

Three cortical stages of colour processing in the human brain

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Summary

We used the technique of functional magnetic resonance imaging to chart the colour pathways in the human brain beyond V4. We asked subjects to view objects that were dressed in natural and unnatural colours as well as their achromatic counterparts and compared the activity produced in the brain by each condition. The results showed that both naturally and unnaturally coloured objects activate a pathway extending from V1 to V4, though not overlapping totally the activity produced by viewing abstract coloured Mondrian scenes. Normally coloured objects activated, in addition, more anterior parts of the fusiform gyrus, the hippocampus and the ventrolateral frontal cortex. Abnormally coloured objects, by contrast, activated the dorsolateral frontal cortex. A study of the cortical covariation produced by these activations revealed that activity in large parts of the occipital lobe covaried with each. These results, considered

against the background of previous physiological and clinical studies, allow us to discern three broad cortical stages of colour processing in the human brain. The first is based on V1 and possibly V2 and is concerned mainly with registering the presence and intensity of different wavelengths, and with wavelength differencing. The second stage is based on V4 and is concerned with automatic colour constancy operations, without regard to memory, judgement and learning. The third stage, based on the inferior temporal and frontal cortex, is more concerned with object colours. The results we report, as well as the schema that we suggest, also allow us to reconcile the computational theory of Land, implemented without regard to cognitive factors such as memory and learning, and the cognitive systems of Helmholtz and Hering, which view such factors as critical in the determination of colours.

Keywords: colour vision; V4; hippocampus; functional MRI; inferior temporal cortex

Abbreviations: fMRI = functional magnetic resonance imaging; SPM = statistical parametric map; $SPM\{t\}$ = SPM of the t statistic; $SPM\{Z\}$ = $SPM\{t\}$ transformed to the normal distribution; TE = time to echo; TR = time to repeat

Introduction

'If the sensation which we call colour has any laws it must be something in our own nature that determines the form of these laws . . . The science of colour must therefore be regarded as essentially a mental science.'

James Clerk Maxwell, 1872

The aim of the work reported here was to chart the colour pathways of the brain beyond area V4, by asking what areas are activated when normal humans view colours as properties of objects rather than as abstract compositions, as in the coloured Mondrians that we and others have used in previous studies.

What we call colour is the result of a complex operation undertaken by the brain, whose essence lies in a comparison of the wavelength composition of the light reflected from

one surface with that reflected from surrounding surfaces (Land, 1974, 1983). It is this remarkable capacity that leads to the phenomenon that we call colour constancy, the ability to assign a constant colour to a surface regardless of the spectral composition of the light in which it is viewed. It constitutes the single most important property of the colour system, for without it colour vision would lose its importance as a biological signalling mechanism. We know a little of the way in which the brain implements such an operation. It almost certainly involves several steps centred on at least three different areas: V1, V2 and V4 (Zeki, 1984, 1993). Computational theories have outlined ways in which such an operation can be implemented (Land, 1974; Courtney *et al.*, 1995). But of how the brain undertakes these operations and of whether its implementation differs from that suggested by

computational theories of colour vision we are more or less ignorant.

Computational theories emphasize the implementation of an operation that is undertaken without regard to memory, learning or judgement (e.g. Land, 1974). Land coined the term *retinex* to indicate that the crucial comparisons might occur anywhere between the *retina* and the *cortex*, although we now know that the most likely site is the *cortex*, and more specifically area V4 (Zeki, 1993). There have been other, more vaguely formulated, views that have considered factors such as memory and learning to be critical for colour constancy, and have thus also implicated the *cortex*. Helmholtz (1867) wrote of the importance of judgement in 'discounting the illuminant', through the undefined process of the 'unconscious inference' (Helmholtz, 1867). Hering (1877/1964) emphasized memory. However ill defined such factors may seem, and however vague the role imputed to them in the generation of constant colours, the terminology leaves little doubt that, implicitly at least, the involvement of higher cognitive functions and therefore of the cerebral *cortex* was deemed to be critical.

Our previous physiological and imaging work on colour vision used Mondrian stimuli (Zeki, 1983a,b; Zeki *et al.*, 1991; McKeefry and Zeki, 1997). These are relatively simple multicoloured abstract scenes with no recognizable objects, thus ensuring that factors such as memory and learning do not play a significant role. Indeed it is for this very reason that Land settled on the Mondrian stimulus and Mondrian himself settled on his compositions, since he wanted to abstract forms and represent their constant elements (Mondrian, 1937). But colour is usually a property of recognizable objects and surfaces and here the emphasis on knowledge, memory and learning—highlighted by Helmholtz, Hering and others—might be of critical importance, not to the exclusion of the operations of the brain to generate constant colours, but in addition to them. We therefore thought it interesting to extend our previous work and learn whether the same pathways are involved when subjects view colours as abstract compositions and when they view them as properties of objects, our supposition being that areas beyond V4 would be recruited in the latter instance. Here we became inspired by fauvism, an art movement that had many aims. The aim that is of interest to us in this context is that of the 'liberation of colour' to give it greater emotional and expressive power (Arnason, 1977), an aim also pursued by non-fauvist artists such as František Kupka and Adolf Hoelzel, who were more interested in non-iconic colour abstraction. But what was colour to be liberated from? The impossibility of liberating it from form on a two-dimensional canvas led the fauvists to adopt the only physiologically viable solution: to 'liberate' colours by investing objects with colours which they are not usually associated with, a classic example being André Derain's painting *Charing Cross Bridge, London* (Fig. 1A). Such compositions, unnatural in colour, also involve knowledge, to the extent that we learn to associate certain colours

with certain objects. We therefore decided to enlarge our experiments further, and enquire not only into what brain areas are activated when we view objects in their natural colours but also how our brains react when we enter this fauvist world and view the same objects when dressed in unnatural colours. The results, taken in conjunction with previous work, incline us to discern three broad cortical stages in human colour perception, with probable subdivisions within each.

Material and methods

Subjects

Nine male subjects with an average age of 27.1 years participated in the experiments. All had normal colour vision and normal or corrected vision. Seven were right-handed and two were left-handed. All gave informed consent and the experiment was approved by the National Hospital for Neurology and Neurosurgery Ethics Committee.

Stimuli

The stimuli consisted of naturally and unnaturally coloured common objects, divided into three groups: (a) 16 scenes of fruits and vegetables, animals and landscapes in their natural colours, of which one example is given in Fig. 1B; (b) the same scenes as in (a) but in abnormal colours (for an example see Fig. 1C); and (c) the achromatic (black, white and grey) version of (a) which acted as the baseline against which to judge colour activation. By achromatic counterpart we mean the black, white and grey versions of the coloured stimuli. We do not mean to imply that black, white and grey are not colours. They are regarded as colours by scientists such as Hering (1877/1964) and Land (1974), as well as by artists (e.g. Matisse, 1972). Without discussing the merits of different classifications, we simply state that the achromatic counterparts were much more restricted chromatically. To equate each individual part of the coloured and grey pictures for luminance would have been an insuperable task; we therefore converted each coloured picture to its grey-scale version using Adobe Photoshop 3.1. This respected the overall luminosity (in the range of 0.28 and 1.72 cd/m) of the coloured versions in relation to the grey ones. (d) The control (rest) condition consisted of a black screen. The results that we obtained made it interesting enough to extend our observations further and include another experiment, done more in the nature of a control. This was identical in design and procedure to the one described by McKeefry and Zeki (1997), in that it used the multicoloured abstract Mondrian scene and its achromatic counterpart, but differed in using additionally the normally coloured objects and their black and white counterparts; we undertook it to learn whether the part of the fusiform gyrus activated by the multicoloured Mondrian is also activated by normally coloured objects. We did not undertake the direct comparison between coloured

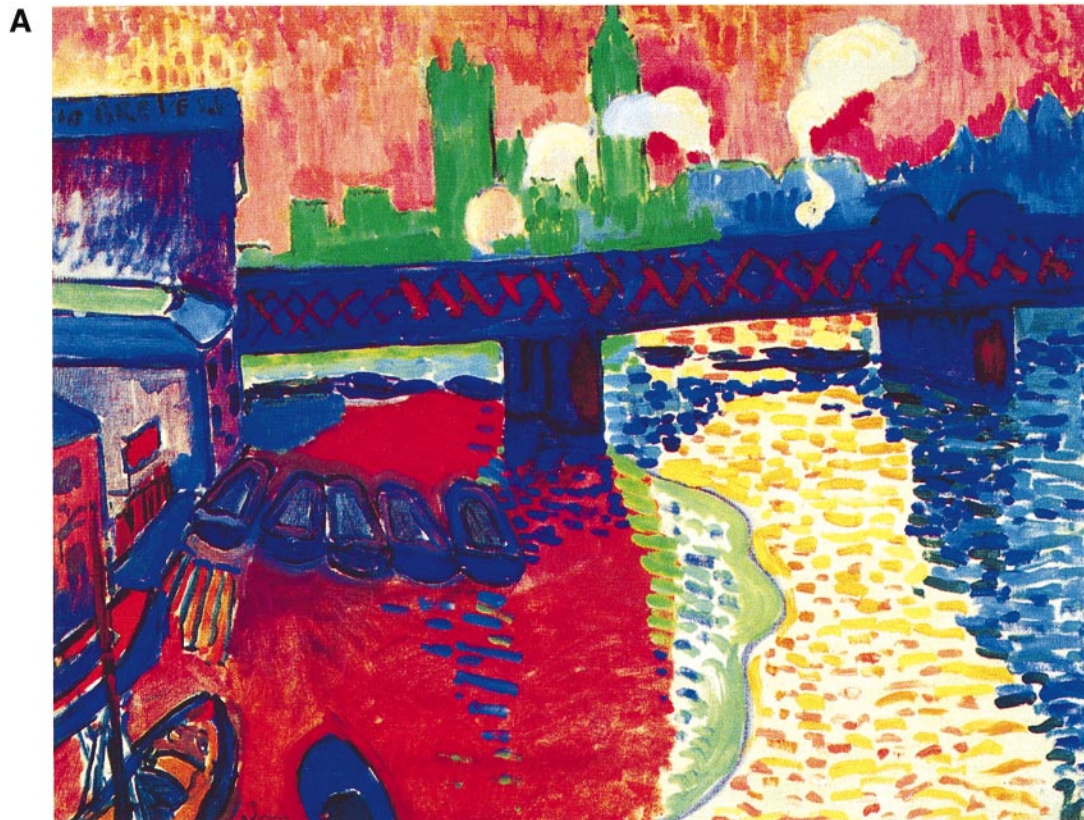


Fig. 1 (A) André Derain's *Charing Cross Bridge, London* (1906), National Gallery, Washington, DC. © ADAGP, Paris and DACS, London 1998. Reproduced with permission. Part (B) is an example of a scene in natural colours used in this study, while (C) shows the same scene in unnatural colours.

