

# The functional logic of cortico-pulvinar connections

S. Shipp

*Wellcome Department of Cognitive Neurology, University College London, Gower Street, London WC1E 6BT, UK  
(s.shipp@ucl.ac.uk)*

The pulvinar is an ‘associative’ thalamic nucleus, meaning that most of its input and output relationships are formed with the cerebral cortex. The function of this circuitry is little understood and its anatomy, though much investigated, is notably recondite. This is because pulvinar connection patterns disrespect the architectural subunits (anterior, medial, lateral and inferior pulvinar nuclei) that have been the traditional reference system. This article presents a simplified, global model of the organization of cortico-pulvinar connections so as to pursue their structure–function relationships.

Connections between the cortex and pulvinar are topographically organized, and as a result the pulvinar contains a ‘map’ of the cortical sheet. However, the topography is very blurred. Hence the pulvinar connection zones of nearby cortical areas overlap, allowing indirect transcortical communication via the pulvinar. A general observation is that indirect cortico-pulvino-cortical circuits tend to mimic direct cortico-cortical pathways: this is termed ‘the replication principle’. It is equally apt for certain pairs (or groups) of nearby cortical areas that happen not to connect with each other. The ‘replication’ of this non-connection is achieved by discontinuities and dislocations of the cortical topography within the pulvinar, such that the associated pair of connection zones do not overlap. Certain of these deformations can be used to divide the global cortical topography into specific sub-domains, which form the natural units of a connectional subdivision of the pulvinar. A substantial part of the pulvinar also expresses visual topography, reflecting visual maps in occipital cortex. There are just two well-ordered visual maps in the pulvinar, that both receive projections from area V1, and several other occipital areas; the resulting duplication of cortical topography means that each visual map also acts as a separate connection domain. In summary, the model identifies four topographically ordered connection domains, and reconciles the coexistence of visual and cortical maps in two of them. The replication principle operates at and below the level of domain structure.

It is argued that cortico-pulvinar circuitry replicates the pattern of cortical circuitry but not its function, playing a more regulatory role instead. Thalamic neurons differ from cortical neurons in their inherent rhythmicity, and the pattern of cortico-thalamic connections must govern the formation of specific resonant circuits. The broad implication is that the pulvinar acts to coordinate cortical information processing by facilitating and sustaining the formation of synchronized trans-areal assemblies; a more pointed suggestion is that, owing to the considerable blurring of cortical topography in the pulvinar, rival cortical assemblies may be in competition to recruit thalamic elements in order to outlast each other in activity.

**Keywords:** cortical topography; visual topography; axis of iso-representation; connection domains; replication principle

## 1. INTRODUCTION

The pulvinar and the lateral geniculate nucleus (LGN) together constitute the thalamic organs of the primate visual system (although the pulvinar also engages other sensory systems). At a cellular level they are similar, composed of relay neurons and interneurons (Wong-Riley 1972; Ogren & Hendrickson 1979*b*). The obvious difference lies in their circuitry. The LGN is the major relay to the cortex from the retina, but retinal input direct to the pulvinar is not substantial (Itaya & Van Hoesen 1983; Nakagawa & Tanaka 1984; O’Brien *et al.* 2001). Instead, most of the input to the pulvinar comes from the cortex. Because the only output from the pulvinar is directed back to the cortex, the pulvinar is regarded as an associative thalamic nucleus (Sherman & Guillery 1996). It has sometimes been referred to as the ‘7th layer’ of the cortex, and

its role is evidently to achieve some form of indirect cortico-cortical communication. In considering the organization of cortico-pulvino-cortical circuitry, the logical question is whether these circuits mimic (or even replace) direct cortico-cortical information transfer, or act in a complementary way to play a more coordinating, regulatory role in cortical activity.

The first step is to document the connections clearly, in the form of a simplified model. There is more to this than an accurate précis of the literature (which is sufficiently taxing, that only aficionados would ever commit much of it to working memory). The root of the problem is that the traditional anatomical framework for this task—the subdivision of the pulvinar into inferior, lateral, medial and anterior (oral) nuclei—is irrelevant. By analogy, it is like trying to document political allegiance by reference to geological boundaries. The task may be possible if the

geology is well defined, but it does not provide the most efficient system of reference; likewise, the partitions within physiological and connectional maps simply fail to coincide with the traditional nuclei. The pulvinar's internal structure is under active re-evaluation, spurred by neurochemical parcellations that also cut across the traditional sub-nuclei (Gutierrez *et al.* 1995; Stepniewska & Kaas 1997). Many emerging studies use these newer units as the framework for documenting connections (Cusick *et al.* 1993; Cavada *et al.* 1995; Gutierrez & Cusick 1997; Beck & Kaas 1998; Gray *et al.* 1999; Adams *et al.* 2000; Soares *et al.* 2001). By contrast, the intention here is to let the connections tell their own story, and subdivide the pulvinar by connectional criteria alone. Discontinuities in the topography of cortical connections are used to distinguish two cardinal connectional 'domains', occupying dorsal pulvinar (DP) and ventral pulvinar (VP) zones, with further subdivision of the latter. The model arising from these considerations echoes the neurochemical structure in some respects, although the exact relationship remains uncertain, for much of the collated connectional data stem from a pre-neurochemical era. The model also has some affinity with hierarchical schemes for cortical organization, which bears further examination. Most importantly, however, the connectional model generates a simple rule of organization (the 'replication principle'), with probable functional implications. Overall, the twin aims are thus:

- (i) to widen the accessibility of the field, by introducing a simplified global model of pulvinar connectivity;
- (ii) to identify general organizing principles, lending insight into the functional role of cortico-pulvinar circuitry.

## 2. CONNECTIONAL TOPOGRAPHY AND TOPOLOGY

A textbook picture of the major nuclei of the thalamus, together with their respective zones of connectivity with the cortex, reveals a global, topographic relationship, as if the convoluted cortex had been shrink-wrapped around the barrel-shaped thalamus. The essence of this relationship is summarized in figure 1. A fronto-occipital axis in the cortex is reproduced as a medio-lateral gradient in the thalamus, and a cortical cingulo-temporal axis rotates to a rostro-caudal gradient in the thalamus (Hohl-Abraham & Creutzfeldt 1991; Adams *et al.* 1997). Henceforward the terms 'cortical gradient' and 'cortical topography' will be used to denote this spatial order, inside the pulvinar, of cortico-thalamic (and thalamo-cortical) connections. Note also that we are treating the cortex as a two-dimensional (2D) sheet. There is no systematic representation of its third dimension (cortical layers) in the thalamus. Thus the thalamus, being a more rotund, three-dimensional (3D) body, has a 'spare' dimension whose employment in mapping is open to query.

At a finer level of analysis, the 'shrink-wrap' picture of topographic relations between thalamus and cortex cannot be sustained, owing to the presence of topological inversions, duplications and dislocations in their point-to-point relationship. The analysis of visual maps makes this point clear. There are 20–30 visual areas in the cortex, each with

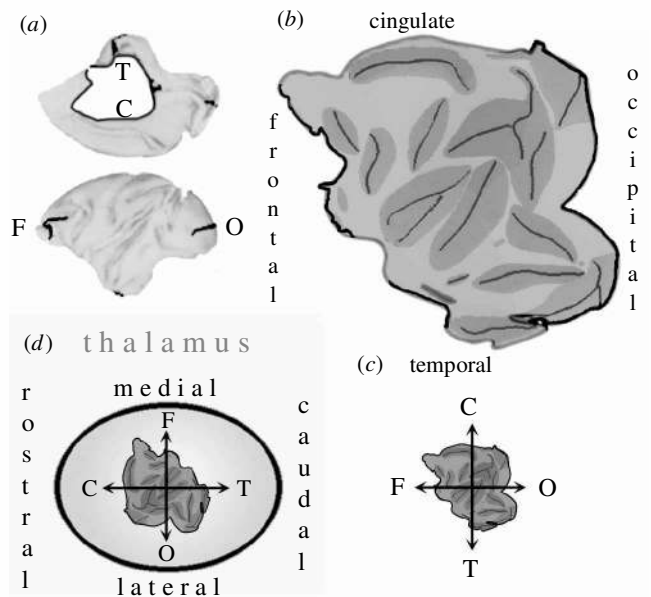


Figure 1. The topography of the cortical sheet is schematically reproduced as a rotated, mirror image in a dorsal view of the thalamus. (a) The normal folded appearance of the cerebral cortex. A left hemisphere of a macaque monkey is shown in a lateral and (above) an inverted medial view. (b,c) The cerebral cortex is shown in flattened format. Considered as a sheet of tissue, it is essentially a 2D structure; two major axes are labelled as fronto-occipital (F-O) and cingulo-temporal (C-T). (d) The cortical 'compass' transposed onto the surface of the thalamus (shown as an ellipse) to indicate how the cortical axes are reproduced relative to the standard anatomical axes of the thalamus (rostro-caudal and medio-lateral). The diagram shows a dorsal view (i.e. from the vantage point of the crown of the head) in which the cortical compass is mirror-transformed and rotated by 90°. Darker parts of the cortical sheet indicate cortex buried within sulci; darker outlines are where 'cuts' have been inserted, to facilitate flattening. (The hemisphere and cortical sheet diagrams are redrawn from Van Essen & Drury (1997) (copyright © 1997 USA Society for Neuroscience).)

some form of retinal (or *retinotopic*) map, admittedly much eroded in the worst cases. All of these areas connect with the pulvinar, which contains just two well-organized visual maps (Bender 1981). If the pulvinar maps are linked retinotopically to the cortical maps, as generally found (Benevento & Rezak 1976; Benevento & Davis 1977; Ungerleider *et al.* 1983; Adams *et al.* 2000; Shipp 2001), there is an obvious problem about the preservation of global cortical topography.

