10.1098/rsta.2001.0968

THE ROYAL SOCIETY

The origins of the concept of interference

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Published online 28 March 2002

The concept of interference is implicit in Newton's explanation of the anomaly of the tides in the Gulf of Tongkin, but Thomas Young was the first to generalize the principle and to apply it to compound tides, to auditory beats, and to the colours of thin films. In his Bakerian Lecture, delivered on 12 and 19 November 1801, he was able to accurately derive the wavelengths of particular hues from Newton's measurements of the colours of thin plates. The first printed statement of the generalized principle of interference appears in the *Syllabus* for his Royal Institution lectures, which was published early in 1802. His celebrated two-slit experiment is first described in his *Course of Lectures on Natural Philosophy and the Mechanical Arts* of 1807.

Keywords: Thomas Young; thin films; Newton's rings; interference colours; colour vision; wavelength

1. 'The Tides at the Bar of Tunkin'

In the 17th century, trade with Tongkin, now Hanoi, was hampered by a treacherous sand bar at the mouth of the river that gave access from the sea, and the danger to British merchantmen was complicated by the curious behaviour of the tides on this coast. The pattern of the tides was set out in a letter published in the *Philosophical Transactions* for 1684 by an English traveller, Francis Davenport, who had resided at a place called Batsha (Davenport 1684). In this region, near the modern Haiphong, there is never more than one flood tide a day, and twice each lunar month, at intervals of 14 days, there is no tide at all. For the next seven days the height of the solitary tide increases and it is maximal when the moon is at its maximum declination. Thereafter it declines again (Cohen 1940; Naval Intelligence Division 1943).

This curiosity had attracted the attention of Edmund Halley, and it was natural that Newton should discuss it in his *Principia* of 1688. Newton attributed the pattern of the tides of Tongkin to the superposition of component tides arriving from different directions. One tide, he suggested, came from 'the sea of China', with a delay of 6 h, and one from 'the Indian sea', with a delay of 12 h. When they were of equal magnitude, their effects cancelled at the port of Batsha (Newton 1688).

Yet Newton, despite his active interest in the colours of thin films and despite his awareness of their periodic nature, did not make the leap from the tides of Tongkin to the fleeting hues of a soap bubble. That leap was made by Thomas Young, and it was only in 1801 that the concept of interference emerged as an explanatory principle

One contribution of 15 to a special Theme Issue 'Interference 200 years after Thomas Young's discoveries'.

Figure 1. Thomas Young (1773–1829). Reproduced from the frontispiece to Peacock (1855).

applicable equally to the interaction of tides, to the beats of sounds of nearly the same frequency, and to the colours of thin films. This principle—he himself called it a general law (Young 1802*c*)—has proved to be the most powerful of Young's several legacies to science and scholarship.

2. Thomas Young

Thomas Young (see figure 1) was born at Milverton in Somerset in 1773, the eldest of the 10 children of a prosperous banker and mercer. According to his own account, he could read at the age of two and had read twice through the Bible by the age of four (Peacock 1855). His formal schooling was intermittent and he was largely self-taught. By the age of 14 he was an accomplished Greek scholar, had learnt Hebrew and Persian, and—the better to construct microscopes and telescopes—had mastered turning. At the age of 17 he read Newton's *Principia* and *Opticks*. His first scientific paper, on the mechanism of visual accommodation, was published in the present journal when he was aged 20 (Young 1793); and this secured his election to The Royal Society in 1794. His uncle, Richard Brocklesby, was a successful London physician and intended Young as his successor. Young studied medicine at Barts and in Edinburgh before spending the academic year of 1795–1796 at the most scientifically distinguished university within the domains of George III, the Georg-August University of Göttingen. We know from his own records that he there attended the lectures of G. C. Lichtenberg on physics at 2 p.m. each day (Peacock

1855). And we know that these lectures contained extensive material on chromatics (Gamauf 1811), and not surprisingly, for Lichtenberg had a long-standing interest in the trichromatic colour system of Tobias Mayer.