Mondrian and coloured pictures, and vice versa, because the different natures of the two types of stimuli (the coloured pictures in fact involved objects, semantic components and a large number of colours, whereas the Mondrian scenes did not) would make the results impossible to interpret.

The stimuli were generated by an Apple 7500/100 computer running Cogent (O. Josephs, Wellcome Department of

Cognitive Neurology, Institute of Neurology, London, UK). The output of the computer was fed to a liquid crystal display projection system. The stimuli were projected onto a translucent screen and the subjects viewed the image via a mirror angled at 45°. Prior to the experiment subjects were informed that they would be viewing both normally and abnormally coloured objects.

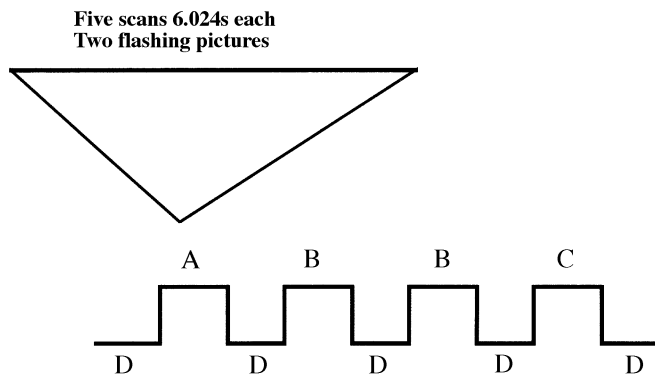


Fig. 2 Schematic representation of the experimental design, where (A) represents scenes of fruits and vegetables, animals and landscapes in their natural colours, (B) represents the same scenes as in (A) but in abnormal colours, (C) represents the achromatic (black, white and grey) version of (A) which acted as the baseline against which to judge colour activation, and (D) represents the rest condition, consisting of a black screen.

The different conditions—normally coloured and abnormally coloured objects and their black and white counterparts—were presented in a random sequence, each followed by a 30.12 s rest condition. Each condition was presented for 30.12 s, during which two different pictures of the same category flashed alternately at the rate of 1 Hz. Each condition was repeated eight times during a session, followed by a 30.12 s rest period, giving a total of 240 scans per individual (Fig. 2).

Image acquisition

Functional images sensitive to blood oxygenation level-dependent contrast were acquired on a Siemens 2T Vision scanner with a head radio-frequency resonator, using a gradient echo planar imaging sequence (TR = 6.024 s, TE = 40 ms). The images consisted of 64 transverse slices, each being 64×64 pixels (voxel size $3 \times 3 \times 3$ mm). T_1 -weighted structural images were obtained in the same session. SPM software, modified for fMRI (Friston *et al.*, 1995a, b, 1996), was used to analyse the results. Each volume was realigned in order to remove motion artefacts and was spatially normalized to the stereotaxic space of Talairach and Tournoux (1988). The images were smoothed with an 8 mm full-width half-maximum Gaussian filter. After specifying the appropriate design matrix, changes in the haemodynamic response produced by the different experimental conditions were assessed at each voxel using a general linear model with a delayed boxcar wave form and a theory of Gaussian fields (Friston *et al.*, 1995c), which constituted SPM. To test hypotheses about regionally specific condition effects, the estimates were compared using linear compounds or contrasts. The resulting set of voxel values for each contrast constitutes a SPM of the t statistic $SPM\{t\}$. The t values constitute the $SPM\{t\}$, which is transformed to the unit normal distribution to give an $SPM\{Z\}$. The resulting set of Z values constituted

the $SPM\{Z\}$, which was then thresholded at $P < 0.05$ (corrected for multiple comparisons).

Analysis

We undertook the following comparisons for the main experiment: (i) visual stimulation versus rest (A + B + C versus D); (ii) normally coloured stimuli versus their achromatic counterparts (A versus C); (iii) abnormally coloured stimuli versus their achromatic counterparts (B versus C); (iv) normally coloured versus abnormally coloured stimuli (A versus B); (v) abnormally coloured versus normally coloured stimuli (B versus A).

Results

Activations without a priori hypothesis

The SPM method, as modified for fMRI (Friston *et al.*, 1995a), is stringent and, in the absence of a priori hypotheses, accepts as valid activations only those that are able to withstand multiple comparisons with all other brain voxels. The stringency can be relaxed when there is an a priori hypothesis. In these studies, our only a priori hypothesis was that the stimuli we used would activate areas V1/V2 as well as area V4. As it happens, they also activated other brain regions consistently and with such high Z scores that no a priori hypothesis was needed. We therefore consider all the activations reported below as being significant and valid at $P < 0.05$ (corrected for multiple comparisons). We present the results obtained by averaging the data from nine subjects, but the same pattern of activation was observed in at least six of the subjects, when these were analysed individually.

We begin with the results we obtained with the multicoloured Mondrian compared with its achromatic version, using three subjects. This was done to validate our previous results generally (McKeefry and Zeki, 1997) and also to provide an anatomical baseline against which the activations produced by the more novel colour stimuli could be compared. The comparison of colour Mondrian versus achromatic Mondrian produced the classical activation of area V1 (and also V2; the two areas were difficult to separate in these relatively low-resolution images). It also produced a bilateral activation of area V4, located in the fusiform gyrus. The position of the latter activation was very similar to the position of V4 as defined in our earlier experiment (Zeki *et al.*, 1991; McKeefry and Zeki, 1997).

Comparison of normally coloured objects with their black and white counterparts

The activations produced by the other comparisons, derived from nine subjects, together with their Z scores, are given in Table 1. The activity produced by naturally coloured objects (Fig. 3) compared with their achromatic counterparts resulted in a large area of activation within the fusiform gyrus. The

Table 1 Co-ordinates and Z scores of the maximally activated voxels for the group-averaged results

Activation	x	y	z	Z score
Normal versus black/white				
Right fusiform	+22	-40	-8	5.68
Right V4	+28	-60	-14	
Left fusiform	-22	-56	-4	4.32
Left V4	-22	-60	-14	
Right middle temporal gyrus	+46	-76	+18	5.14
Right hippocampus	+36	-8	-16	5.51
Left hippocampus	-24	-12	-12	4.72
Right ventrolateral frontal cortex	42	40	-4	5.70
Abnormal versus black/white				
Right V4	+30	-72	-8	5.37
Left V4	-32	-62	-12	5.13
Right dorsolateral frontal cortex	+46	+8	+20	6.01
Left occipitoparietal	-24	-78	+20	5.08
Normal versus abnormal				
Right middle temporal and superior temporal gyri	+62	-12	-12	4.36
Right and left posterior cingulate	-10	-42	+28	4.43
Abnormal versus normal				
Bilateral frontal	-42	+42	+28	4.64
(and anterior cingulate)	+14	+26	+32	

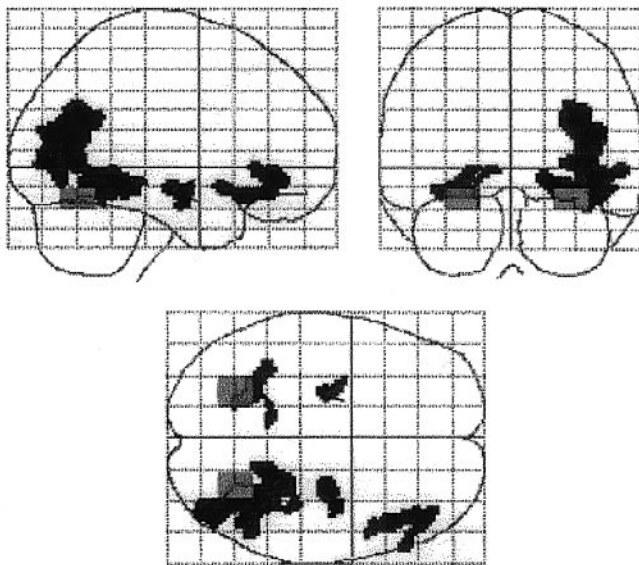


Fig. 3 Diagrammatic representation of the group results of brain activation obtained by comparing the normally coloured objects with their black and white counterparts. Thresholded at $P < 0.0001$. The grey squares represent the area of activation produced by comparing areas of activation produced by multicoloured Mondrian stimuli against their achromatic counterparts in the study of McKeefry and Zeki (1997).

posterior part of this zone of activation overlapped with V4 (Zeki *et al.*, 1991; McKeefry and Zeki, 1997) but, unlike the activation produced by the multicoloured Mondrian in this and previous studies, it extended more anteriorly to involve the posterior two-thirds of the fusiform gyrus; it also extended dorsally to involve more of the occipital lobe. Neither the

more anterior (along the fusiform gyrus) nor the dorsal (in the occipital lobe, extending to parietal cortex) activation was uniform in intensity, but each contained several 'hotter' areas (Fig. 3). In addition, there was an activation of the hippocampus bilaterally, together with a unilateral activation in the ventrolateral (inferior) frontal convolution, which loosely corresponds to Brodmann areas 47 and 11.

We note that the activation of areas V1 and V2 could be observed only when the threshold was dropped to 0.001.

Comparison of abnormally coloured objects with their black and white counterparts

When the same objects described above were given colours with which they are not normally associated (e.g. a blue strawberry; Fig. 1C), and the activity in the brain produced by viewing them compared with that produced by viewing their achromatic versions, the activations were remarkably similar to those produced by the Mondrian stimuli found in this and previous studies, except that there was additional involvement of the right dorsolateral frontal gyrus (corresponding loosely to territory occupied by Brodmann areas 44, 9 and 46), plus an activation of the left occipitoparietal cortex (Fig. 4). Hence, in contrast to the comparison of normal colours versus their achromatic counterparts, the activation now did not extend anteriorly in the fusiform gyrus nor did it involve the hippocampus; there was, however, an activation of areas V1 and V2 when the threshold was dropped to 0.001, again statistically significant when coupled to an a priori hypothesis.