It is a fascinating observation, so far unexplained, that these two pulvinar maps reproduce the topology of the cortical maps in areas V1 and V2. They both represent the contralateral hemifield and are mirror images of each other, adjoined by a shared representation of the vertical meridian (VM) (see figure 2). Like area V2, the secondary (2°) pulvinar map is organized concentrically around the primary (1°) map. It is known as a 'second order transformation' of the visual field, with an outer boundary formed by the horizontal meridian (HM) that is split into two limbs, as a result of the separate representations of the inferior and superior quadrants (Allman & Kaas 1974;

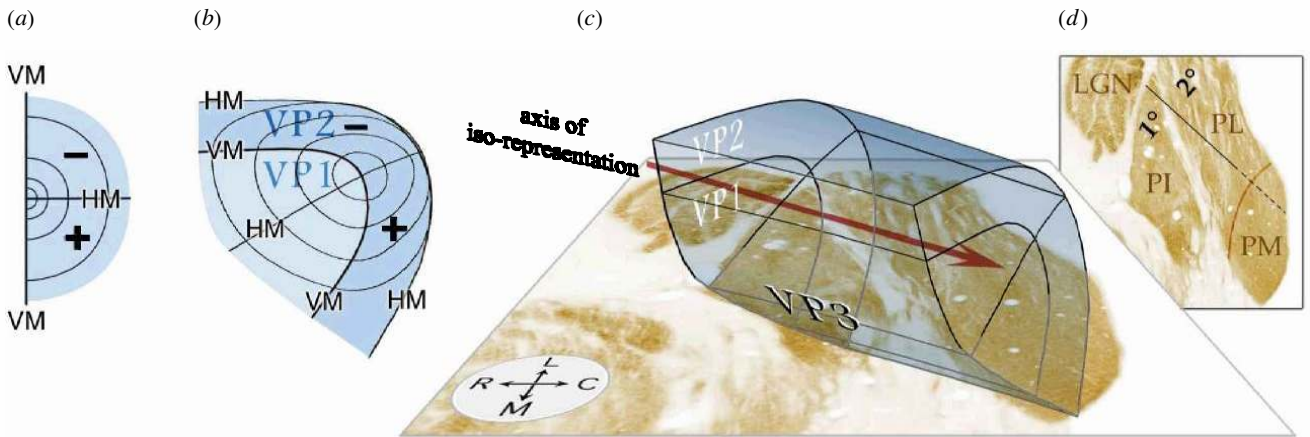


Figure 2. A schematic illustration of the visual mapping volume, superimposed on a horizontal slice through the pulvinar, in perspective view (the dial displays rostro-caudal (R-C) and medio-lateral (M-L) anatomical axes). (c) 3D projection. The visual axis of iso-representation (red arrow) is linear, and runs in a rostrolateral to caudomedial direction. (b) A slice through this volume, orthogonal to the AIR, shows the basic configuration of the  $1^\circ$  and  $2^\circ$  maps. Each of these is a transformation of the contralateral visual field ('standard hemifield map'; (a)). The diagram (a) shows the left visual field as imaged on a right hemi-retina; the horizontal meridian (HM) divides the optically inverted superior (+) and inferior (-) quadrants, and the vertical meridian (VM) divides right and left hemifields. VP1 and VP2 are the connection domains (defined in § 3) that correspond to the  $1^\circ$  and  $2^\circ$  visual maps in the pulvinar; VP3 is a third domain, lying outside the visual mapping volume, on its medial boundary. The inset (d), is a normal view of the pulvinar slice showing the relationship of the  $1^\circ/2^\circ$  (or VP1/VP2) border to the traditional pulvinar nuclei (PI, inferior pulvinar; PL, lateral pulvinar; PM, medial pulvinar).

Bender 1981). The obvious opportunity this creates for preservation of cortical topography in the pulvinar (at least for cortical areas V1 and V2) is dashed by the fact that both V1 and V2 are connected to both the  $1^\circ$  and  $2^\circ$  pulvinar maps (Benevento & Davis 1977; Ogren & Hendrickson 1979*a*; Rezak & Benevento 1979; Ungerleider *et al.* 1983; Kennedy & Bullier 1985; Adams *et al.* 2000). There is thus: (i) duplication of cortical representation; and (ii) topological inversion of neighbourhood relationships (e.g. the projection field of V1 to the  $2^\circ$  pulvinar map, and of V2 to the  $1^\circ$  pulvinar map, must both be topological inversions of the projection of V1 to the  $1^\circ$  pulvinar map). The preservation of retinotopic order in these connections, and in many others, acts to disrupt the global cortical topography of the pulvinar, so we must examine what form of cortical topography is retained.

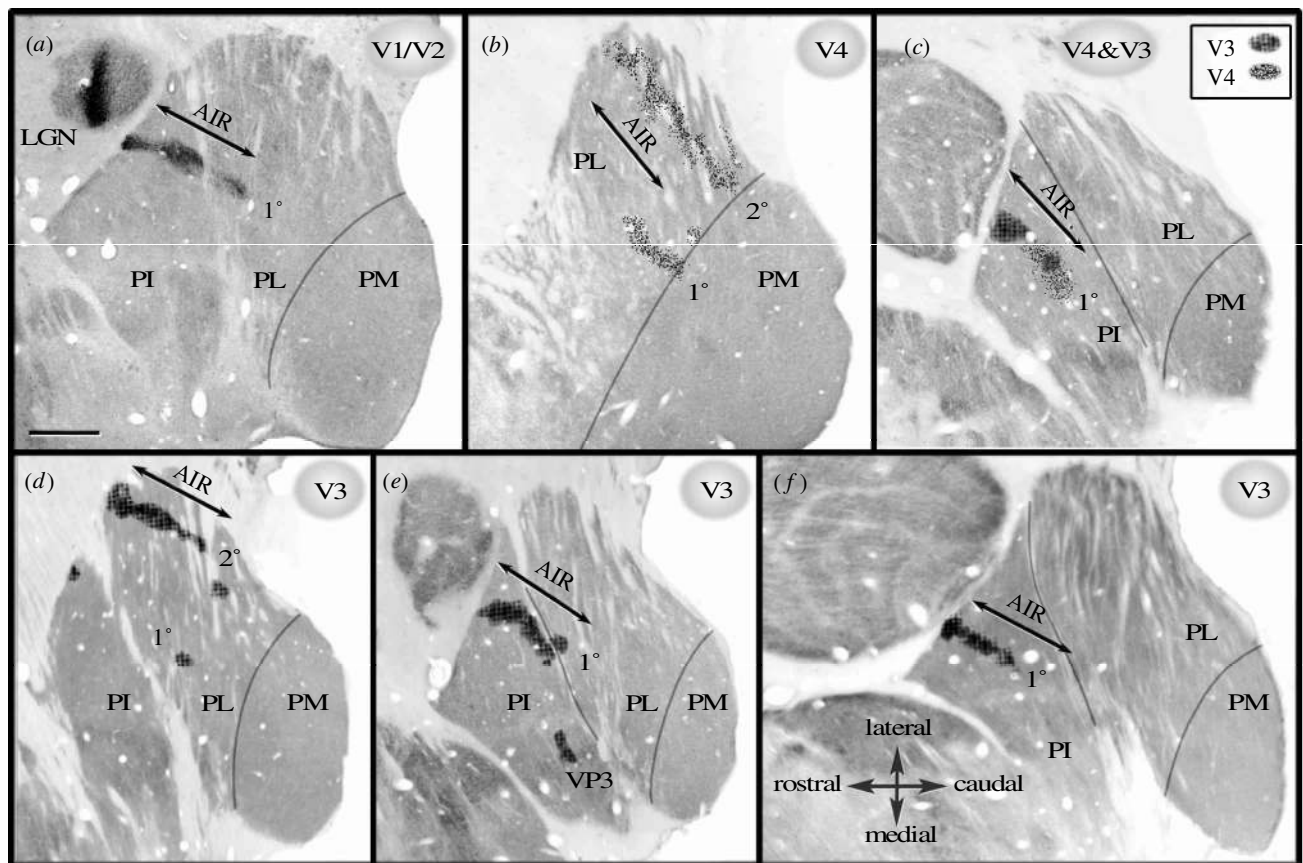
#### (a) *Dual topography of visual field and cortex*

A representation of the visual field (or the retina) is inherently two-dimensional. In the LGN, it is composed of triplicate hemifield representations from either eye, but these are stacked in register across the six layers, such that a point in the visual field maps to a line passing roughly perpendicular to the (local) plane of layering; it is referred to as a 'line of iso-representation'. By contrast, the pulvinar lacks any form of layered architecture to signify the axis of these lines. The pulvinar axis of iso-representation (AIR) has instead been inferred from physiological receptive field mapping studies (Allman *et al.* 1972; Bender 1981), or visualized anatomically in the pattern of cortico-pulvinar projections from identified points in cortical areas with well-ordered visual maps (Shipp 2001). Figure 2 shows a semi-schematic rendition of the 3D mapping volume in the pulvinar. Essentially, the  $1^\circ$  and  $2^\circ$  maps are projected along the AIR, such that any slice through the volume perpendicular to the AIR contains a similar pair of visual maps.

Evidence that  $1^\circ$  and  $2^\circ$  pulvinar maps have basically linear and parallel AIRs, adopting a rostrolateral-caudomedial alignment, as shown in figure 2, derives from a recent anatomical study (Shipp 2001; see figure 3). This conclusion differs in detail from the charts of Bender (1981), which had been the standard account for two decades. The latter depict the AIR as linear but rostro-caudal in the  $1^\circ$  map, and as nonlinear, curving from a rostro-caudal to medio-lateral orientation, in the  $2^\circ$  map. Otherwise, the topology of the  $1^\circ$  and  $2^\circ$  visual maps derived from anatomical analysis is not in conflict, as agreed by several earlier studies (Rezak & Benevento 1979; Ungerleider *et al.* 1983, 1984; Adams *et al.* 2000). The adjustment to the angle of the AIR was the key for charting the residual cortical topography within these maps. It transpires that the AIR is the very axis that expresses a unidimensional cortical topography, a clear occipito-temporal cortical gradient that stretches across the visually mapped volume within the pulvinar. Several components of this anatomical gradient have been described (or illustrated) before, but not in the context of a global model incorporating visual topography.

