COMMENTARY

All the colours of the rainbow – a bridge between medieval and modern science.

Our perception of colour has always been a source of fascination, so it's little wonder that studies of the phenomenon date back hundreds of years. What, though, can modern science learn from medieval literature — and how do we go about it?

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The Matisse exhibition featured in this issue of *Nature Physics* reminds us of the artist's renowned fascination with the colours of the natural world. Of these, none is more vivid, changeable and elusive, than those of the rainbow. Indeed, Matisse created a work entitled '*Arc-en-Ciel*' ('Rainbow') — but surprisingly it is neither a landscape, nor is it in colour. Instead, it is a lithograph of a girl's face, drawn in sparing lines. Her eyes are the most striking feature of the image — perhaps urging us to think of colour as a creation of the eyes and mind, as much as a physical phenomenon. But the study of colour has a much longer history than Matisse's meditation on rainbows, as eight-hundred-year-old texts by the great medieval English thinker Robert Grosseteste demonstrate. Interpreting Grossteste's ideas within the context of our modern scientific understanding proves just as enlightening as it is challenging — demanding interdisciplinary collaboration[1] and some very creative thinking.

Far from being a period in which scientific thought stagnated and technology rudimentary at best, the European Middle Ages era saw remarkable development in both endeavours. During this time, most of Aristotle's works on natural phenomena, never before available in the medieval West, were translated into Latin from Arabic versions of the Greek originals. Also translated were commentaries by Muslim scholars of the earlier Middle Ages. The effect of this Aristotelian invasion was to inspire generations of thinkers with different questions: of light, motion, geography and cosmology. Responses to these questions were not necessarily abstract — some drove real technological change. Optics, for example, was not by the end of the thirteenth century a purely theoretical discipline: the Latin word *perspicuum* was used for 'diaphanous medium' before 1200, but by 1300 it was used almost universally for 'lens'.

Grosseteste's set of related treatises on the nature of light[2] — *De colore* (on colour), *De iride* (on the rainbow) and *De luce* (on light) —provides unique insight into the development of our modern understanding of natural phenomena. A careful reading brings to light some of the creative steps that Grosseteste made in his contemplation of what the human mind can hope to learn about the material world. *De luce*, for example, contains a detailed account of how the medieval cosmos of nested planetary spheres might have formed from an initial explosion of light, in terms of Aristotelian physics. Grosseteste conjectured the existence of six fundamental cosmological laws and it turns out that, mathematically, these laws can indeed recreate a geocentric cosmos[3].

In the first treatise, *De colore*, Grosseteste also uses mathematical concepts to frame his account of colour, proposing a three-dimensional space mapped out by three bipolar qualities, identified not by algebraic quantities, but by the Latin word-pairings *multa-pauca*, *clara-obscura* and *purum-impurum*. These pairs were used in combination to account for all possible colours[4].

Grosseteste moved away from the Aristotelian one-dimensional scale of seven colours between white and black by noting that colours can differ categorically in the number of these qualities they share with either whiteness or blackness, and continuously by degree. Geometrically and combinatorially, these relationships correspond convincingly to a three-dimensional colour-space[4].

The three dimensionality of Grosseteste's scheme piques the interest of any modern colour scientist. The results of colour-matching experiments, formalized in the seventeenth century, showed that any light can be matched by a mixture of three primary lights and therefore suggest that human colour vision can be described within a three-dimensional space. In 1801, Thomas Young[5] presented a physiological trichromatic theory, proposing that the retina must contain just three types of sensor each tuned to a different part of the spectrum, such that lights that produce the same effects in these sensors are indistinguishable. The three types of colour-sensitive 'cone' photoreceptors found in the human retina perform just the projective role that Young envisaged — representing the effectively infinite dimensionality of a full-frequency spectrum of light by the triplet 'quantal catches' of the cone cells. 'Colour' as we now understand it, emerges from this interplay of physics and physiology.