But Young's interest in sound also derived from his period in Göttingen. In a later essay—defending his optical papers against the notorious criticisms published in the *Edinburgh Review* by Lord Brougham—he gives an account of how his ideas developed.

> When I took a degree in physic at Göttingen it was necessary, besides publishing a medical dissertation, to deliver a lecture upon some subject connected with medical studies: and I chose for this, the formation of the human voice. A few pages, containing a table of articulate sounds, were printed at the end of my dissertation, *On the Preservative Powers of the Animal Economy*. My uncle, Dr. Brocklesby, at the instance of the late most respectable Dr. Herbenden, repeatedly urged me to give further explanation of the subject to which these characters related. When I began the outline of an essay on the human voice, I found myself at a loss for a perfect conception of what sound was, and during the three years that I passed at Emmanuel College, Cambridge, I collected all the information relating to it that I could procure from books, and I made a variety of original experiments on sounds of all kinds, and on the motions of fluids in general. In the course of these inquiries, I learned to my surprise, how much further our neighbours on the continent were advanced in the investigation of the motions of sounding bodies and of elastic fluids, than any of our countrymen; and in making some experiments on the production of sounds I was so forcibly impressed with the resemblance of the phenomena that I saw, to those of the colours of thin plates, with which I was already acquainted, that I began to suspect the existence of a closer analogy between them than I could before have easily believed.
>
> *Reply to the Animadversions of the Edinburgh Reviewers, on some papers published in the Philosophical Transactions*, London, 1804.

Although Brocklesby died in 1797, leaving to his protegé his London house, his library and paintings, and £10 000, Young could not start in practice because he needed further residence in a British university in order to be licensed by the Royal College (Gurney 1831). It was to satisfy this requirement that he entered Emmanuel College, Cambridge, as a Fellow Commoner, that is, a gentleman entitled to dine with the Fellows although *in statu pupillari*. Our best estimate of his period of residence comes from the College's surviving Coal Books, which show that coal was supplied to a Mr Young from mid-1797 to mid-1800 (Bendall *et al*. 1999).

One of Young's contemporaries records that he was known in Emmanuel as 'Phaenomenon Young' and writes:

> ... his room had all the appearance of belonging to an idle man. I once found him blowing smoke though long tubes, and I afterwards saw a representation of the effect in the Transactions of the Royal Society to illustrate one of his papers upon sound; but he was not in the habit of making experiments.
>
> (Peacock 1855)

The paper referred to must be Young's 'Outline of experiments and inquiries respecting sound and light', published in the *Philosophical Transactions* for 1800. In this paper he applies the principle of interference to acoustics but does not yet generalize it to optics. Most of the paper is devoted to acoustics, but he does suggest (in § 10) an analogy between the colours of thin plates and the resonance of organ pipes. He rests this analogy upon Newton's observation that the same colour recurs whenever the thickness of the plate corresponds to the terms of an arithmetical progression. He is close to the critical insight, but the ordering of the sections shows us that he is not yet there. For it is only in § 11 ('Of the coalescence of musical sounds') that he returns to acoustics and uses the yet-unnamed principle of interference to explain the beating, the waxing and waning of amplitude, that is heard when two tones are of very similar but not identical frequency. When sound waves interact, he insists, each particle of air must exhibit the resultant motion of the components, in contrast to the common 18th-century notion that individual molecules may have separate motions (Young 1800).

The *Parlour Book* of Emmanuel College records a wager dated 14 March 1799 between Young and Pemberton that 'Young will produce a pamphlet or paper on sound more satisfactory than anything that has already appeared, before he takes his Bachelor's degree'. An Audit of Wagers in 1802 records that Young was judged to have lost the bet.

College legend holds that Young first observed interference patterns in the ripples generated by a pair of swans on the pond in the Paddock at Emmanuel, which in his day retained the rectangular form of a Dominican fish pond (Bendall *et al.* 1999). Certainly he explicitly uses a lacustrine model of this kind in his response to the criticisms of Lord Brougham.

> Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose then another similar cause to have excited another equal series of waves, which arrive at the same channel at the same time, with the same velocity, and at the same time with the first. Neither series of waves will destroy the other, but their effects will be combined: if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment.
>
> (Young 1804*b*)

3. The colours of thin plates

It was only in May 1801, according to his own account, that Young grasped that interference could explain the colours of thin plates. He hints at his explanation in a letter to *Nicholson's Journal*, dated 13 July (Young 1801), and the hypothesis was set out explicitly in his Bakerian Lecture read to The Royal Society in two parts, on 12 and 19 November 1801. On both occasions the manuscript *Journal Book* of the

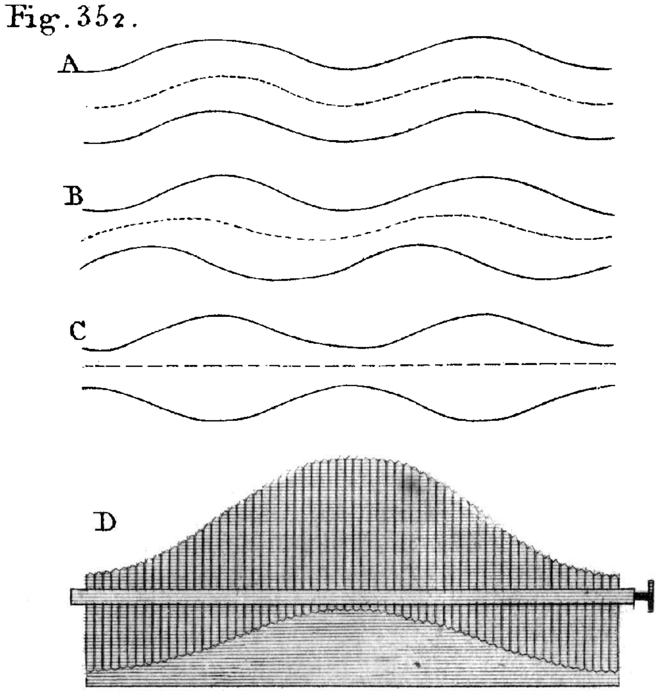

Figure 2. A figure from Young's *Lectures on Natural Philosophy* showing constructive and destructive interference of waves. The solid lines show the two component waves and the central, broken, line shows the compound vibration reduced to half its real extent. Lines A–C show the component waves in different phase relationships. Line D represents an instructional device for finding the combined effect of two waves: one component wave is formed by sliders of different length, the second by a shaped board on which the first can be placed (Young 1807).

Society records that the audience included Humphry Davy, Young's fellow lecturer at the newly founded Royal Institution. The Bakerian Lecture was published in the *Philosophical Transactions* for the following spring (Young 1802*a*) but the first printed account of his theory occurs in the *Syllabus* for his Royal Institution lectures, which was published at the beginning of the year (Young 1802*c*). In the *Syllabus* he writes (p. 117):

> But the general law, by which all these appearances are governed, may be very easily deduced from the interference of two coincident undulations, which either cooperate, or destroy each other, in the same manner as two musical notes produce an alternate intension and remission, in the beating of an imperfect unison.

In the manuscript notes for his Royal Institution lectures, Young makes explicit the analogy with compound tides and the Batsha anomaly (University College London Archives, *Ms. Add. 13*). And, to assist the understanding of his fashionable audience, he constructed a mechanical apparatus to illustrate the superposition of two waves (Young 1802*b*). One component was represented by a set of vertical sliding rods, varying in length so as to represent a sinusoidal wave. This set of sliders could be placed on a wooden board, which had been shaped to represent the profile of a second sinusoidal wave (see figure 2).

It is important to distinguish between, on the one hand, the concept of interference, which follows analytically from the linear superposition of waves, and, on the other, Young's particular version of the wave theory of light. He himself encouraged his audience to make this distinction. He supposed that light consisted of waves in an all-pervading ether. Different wavelengths correspond to different hues, the shortest wavelengths appearing violet, the longest red. In his initial model, however, the undulations are longitudinal ones, rather than transverse (as Fresnel was later to show them to be). His ether consists of mutually repelling subtle particles, which are attracted to particles of matter; and thus the ether is denser within dense bodies than in rare ones (Cantor 1970). When light waves pass through a denser medium, their velocity is reduced, the retardation being greatest for the most frequent undulations.