#### (b) *Overlap and offset in cortico-pulvinar projection zones along the axis of iso-representation*

The traditional subunits of the (visual) pulvinar are the medial (PM), lateral (PL) and inferior (PI) pulvinar nuclei. The  $1^\circ$  map occupies much of the PI and part of the ventral PL. The  $2^\circ$  map occupies the remainder of the ventral half of the PL (see figure 2*d*). Both maps may also invade part of the ventral PM. Viewed in horizontal sections, the AIR of the  $1^\circ$  map is oriented roughly perpendicular to the interface of the PI with the LGN. Projections to the PI from cortical areas V1, V2 and V3 all extend up to this facet, which forms the rostrolateral limit of the PI (Ungerleider *et al.* 1983; Shipp 2001). Thus,



**Figure 3.** Anatomical demonstration of the alignment of the AIR. Four experiments where tracer has been placed at a particular visual locus in a cortical area and, in these horizontal sections through the pulvinar, demonstrates columnar connections to the corresponding lines of isorepresentation in the 1° or 2° visual maps. (a) Connections with a site at the area V1/V2 border, whose visual locus is on the inferior VM; in this section, tracer is visible in the LGN, as well as the 1° pulvinar map. Scale bar, 1 mm. (b,c) Dual tracers were placed at equivalent visual loci (paracentral inferior field) in areas V3 and V4, in the same brain hemisphere. In (b) there are columns of V4 tracer in both 1° and 2° maps; in (c) (a section taken at a more ventral level) there is overlap of V3 tracer and V4 tracer within a continuation of the 1° column. (d,e) Tracer placed in area V3, showing both 1° and 2° columns of tracer; (e) (taken at a more ventral level than (d)) also has a small patch more medially, within the connection domain termed 'VP3'. (f) Tracer placed in area V3; note that this is a more eccentric visual locus than the case shown in (d,e), with the result that the 1° column of label in (f) is situated further rostromedially, in accord with the layout of the 1° map. (NB Tracer is rendered artificially in (b-f), using graphics stippling tools. The grey matter in these sections has been stained according to the activity of the metabolic enzyme cytochrome oxidase.) Abbreviations: VP3, ventral pulvinar 3; V1, primary visual cortex; V2–V4, areas of prestriate/occipital cortex; PM, PL, PI, medial, lateral and inferior pulvinar.

projections from these, most occipital areas, occupy the rostromedial pole of the AIR. Projections from area V4 (situated closer to the cortical occipito-temporal junction) overlap them heavily, but do not quite reach the interface with the LGN, and do extend a little further caudomedially (Yeterian & Pandya 1997; Shipp 2001). Thus, the centre of gravity of the projections from V4 is significantly offset from the rostromedial pole of the AIR.

None of these projections respect the traditional demarcation of PI from PL. Because comparisons between different individual animals (and laboratories) are fraught with difficulty, it is studies using dual tracers placed at separate locations in a single cerebral hemisphere that afford the most valuable, direct comparison between the projection zones of different areas. Alternatively, depending on the nature of the neural tracer placed in the cortex, the source zones of reciprocal pulvino-cortical projections can be examined. As shown in figure 4, all experiments of this nature yield consistent descriptions of cortical topography. For example, although the source

zones of connections to V1 and V2 seem to overlap precisely (Kennedy & Bullier 1985; Adams *et al.* 2000), there is a clear caudomedial displacement of the V4 source zone with respect to the V1 source zone (Lysakowski *et al.* 1988; figure 4a). Similarly, the source zones of connections to V2 and V3 are less caudomedial than that of V4, though the amount of offset is a little less (Adams *et al.* 2000; Shipp 2001; figures 4b and 3c). In the cortex, V1–V4 are all serially connected areas, and this sequence continues through areas TEO and TE, i.e. through the occipito-temporal junction to the temporal pole of the temporal lobe (sometimes collectively identified as the 'ventral visual pathway'). It has been thought for some time that a rostro-caudal sequence of sites in the temporal lobe is roughly inverted, topographically, within the ventral pulvinar (Benevento & Rezak 1976; Iwai & Yukie 1987). More recent studies using dual tracers have refined this gradient, and demonstrate that the successive areas V4, TEO and TE are connected to overlapping, but progressively more caudomedial zones (Baleydier & Morel 1992;

Webster *et al.* 1993), so continuing the occipito-temporal cortical gradient up to the caudomedial pole of the ventral pulvinar (figure 4*c,d*).

Cortico-thalamic projections originate from distinct types of neuron in layers 5 and 6 of the cortex, and it is possible that the microtopography of each layer's projections differ in detail (see § 6). However, none of the studies reviewed above was designed to separate them. Taking the two layers' outputs together, along with the sources of pulvino-cortical projections, the overall picture reveals a great deal of mutual overlap between successive cortical connection zones. Hence any single point along the cortical gradient in the ventral pulvinar will actually connect to roughly equivalent sites in the visual maps of several different areas (see § 4). Yet, however blurred, these serial pulvinar zones also retain some analogy to the structure of the LGN: a series of laminae with registered visual maps. If the LGN, as a laminated unit, is considered a unitary visual map, so too should the 1° and 2° maps of the pulvinar. And extending this analogy to the discrete layers of the LGN, it is possible to refine the topographic model to incorporate the successive reversals in connective topology associated with the alternating polarity of cortical maps V1, V2, V3, etc. This is illustrated in figure 5, giving a 'concertina' model of cortical topography in two dimensions, rather than a unidimensional cortical gradient.

### (c) Connections of the dorsal pulvinar

The dorsal pulvinar incorporates most of the medial and anterior pulvinar nuclei (PM and PA), plus the dorsal part of PL, and it too displays a continuity of cortical topography that pays scant regard to the demarcation of these traditional subunits. More importantly, as illustrated in figure 6, the cortical topographies of the dorsal and ventral pulvinar run parallel to each other, because parallel axes in these pulvinar divisions correspond to similarly oriented gradients in the cortical sheet. Again, the local topography in the dorsal pulvinar is well known, but the global correspondence has not previously been noted. In detail, figure 6 shows that the rostralateral-caudomedial thalamic axis corresponds to a cortical gradient running from the medial occipito-parietal junction to the anterior supero-temporal lobe (Yeterian & Pandya 1989, 1991; Romanski *et al.* 1997; Gutierrez *et al.* 2000). This gradient begins in the superior parieto-occipital cortex (i.e. area V6A, which connects to the dorsolateral part of PL; Shipp *et al.* (1998)), and then passes from the superior to the inferior parietal lobe (Schmahmann & Pandya 1990; Yeterian & Pandya 1997). For instance, the connections of area LIP span the junction of PL with PM, but those of 7A are largely restricted to PM (Asanuma *et al.* 1985; Hardy & Lynch 1992). The gradient continues through the superior temporal cortex (Yeterian & Pandya 1989, 1991), including the auditory areas (Pandya *et al.* 1994; Hackett *et al.* 1998) and parts of the neighbouring insula, to terminate in the rostral temporal pole, which connects with the extreme caudomedial pole of PM (Yeterian & Pandya 1989, 1991; Romanski *et al.* 1997). Much of this swathe of cortical territory is cross-modal association cortex; visuo-somesthetic in the parietal lobe, visuo-auditory in the superior temporal gyrus, and at least one documented area of trimodal association, the polysensory area of the

superior temporal sulcus (Bruce *et al.* 1981; Hikosaka *et al.* 1988).

Cortical topography in the dorsal pulvinar displays a general topological inversion and rotation, in accordance with figure 1. This is because the cortical axis orthogonal to the parieto-superotemporal one (i.e. occipitotemporal-frontocingulate) is aligned roughly caudolateral-rostromedially in the thalamus. There are local signs of this pattern in the connections of single areas (e.g. area 7A; Asanuma *et al.* (1985)), but it is easier to detect at a more global level: for example, area 7B, located on the anterior margin of 7A, connects with the PA nucleus, situated rostral to the PL/PM border (see figure 6) (Yeterian & Pandya 1985; Schmahmann & Pandya 1990). Hence, in the simplest terms, a horizontal plane through the dorsal pulvinar holds a mirror image of a flattened cortical sheet. What, if anything, is represented in the vertical axis orthogonal to this plane? Given the absence of regular visual topography over much of parietal and superior temporal cortex, it cannot be determined whether there are regular 'corrugations' in the topography of the cortical sheet, as in the concertina model for ventral pulvinar. Forms of local duplication, or discontinuities in the patterns of projection from a single area have actually been observed. For instance, connections with inferior parietal areas 7A and LIP form interdigitating disks, separated dorsoventrally in the PM (Asanuma *et al.* 1985; Hardy & Lynch 1992). Although 7A and LIP are adjacent areas of the cortex, they participate in recognizably different cortical circuits. Hence, in dorsal pulvinar, the 'spare' dimension might be used for isolating the connections of some areas, whereas longer-range overlap continues to occur within the plane of cortical topography. The general significance of this observation is explored further (see § 4).

## 3. THE IDENTIFICATION OF CONNECTION 'DOMAINS'

The aim, so far, has been to establish regularity in topography, the fact that independent reports of local elements of topography are consistent with each other, and that they summate to a global cortical gradient expressed along particular anatomical axes in the pulvinar. The focus now switches to topographic irregularities—failures of the simple 'shrink-wrap' concept, such as duplications or dislocation of the cortical map—which allow the discrimination of distinct topographic units. These are here referred to as connection 'domains'.