There's certainly no evidence that Grosseteste had any inkling of the biological reasons for three-dimensional colour perception. Yet, *De colore* poses a puzzle to the modern reader: how we are to interpret its abstract three-dimensional structure? *De colore* includes no colour terms, nor examples of objects with diagnostic colour. Wonderfully, however, Grosseteste's later treatise *De iride* revisits his theory of colour generation, explicitly linking his terminology to the properties of rainbows[6].

In *De iride*, Grosseteste describes the three dimensions of his colour space with three physical variables: scattering angle (to produce colour variation within a rainbow), the 'purity of the scattering medium' (to produce variation between different rainbows), and altitude of the sun (to produce variation in the light incident on a rainbow). From a modern point of view, one might well ask whether this parametrization really provides a meaningful formulation of colour space. Remarkably, using these variables, the loci of colour variations in natural rainbows (modelled with Mie scattering theory and produced with incident solar spectra at varying optical atmospheric depths) do span perceptual space effectively, albeit with an unusual coordinate system. To formalize the modelling we need only to identify his descriptor of difference between rainbows — the 'purity' of the medium — as arising from differently sized water droplets. The two dimensions of scattering angle and droplet size generate a system of interlocking spirals (Fig. 1a, 1b and 1c). This turns out to be a distorted variation of a known coordinate system — the logarithmic polar family, within which the familiar radial-polar system is one extreme in which the radial lines are created from completely unwound spirals. The third variable of solar reddening from atmospheric absorption sweeps this spiral coordinate net through the perceptual colour space (Fig. 1d).

The science inspired by *De iride* resolves a puzzle set out in *De colore*. The polar-coordinate system of hue and saturation is one candidate for interpreting two of Grosseteste's colour axes. But this presents a conundrum: with the circumferential dimension of hue, it is not possible for all three axes of variation to end at white, as suggested in *De colore*. The spiral system, generated by a logarithmic-polar transformation of the Cartesian grid, allows the central point to lie at one extremity of both dimensions spanning the chromatic plane (Fig. 2). Almost 800 years after their publication, Grosseteste's writings have prompted exploration of a new coordinate system for colour. Surprisingly, it seems that Grosseteste's scheme really does reflect the insight that one may navigate perceptual colour space with three independent variables.

Scientific collaboration with a medieval thinker requires an interdisciplinary effort. Handwritten manuscripts, often damaged or quirky in their penmanship, are challenging to transcribe, using an evolving Latin language in which the precise meaning of words is not easy to pin down. This is not a place for amateurs to dabble — and there are certainly no short-cuts. Yet such collaboration yields dividends for humanities as much as it does for modern science. Even at the level of edition and translation of the texts, a collective understanding of their meaning — a 'functional analysis' — creates better results. One example is the translation of Grosseteste's description of the way various colour 'directions' from the white and black poles 'meet at a point in the middle'. This would be an appropriate translation had Grosseteste simply reproduced an Aristotelian colour line. But by taking into account the abstract geometry of his thinking, a secondary meaning allowed by the Latin becomes the primary translation: 'meet together in a middle space' (Fig. 3).

Apart from intellectual curiosity, what can science today learn from revisiting these old texts? Just as Grosseteste sought to impose order on the colour variation he observed, modern colour scientists continue to search for ways in which similarity and dissimilarity of appearance might be captured in a metric space. What is it about our environment or our make-up that sets these perceptual relationships? Quite apart from offering new insight into rainbows and colour spaces, the process of engaging with these texts is a useful reminder of scientific best practices, drawing out two characteristics of scientific research that are frequently overlooked. First, science is inherently creative, and these texts are rich sources of inspiration. They remind us of the essential and supremely difficult task of identifying those questions that are tractable and follow naturally from our observations. Second, science is never 'done' — and seeing modern scientific endeavour as part of a continuum keeps us honest. By admitting that we may be almost as far from a full understanding of colour as our thirteenth-century collaborators reminds us to doubt — and that, after all, is the only way to progress.

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