Not surprisingly, the comparison of the activation produced

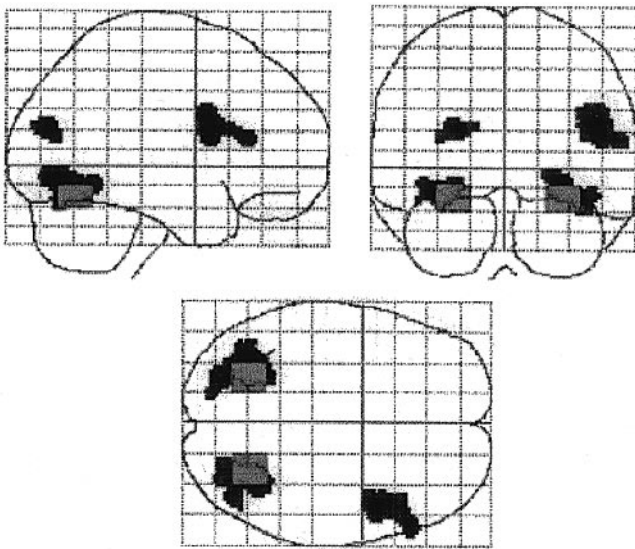


Fig. 4 Diagrammatic representation of the group results obtained by comparing the abnormally coloured objects with their black and white counterparts. As in Fig. 3, the grey squares represent the area of activation produced by comparing multicoloured Mondrian stimuli against their achromatic counterparts (McKeefry and Zeki, 1997). Thresholded at $P < 0.0001$.

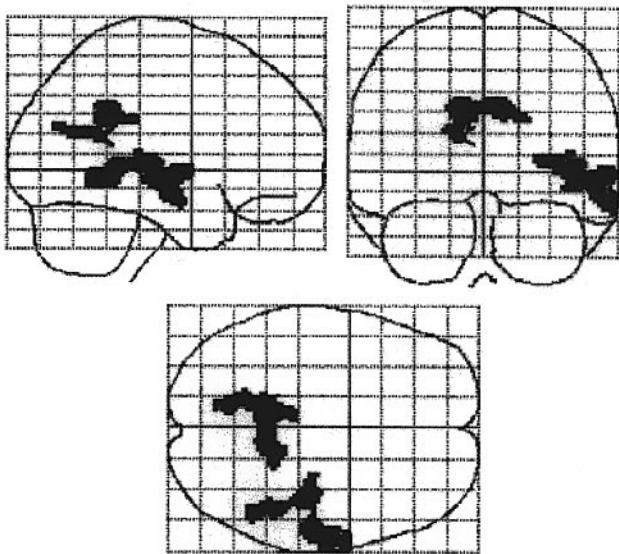


Fig. 5 Diagrammatic representation of the group results obtained by comparing the activity produced by normally and abnormally coloured stimuli.

by the normal colours versus abnormal colours resulted in a pattern that excluded V4, but included activation of the more anterior parts of the fusiform gyrus (Fig. 5). But an area of differential activation, not seen in the previous comparisons, now occurred in the posterior cingulate gyrus. By contrast, the reverse comparison—of abnormal versus normal colours—resulted in a large bilateral differential activation of the

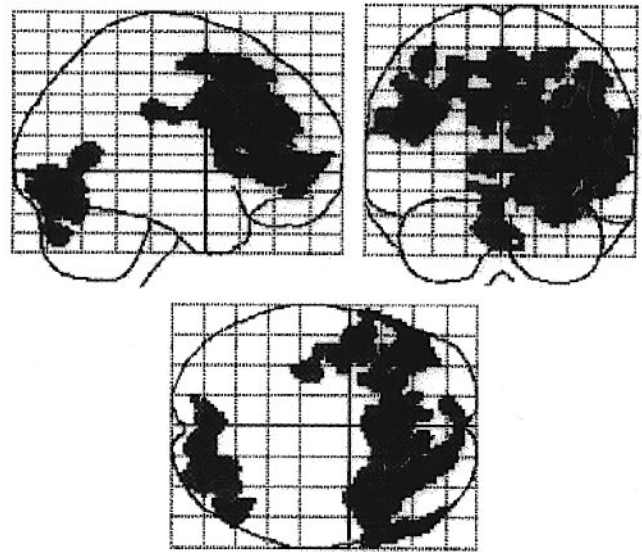


Fig. 6 A diagrammatic representation of the group results obtained by comparing the activity produced by abnormally versus normally coloured stimuli.

frontal lobes (Fig. 6); this extended to the anterior part of the cingulate gyrus and consisted of several activation foci, mainly on the right. Collectively, these foci fell within Brodmann areas 46, 9, 44 and 10. The activation of the occipital lobe shown in Fig. 5 did not reach significance.

Studies of connectivity inferred from analysis of covariation

Analysis of covariation reveals networks of activation across brain regions, within areas that act together, without reference to any of the four stimulus conditions. A covariation study differs fundamentally from a comparison (contrast) study. The latter reveals the subset of areas that are especially active in any given comparison, without necessarily indicating whether other areas are perturbed by the activation. A covariation study reveals all the areas in which activity covaries with the areas highlighted in the comparison study, and may therefore reveal that two conditions, for example the normally and abnormally coloured pictures, may produce an overall perturbation in areas that may be the same or different. The analysis of covariation is done by choosing a voxel of interest, which is likely to be the maximum of an activated cluster, and asking what other voxels in the brain show activity that covaries consistently with that in the chosen voxel, during the course of all experiments and in all conditions, i.e. in all 240 scans per subject. We were especially interested in the following: (i) the covariation with the activity produced in the frontal lobe at a site found by contrasting normally and abnormally coloured stimuli with their achromatic counterparts. Two such frontal foci, separated in space, were found, constituting two separate covariation studies; (ii) the covariation of activity with that in V4,

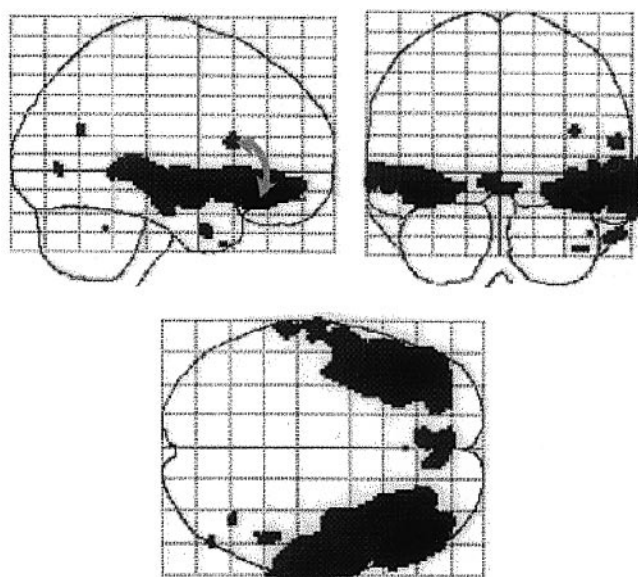


Fig. 7 Diagrammatic representation of the parts of the cortex that covary with activation of the hottest voxel in the ventrolateral frontal cortex, activated by normally coloured objects. Thresholded at $P < 1 \times 10^{-12}$. The arrow indicates the areas that are activated by the normally coloured stimuli (lower point) and the abnormally coloured stimuli, located in the dorsolateral frontal cortex.

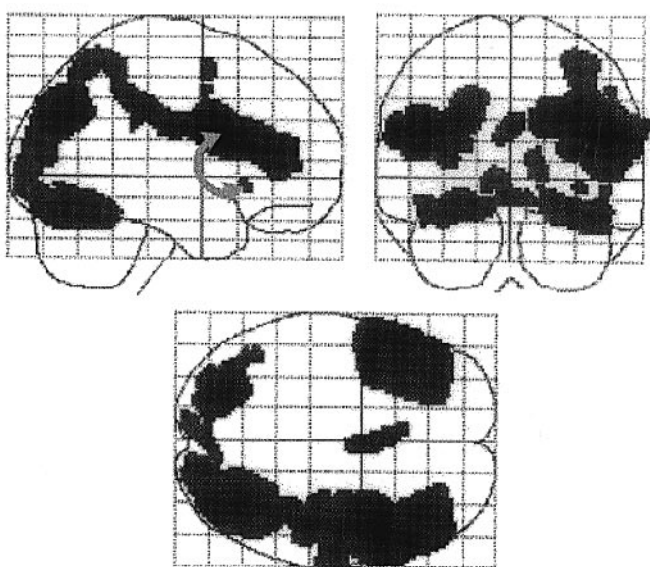


Fig. 8 Diagrammatic representation of the parts of the cortex that covary with activation of the hottest voxel in the dorsolateral frontal cortex, activated by abnormally coloured objects. The arrow indicates the areas that are activated by the abnormally (upper panel) and normally coloured stimuli, located in the ventrolateral frontal cortex. Thresholded at $P < 1 \times 10^{-12}$.

identified by the same two stimuli, which constituted two further covariation studies.

The results shown in Figs 7 and 8 reveal that, when the probe was placed in the part of the ventrolateral frontal gyrus activated by normal colours, a large zone extending from the

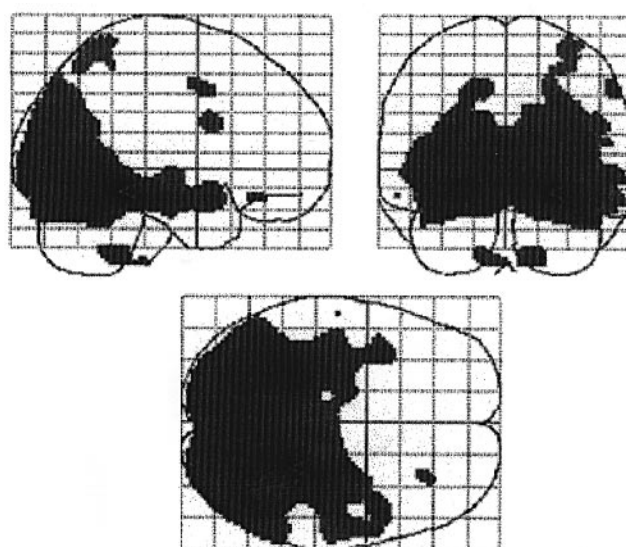


Fig. 9 Diagrammatic representation of the parts of the cortex that covary with activation of the hottest voxel in the right fusiform gyrus, produced by the normally coloured stimuli. Thresholded at $P < 1 \times 10^{-8}$.

inferior frontal convolution posteriorly to the middle and superior temporal convolutions was found to show correlated activity. It is interesting to note that these zones of activation were obtained with extremely high thresholds and withstood multiple comparisons; relaxation of the thresholds, but still within the margins acceptable for multiple comparisons, did not result in new areas but extended the zones already demonstrated considerably, both posteriorly and inferiorly. We were especially interested to note that when the probe was placed in the ventrolateral frontal cortex (the area activated by the normally coloured stimuli, group a versus group c), there was an area of activation located in the dorsolateral frontal cortex, within territory that was activated with abnormal colours. Equally, when the probe was placed in the dorsolateral frontal cortex (the area activated by the abnormally coloured stimuli; group b versus group c) the covarying zone included the region activated by normally coloured stimuli, as if the two areas were effectively connected. But the area revealed by such a covariation study was much more extensive and extended posteriorly across the frontal and parietal lobes to the occipital lobe and included area V4 in the fusiform gyrus.