### (a) Subdivision of the ventral pulvinar

Terminology for subdivision of the pulvinar by connective criteria was first introduced by Ungerleider *et al.* (1984), who used the terms P1, P2 and P3 to index three distinct fields of connection with the cortical 'motion area', V5/MT. P1 and P2 were thought to be co-extensive with (i.e. occupying the same territory as) the 1° and 2° maps, whereas P3 was a separate zone outside of these maps whose retinotopic organization was much less evident. Subsequently, P1, P2 and P3 have been recognized to connect with several areas in addition to V5 (Adams *et al.* 2000), and are now regarded as pan-connective fields: i.e. 'domains' within the ventral pulvinar. It is pro-

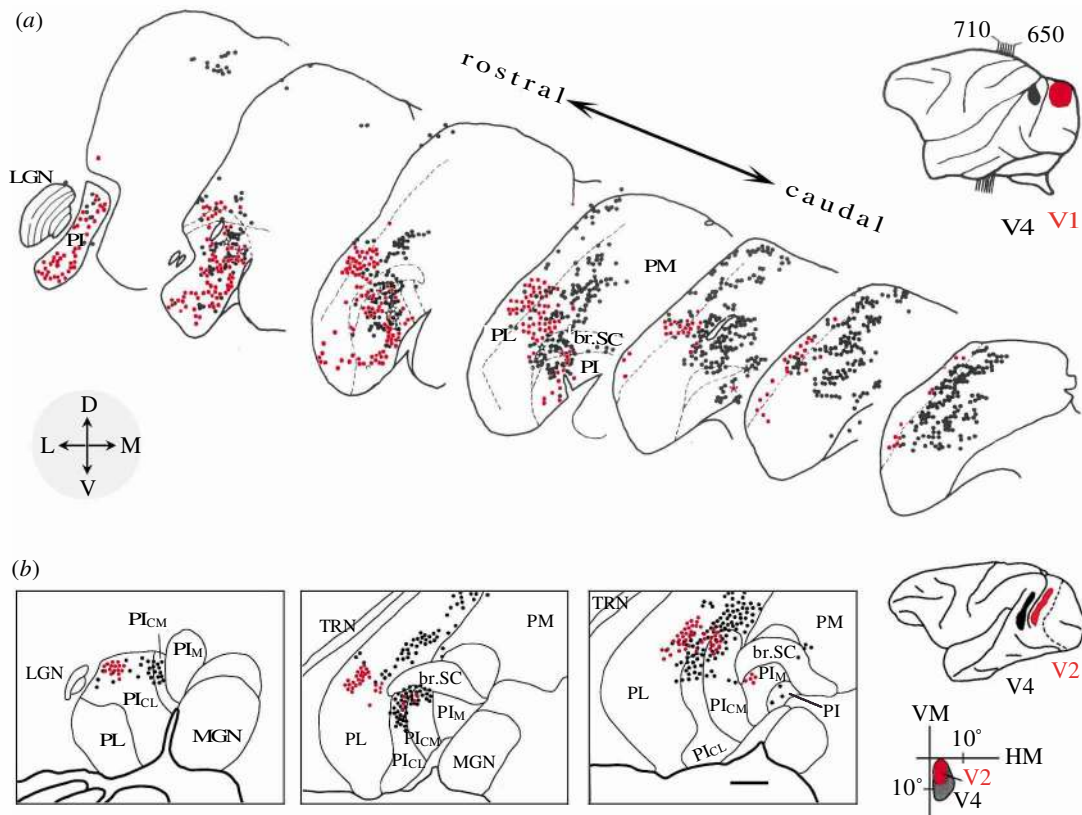


Figure 4. The occipito-temporal gradient of cortical topography in ventral pulvinar. Six hemispheres are illustrated from the four studies that have used dual tracers to compare the connections of a pair of nearby areas in the occipitotemporal cortex. The sections have been redrawn with a common orientation and with connections of the more occipital area in each pair shown in red. The field of 'red' labelled neurons (or terminals) is relatively rostralateral to the field of 'black' neurons (or terminals). Thus, in comparison to the 'black' field, the 'red' field tends (i) in any given section, to be more to the left (i.e. lateral, as shown by the dial in *a,d*); (ii) to be concentrated towards the leftward (more rostral) sections of each series (less evident in the less extensive series of sections reproduced in *b* and *d*). (a) Retrogradely labelled cells after fluorescent dye injections of 'nuclear yellow' in area V1 and 'granular blue' in area V4. (b) Cells labelled by retrograde tracers 'fluororuby' in area V2 and 'diamidino yellow' in area V4. (c) Two cases showing cells labelled by retrograde tracers 'diamidino yellow' in area V4, and 'fast blue' in area TEO or in area TE. (d) Two cases showing axon terminals labelled by orthograde tracers, WGA-HRP in area TEO and tritiated amino acid in area TE in the case shown above, and vice versa in the case shown below. It is worth noting that none of these examples involves a direct comparison between retrograde and orthograde tracers, whose outcome might distort the apparent cortical topography were the zone of cortico-pulvinar projection, and the source of the reciprocal pulvino-cortical projection, to be non-equivalent. (*b,d*) Scale bar, 1 mm. Abbreviations: br.SC, brachium of superior colliculus; MGN, medial geniculate nucleus; Li, nucleus limitans; PI, PL, PM, inferior, lateral and medial inferior pulvinar; TRN, thalamic reticular nucleus; TEO, TE, TF, von Economo's terminology for areas on inferior temporal cortex; PI<sub>CL</sub>, PI<sub>CM</sub>, PI<sub>M</sub> and PI<sub>P</sub>, centrolateral, centromedial, medial and posterior divisions of inferior pulvinar; PI<sub>LS</sub>, PI<sub>L</sub>, PI<sub>C</sub>, PI<sub>M</sub> and PI<sub>P</sub>, lateral-shell, lateral, central, medial and posterior divisions. (Redrawn from (a) Lysakowski *et al.* (1988), with permission from Springer-Verlag; (b) Adams *et al.* (2000) with permission from Wiley-Liss Inc; (c) Baleydiér & Morel (1992), with permission from Cambridge University Press; (d) Webster *et al.* (1993) with permission from Wiley-Liss Inc.)

posed, here, to modify the terminology to VP1, VP2 and VP3 (ventral pulvinar 1, 2 and 3). This is to signify that the classification is not restricted to V5 connectivity, while preserving the link with the original forms. It also allows scope for DP1 (dorsal pulvinar 1) etc., if required.

VP1 is bordered caudolaterally by VP2, and medially by VP3 (see figure 7), but each border is defined by a different criterion. VP1 is coextensive with the 1° map, and VP2 with the 2° map, so their border is defined by the local inversion of cortical topology, the fact that the 1° and 2° connection zones of an area (e.g. V4) are roughly mirror images of each other. There is a greater difficulty in distinguishing VP1 and VP2 towards the caudomedial pole, where retinotopic order is very poor (Bender 1981; Benevento & Miller 1981), presumably reflecting input from the inferotemporal cortex whose

retinotopy itself is weak (Boussaoud *et al.* 1991). Yet this gradual erosion of visual topography makes a poor criterion to define the caudomedial pole as a separate zone, given the evident continuity of connectivity along the occipito-temporal gradient; it is, therefore, arguably preferable to regard VP1 and VP2 as provisionally separate entities, even in this caudomedial region. It is possible that a series of small, strategically placed injections of tracer into the inferotemporal cortex might succeed in demonstrating the requisite inversion of cortical topography, even in the absence of a regular retinotopic organization.

VP3 contains a third, separate field of V5 connections that is centred in the medial part of the PI, but also extends above the ceiling of the PI (formed by a fibre tract known as the brachium of the superior colliculus) into the PM (Standage & Benevento 1983). Because VP3 lacks a

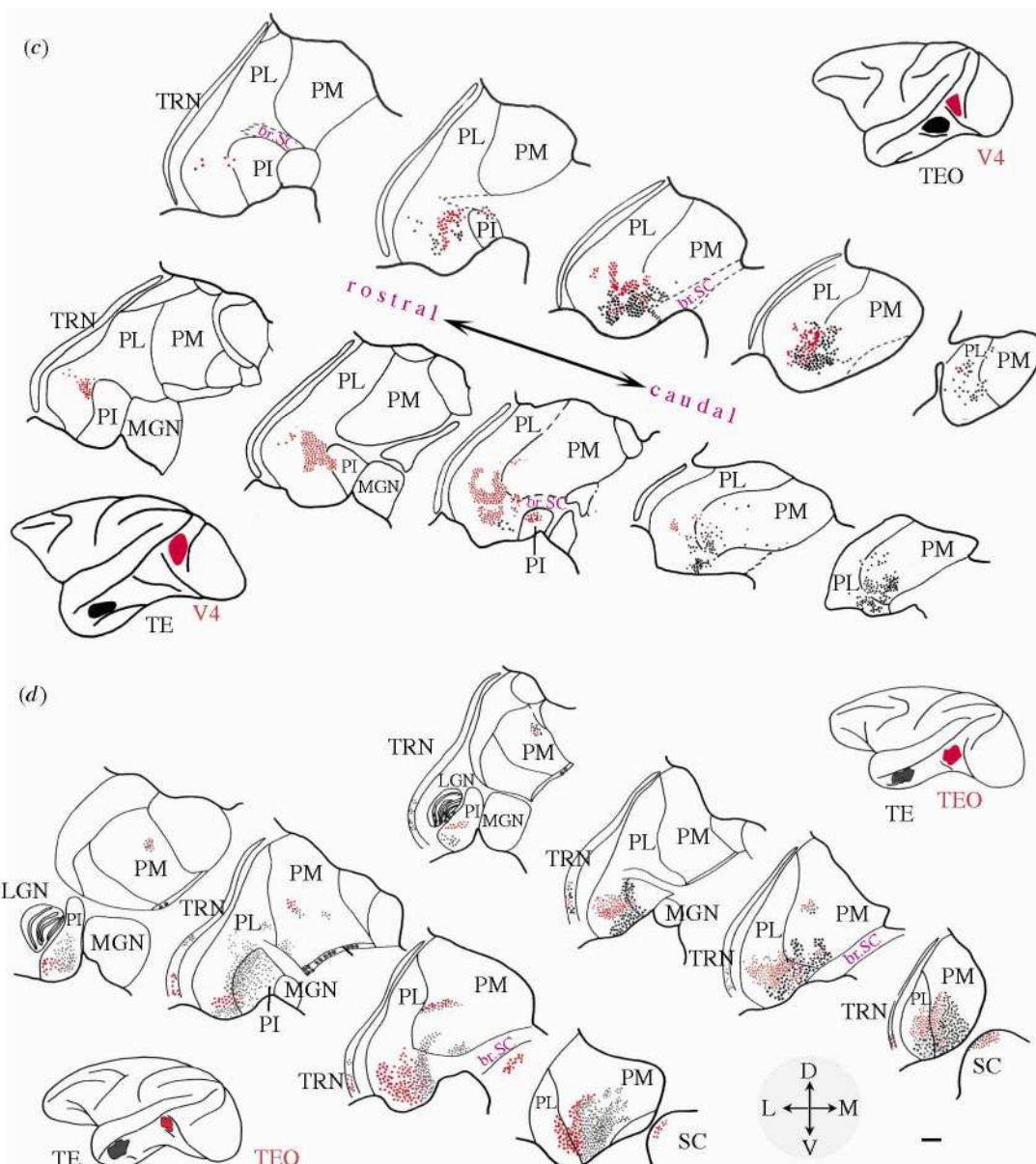


Figure 4. (Continued.)

