. But as soon as the white paper was taken away the black surface went precipitously back to white, demonstrating that perception was impermeable to the knowledge of the 'real' colour of the disc.

The Gelb effect shows, as later experiments have confirmed,[2] that the highest luminance in a scene appears white. It follows that the moon looks white simply because it is the brightest region in the nocturnal sky. On earth, samples of moon rocks and dust look dark because the scene context has shifted – not from evolutionarily unnatural to natural, but from the dim surroundings to an ample range of luminances, some of which are higher than those of the moon pieces themselves.

The perceived shade of the moon changes very much depending on whether the moon is up there or down here, but is also affected more subtly by skylight and lunar altitude. A moon rising before sunset, when the sky is still quite bright, can be so faint that it is even difficult to detect. Besides, moonlight passes through nearly 40 times as much atmosphere at the horizon as it does at zenith, and for this reason moon luminance increases rapidly with altitude, from 2 cd/m^2 up to over 4000.[3] Accordingly, the moon can appear off-white, white, fluorescent, or luminous – variations that are not predicted by Retinex theory.

Both the colour and the mutable appearance of the moon are explained well by models based on luminance anchoring within a visual scene, such as the double-anchoring model of lightness.[4,5] In this model, the shade of grey (technically, the 'lightness') of any given region is computed by taking a weighted average of the ratios of the region's luminance to two 'anchors': the surround luminance and the highest luminance in the scene. Such anchors are both given a default value of white. As the brightest object in the night sky, at the highest-luminance anchoring stage the moon is always perceptually white, whatever its actual luminance. However, at the surround anchoring stage, it is lighter than white (and thereby perceptually glowing), and the extent of this component depends on the moon's luminance ratio to the surrounding sky. From the standpoint of anchoring models of lightness, the shade of the moon is a spectacular, but otherwise predictable, instance of the general principle that the achromatic colour of objects results from luminance anchoring within the visual scene.

■ *Correspondence:* Dr Paola Bressan, Dipartimento di Psicologia Generale, Università di Padova, Italy. Email: paola.bressan@unipd.it

References

1. Gelb A. Die 'Farbenkonstanz' der Sehdinge. In: Von Bethe WA, ed. *Handbuch der Normal und Pathologische Psychologie*, **Vol. 12**. Berlin: Springer, 1929; 594–678.
2. Gilchrist A, Kossyfidis C, Bonato F *et al.* An anchoring theory of lightness perception. *Psychol Rev* 1999; **106**: 795–834.
3. Conrad J. *Getting the Right Exposure when Photographing the Moon.* 2000. Accessed 6 Jul 2005. Available from: http://www.calphoto.com/moon.htm
4. Bressan P. Explaining lightness illusions. *Perception* 2001; **30**: 1031–46.
5. Bressan P. The place of white in a world of greys: a double-anchoring theory of lightness perception. *Psychol Rev* (in press).

Confusing the moon's whiteness with its brightness

David H Foster DSc FInstP
Faculty of Life Sciences, The University of Manchester,
Manchester, UK

The moon reflects about one-tenth of the light incident upon it. Its apparent whiteness, and that of other brightly lit dark surfaces, presents an intriguing visual phenomenon that has been exploited in laboratory demonstrations of the Gelb effect. Here, a large black disc is presented on a dark background and illuminated so that white light falls only on the disc. The disc then appears white, but if a small white or grey object is placed on the disc, the apparent whiteness of the

■ *Correspondence:* Professor David H Foster, Faculty of Life Sciences, Moffat Building, The University of Manchester, Manchester M60 1QD, UK. Email: d.h.foster@manchester.ac.uk

disc decreases markedly.[1] This is because the small object is seen to be illuminated by the same light as that on the disc, thereby allowing the eye to form a more accurate estimate of the disc's reflectance, without necessarily any knowledge of the illuminant itself.[1,2]

For the moon of course there are no white objects on its surface also illuminated by the sun that can be used for comparison. The only objects available are on the surface of the Earth, but these are illuminated by a much weaker moonlight. If the eye makes the default assumption that the scene as a whole (Earth and moon) is illuminated by a common light, then the brightness of the moon is interpreted, incorrectly, as being due to its high reflectance.

This relational interpretation of whiteness or lightness perception can be traced back long before Land's Retinex theories of colour vision,[3,4] and it owes much to the work of the Gestalt theorists, particularly Koffka,[5] who emphasized the role of 'belongingness' in determining the influence of the perception of one part of a scene on the perception of another. These ideas have been developed more comprehensively by Gilchrist *et al*.[6]

Interestingly, Land's Retinex theories were based on an assumption that the spatial ratios of excitations in the receptors of the eye arising from light reflected from surfaces in a scene remain largely constant under changes in the colour of the incident light. It is only recently that this assumption has been experimentally verified for natural scenes,[7] with the aid of hyperspectral imaging techniques.

References

1. Wallach H. Brightness constancy and the nature of achromatic colors. *J Exp Psychol* 1948; **38**: 310–24.
2. Foster DH. Does colour constancy exist? *Trends Cogn Sci* 2003; **7**: 439–43.
3. Land EH, McCann JJ. Lightness and retinex theory. *J Opt Soc Am* 1971; **61**: 1–11.
4. Land EH. Recent advances in retinex theory and some implications for cortical computations: color vision and the natural image. *Proc Natl Acad Sci USA* 1983; **80**: 5163–9.
5. Koffka K. *Principles of Gestalt Psychology*. London: Routledge and Kegan Paul, 1935.
6. Gilchrist A, Kossyfidis C, Bonato F *et al.* An anchoring theory of lightness perception. *Psychol Rev* 1999; **106**: 795–834.
7. Nascimento SMC, Ferreira FP, Foster DH. Statistics of spatial cone-excitation ratios in natural scenes. *J Opt Soc Am* 2002; **19**: 1484–90.