When the probe was placed in the part of V4 activated by the normally coloured stimuli versus their achromatic counterparts (group a versus group c), there was a wide area of activation that included almost the whole of the occipital lobe and extended to the parietal cortex superiorly and to the temporal lobe and the hippocampus anteriorly (Fig. 9). The covarying areas in the frontal lobe were far less extensive and included small zones in both the dorsolateral as well as the ventromedial frontal cortex. When we placed the probe in the part of V4 activated by abnormally coloured stimuli versus their achromatic counterparts (group b versus group

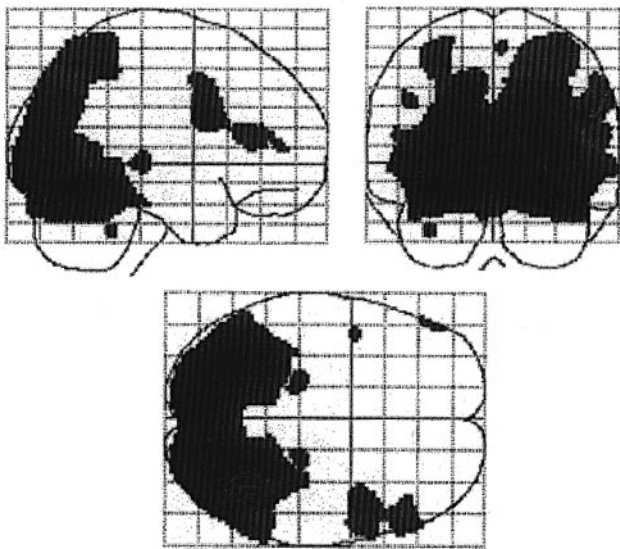


Fig. 10 Diagrammatic representation of the parts of the cortex that covary with activation of the hottest voxel in the left fusiform gyrus produced by abnormally coloured stimuli. Thresholded at $P < 1 \times 10^{-8}$.

c), the distribution was also very wide within the occipital lobe and it extended to the parietal cortex (Fig. 10). Unlike the previous covariation, however, there was no involvement of the hippocampus, and no involvement of the anterior two-thirds of the temporal lobe. In the frontal lobes there was an extensive, bilaterally distributed, zone of covariation which included the territory of cortex activated by the abnormally coloured stimuli and extended well beyond.

The two different foci of V4 activated by the normally and abnormally coloured stimuli, both of which occur within the territory of V4 as defined by the results of McKeefry and Zeki (1997), thus seem to covary with two very different networks of areas. To map the difference in the areas that covary with activity with each focus in V4, we analysed the interaction of the two covariation studies by subtracting the areas covarying with V4 in one condition (normal) and those covarying with it in the other (abnormal) condition. The result, as we expected from the covariation studies reported above, involved a wide region that included the temporal areas and the hippocampus bilaterally (Fig. 11). This confirms that different cortical areas covary with V4 when activated by normally and abnormally coloured visual stimuli.

Discussion

The main result reported here is that when humans view colours in relation to objects, much larger parts of the brain are activated than when they view them in a more abstract context, and that there is a pronounced difference in brain areas that are activated when objects are dressed in natural and unnatural colours. These results confirm our earlier ones in showing that V1 and V2, together with V4, are important centres for colour vision, but they also extend them and

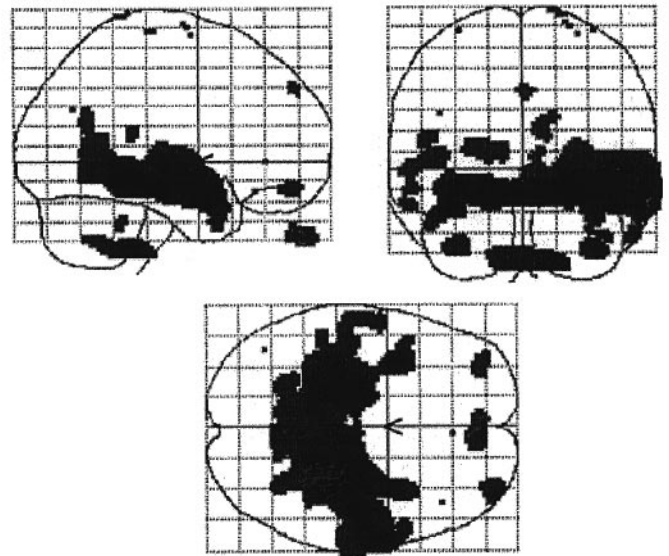


Fig. 11 Diagrammatic representation of the results of an interaction of two covariations studies. We subtracted the areas covarying with V4 when V4 was activated by the abnormal colours, from the areas covarying with V4 when it was activated by the normal colours.

provide us with a basis for considering the general role of the cerebral cortex in colour vision. We do so in a broad context, without concentrating on each of the activated areas, about some of which we have no specific hypotheses and whose role requires more detailed experimentation. In spite of the difficulties in interpreting the precise role of some of the activated areas, the overall picture that we have obtained allows us to enquire into the relationship between computational and cognitive theories of colour vision and propose a general three-stage theory of cortical colour processing in the human visual brain.

Some of the results reported here are puzzling, and we begin by discussing them.

The activation of the fusiform gyrus, lateral occipital lobe, the hippocampus and the frontal lobes

The results that we describe here are similar to those described earlier (e.g. Zeki *et al.*, 1991; McKeefry and Zeki, 1997) up to the level of area V4. The differences emerge after that. Specifically, the Mondrian stimulus does not activate regions beyond V4 while the normally and abnormally coloured stimuli do, each activating a separate system. What role these additionally activated areas play in colour vision is difficult to gauge and requires further experiments, which we are currently undertaking. What is clear is that many of the areas activated by the normally and abnormally coloured stimuli lie in regions which can be inferred to be connected with V4 from monkey anatomy. It is naturally difficult to determine exact homologies between the monkey and the human visual brain, especially in the region of the inferior and medial

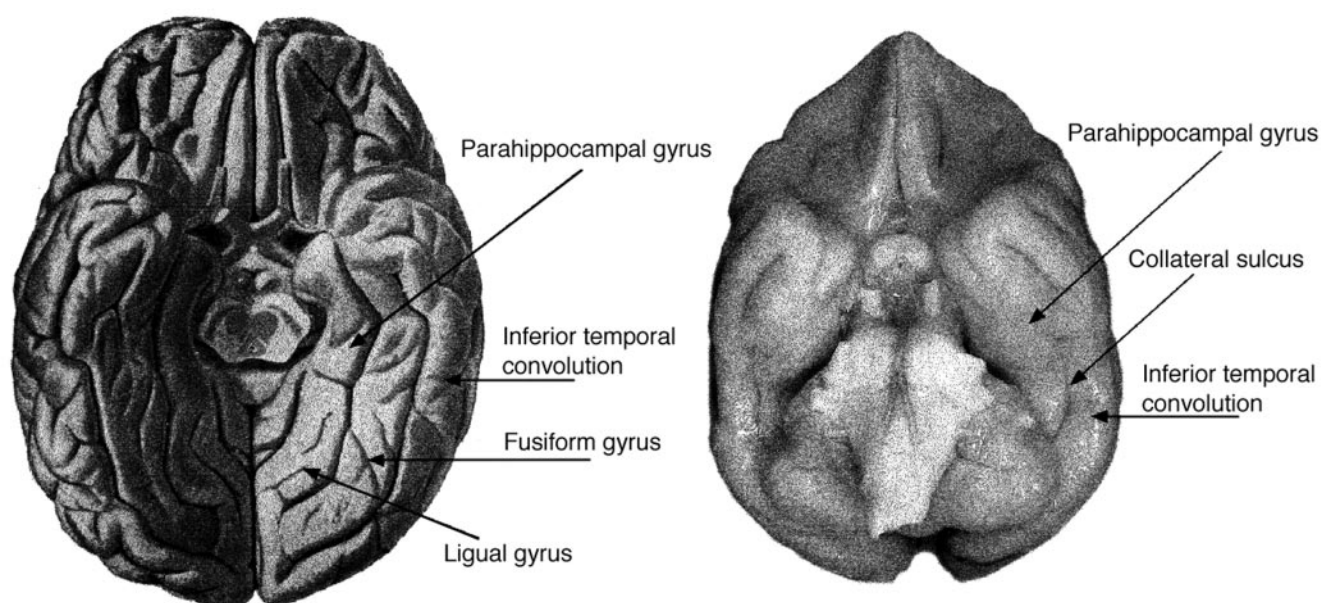


Fig. 12 Ventral view of the human brain (left) and the macaque brain (right) to show the position of the parahippocampal gyrus in the two species (in the human this becomes the fusiform gyrus posteriorly) and the absence of a lingual gyrus in the macaque. The two are not scaled to size.

temporal lobes. Figure 12 shows that the inferior temporal convolution in the monkey lies between the collateral sulcus medially and the inferior temporal sulcus laterally. There is no distinction between the fusiform gyrus and the parahippocampal/lingual gyri in the monkey (and we therefore refer to the whole region as the parahippocampal gyrus). In man, by contrast, the distinction is quite clear, the two gyri (fusiform and the lingual–parahippocampal) being separated from one another by the collateral sulcus. We should therefore be a little cautious in attempting homologies, even at the gross macroscopical level. Even in spite of these difficulties, however, monkey studies have shown that V4 is strongly connected with the inferior temporal areas lateral to the collateral sulcus as well as with the parahippocampal gyrus, which lies medial to the same sulcus (Kuypers *et al.*, 1965; Rockland and Pandya, 1979; Desimone *et al.*, 1980; Boussaoud *et al.*, 1991; DeYoe *et al.*, 1994). It would be surprising if the same general tendency does not exist in the human, though the details may differ. Equally, projections from V4 to the frontal cortex have been described (Goldman-Rakic *et al.*, 1984) but they are not necessarily to the specific areas that we have activated in our studies, assuming there to be a straightforward homology, which seems doubtful.