well-ordered visual map, it is not possible to identify a topological inversion across its border with VP1. The distinction here rests on a clear *discontinuity* in cortical connectivity. The VP3/VP1 border can be visualized, for instance, as the mutual boundary of the connection zones of V5 and V4 (Shipp 2001). When tracers are placed at corresponding locations of the visual maps of these two areas, the resulting fields of pulvular label may abut each other, but show virtually no overlap (Shipp 2001). V5 is a near neighbour of V4 in the cortex, so this mutual avoidance is in marked contrast to the relationship of V4 with, say, V2, or TEO, areas whose connection zones (in VP1 and VP2) overlap heavily with that of V4. The connections of V4 and V5 are one specific means of distinguishing VP3 from VP1, but are these domains distinct in other respects as well? The difference in visual topography is quite obvious, because the same case comparisons demonstrating good retinotopy in VP1 and VP2 produce very poor evidence of visual topography in VP3 (Ungerleider *et al.* 1984; Adams *et al.* 2000; Shipp 2001).

However, there is some sign of a peripheral-to-central visual field vector aligned rostral-caudally within VP3 (Standage & Benevento 1983; Cusick *et al.* 1993; Shipp 2001). The precise cortical topography of VP3 is equally obscure, although connections with several other areas are known, such as V1, V2 and V3 (Gutierrez & Cusick 1997; Beck & Kaas 1998; Adams *et al.* 2000), and MST and FST (areas neighbouring V5 in the superior temporal cortex; Boussaoud *et al.* 1992). Below, it is suggested that VP3 could be considered as an extension of the DP topography.

Finally, it is necessary to point out a significant anomaly. As shown in figure 7, the V5 connections within VP1 and VP2 occupy a surprising location: the extreme rostral-lateral margin (Shipp & Zeki 1995; Shipp 2001). This corresponds to the occipital pole of the occipito-temporal cortical gradient. Thus, the rostral-lateral V5 connection zone is superimposed on the connection zones of areas V1, V2 and V3 and adjoins without overlap to the connection zone of V4; it does not occupy the full volume of VP1

and VP2, and is therefore also separate from the medial V5 zone, VP3. This discontinuity in cortical topography is a form of 'displacement', as if the V5 zone in VP1 and VP2 were being exuded towards the occipital pole in order to avoid the V4 zone. Hence all the connection zones of V5 avoid the V4 zone, but because the V5 zones within VP1 and VP2 conform to the local visual topography, it seems reasonable that only VP3 should be recognized as a separate connection domain.

#### (b) *The dorsoventral subdivision*

It is notable that the dorsal and ventral pulvinars express similar cortical topography, i.e. they display parallel cortical gradients along parallel thalamic axes (figure 6). What, therefore, are the forms of topographic discontinuity that justify the segmentation of the pulvinar into dorsal and ventral connection domains?

- (i) There is a dual representation of occipital areas in VP1 and VP2 (possibly a triple representation if VP3 is added). Nothing strictly comparable is known for the dorsal domain (DP).
- (ii) The dorsal border of the ventral pulvinar is defined as the representation of inferior visual field, bounded by the HM, of VP2 (see figure 2). However, in the cortex, the HM is not found along the common external envelope of the areas communicating with VP2, but at their internal borders. Thus, there is a 'fault line', a form of local discontinuity running along the boundary between the cortical topographies of the ventral and dorsal domains.
- (iii) Superimposed on the parieto-temporal gradient in domain DP are weaker gradients from remote areas of frontal and cingulate cortex. Specifically, there is a forked frontal gradient that runs away from dorso-lateral prefrontal cortex both ventrally and dorsomedially (Stanton *et al.* 1988; Barbas *et al.* 1991; Romanski *et al.* 1997); and a gradient from posterior to anterior cingulate cortex (Romanski *et al.* 1997; figure 6). Thus a site in dorsal pulvinar may connect with totally separate regions of the brain: frontal, parieto-temporal and cingulate, unlike ventral pulvinar, whose sum connectivity is restricted to the lone occipito-temporal zone.

There have been at least two studies using dual tracers for simultaneous demonstration of parietal and inferotemporal connection fields in the pulvinar (Baleydier & Morel 1992; Baizer *et al.* 1993). Both indicate that these fields are largely separate (in dorsal and ventral pulvinar, respectively), but not entirely so. Some degree of overlap was found, which is indicative of a fourth principle of connectivity, acting in counterpoint to all the others: that whatever regularities in topographic pattern can be discerned, they tend to be rather blurred. For example, connections traced from sectors of superior field representation in areas V2–V4 are densest ventrally, within the retinotopically equivalent sectors of VP1 and VP2, but some connections may be traced to far more dorsal levels, probably beyond the dorsal limit of VP2 (see Yeterian & Pandya 1997). Thus domain DP does maintain some links with ventral prestriate visual cortex, adding a degree of occipito-temporal topography to its diverse repertoire.

## 4. REGULARITY IN CORTICO-PULVINAR CIRCUITRY: THE REPLICATION PRINCIPLE

Imagine for a moment that cortical topography *were* perfectly replicated in the thalamus. This would imply a set of strictly reciprocal, point-to-point relationships, and it would also imply that there could be no cortico-pulvinar-cortical (c-p-c) route for transcortical communication. The latter is only possible because of the substantial blurring of local topography, within the preserved global framework of any one connection domain. Now, within the sphere of transcortical connectivity, it is known that cortical areas make many connections with nearby areas, and fewer over longer distances (e.g. Young 1992). Hence, local blurring of cortico-thalamic topography tends to produce a matching set of c-p-c connections. The nearest approximation to a 'law' of cortico-thalamic connectivity is that c-p-c connections tend to replicate direct cortico-cortical ones: in other words, if two cortical areas communicate directly, they are likely to have overlapping thalamic fields; if not, their thalamic fields avoid each other (totally separate, or perhaps interdigitating). There have been repeated demonstrations and discussions of this principle as applied to specific pairs of areas (see Benevento & Davis 1977; Baleydier & Mauguier 1987; Hardy & Lynch 1992; Gutierrez *et al.* 2000). For want of an existing name and for ease of reference, it is termed here the 'replication principle' (see figure 8).

The replication principle cannot be sustained wholly by local blurring of cortical topography in the thalamus. Longer-range cortico-cortical connections and examples of neighbouring cortical areas that do not interconnect require distortions of cortical topography to be 'replicated'. To cite some obvious examples:

- (i) The connection zone of V5 at the rostralateral pole of VP1 and VP2 overlaps that of V1 and avoids that of V4, sited a trifle more caudomedial, mirroring the longer range cortical connection of V5 with V1, and the minimal neighbourhood connectivity of V5 with V4 (Shipp & Zeki 1995; Shipp 2001).
- (ii) Inferior parietal areas LIP and 7A maintain separate connection fields in domain DP; likewise, they have separate fields of connectivity in nearby cortical areas and relatively minor direct interconnections (Hardy & Lynch 1992).
- (iii) There are extensive parieto-frontal connections in the cortex, mirrored by frontal connections to medial DP (i.e. traditional PM) (e.g. Stanton *et al.* 1988; Barbas *et al.* 1991; Romanski *et al.* 1997). In some cases, topographic overlap between parietal and frontal connection fields in PM has been directly demonstrated (Asanuma *et al.* 1985; Selemon & Goldman-Rakic 1988).

Each of the above examples refers to the internal organization of a connection domain. Can the replication principle also explain the fractionation of the pulvinar into the four domains VP1, VP2, VP3 and DP? The short answer is 'no', because it cannot account for the duplicate representation of occipito-temporal areas in VP1 and VP2. Yet, if VP1 and VP2 are considered as a unit, the principle has some mileage. This is because there is an obvious par-



allel of pulvinar domains VP1/VP2 and DP with, respectively, the ventral and dorsal streams in the cortex (Gutierrez *et al.* 2000). Indeed, studies showing relatively minor transcortical connections between the two streams (e.g. between inferior temporal and inferior parietal lobes; Morel & Bullier (1990); Baizer *et al.* (1991)) are mirrored by analogous studies showing little overlap of their respective connection fields within the pulvinar (Baleydier & Morel 1992; Baizer *et al.* 1993).

Two anomalies have been advanced to argue that VP should not be considered a parallel entity to the cortical ventral stream (Adams *et al.* 2000): (i) cortical areas V1 and V2 are the sources of both streams, yet connect to VP only; (ii) area V5 is a key component of the dorsal stream, yet connects mainly to VP1, VP2 and VP3, but not to DP. To rectify these anomalies, let us consider VP3 as an adjunct of DP. The link may be made by considering the pulvinar connections of areas MST and FST, which are cortical neighbours of area V5. The connection zones of these areas lie at an appropriate location in the parieto-superotemporal gradient of DP, being centred dorsal and caudal to VP3 but, importantly, also invading VP3 (Boussaoud *et al.* 1992). This establishes connectional continuity of VP3 with the DP, as if the dorsal cortical topography extends a tongue ventrally, alongside the medial border of VP1. It is worth noting that the arrangement of the visual map of VP3 (albeit crude) matches that of area V5, as this idea would predict (see figure 6). VP3 is, of course, the chief projection zone of V5 (Standage & Benevento 1983; Ungerleider *et al.* 1984), but it also receives substantial input from V1 (Gutierrez & Cusick 1997). Thus, again, there is nothing here to violate the principle of replication, the serial (dorsal) cortical pathway from V1, via V5 and MST, to area 7A being replicated by an equivalent thalamo-cortical connectivity gradient from VP3 into DP.