So what Young offers his audience in 1801 is rather too close an analogy between the way in which vibrations of particles of air produce sound and the way that the vibration of particles of ether produce light. The critical Proposition VIII of the Bakerian Lectures reads:

> When two Undulations from different Origins, coincide either perfectly or very nearly in Direction, their joint effect is a Combination of the Motions belonging to each.
>
> (Young 1802*a*)

In both the printed version and in the *Journal Book*, the unfortunate phrase 'from different Origins' is found. He does not yet require that the components have a common source. Nevertheless, the *Journal Book* recognizes the potential of this proposition:

> This is the eighth proposition, which at first sight, appears so consistent with the most obvious mechanical principles, as scarcely to need any illustration. Yet its extensive utility in explaining the Phaenomena of Colours, renders it perhaps the most important in the Lecture.

To explain the celebrated colours of thin films described by Boyle and by Hooke and measured by Newton, Thomas Young invoked constructive and destructive interference between the component of the incident light that is reflected at the first surface and the component that is reflected at the second. In his *Syllabus* he writes:

> Where two portions of the same light arrive at the eye by different routes, either exactly or very nearly in the same direction, the appearance or disappearance of various colours is determined by the greater or less difference in the lengths of the paths: the same colour recurring, when the intervals are multiples of a length, which, in the same medium, is constant, but in different mediums, varies directly as the sine of refraction.
>
> (Young 1802*c*)

Newton had systematically studied the case of the colours generated when two glass surfaces are separated by a thin film of air. He placed a convex lens on a glass plate and thus, knowing the curvature of the convex surface, he could estimate accurately

Colours.	Length of an Undulation in parts of an Inch, in Air.	Number of Undulations in an Inch.	Number of Undulations in a Second.	Wavelength (nm)
Extreme -	.0000266	37640	463 millions of millions	
Red - -	.0000256	39180	482	650
Intermediate	.0000246	40720	501	
Orange - -	.0000240	41610	512	609
Intermediate	.0000235	42510	523	
Yellow -	.0000227	44000	542	576
Intermediate	.0000219	45600	561 (= 2^{48} nearly)	
Green - -	.0000211	47460	584	536
Intermediate	.0000203	49320	607	
Blue - -	.0000196	51110	629	497
Intermediate	.0000189	52910	652	
Indigo - -	.0000185	54070	665	469
Intermediate	.0000181	55240	680	
Violet - -	.0000174	57490	707	444
Extreme - -	.0000167	59750	735	

Figure 3. Young's estimates of the wavelengths and frequencies corresponding to particular hues (Young 1802*a*). Values of wavelength in nanometres are added to the right.

the thickness of the air film at a given distance from the point of contact. When white light was allowed to fall normally on the air film, Newton observed series of concentric rings of colour. If observations were made of light that had passed through both the lens and the plate, then coloured rings were again seen, but these were complementary in hue to those reflected. If light from only one part of the spectrum were used, then isolated bright bands were seen at certain distances from the centre point. Newton supposed that each of the constituent colours of white light produced its own system of rings and that the colours observed with a white illuminant were due to the overlapping of the individual components. When using light of one colour only, he could measure about 30 successive rings and he found that in moving from one ring to the next the corresponding thickness of the air film always increased by the same amount (Newton 1730).