The fusiform gyrus

The work of the past few years has shown that the fusiform gyrus is a critical visual centre in the human brain, and imaging as well as stimulation studies have suggested that it must consist of several different areas (Corbetta *et al.*, 1991; Zeki *et al.*, 1991; Allison *et al.*, 1993; Martin *et al.*, 1995). In fact, Lungwitz (1937) published a paper in which he

proposed several subdivisions within the fusiform gyrus on architectural grounds, although he had little confidence in his own results and proposed that, before being taken seriously, they should be confirmed by functional studies. The extent of subdivision of labour within the lingual and fusiform gyri revealed in the past few years naturally raises the question of the extent of specialization in each area, a problem that can be addressed only when the brains of the same subjects are presented with many different stimuli and the activation sites compared. What is obvious from this study is that the use of naturally coloured objects as stimuli activates, in addition to V4, a part of the fusiform gyrus that lies immediately in front of V4, a zone that is not activated either by stimuli in which the same objects are unnaturally coloured or by abstract Mondrian stimuli. The absence of an activation in this area with these two latter conditions implies that the area is concerned not so much with the identification or recognition of colour, but with the experientially non-conflicting relationship between colour and object, although it may of course have other functions as well. Moreover, the fact that the comparison of abnormally coloured stimuli versus their achromatic counterparts did not produce an activation of the zone anterior to V4 suggests that this area is not particularly concerned with the objects themselves, but confirms that it is more concerned with the relationship of colour to object. Recent computational studies (Wray and Edelman, 1996) have proposed a role for the inferior temporal cortex, which may include the fusiform gyrus. This role supposes that the cells of the inferior temporal cortex explicitly represent a given colour. In view of the results reported here we depart from this interpretation and emphasize instead the importance of the relationship of colour to object.

Occipital lobe

We note that there were two areas of activation in the occipital lobe, of which the smaller was ventrally situated and may coincide with area LO, an area that has been implicated in object recognition (Malach *et al.*, 1995). But we are puzzled that this same area was not activated when the same objects were dressed in abnormal colours, which suggests that it is not concerned with objects *per se*. It would also seem that the more posterior and superior activation produced by the normally coloured objects does not coincide in position with the smaller posterosuperior activation produced by the abnormally coloured objects. It is difficult to speculate on the precise significance of these activations, save to say that a much more extensive part of the occipital lobe is mobilized when we look at coloured objects as opposed to colours in a more abstract sense, as in the multicoloured Mondrians. This same impression of a large mobilization of the occipital lobe is also gained from the covariation studies reported above, which show that a large part of the occipital lobe covaries in activity with V4, whether normal or abnormal colours are used.

The hippocampus

The involvement of the hippocampus with naturally coloured objects obviously suggests a memory component. It was thus surprising that the hippocampus was not activated by the abnormally coloured stimuli. To designate a stimulus as being abnormally coloured would, on the face of it, involve a comparison with a memory trace that would indicate what normal colour an object should have. Our covariation studies have shown that activity in the hippocampus covaries with that in area V4 for normally coloured stimuli but not abnormally coloured ones, as if the hippocampus is completely bypassed with the latter stimuli. The published literature (Knight, 1996; Stern *et al.*, 1996) suggests that the hippocampus is involved in novelty detection; we therefore supposed that it would also be activated by our stimuli. Our results imply that the hippocampus is a good deal more selective than that and raises the question of whether it is more selective for some kinds of visual memories than for others; it is, for example, plausible to suppose that the occasional view of an abnormally coloured object is not stored in memory. But this raises the question of how the brain classifies an object as being abnormally coloured except by reference to a memory system that has already classified objects according to normal colours. At face value, therefore, the fact that normally and abnormally coloured stimuli activate different pathways would imply that these could have specialized roles in memory, but what these roles are no one knows.

The frontal lobes

With the frontal lobes we are confronted with interpreting the role of two separate foci of activation rather than the

absence of activation for one condition but not the other; one locus was situated ventrally and activated by normally coloured objects and the other situated dorsolaterally and activated by abnormally coloured objects. These two general zones have been found to be activated with other tasks in which visual stimuli were linked to factors such as memory, spatial location and attention (McCarthy *et al.*, 1994; Desmond *et al.*, 1995; Smith *et al.*, 1995, 1996; Baker *et al.*, 1996). We are not in a position to say whether the areas of the dorsolateral and ventrolateral cortex that have been activated in our studies are identical to those that have been activated in previous studies (Fletcher *et al.*, 1996). What is clear is that, in our studies, the two zones were activated by visual stimuli that were in every respect identical save that in one the objects were dressed in normal colour while in the other they were abnormally coloured. It would thus seem that the two separate zones of the frontal lobe do not deal with different modalities but with the kind of processing that the relationship of two attributes demands. It is therefore interesting to note that the same general zone of the frontal lobe that was activated with our *sui generis* coloured stimuli was also activated with non-canonical views in the study of Kosslyn *et al.* (1994).

Whatever may be the precise involvement of the frontal lobes in colour vision, it is clear that it is with more complex colour tasks, since the frontal lobes were not activated by simple Mondrian stimuli. There are currently two alternative views of the functional significance of the activated regions of the frontal lobes, both related to memory (for a review, see Owen, 1997). One supposes that there is a specialization of function according to the modality of the information being processed while the other suggests that the specialization is for the nature of the processing that is required, irrespective of the actual modality. We are not at present able to support one view against the other and are currently undertaking further experiments that might help us decide between the two alternatives.

The construction of colour by the brain

In spite of these difficulties in interpreting the precise role of the activated regions in cortical colour vision, the overall picture allows us to formulate a general three-stage theory of cortical processing in colour vision. We do so within the context of the single most important feature of the colour system, generally referred to by psychologists as colour constancy, a rather unfortunate term since it implies that there is colour inconstancy. How the brain is able to assign a constant colour to a surface in spite of wide fluctuations in the wavelength composition of the light reflected from it remains a mystery. There are nevertheless certain strategies that the brain must adopt in executing this task, which we outline below. Whatever the level, we suppose that it is within what we may call the colour pathways in the brain that the strategies are executed. That we can speak of colour pathways in the brain implies that they are to some extent

segregated and the weight of anatomical and physiological evidence broadly supports this notion, although there have been dissenting voices, chiefly those of Lennie *et al.* (1990) and Leventhal *et al.* (1995). However, neither of these studies has the compelling anatomical evidence that is the hallmark of papers showing functional segregation at the level of V1 (Livingstone and Hubel, 1984*b*) and V2 (Livingstone and Hubel, 1984*b*; Shipp and Zeki, 1985; Zeki and Shipp, 1989; Roe and Ts'o, 1995) and are therefore less convincing.

Determination of the wavelength composition of the light from every point in the field of view

A vital initial step is of course to register the presence and intensity of different wavebands of light coming from every part of the field of view, a function seemingly vested in V1, and possibly also V2 (Zeki, 1983*a, b*), both of them areas with a highly topographic map of the visual field (Cragg, 1969; Zeki, 1969; Van Essen and Zeki, 1978). The cells in the former area have relatively small receptive fields and most are concentrated within compartments that stain richly for the metabolic enzyme cytochrome oxidase (Livingstone and Hubel, 1984*a*; Shipp and Zeki, 1985; Ts'o *et al.*, 1990; Born and Tootell, 1991; Bartfeld and Grinvald, 1992; Blasdel, 1992; Obermayer and Blasdel, 1993; Levitt *et al.*, 1994*a*; Roe and Ts'o, 1995). Most also apparently respond to what is in their receptive field without regard to what occurs in the surround, in spite of the fact that there are rich horizontal connections capable of linking the specialized zones in which the wavelength-selective cells are concentrated (Levitt *et al.*, 1994*b*; Yoshioka *et al.*, 1996). The wavelength-selective cells are, on the whole, indifferent to the colour of the surface in their receptive fields and respond only if a sufficient amount of light of their preferred wavelength is reflected from it, the cells often increasing their discharge rate with an increase in intensity. In a somewhat abstract sense, these cells do in fact undertake a comparative operation, since their responses are dictated by the amount of light of a given waveband in relation to the amount of light of other wavebands in the light reflected from their receptive fields, as well as by the sequence with which they are stimulated by lights of different wavebands (Zeki, 1983*a, b*). As an example, a middle-wave (green)-selective cell will respond to a green surface (or a yellow or a blue one) if the amount of middle-wave light reflected from its receptive field is in a certain balance with lights of other wavebands reflected simultaneously, irrespective of the colour. On the other hand, the sequence with which the cell is activated by lights of different wavebands will determine whether it will respond to a surface or not, again regardless of colour (Zeki, 1983*b*). But these comparisons are with what happens at a given point in the field of view (defined as the receptive field). Indifferent to what happens in the surrounds of their receptive fields, such cells seem to be ill-suited to indulge in the ratio-taking operations that are at the heart of colour-generating operations.

Like the compartmentalization of the wavelength-selective cells of V1, those of V2, which have not been studied in such great detail, are also concentrated in stripes of high cytochrome oxidase content, known as the thin stripes (DeYoe and Van Essen, 1985; Hubel and Livingstone, 1985; Shipp and Zeki, 1985), each thin stripe representing a given portion of the visual field (Zeki and Shipp, 1989; Roe and Ts'o, 1995). These thin stripes are also interconnected by a system of horizontal fibres (Levitt *et al.*, 1994*b*), but such connections appear to be ineffective in enlarging the receptive field properties of cells and thus allowing them to collate information from large parts of the field of view. Based on a study of relatively few cells, it has been suggested that there may be cells in V2 that are involved in an initial spatial wavelength-differencing operation (Zeki, 1985), an operation that could be undertaken by the double-opponent cells (Daw, 1968; Livingstone and Hubel, 1984*a*). But given the relatively small size of their receptive fields, their operations would be expected to be limited to restricted parts of the field of view. Most of this evidence comes from physiological studies in monkeys. However, given the close similarity between the metabolic architecture of V1 and area V2 in the monkey and in man (Horton and Hedley White, 1984; Burkhalter and Bernardo, 1989), it is plausible to suggest that a similar strategy is used in man. This is reinforced by the observation that humans and monkeys with lesions in V4 but with a totally or partially intact V1 are able to discriminate between different wavelengths, though with an elevated threshold and without being able to assign colours to them (Fries and Zeki, 1979; Vaina, 1994).

In summary, the first stage in colour processing by the brain may be said to be the gauging of the wavelength composition of the light coming from every point in the field of view, registering changes in that wavelength composition and undertaking the first wavelength-differencing operations (Zeki, 1983*a, b*, 1985).