In the cortex, the dorsal and ventral streams only emerge gradually as separate anatomical pathways, and their mutual distinction is realized most fully at higher parietal and temporal lobe levels (Young 1992). The two streams do not dovetail in any simple fashion to earlier levels of parallelism, i.e. cytochrome oxidase modules in V2 and V1, or subcortical magno- and parvocellular channels (Shipp 2002). Thus, it is conceivable that the implicit presence of dual pathways through prestriate cortex is actually replicated more explicitly in the pulvinar, in the form of domains VP1/VP2 and VP3/DP.

## 5. CORRELATION OF CONNECTIONAL DOMAINS AND NEUROCHEMICAL ZONES

Compared with traditional architectural analysis, neurochemical methods offer a more probable index of functional subdivisions: they may target components of molecular physiology (e.g. calcium-binding proteins calbindin and parvalbumin), or specific transmitter systems (e.g. acetylcholinesterase (AChE)). Calbindin and AChE are generally found to display complementary patterns of distribution, defining zones that are supported by a variety of other methods.

Figure 9 illustrates the relationship between neurochemical zones and connectional domains. There are two current neurochemical schemes, one of which, figure 9b

(Cusick *et al.* 1993; Gutierrez *et al.* 1995; Gray *et al.* 1999) provides a better fit to the connectional domains. The outlines of this scheme (figure 9b), conventionally illustrated in the coronal plane, are also projected onto a horizontal section through VP. It can be seen that the neurochemical subunits form a series of shells around the core zone (PI<sub>P</sub>), such that the 'neurochemical axis' runs obliquely across all three ventral connection domains. To a first approximation, the three innermost neurochemical zones (PI<sub>P</sub>, PI<sub>M</sub> and PI<sub>C</sub>) constitute VP3, and the outer zones (PI<sub>L</sub> and PI<sub>Ls</sub>) equate to the sum of VP1 and VP2. The border between VP1 and VP2 has no neurochemical correlate. This is not so surprising, as VP1 and VP2 have very similar connectivity and the distinction is one of topology. The neurochemical profile of PI<sub>L</sub> is a light calbindin density, the outer-shell region (PI<sub>Ls</sub>) being distinguished by a modestly denser neuropil with sporadic, very intense calbindin-positive neurons (Gutierrez *et al.* 1995; Gray *et al.* 1999). It is possible that PI<sub>Ls</sub> correlates with the V5 connection zone at the rostrolateral pole of VP1 and VP2, because it shares the same location and is comparable in width (Shipp 2001). However, there is no necessary link between V5 connectivity and intensity of calbindin *per se*. The medial focus of connections with V5 (i.e. VP3) incorporates PI<sub>M</sub>, whose chief characteristic is a very low density in calbindin; this relationship has been confirmed in many studies, including several New World primate species. Also, VP3 is notably larger than PI<sub>M</sub> and includes V5/MT-efferent cells located within PI<sub>C</sub> and PI<sub>P</sub> (Stepniewska *et al.* 1999, 2000; Adams *et al.* 2000). To define the VP1/VP3 border by the transition between the V4 and (medial) V5 connection zones, as proposed here, the V4 zone must fit within PI<sub>L</sub> and the V5 zone (i.e. VP3) should include all of PI<sub>C</sub>, as well as PI<sub>M</sub>. According to Adams *et al.* (2000), V4-efferent cells are common in PI<sub>L</sub>, sparser in PI<sub>C</sub> and absent from PI<sub>M</sub>, implying a less focal V4/V5 transition than that described by Shipp (2001). In fact, Adams *et al.* (2000) do place PI<sub>C</sub> within VP3 (along with PI<sub>M</sub> and PI<sub>P</sub>): not on the basis of connections, but by transposition of Bender's original visual maps to delineate VP1. Another good reason for including all of PI<sub>C</sub> within VP3 is that PI<sub>C</sub> and PI<sub>P</sub> are neurochemically identical. Both are high calbindin, low AChE, high substance P, and are actually continuous with each other caudoventrally to PI<sub>M</sub> (Gray *et al.* 1999; Stepniewska *et al.* 2000).

The neurochemical dorsal/ventral subdivision appears as a change in the pattern of compartmentation (figure 9b). Although, as a connectional domain, DP is a continuum, the neurochemical picture reveals three zones, of heavy, medium and light density in an AChE stain (and the complementary appearance under calbindin) (Gutierrez *et al.* 2000); the conservative terminology, PLd, PMl and PMm (for dorsal lateral pulvinar, lateral and medial subdivisions of medial pulvinar) reflects a similarity to the older definitions of these structures, but they are not identical. As apparent in figure 9b, there is an additional, dorso-ventral component to the neurochemical axis. PLd, PMl and PMm naturally display different sum-connectivities, because they correspond to different zones within the overall parieto-superotemporal gradient of DP. However, because the neurochemical axis deviates from the axis of cortical topography (due to the dorsoventral component of the former), it is possible that local topo-

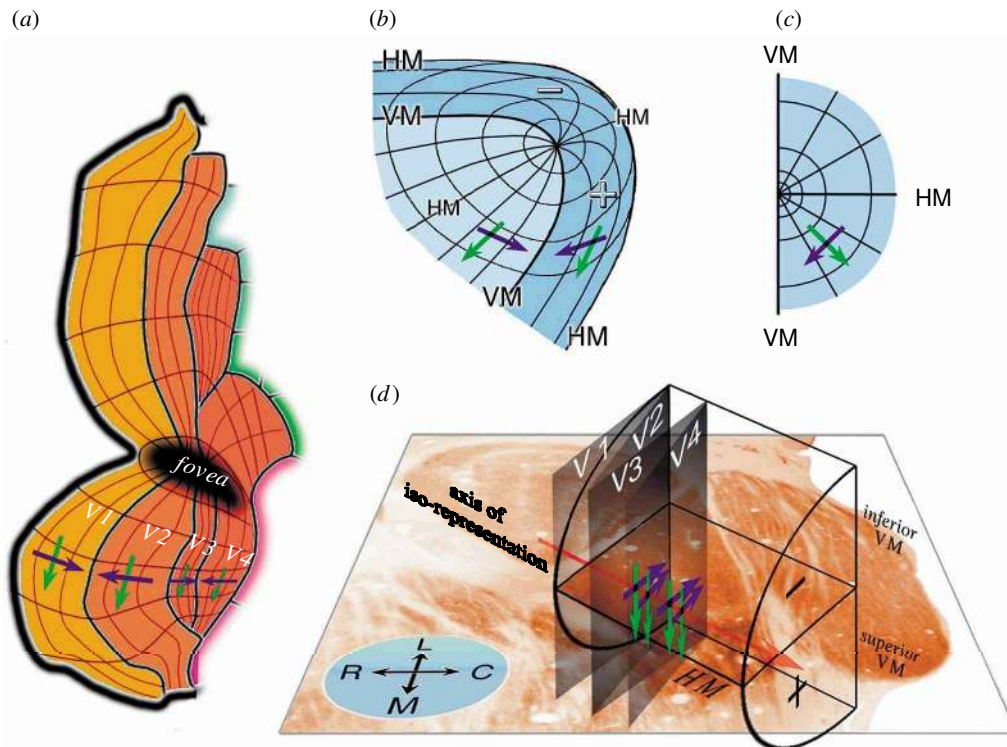


Figure 5. The concertina model. To illustrate the relationship between idealized visual maps in the pulvular and cortex, an equivalent pair of orthogonal vectors (purple: iso-eccentric; green: isopolar) is marked on each map. (a) The maps of cortical areas V1–V4; (b) the transformed 1° and 2 maps of the pulvular; (c) the standard hemifield map of the retina. In the cortex, these vectors run parallel to the major axes of the areas V2, V3 and V4, because these areas all have maps which are similar ‘second order’ transforms of the visual field; the discontinuity within V1 (to facilitate flattening the cortical sheet) effects a similar, artificial, transformation in V1. Importantly, successive cortical maps are mirror-image transforms of each other, such that the purple vector reverses direction in successive maps, whilst the green vectors remain parallel. Because these areas all connect with a single pulvular map (i.e. with a fixed orientation of the vectors, (d)), there must be successive reversals of the cortical topology in the connection zones of successive areas. (d) Illustrates this for the 1° map of the pulvular shown, for simplicity, in schematic form. The intersection of the green and purple vectors is a fixed visual point, found along a particular AIR. If the connection zones of V1, V2, V3 and V4 are schematized as single planes, rather than as diffusely overlapping regions, then the cortical sheet can be pictured as folding, concertina fashion, into the volume occupied by the 1° map. The concertina principle applies equally to both the 1° and 2° maps, but the real 3D structure of the corrugated topography is awkward to illustrate for both maps at once. Overall, the arrangement can be seen as a means of minimizing discontinuity in the cortical topography of the pulvular. Abbreviations: HM, horizontal meridian; VM, vertical meridian. (The cortical diagram is redrawn from Van Essen & Drury (1997) (copyright © 1997 USA Society for Neuroscience).)

graphic discontinuities, for example, the non-overlap of the connection zones of areas LIP and 7A, mentioned above, may correlate in some fashion with the neurochemical borders (Gutierrez *et al.* 2000).