Young was to make powerful use of Newton's quantitative data. It is not always noticed that Young's Bakerian Lecture of 1801 contains the first estimates of the wavelengths that correspond to particular hues; and that these estimates, once converted from fractions of an inch to nanometres, are remarkably accurate. His table is shown in figure 3, with modern conversions added. Especially striking is the value for yellow, for it is in this region of the spectrum that hue changes most rapidly with wavelength. Young's value converts to 576 nm and this is within a nanometre of typical modern estimates of the wavelength that appears pure yellow, the yellow that looks neither reddish nor greenish to an average eye in a neutral state of adaptation (Ayama *et al.* 1987). His values for orange, green and violet are very reasonable. The value for blue, 497 nm, is a longer wavelength than would be taken as the exemplar of blue today, but Newton's 'blew', in a spectrum that had to accommodate indigo, may have been close to cyan, resembling the modern Russian 'golyboi'.

Young places the limits of the spectrum at 675 nm and 425 nm. These values make the visible spectrum 50 nm shorter than the modern convention of 400–700 nm, but we now know that the limits are quite arbitrary and are dependent on the radiance, since the sensitivity curve of the long-wave photoreceptor (at the red end) and the absorption of the lens of the eye (at the violet end) do not cut off sharply (Wyszecki & Stiles 1967).

4. The two-slit experiment

Young derived his estimates of wavelengths from Newton's estimates of the separations of glass surfaces that gave bright bands for particular hues, and it is the precision of Newton's 17th-century measurements that we should admire. Certainly it cannot be claimed that Thomas Young was a committed experimentalist. His close friend and first biographer, Hudson Gurney, records:

> ...he was afterwards accustomed to say, that at no period of his life was he particularly fond of repeating experiments, or even of very frequently attempting to originate new ones; considering that, however necessary to the advancement of science, they demanded a great sacrifice of time, and that when the fact was once established, that time was better employed in considering the purposes to which it might be applied, or the principles which it might tend to elucidate.
>
> (Gurney 1831)

Similarly, his second biographer, Dean Peacock quotes Young as saying: '...acute suggestion was...always more in the line of my ambition than experimental illustration' (Peacock 1855).

And later in life, Young opposed any addition to the fund that Wollaston had left to The Royal Society for the support of experimental science, declaring:

> For my part, it is my pride and pleasure, as far as I am able, to supersede the necessity of experiments, and more especially of expensive ones.
>
> (Mayer 1875)

And yet, despite this preference for modelling rather than experimenting, one of Young's most powerful legacies was his two-slit experiment, perhaps the single most influential experiment in modern physics. In its standard form, the two-slit experiment does not appear in his earliest papers. But it is anticipated in the third of his Bakerian Lectures, given in November 1803 (Young 1804*a*). Here he describes how he made a hole in a window shutter and covered it with thick paper, which he had perforated with a fine needle. This arrangement provided him with a narrow beam of sunlight, which he directed horizontally across the room with a mirror. He placed in the beam a narrow strip of card, about one-thirtieth of an inch wide. On the wall opposite appeared a pattern of fringes. The centre of this pattern, reached over equal paths by light from the two sides of the strip of card, was always light. When Young introduced a small screen, to obstruct the light passing on one side of the strip, then the pattern of fringes was abolished.

Fig. 267.

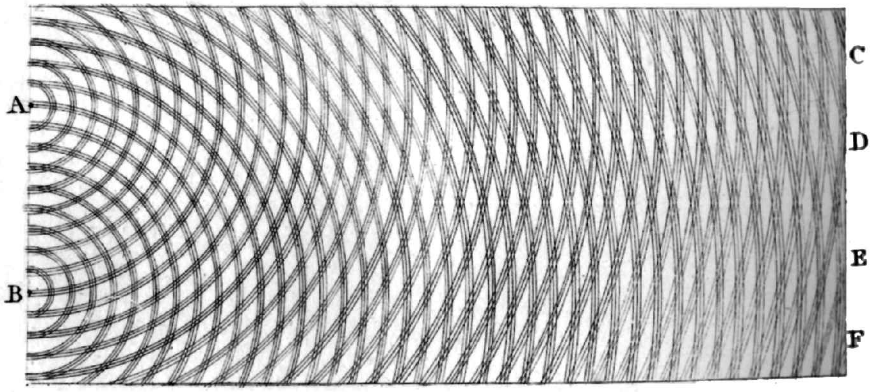

Figure 4. A diagram from Young's *Lectures* (Young 1807) showing the pattern of wave interaction 'obtained by throwing two stones of equal size into a pond at the same instant'. The diagram is to illustrate a lecture on hydraulics, but he explicitly makes the analogy with acoustics and optics.