Comparison of the wavelength composition of the light reflected from one surface with that reflected from surrounding surfaces

The second stage is largely centred around V4, which receives input from the thin stripes and interstripes of V2 (Zeki and Shipp, 1989) and from foveal V1 (Zeki, 1978; Nakamura *et al.*, 1993). Its cells have larger receptive fields than those in V1 and, correspondingly, its topography is less precise in retinotopic terms (Van Essen and Zeki, 1978). Anatomical and physiological evidence shows that there is some functional parcellation within V4, though its significance remains obscure. Wavelength- and colour-selective cells that are indifferent to the form (orientation) of the stimulus appear to be concentrated and separated from cells for which orientation selectivity is a prominent feature, in addition to wavelength bias or preference (Zeki, 1983*d*; Desimone and Schein, 1987). This second stage would appear to involve a

greater spatial comparison across larger segments of the field of view, implicit in the larger receptive fields of cells in V4 and the strong influences from the surround that have been detected in them (Zeki, 1983*d*; Desimone and Schein, 1987). It is indeed this capacity to undertake comparisons across distant points in the field of view—even when the points are in separate hemispheres (e.g. Land *et al.*, 1983)—that has led to the suggestion that the first possible site for large-scale spatial comparisons must be in V4 (Zeki, 1993), since V4 is the first area beyond V2 that has wavelength-selective cells and callosal connections extensive enough to unite the representation of zones well beyond the midline (Zeki, 1970; Van Essen and Zeki, 1978; Desimone *et al.*, 1993). This is consistent with physiological evidence which has shown the existence within V4 of cells whose responses correlate with the human perception of colours, regardless of the precise wavelength composition of the light reflected from the cells' receptive fields (Zeki, 1983*a*). This second stage, of spatial comparison of the wavelength composition of the light reflected from one surface and from surrounding surfaces, must involve at least two processes, assuming that the neural implementation used by the brain to construct colours is anything like that posited by computational theories (Land, 1974). One process would consist of generating a lightness at a given waveband for a given surface in the field of view, by comparing the intensity of light reflected from that surface with the intensity of the same light reflected from other surfaces. The second comparison would be to compare the lightness of a patch produced by at least two different wavebands, the comparison of comparisons leading to colour (Land, 1974, 1984). In general, we suppose that these comparative stages occur outside V1 and V2 because the topographic organization of V4 and the larger receptive fields of cells in it are more hospitable to such an undertaking (see also Courtney *et al.*, 1995). We note that imaging evidence shows that V4 is strongly activated with Mondrian colour stimuli, without entailing activation of other cortical zones (beyond V1 and V2) (Lueck *et al.*, 1989; Zeki *et al.*, 1991; Sakai *et al.*, 1995; McKeefry and Zeki, 1997). But we cannot of course be sure that such a comparison cannot be taken at a more restricted level by the cells of V2, for example, the double opponent cells.

In summary, although we have no notion of the precise neural mechanisms that may be deployed in such undertakings, these comparative ratio-taking processes may all be grouped together to constitute the second stage of cortical colour processing. We of course emphasize that these two initial stages in cortical colour processing are part of a continuous process and cannot be compartmentalized as independent processes. The anatomy of the connections between V1, V2 and V4 is two-way (Zeki, 1971; Zeki and Shipp, 1989; Desimone *et al.*, 1993) and this strongly suggests that the results of the operations undertaken by V4 are relayed back to both areas, just as the results of the operations undertaken by V1 and V2 are communicated to V4.

Since we have relied heavily on monkey studies in

interpreting the role of the cortex in colour vision, it is as well to emphasize the fact that behavioural studies in monkeys with lesions in V4 show that colour constancy mechanisms in them are impaired (Walsh *et al.*, 1993), as in humans with subtotal lesions in V4 (Kennard *et al.*, 1995). Moreover, deoxyglucose studies, as well as optical imaging studies and PET studies in monkeys show that V4 is activated with colour stimuli (Ts'o and Ghose, 1997; Takechi *et al.*, 1997; Vanduffel *et al.*, 1997; see also Zeki, 1996). Finally, the fact that the topography within human V4 is essentially similar to that of monkey V4 (McKeefry and Zeki, 1997) makes it not entirely implausible that the two areas may be homologous, although such a homology has been strongly disputed (Heywood and Cowey, 1987; Heywood *et al.*, 1991, 1992, 1994, 1995).

Investment of objects with colours

The first two stages are really concerned with the automatic computation of colour, without regard to objects. In such a computation there is no 'right' or 'wrong' colour since the colour belongs to an abstract composition and has no relevance to an object. The third stage uses the results provided by the first two and is much more concerned, not with computing colours in an abstract sense, but with object and surface colours. The cortical site of this third stage would seem to be largely beyond the V4 complex but in fact may also involve V4. It was interesting to note, for example, that the activity produced by normally coloured objects overlapped the territory of V4 (as determined in the study of McKeefry and Zeki, 1997) to a lesser extent than that produced by abnormally coloured objects. In the macaque monkey, orientation-selective cells (which are assumed to be important for form perception) have been found in V4 (Zeki, 1975, 1983*a, b*; Desimone and Schein, 1987), although many of these have variable degrees of colour preference and in general have broader orientational tolerances than their counterparts in areas V2, V3 and V3A (Zeki, 1997). Moreover, physiological evidence suggests that there is a compartmentalization within V4 itself, regions of heavy concentration of orientation-selective cells being separated from each other by cells with strong colour or wavelength selectivities (Zeki, 1983*c*), a finding reflected in the results of recent imaging experiments, which also show islands of colour-activated cells within V4 (Ts'o *et al.*, 1997; Vanduffel *et al.*, 1997). It is of course possible that the process of compartmentalization has gone further in the human and that V4 may in fact consist of two or more subdivisions, of which some are more concerned with form than others. Behavioural and clinical experiments do not help us much here because they have been controversial, some claiming a deficit in form perception after V4 lesions, and others not (Heywood and Cowey, 1987; Heywood *et al.*, 1991, 1992, 1994, 1995; Kulikowski *et al.*, 1994). Thus, neither the animal nor the human evidence resolves the precise role of V4 in form perception and its relation to colour.

What is more suggestive is the involvement of the fusiform and the parahippocampal gyri in the experiments reported here. This broad zone, located inferiorly and medially in the temporal lobe is one that, in the monkey, is reciprocally connected with the V4 complex (Desimone *et al.*, 1980; DeYoe *et al.*, 1994). It is therefore interesting to note that colour-coded cells have been detected there by single-cell physiology (Mikami and Kubota, 1980; Fuster and Jervey, 1982; Komatsu *et al.*, 1992). It is obvious that here the relationship of the colour to the object that it invests becomes important, and it is obvious, too, that recognition and memory must therefore play a role. What was surprising to us was the extent of the cortical machinery that is mobilized in this task because, in addition to the zone mentioned above, the frontal cortex as well as the hippocampus become involved. One may have supposed somewhat naively that identical pathways and areas would be involved in determining whether an object is invested with the right or the wrong colour; instead our results showed that disparate areas and pathways are involved. This raises the interesting question about where the decision to use one pathway or another is taken, which we discuss below.

We of course emphasize that we are speaking of three broad stages of colour processing; each almost certainly involves substages of varying difference. In a sense, all three stages can be thought of as undertaking a comparison: at the level of V1 and V2 it is a comparison of the amount of light of different wavebands coming from a given point in the field of view, and a comparison of the wavelength composition of the light from that point at successive times (Zeki, 1983*a*, *b*); in V4 the emphasis is on a greater spatial comparison, and in the regions beyond it is on a comparison with the stored memory records.

The far from complete pathological evidence lends some support to this three-stage processing system. Patients with lesions in V1 are obviously blind but those with lesions in V4 are impaired in their colour vision, seeing the world in dirty shades of grey (for a review, see Zeki, 1990), in spite of the fact that they are able to distinguish between different wavelengths of light, though with elevated thresholds (Vaina *et al.*, 1990; W. Fries and S. Zeki, unpublished results). This implies that they are able to detect the wavelength composition of the lights coming from a point but unable to effect the long-range spatial comparisons that are essential for colour vision. Colour constancy mechanisms are compromised in such patients (Kennard *et al.*, 1995). Our recent studies (S. Zeki, S. Aglioti, D. McKeefry and G. Berlucchi, unpublished data) of a patient who had been rendered blind following vascular insufficiency but who had retained his colour vision (Wechsler, 1933; Hécaen and Ajuriaguerra, 1956; Hécaen *et al.*, 1974; Humphrey *et al.*, 1995) have shown that his colour vision is largely, though not exclusively, wavelength-based. The patient is heavily dependent upon wavelength composition in assigning colours to surfaces; correspondingly, psychophysical studies show that he is largely unable to effect the kind of long-range

spatial comparisons that are essential for the construction of colours. It is not surprising to find, therefore, that colour constancy mechanisms are largely compromised in him, just as they are in patients with V4 lesions (Kennard *et al.*, 1995). Brain activation studies using fMRI have shown that, unlike what happens in normal subjects (where both V1 and V4 are active), it is V1 that is mainly activated when this patient views colours. The earlier studies of Humphrey *et al.* (1995) had shown that the patient was severely compromised in his ability to perceive forms and our studies confirm that he cannot assign forms to the colours that he can characterize correctly, largely on the basis of wavelength composition alone. This pathological state, which is the closest that one seems to be able to get to the fauvist dream of liberating colours from forms, lends striking support to the existence of a separate colour system, independent of the system concerned with form.

Computational versus cognitive theories of colour vision

Land (1974) conceived of his retinex system as a largely abstract computational implementation without reference to faculties such as memory learning, judgement and recognition. The paradigm he used, that of a multicoloured abstract scene with no recognizable objects, has in fact been used successfully in both physiological and imaging experiments and part of its appeal was indeed the absence within the stimulus of what are overtly recognizable objects. It is interesting to note that the use of the Land colour Mondrian stimulus activates relatively early parts of the visual pathways, including V4, but that the activity does not spread more anteriorly within the temporal lobe and does not involve the hippocampus or the frontal lobe, regions of the brain traditionally associated with higher cognitive functions. The Land system has been pitted against what we shall refer to as the cognitive systems of Helmholtz, Hering and others. Helmholtz invoked ill-defined factors to account for colour constancy, and among these were judgement and learning. He thought of colour vision as being 'due to an act of judgement, not an act of sensation', although he implied that some of the processes involved in assigning constant colours to objects may be computational in nature, i.e. not to involve higher cognitive functions, since he thought that these acts of judgement may be executed 'unconsciously and involuntarily' (Helmholtz, 1867). Ewald Hering (1877/1964), emphasized memory instead, writing that 'all objects that are already known to us from experience, or that we regard as familiar by their color, we see through the spectacles of memory color, and on that account quite differently from the way we would otherwise see them'. In many ways, the results of the present study vindicate both views and show that the automatic computation of colour in the abstract, without reference to particular objects or scenes, is always undertaken by the brain in specific areas but that memory,

learning and judgement are important additional faculties used by the colour system when colours invest objects and are part of them. The latter is the more usual condition and recruits additional cortical areas, well beyond the automatic computational stage that computes colours without reference to the actual objects. The kind of elementary computation that Land is referring to is implicit in the Helmholtz–Hering cognitive system, which simply goes beyond that computational level. It is interesting to note, therefore, that whether one uses the Land Mondrian or more naturalistic images invested with normal or abnormal colours, V4 is always activated. The differences emerge beyond that level.