## 6. HIERARCHICAL ORGANIZATION OF THE PULVULAR (?)

The hierarchical organization of cortical areas, at least within the confines of the sensory cortices, is well known (Felleman & Van Essen 1991; Hilgetag *et al.* 1996, 2000). Precise ranks, or strata, in the hierarchy are defined by anatomical criteria, concerning the laminar origin and termination of ascending (‘driving’) and descending (‘feedback’) cortico-cortical connections. Crick & Koch (1998) have proposed, in their ‘no strong loops’ hypothesis, that the pulvular is linked to the known hierarchy of cortico-cortical circuitry by the dictum that directly reciprocal c-p-c links should not be forged by ‘driving’ connections in both directions. The aim of this section is to explore this notion for the occipito-temporal gradients

in VP1 and VP2, which accord with a serial hierarchy of cortical areas. Is there any possibility that the pulvular, too, has a hierarchical organization?

The pulvular is regarded as a higher-order thalamic nucleus than the LGN, because most of its primary (or driving) afferents derive from the cortex (Guillery 1995; Sherman & Guillery 1996). Again, the basis of the classification is anatomical. Primary afferents, exemplified by retinal terminals in the LGN, have relatively large axonal terminations and make synapses on proximal dendrites. In the pulvular, cortical afferents of this type derive from layer 5 alone. The more numerous cortico-pulvular afferents (and all cortico-geniculate afferents) arise from layer 6; they have smaller terminals and more elongated terminal fields. The distinction holds for many species, and in primate pulvular the two types have also been termed R-type (layer 5) and E-type (layer 6) (Rockland 1996, 1998). The retinal terminals in LGN form an archetypal example of a ‘driving’ input, because they would appear to confer the receptive field properties of their geniculate target neurons; by contrast, the layer 6 cortico-geniculate

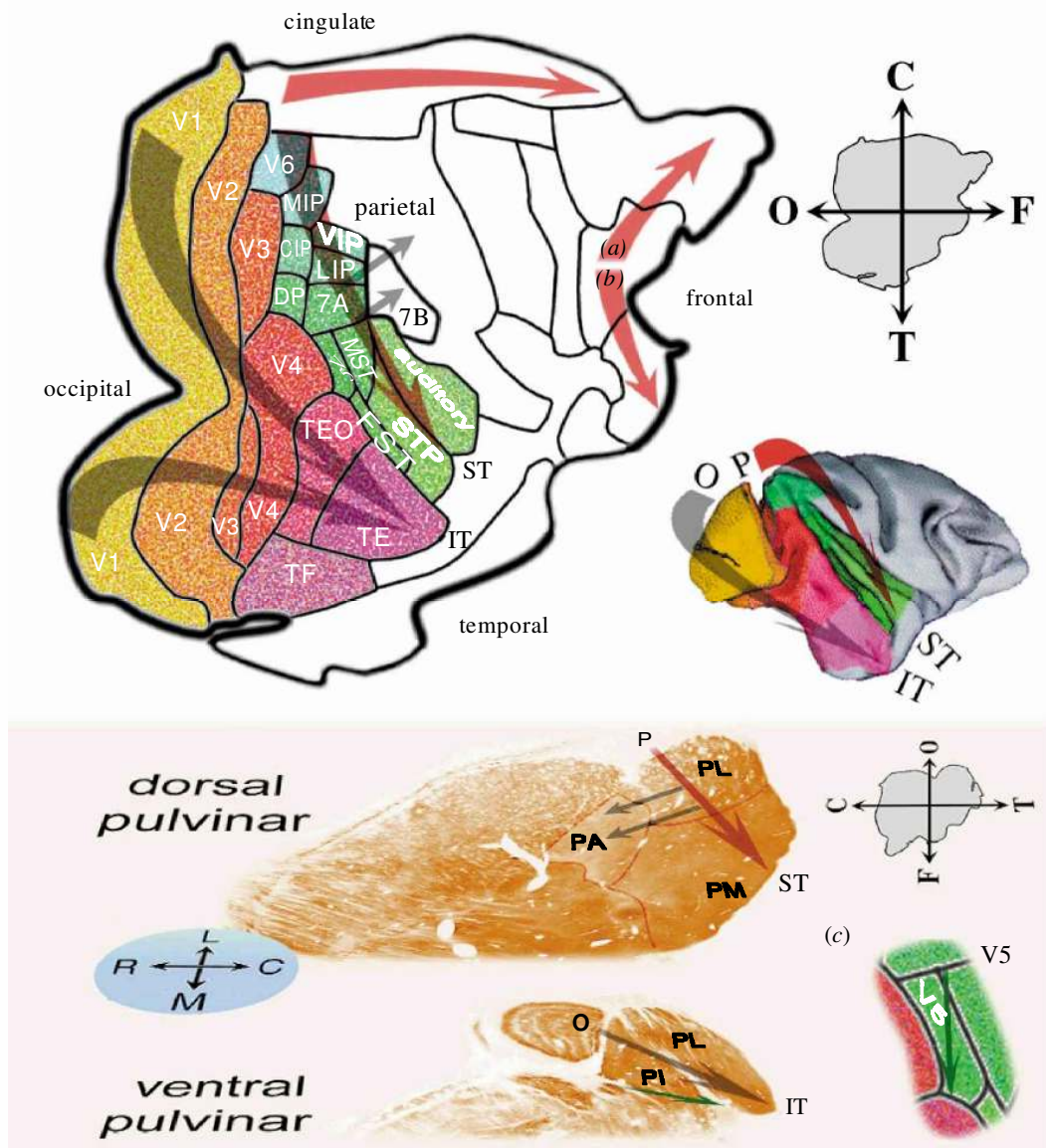


Figure 6. Topographic relationships between the cortical sheet and the pulvina. The two major vectors, parieto–superotemporal (P–ST) in red, and occipito–inferotemporal (O–IT) in grey, are shown on a whole brain view, on the flattened cortical sheet, and on two horizontal sections at dorsal and ventral levels in the pulvina (lower panel with background shading), where they run rostralolateral–caudomedially. The thicker margins of the cortical sheet indicate where a ‘tear’ (i.e. an artificial discontinuity) has been introduced to facilitate flattening; the O–IT vector in the cortical sheet has been split into two components, mirroring the tear made in V1. The additional large red vectors in the cortical sheet represent topographic gradients in cingulate and frontal cortex that are expressed in parallel to the P–ST gradient in dorsal pulvina. The frontal vectors lead from the lateral prefrontal cortex, i.e. Brodmann areas 8 and 46 (a) towards medial areas 9, 10 14 and 32; (b) towards ventral areas 45, 12 and 11. The small vectors in the sheet perpendicular to the P–ST vector (i.e. heading from area 7A to 7B) adopt a caudolateral–rostromedial course in the pulvina, leading into the anterior pulvina (PA) nucleus. This demonstrates a mirror reversal of topology with respect to the cortex, summarized by the two cortical ‘compasses’: the lower one, pertaining to cortical topography in the pulvina, is a rotated, mirror image of the first. (c) The part of the sheet containing area V5 (or MT) is enlarged to show the centripetal visual axis (Gattass & Gross 1981); the corresponding green arrow in the ventral pulvina shows the predicted centripetal visual axis if the cortical topography in this sector of the pulvina (i.e. within the domain VP3) is an extension of the cortical topography in the dorsal pulvina; it is roughly rostro–caudal, in agreement with experimental data. Abbreviations: V1, primary visual cortex; V2–V6, areas of prestriate/occipital cortex; VP1–VP3, ventral pulvina 1–3; PI, PL, PM, PA, inferior, lateral, medial and anterior pulvina nucleus; MIP, CIP, VIP and LIP, medial, caudal, ventral and lateral intraparietal areas; DP, dorsal prelunate area; MST and FST, medial and fundal superior temporal areas; TEO, TE, TF, von Economo’s terminology for areas in inferior temporal cortex; 7A and 7B, Brodmann’s terminology for areas of parietal lobe; 8–14, 32, 45 and 46, Brodmann’s terminology for areas in frontal lobe. (The cortical sheet and brain are redrawn from Van Essen & Drury (1997) (copyright © 1997 USA Society for Neuroscience) with the authors’ permission and with modification/rationalization of some visual areas to match the simplified terminology employed here (e.g. area V3A has been subsumed within area V3).)

afferents are likely to have a modulatory effect on neuronal activity (Sherman & Guillery 1998). In the absence of direct evidence, the relative physiological action of primary and non-primary afferents to the pulvinar is assumed to be similar. Crick & Koch (1998) make the further supposition that driving and modulatory *pulvino-cortical* afferents can also be identified anatomically (because they terminate in cortical layer 4 or 1, respectively). Thus, they propose that any reciprocal link between specified sites in cortex and pulvinar should consist of a driving connection in one direction and modulatory feedback in the other, just as in the cortical hierarchy.

Added to this may be a neurochemical distinction between driving and modulatory pulvino-cortical projections, because projections to the middle layers (4 and 3) are found to arise only from parvalbumin-positive projection neurons, whereas the more diffuse projections to superficial layers, including layer 1, are made by calbindin-positive projection neurons (Jones 1998, 2001). Thus the possible expression of hierarchy in cortico-thalamic relations would actually predict regularity of up to eight anatomical characteristics, listed in table 1, and illustrated in an idealized scheme in figure 10. The scheme envisages a gradient of hierarchical 'rank', realized in discrete steps (or perhaps as a continuum) within the pulvinar. Any given level in the cortical hierarchy (i.e. a single area) should have two distinct connectional fields (a 'driving' field and a 'modulatory' field) within the pulvinar gradient. Likewise, a discrete level in this pulvinar gradient should have two anatomically distinct fields of cortical connectivity belonging to higher and lower strata in the occipito-temporal hierarchy.