The two-slit experiment finally appears in his *Lectures on Natural Philosophy* of 1807:

> In order that the effects of two portions of light may be thus combined, it is necessary that they be derived from the same origin, and that they arrive at the same point by different paths, in directions not much deviating from one another... the simplest case appears to be, when a beam of homogeneous light falls on a screen in which there are two very small holes or slits, which may be considered as centres of divergence, from whence the light is diffracted in every direction. In this case, when the two newly formed beams are received on a surface placed so as to intercept them, their light is divided by dark stripes into portions nearly equal, but becoming wider as the surface is more remote from the apertures....
>
> (Young 1807)

For illustration, Young refers his readers to a figure from his lectures on hydraulics, a figure which is reproduced here as figure 4 and which represents the pattern of interacting waves produced by throwing two stones simultaneously into a pond.

The text of his *Lectures* implies that he used the two-slit experiment to make fresh estimates of the wavelengths corresponding to different hues; and certainly he now gives slightly different values for the limits of the spectrum, 1/36 000 of an inch (705 nm) and 1/60 000 of an inch (423 nm). Frustratingly, he never published a systematic experimental paper using the two-slit arrangement, and he did not sharpen up the definition of what it meant to say, that the light must be derived 'from the same origin'. Nevertheless, he clearly judged that his vibration theory of light was strengthened by the quantitative coincidence of values derived from Newton's measurements of thin films and his own measurements of interference patterns.

Commentators have traditionally asked aloud why the two-slit experiment did not immediately lead to an acceptance of the wave theory of light. And the traditional answers were that:

(i) few of Young's contemporaries were willing to question Newton's authority,

(ii) Young's reputation was severely damaged by the attacks of Lord Brougham in the *Edinburgh Review*, and that

(iii) Young's style of presentation, spoken and written, was obscure.

Recent historians, however, have looked instead for an explanation in the actual theory and in its corpuscular rivals (Kipnis 1991; Worrall 1976). Young had no explanation at the time for the phenomena of polarization: why should the particles of his ether be more willing to vibrate in one plane than another? And the corpuscular theorists had been dealing with diffraction fringes since Grimaldi described them in the 17th century: elaborate explanations were available in terms of the attraction and repulsion of corpuscles as they passed by material bodies.

So Young's wave theory was thus very much a transitional theory. It is his 'general law of interference' that has stood the test of time, and it is the power of this concept that we celebrate on the bicentennial of its publication in his *Syllabus* of 1802.

5. Trichromacy

In a colour-mixing experiment, any colour can be matched by a mixture of three primary colours, provided that none of the chosen primaries can be matched by a mixture of the other two and that the experimenter has the freedom to mix one of the primaries with the test light (Wyszecki & Stiles 1967). This trivariance of colour mixing was already recognized in a simple form during Newton's lifetime (Boutet 1708) and was the subject of increasingly sophisticated studies as the 18th century progressed (Castel 1740; Mayer 1775; Wünsch 1792). But 18th-century commentators almost universally miscategorized the trivariance of colour mixing, treating it as a fact of physics rather than as one of human physiology. This category error held back the understanding of physical optics more than has been generally realized: many 18th-century scientists concluded that there must be only three types of light and that Newton was mistaken in supposing that the physical variable underlying hue was a continuous one. Persuaded that colour corresponded to a continuous variable, wavelength, Thomas Young was able to grasp that trichromacy must be imposed by our visual system.