Alternative pathways beyond V4

That normally and abnormally coloured stimuli activate strikingly different pathways beyond V4 implies not only that V4 has connections, direct or indirect, with a large part of the brain but also that the part of the network that is mobilized depends upon the nature of the stimulus. In the absence of more detailed evidence, it is difficult to know with any certainty whether there is a particular cortical stage at which one pathway or another is mobilized, but we are inclined to think that it is at the level of the commonly activated V4, although even this is not certain since normally and abnormally coloured stimuli may activate different subdivisions within V4. At any rate, the results presented here imply that the colour system of the brain is able to distinguish physiologically between normally and abnormally coloured objects, since which part of the extensive outward network from V4 gets activated depends upon the features of the stimulus.

The neurology of representational and abstract art

We are aware that we are exposing ourselves to possible ridicule when we say that part of the inspiration for these experiments was derived from the fauvist school of painting. Yet it is difficult to deny that that inspiration has resulted in interesting results about the functioning of the visual brain. In particular, it is evident that fauvist art had, unknowingly, used cerebral pathways that are quite distinct from those used by representational art that uses correct colours. This in turn supports our view (Zeki and Lamb, 1994) that artists are in a sense experimenting with the potentials of the visual brain, and unknowingly uncovering laws about its organization.

Perhaps the most interesting feature that comes from this study is that abstract paintings, such as the multicoloured Mondrians that we used in these and previous studies, do not activate as extensive a region of the brain as the use of coloured objects, though they activate the same regions as V4. Abstraction, by which we mean non-iconic abstraction (i.e. art which does not represent or symbolize objects), has

been a very dominant tendency in modern art. Through it artists like Mondrian, Malevich and many others have tried to reduce the many features in the visual world to their constant elements (Mondrian, 1937). In this, abstract art differs from the more pervasive representational and narrative art. What our studies have shown is that, when applied to colour vision, the two broad kinds of art use common pathways up to a point and then divergent pathways beyond. The Mondrian experiments result in activation of areas up to V4 and not beyond; the experiments reported here, in which more naturalistic images were used, activate area V4 and other areas beyond. We would be surprised if a study that is undertaken with real works of art, representing the two broad subdivisions that we have alluded to above, does not result in the activation of similar pathways to the ones that we describe here. Thus, what started off as a relatively simple experiment, inspired by the fauvist habit of painting common objects and scenes in the ‘wrong’ colours, has ended up by involving us not only in problems which we had never thought of visiting—of the difference between surface colour and object colour, of the role of memory and of the hippocampus in colour vision and of the monitoring systems in the frontal lobe—but has also, we hope, provided small insights into the grander problem of the relationship between brain physiology and visual aesthetics.

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References

- Allison T, Begleiter A, McCarthy G, Roessler E, Nobre AC, Spencer DD. Electrophysiological studies of color processing in human visual cortex. *Electroencephalogr Clin Neurophysiol* 1993; 88: 343–55.
- Arnason, HH. A history of modern art. London: Thames and Hudson; 1977.
- Baker SC, Frith CD, Frackowiak RS, Dolan RJ. Active representation of shape and spatial location in man. *Cereb Cortex* 1996; 6: 612–9.
- Bartfeld E, Grinvald A. Relationships between orientation-preference pinwheels, cytochrome oxidase blobs, and ocular-dominance columns in primate striate cortex. *Proc Natl Acad Sci USA* 1992; 89: 11905–9.
- Blasdel GG. Orientation selectivity, preference, and continuity in monkey striate cortex. *J Neurosci* 1992; 12: 3139–61.
- Born RT, Tootell RB. Spatial frequency tuning of single units in macaque supragranular striate cortex. *Proc Natl Acad Sci USA* 1991; 88: 7066–70.

- Boussaoud D, Desimone R, Ungerleider LG. Visual topography of area TEO in the macaque. *J Comp Neurol* 1991; 306: 554–75.
- Burkhalter A, Bernardo KL. Organization of corticocortical connections in human visual cortex. *Proc Natl Acad Sci USA* 1989; 86: 1071–5.
- Corbetta M, Miezin FM, Dobmeyer S, Shulman G L, Petersen SE. Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *J Neurosci* 1991; 11: 2383–402.
- Courtney SM, Finkel LH, Buchsbaum G. Network simulations of retinal and cortical contributions to color constancy. *Vision Res* 1995; 35: 413–34.
- Cragg BG. The topography of the afferent projections in circumstriate visual cortex of the monkey studied by the Nauta method. *Vision Res* 1969; 9: 733–47.
- Daw NW. Colour-coded ganglion cells in the goldfish retina: extension of their receptive fields by means of new stimuli. *J Physiol (Lond)* 1968; 197: 567–92.
- Desimone R, Schein SJ. Visual properties of neurons in area V4 of the macaque: sensitivity to stimulus form. *J Neurophysiol* 1987; 57: 835–67.
- Desimone R, Fleming J, Gross CG. Prestriate afferents to inferior temporal cortex: an HRP study. *Brain Res* 1980; 184: 41–55.
- Desimone R, Moran J, Schein SJ, Mishkin M. A role for the corpus callosum in visual area V4 of the macaque. *Vis Neurosci* 1993; 10: 159–71.
- Desmond JE, Sum JM, Wagner AD, Domb JB, Shear PK, Glover GH, et al. Functional MRI measurement of language lateralization in WADA-tested patients. *Brain* 1995; 118: 1411–9.
- DeYoe EA, Van Essen DC. Segregation of efferent connections and receptive field properties in visual area V2 of the macaque. *Nature* 1985; 317: 58–61.
- DeYoe EA, Felleman DJ, Van Essen DC, McClendon E. Multiple processing streams in occipitotemporal visual cortex [published erratum appears in *Nature* 1994; 371: 812]. *Nature* 1994; 371: 151–4.
- ffytche DH, Walker S, Guy C, Zeki S. A comparison of the latency of signals in human v1 and v5, using the technique of visual evoked response to motion (VERM). *J Physiol (Lond)* 1994; 477P: 57P.
- Fletcher PC, Shallice T, Frith CD, Frackowiak RS, Dolan RJ. Brain activity during memory retrieval. The influence of imagery and semantic cueing. *Brain* 1996; 119: 1587–96.
- Fries W, Zeki SM. Effect of bilateral prestriate cortex (V4) lesions on wavelength discrimination in monkeys. *Pflügers Arch* 1979; 382.
- Friston KJ, Ashburner J, Frith CD, Poline JB, Heather JD, Frackowiak RS. Spatial registration and normalization of images. *Hum Brain Mapp* 1995a; 3: 165–89.
- Friston KJ, Frith CD, Turner R, Frackowiak RS. Characterizing evoked hemodynamics with fMRI. *Neuroimage* 1995b; 2: 157–65.
- Friston KJ, Holmes AP, Worsley KJ, Poline JB, Frith CD, Frackowiak RS. Statistical parametric maps in functional imaging: a general linear approach. *Hum Brain Mapp* 1995c; 2: 189–210.
- Friston KJ, Williams S, Howard R, Frackowiak RS, Turner R. Movement-related effects in fMRI time-series. *Magn Reson Med* 1996; 35: 346–55.
- Fuster JM, Jervey JP. Neuronal firing in the inferotemporal cortex of the monkey in a visual memory task. *J Neurosci* 1982; 2: 361–75.
- Goldman-Rakic PS, Selemon LD, Schwartz ML. Dual pathways connecting the dorsolateral prefrontal cortex with the hippocampal formation and parahippocampal cortex in the rhesus monkey. *Neuroscience* 1984; 12: 719–43.
- Hécaen H, Ajuriaguerra J de. Agnosie visuelle pour les objets inanimés par lésion unilatérale gauche. *Rev Neurol (Paris)* 1956; 94: 222–33.
- Hécaen H, Goldblum MC, Masure MC, Ramier AM. Une nouvelle observation d'agnosie d'objets. Déficit de l'association de la catégorisation spécifique de la modalité visuelle? *Neuropsychologia* 1974; 12: 447–64.
- Helmholtz HLF von. *Handbuch der physiologischen Optik*. Leipzig: Leopold Voss; 1867. 2nd edition 1911.
- Hering E. *Outlines of a theory of the light sense*. Translated by L.M. Hurvich and D. Jameson. 1877/1964. Cambridge (MA): Harvard University Press.
- Heywood CA, Cowey A. On the role of cortical area V4 in the discrimination of hue and pattern in macaque monkeys. *J Neurosci* 1987; 7: 2601–17.
- Heywood CA, Cowey A, Newcombe F. Chromatic discrimination in a cortically colour blind observer. *Eur J Neurosci* 1991; 3: 802–12.
- Heywood CA, Gadotti CA, Cowey A. Cortical area V4 and its role in the perception of colour. *J Neurosci* 1992; 12: 4056–65.
- Heywood CA, Cowey A, Newcombe F. On the role of parvocellular (P) and magnocellular (M) pathways in cerebral achromatopsia. *Brain* 1994; 117: 245–54.
- Heywood CA, Gaffan D, Cowey A. Cerebral achromatopsia in monkeys. *Eur J Neurosci* 1995; 7: 1064–73.
- Horton JC, Hedley-White ET. Mapping of cytochrome oxidase patches and ocular dominance columns in human visual cortex. [Review]. *Philos Trans R Soc Lond B Biol Sci* 1984; 304: 255–72.
- Hubel DH, Livingstone MS. Complex-unoriented cells in a subregion of primate area 18. *Nature* 1985; 315: 325–7.
- Humphrey GK, Goodale MA, Corbetta M, Aglioti S. The McCollough effect reveals orientation discrimination in a case of cortical blindness. *Curr Biol* 1995; 5: 545–51.
- Kennard C, Lawden M, Morland AB, Ruddock KH. Colour identification and colour constancy are impaired in a patient with incomplete achromatopsia associated with prestriate cortical lesions. *Proc R Soc Lond B Biol Sci* 1995; 260: 169–75.
- Knight R. Contribution of human hippocampal region to novelty detection. *Nature* 1996; 383: 256–9.
- Komatsu H, Ideura Y, Kaji S, Yamane S. Color selectivity of neurons in the inferior temporal cortex of the awake macaque monkey. *J Neurosci* 1992; 12: 408–24.

- Kosslyn SM, Alpert NM, Thompson WL, Chabris CF, Rauch SL, Anderson AK. Identifying objects seen from different viewpoints. A PET investigation. *Brain* 1994; 117: 1055–71.
- Kulikowski JJ, Walsh V, McKeefrey D, Butler SR, Carden D. The electrophysiological basis of colour processing in macaques with V4 lesions. *Behav Brain Res* 1994; 60: 73–8.
- Kuypers HG, Szwarcbart MK, Mishkin M, Rosvold HE. Occipitotemporal corticocortical connections in the rhesus monkey. *Exp Neurol* 1965; 11: 245–62.
- Land E. The retinex theory of colour vision. *Proc R Inst Gt Br* 1974; 47: 23–58.
- Land EH, Hubel DH, Livingstone MS, Perry SH, Burns MM. Color generating interactions across the corpus-callosum. *Nature* 1983; 303: 616–18.
- Lennie P, Krauskopf J, Sclar G. Chromatic mechanisms in striate cortex of macaque. *J Neurosci* 1990; 10: 649–69.
- Leventhal AG, Thompson KG, Liu D, Zhou Y, Ault SJ. Concomitant sensitivity to orientation, direction, and color of cells in layers 2, 3, and 4 of monkey striate cortex. *J Neurosci* 1995; 15: 1808–18.
- Levitt JB, Kiper DC, Movshon JA. Receptive fields and functional architecture of macaque V2. *J Neurophysiol* 1994a; 71: 2517–42.
- Levitt JB, Yoshioka T, Lund JS. Intrinsic cortical connections in macaque visual area V2: evidence for interaction between different functional streams. *J Comp Neurol* 1994b; 342: 551–70.
- Livingstone MS, Hubel DH. Anatomy and physiology of a color system in the primate visual cortex. *J Neurosci* 1984a; 4: 309–56.
- Livingstone MS, Hubel DH. Specificity of intrinsic connections in primate primary visual cortex. *J Neurosci* 1984b; 4: 2830–5.
- Lueck CJ, Zeki S, Friston KJ, Deiber M-P, Cope P, Cunningham VJ, et al. The colour centre in the cerebral cortex of man. *Nature* 1989; 340: 386–9.
- Lungwitz W. Zur myelonarchitektonischen Untergliederung der menschlichen Area praeoccipitalis (Area 19 Brodmann). *J Psychol Neurol* 1937; 47: 607–38.
- Malach R, Reppas JB, Benson RR, Kwong KK, Jiang H, Kennedy WA, et al. Object-related activity revealed by functional magnetic resonance imaging in human occipital cortex. *Proc Natl Acad Sci USA* 1995; 92: 8135–9.
- Martin A, Haxby JV, Lalonde FM, Wiggs CL, Ungerleider LG. Discrete cortical regions associated with knowledge of color and knowledge of action. *Science* 1995; 270: 102–5.
- Matisse H. *Ecrits et propos sur l'art*. Paris: Hermann; 1972.
- Maxwell JC. On colour vision. *Proc R Inst Gt Br* 1872; 6: 260–71.
- McCarthy G, Blamire AM, Puce A, Nobre AC, Bloch G, Hyder F, Goldman-Rakic P, Shulman RG. Functional magnetic resonance imaging of human prefrontal cortex activation during a spatial working memory task. *Proc Natl Acad Sci USA* 1994; 91: 8690–4.
- McKeefrey D, Zeki S. The position and topography of the human colour centre as revealed by functional magnetic resonance imaging. *Brain* 1997; 120: 2229–42.
- Mikami A, Kubota K. Inferotemporal neuron activities and color discrimination with delay. *Brain Res* 1980; 182: 65–78.
- Mondrian P. Plastic art and pure plastic art. In: Holtzman H, James MS, editors. *The new art—the new life: the collected writings of Piet Mondrian*. Boston: G. K. Hall; 1937. p. 288–300.
- Nakamura M, Gattass R, Desimone R, Ungerleider LG. The modular organization of projections from areas V1 and V2 to areas V4 and TEO in macaques. *J Neurosci* 1993; 13: 3681–91.
- Obermayer K, Blasdel GG. Geometry of orientation and ocular dominance columns in monkey striate cortex. *J Neurosci* 1993; 13: 4114–29.
- Owen AM. The functional organization of working memory processes within human lateral frontal cortex: the contribution of functional neuroimaging. *Eur J Neurosci* 1997; 9: 1329–39.
- Rockland KS, Pandya DN. Laminal origins and terminations of cortical connections of the occipital lobe in the rhesus monkey. *Brain Res* 1979; 179: 3–20.
- Roe AW, Ts'o DY. Visual topography in primate V2: multiple representation across functional stripes. *J Neurosci* 1995; 15: 3689–715.
- Sakai K, Watanabe E, Onodera Y, Uchida I, Kato H, Yamamoto E, et al. Functional mapping of the human colour centre with echo-planar magnetic resonance imaging. *Proc R Soc Lond B Biol Sci* 1995; 261: 89–98.
- Shipp S, Zeki S. Segregation of pathways leading from area V2 to areas V4 and V5 of macaque monkey visual cortex. *Nature* 1985; 315: 32–5.
- Smith EE, Jonides J, Koeppel RA, Awh E, Schumacher EH, Minoshima S. Spatial versus object working memory: PET investigations. *J Cogn Neurosci* 1995; 7: 337–56.
- Smith EE, Jonides J, Koeppel RA. Dissociating verbal and spatial working memory using PET. *Cereb Cortex* 1996; 6: 11–20.
- Stern CE, Corkin S, Gonzalez RG, Guimaraes AR, Baker JR, Jennings PJ, et al. The hippocampal formation participates in novel picture encoding: evidence from functional magnetic resonance imaging. *Proc Natl Acad Sci USA* 1996; 93: 8660–5.
- Takechi H, Onoe H, Shizuno H, Yoshikawa E, Sadato N, Tsukada H, et al. Mapping of cortical areas involved in color vision in non-human primates. *Neurosci Lett* 1997; 230: 17–20.
- Talairach J, Tournoux P. *Co-planar stereotaxic atlas of the human brain*. Stuttgart: Thieme; 1988.
- Ts'o DY, Ghose GM. The organization of color-specific domains in primate V4 [abstract]. *Soc Neurosci Abstr* 1997; 23: 2229.
- Ts'o DY, Frostig RD, Lieke EE, Grinvald A. Functional organization of primate visual cortex revealed by high resolution optical imaging. *Science* 1990; 249: 417–20.
- Vaina LM. Functional segregation of color and motion processing in the human visual cortex: clinical evidence. *Cereb Cortex* 1994; 4: 555–72.
- Vaina LM, LeMay M, Bienfang DC, Choi AY, Nakayama K. Intact 'biological motion' and 'structure from motion' perception in a

- patient with impaired motion mechanisms: a case study. *Vis Neurosci* 1990; 5: 353–69.
- Van Essen DC, Zeki SM. The topographic organization of rhesus monkey prestriate cortex. *J Physiol (Lond)* 1978; 277: 193–226.
- Vanduffel W, Tootell RB, Orban GA. Macaque visual cortical areas involved in color processing: a double-label deoxyglucose study [abstract]. *Soc Neurosci Abstr* 1997; 23: 845.
- Walsh V, Carden D, Butler SR, Kulikowski JJ. The effects of V4 lesions on the visual abilities of macaques: hue discrimination and colour constancy. *Behav Brain Res* 1993; 53: 51–62.
- Wechsler IS. Partial cortical blindness with preservation of color vision: report of a case following asphyxia (carbon monoxide poisoning?). *Arch Ophthalmol* 1933; 9: 957–65.
- Wray J, Edelman G. A model of color vision based on cortical reentry. *Cereb Cortex* 1996; 6: 701–16.
- Yoshioka T, Blasdel GG, Levitt JB, Lund JS. Relation between patterns of intrinsic lateral connectivity, ocular dominance, and cytochrome oxidase-reactive regions in macaque monkey striate cortex. *Cereb Cortex* 1996; 6: 297–310.
- Zeki SM. Representation of central visual fields in prestriate cortex of monkey. *Brain Res* 1969; 14: 271–91.
- Zeki SM. Interhemispheric connections of prestriate cortex in the monkey. *Brain Res* 1970; 19: 63–75.
- Zeki SM. Cortical projections from two prestriate areas in the monkey. *Brain Res* 1971; 34: 19–35.
- Zeki SM. The functional organization of projections from striate to prestriate visual cortex in the rhesus monkey. *Cold Spring Harb Symp Quant Biol* 1975; 40: 591–600.
- Zeki SM. The cortical projections of foveal striate cortex in the rhesus monkey. *J Physiol (Lond)* 1978; 277: 227–44.
- Zeki S. Colour coding in the cerebral cortex: the reaction of cells in monkey visual cortex to wavelengths and colours. *Neuroscience* 1983a; 9: 741–65.
- Zeki S. Colour coding in the cerebral cortex: the responses of wavelength-selective and colour-coded cells in monkey visual cortex to changes in wavelength composition. *Neuroscience* 1983b; 9: 767–81.
- Zeki S. The distribution of wavelength and orientation selective cells in different areas of monkey visual cortex. *Proc R Soc Lond B Biol Sci* 1983c; 217: 449–70.
- Zeki S. The construction of colours by the cerebral cortex. *Proc R Inst Gt Br* 1984; 56: 231–57.
- Zeki S. Colour pathways and hierarchies in the cerebral cortex. In: Ottoson D, Zeki S, editors. *Central and peripheral mechanisms of colour vision*. Basingstoke (UK): MacMillan Press; 1985. p. 19–44.
- Zeki S. A century of cerebral achromatopsia. [Review]. *Brain* 1990; 113: 1721–77.
- Zeki S. *A vision of the brain*. Oxford: Blackwell; 1993.
- Zeki S. Are areas TEO and PIT of monkey visual cortex wholly distinct from the fourth visual complex (V4 complex)? *Proc R Soc Lond B Biol Sci* 1996; 263: 1539–44.
- Zeki S. The color and motion systems as guides to conscious visual perception. In: KS, Kaas JH, Peters A, editors. *Cerebral cortex, Vol. 12*. New York: Plenum Press; 1997. p. 777–809.
- Zeki S, Lamb M. The neurology of kinetic art. [Review]. *Brain* 1994; 117: 607–36.
- Zeki S, Shipp S. Modular connections between areas V2 and V4 of macaque monkey visual cortex. *Eur J Neurosci* 1989; 1: 494–506.
- Zeki S, Watson JD, Lueck CJ, Friston KJ, Kennard C, Frackowiak RS. A direct demonstration of functional specialization in human visual cortex. *J Neurosci* 1991; 11: 641–9.
- Zeki S, Aglioti S, McKeefry D, Berlucchi G. The neurological basis of conscious colour perception in a blind patient. In press 1998.

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