> So far as I know, Thomas Young was the first who, starting from the well-known fact that there are three primary colours, sought for the explanation of this fact, not in the nature of light, but in the constitution of man.
>
> (Maxwell 1871)

In his Bakerian Lecture of 1801, Young introduced the idea that the retina contains just three types of resonators:

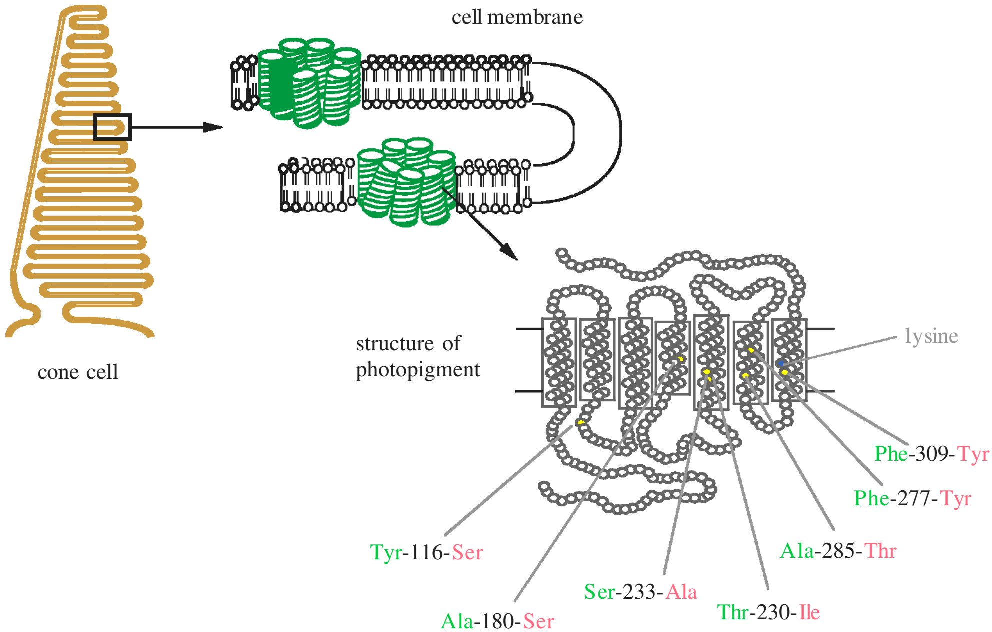

Figure 5. Young's retinal resonators as they are now understood. To the left is shown the infolded membrane of the outer segment of a cone cell. In the centre are represented the opsin protein molecules embedded in the lipid membrane, and to the bottom right is a cartoon of the amino-acid sequences of the long- and middle-wave opsins of the human retina. The diagram identifies the small number of critical amino acids that are thought to be responsible for the difference in peak spectral sensitivity between the long-wave (indicated in red) and middle-wave (indicated in green) photopigments. The chromophore, 11-*cis*-retinal, is bound to a lysine residue in the seventh transmembrane helix.

> Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance, to the three principal colours, red, yellow, and blue.
>
> (Young 1802*a*)

The resonators, he supposed, were broadly tuned, so 'that each of the particles is capable of being put in motion less or more forcibly, by undulations differing less or more from a perfect unison'.

We now know that Young's three resonators correspond to opsin photoreceptor molecules, embedded in the multiply infolded membranes of retinal cones (figure 5). The different opsins, with peak sensitivities near 420, 530 and 560 nm, are segregated in different cones (Dartnall *et al.* 1983). The opsins are members of the superfamily of G-protein-coupled receptors or 'heptahelicals' and are characterized by seven helices that straddle the cell membrane and form a splayed palisade around the chromophore, 11-*cis*-retinal (Hargrave *et al.* 1984; Nathans *et al.* 1986). Absorption of a photon by the 11-*cis*-retinal causes its isomerization to all-*trans*-retinal, leading to a conformational change in the protein. Thomas Young would have been pleased to learn how his own concept of interference has been used in modern crystallographic methods to derive the structure of the light-absorbing molecules of this class (Palczewski *et al*. 2000; Schertler *et al*. 1993). An account of such work is given by Subramaniam *et al*. (2002) in this issue.

For historical assistance I am grateful to Dr Kim Taylor, Professor B. R. Webber and the archival staff of Emmanuel College, Cambridge, of University College London and of The Royal Society.

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