How realistic is this scheme? The relevant anatomical data are sparse, but many of them are anomalous. The reason the data are sparse is that relatively few studies have documented the laminar organization of pulvino-cortical terminals, or the distribution of the source cells of cortico-pulvinar afferents that, experimentally, require deposition of neural tracers within the pulvinar itself. Furthermore, such tracer deposits in the pulvinar are imperfectly focal—possibly involving a range of rank, rather than a single rank—which might anticipate some overlap between the two predicted cortical fields. In fact, pulvino-cortical terminals are found to be fully co-extensive in layer 3/4 and layer 1, across broad sweeps of prestriate cortex (Benevento & Rezak 1976; Rezak & Benevento 1979). This result is best described as a uniform connection field, with mixed characteristics. It is also reported that terminals in layer 3/4 and 1 can arise from the same individual axon (Rockland *et al.* 1999), contrary to the hierarchical scheme. Hence, there is no sign of the predicted asymmetry in the distribution of terminals in layers 1 and 4, which might distinguish the two predicted fields. The hierarchical hypothesis might be rescued, in reduced form, by restricting the low-ranking cortical field solely to V1 (where pulvino-cortical afferents do terminate predominantly in layer 1; Benevento & Rezak 1976; Ogren & Hendrickson 1977; Rezak & Benevento 1979). This would imply a simpler, three-stage joint pulvino-cortical hierarchical system, with the pulvinar forming an undifferentiated middle stage (i.e. ranking above V1, but below all of prestriate cortex).

The complementary prediction is that primary and non-primary cortico-pulvinar afferents from a given cortical site should form distinct fields in the pulvinar, offset along the axis of hierarchy. The observational data here are more equivocal: all areas so far studied (V2, V5, TEO, TE and TF) produce some pulvinar foci where primary and non-primary afferent terminals are mingled, and others where they are separate (Rockland 1996, 1998). One example of the latter are the exclusively non-primary (E-type) terminations in rostrolateral VP1 and VP2, provided by areas TF, TE and TEO (Rockland 1996), which the full hierarchical model would interpret as feedback from relatively high-ranking cortical areas to the low-ranking pole of the pulvinar. The 'reduced' (3-stage) hierarchical model would do likewise, but it cannot tolerate the observed presence of primary (R-type) afferents to the pulvinar from prestriate cortex, because it predicts that these should arise only from V1.

Unfortunately, there is no useful information about the distribution of cortico-pulvinar or (neurochemically identified) pulvino-cortical projection neurons to add to this picture. In summary, therefore, and despite a cortical gradient mimicking the serial, ventral cortical pathway, the available anatomical evidence does not lend itself to any scheme partitioning the pulvinar into zones of fixed rank vis-à-vis the cortical hierarchy. By itself, this does not dispel the underlying logic of the 'no-strong loops' dogma, and one possible solution may be that hierarchical order in thalamo-cortical interactions is organized on a strictly local basis. Crick & Koch (1998) have already touched on this possibility, noting that the limited range of intrinsic interactions within pulvinar could enable neighbouring locales to act independently of each other. This would be a kind of 'mosaic' organization, with separate local patches of primary and non-primary terminal fields, and clusters of different types of thalamo-cortical projection neurons. If so, the various elements of pulvinar circuitry related to a specific site in the cortex would not fully overlap each other, roughly as noted by one recent study of spatial reciprocity in PM (Darian-Smith *et al.* 1999). It is apparent that much more work of this nature is required to form a clearer picture of putative pulvino-cortical hierarchical relationships.

## 7. FUNCTIONAL LOGIC OF THE REPLICATION PRINCIPLE

The replication principle implies that for every cortico-cortical connection, there is a shadow c-p-c linkage. This might suggest redundancy in the circuitry, as if the pulvinar acts as a central telephone exchange, providing an alternative route for the transfer of specific sensory information. Pulvinar circuitry has indeed been discussed in these terms, with the added suggestion that it may broaden the range of contacts established by direct cortical projections (e.g. Rezak & Benevento 1979; Ungerleider *et al.* 1983). However, the fact that c-p-c circuitry (as codified by the replication principle) fails to rectify certain 'deficiencies' in cortical circuitry (e.g. the absence of reciprocal connections from V4 to V5) does not encourage this view. Indeed, the whole notion of pulvinar circuitry as 'alternative' to cortical circuitry is unhelpful, given the obvious differences in anatomy and physiology of these

Table 1. Elemental anatomical characteristics for a cortico-thalamic hierarchy.

	ascending/driving	feedback/modulatory
cortico-thalamic		
source	large layer 5 neurons	smaller layer 6 neurons
termination	R-type axons: (thick axons, rounded terminal fields)	E-type axons: (thin axons, elongated terminal fields)
thalamo-cortical		
source	parvalbumin-positive projection neurons (?)	calbindin-positive projection neurons (?)
termination	layer 4/3 of cortex	layer 1 of cortex

indirect relays. The logic of what follows, therefore, is to suppose that c-p-c linkages enable functions that are not an exact duplication of direct cortico-cortical information transfer, but which may play a more regulatory or coordinating role in cortical signal processing.

#### (a) *Cortico-thalamic oscillations and synchronization*

Let us start by considering a strictly reciprocal c-p-c loop, involving a single cortical area (heuristically, taking the pulvinar to act as a 'seventh' cortical layer). Reverberating activity in such a loop has been proposed, for example, to sustain a visual image during periods of brief interruption of the optical signal, such as blinking (Billock 1997). The proposal was put forward specifically for geniculostriate interactions, but is equally applicable to pulvinar-prestriate reciprocal circuits, and similar in principle to the idea of the thalamus as an 'active blackboard' for the cortex (Mumford 1991). A further important property is that resonant interactions between thalamus and cortex act to synchronize neural firing (Steriade 1997). One demonstration is that cortical feedback to the LGN from V1 in cats acts to synchronize activity among simultaneously recorded geniculate projection neurons (Sillito *et al.* 1994). The synchronized signals arise in neurons driven by a single extended contour (i.e. a simple bar stimulus) and re-entered into the cortex, are likely to provide a stronger drive to V1 cells of matching orientation selectivity, so enhancing the signal-to-noise for that stimulus (Sillito *et al.* 1994). More generally, there is, of course, a wealth of evidence that the cortex and thalamus (incorporating the inhibitory thalamic reticular nucleus) operate as a unified oscillatory system, whose frequencies and levels of spatio-temporal coherence determine different states of sleep and waking (Steriade 1997, 2000; Llinas *et al.* 1998). Alert behaviour is characterized by frequencies centred at *ca.* 40 Hz displaying highly localized patterns of synchronization (Steriade *et al.* 1996*a,b*), in contrast to slow wave sleep (but not rapid-eye-movement sleep) where lower frequencies predominate, with virtually global synchronization across the thalamus (Steriade 2000). Coherent fast oscillations have been proposed to provide a mechanism for transient binding of diverse object features, registered in separate sensory areas (von der Malsburg & Schneider 1986; Eckhorn 1994; Singer & Gray 1995; Gray 1999; Singer 1999). The scheme requires that multiple groups of neurons, distributed within and across separate areas, be capable of attaining synchronous firing by means of re-entrant circuitry (Tononi *et al.* 1992). It is by facilitating this process that

the pulvinar could play a coordinating role in cortico-cortical communication.

To illustrate this potential role by a thought experiment, put the pulvinar as an analogue of the LGN in the experimental paradigm of Sillito (Sillito *et al.* 1994). As noted above, layer 5 of V1 is a rich source of primary afferents to the pulvinar, and modulatory (or feedback) input is provided by layer 6 cortico-thalamic neurons of the extrastriate cortex. So, for our analogue circuit, the elements *retina-LGN-V1* are replaced by *V1-pulvinar-extrastriate area* (e.g. V3). The analogy implies that feedback from (say) V3 will act to synchronize pulvinar units activated by V1, and the immediate effect may be to initiate coherent oscillations between V3 and its pulvinar connection zone. The analogy may now be extended by considering additional elements of circuitry. There are feedback connections to V1 from both V3 and the pulvinar, terminating in layer 1 (Benevento & Rezak 1976; Ogren & Hendrickson 1977; Rezak & Benevento 1979; Levitt *et al.* 1995; Felleman *et al.* 1997); these are envisaged to condition the temporal patterning of activity (Engel *et al.* 2001; Jones 2001) for example, acting to synchronize V1 cortico-cortical and cortico-thalamic neurons, ultimately recruiting elements of V1 to the coherently oscillating neural assembly.

#### (b) *Specificity of information transfer*

Crucially, the above compilation of current theories has yet to highlight the functional distinction between direct and indirect pathways of cortico-cortical communication. That issue is tackled by Sherman & Guillery (1998), who propose that the major functional drive goes through the thalamus and that, as an 'extreme corollary', most cortico-cortical pathways would be modulatory in function. But is the indirect c-p-c circuit well equipped for this role of specific information transfer? There are several obstacles to this view, which it is convenient to document by continuing the above example of input to V3 from V1, and contrasting the indirect circuit via layer 5 and pulvinar with the direct forward projection to V3 arising from layer 4B (Felleman *et al.* 1997).

- (i) Layer 4B of V1 has a specific set of properties, among them orientation, direction and disparity selectivity (Dow 1974; Orban *et al.* 1986; Hubel & Livingstone 1990), which are similar to those of V3 (Zeki 1978; Felleman & Van Essen 1987; Gegenfurtner *et al.* 1997). Layer 5 neurons have properties that are somewhat more similar to those of V1 as a whole. Yet their receptive fields are relatively large

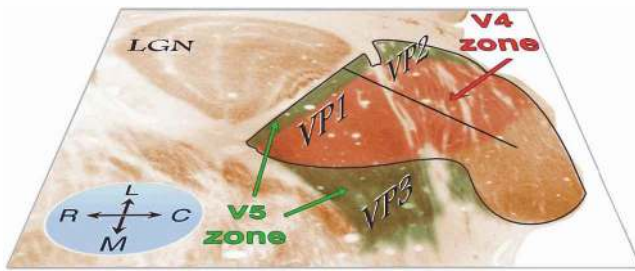


Figure 7. Perspective view of a horizontal slice through the pulvina, showing the outline of domains VP1 and VP2, and the non-overlap of the connection zones of V5 (green tinge) and the single V4 zone (red tinge). The location of VP3, coinciding with the medially located V5 zone, implies concave curvature of the outer boundary of VP1. Abbreviations: VP1-VP3, ventral pulvina 1-3.

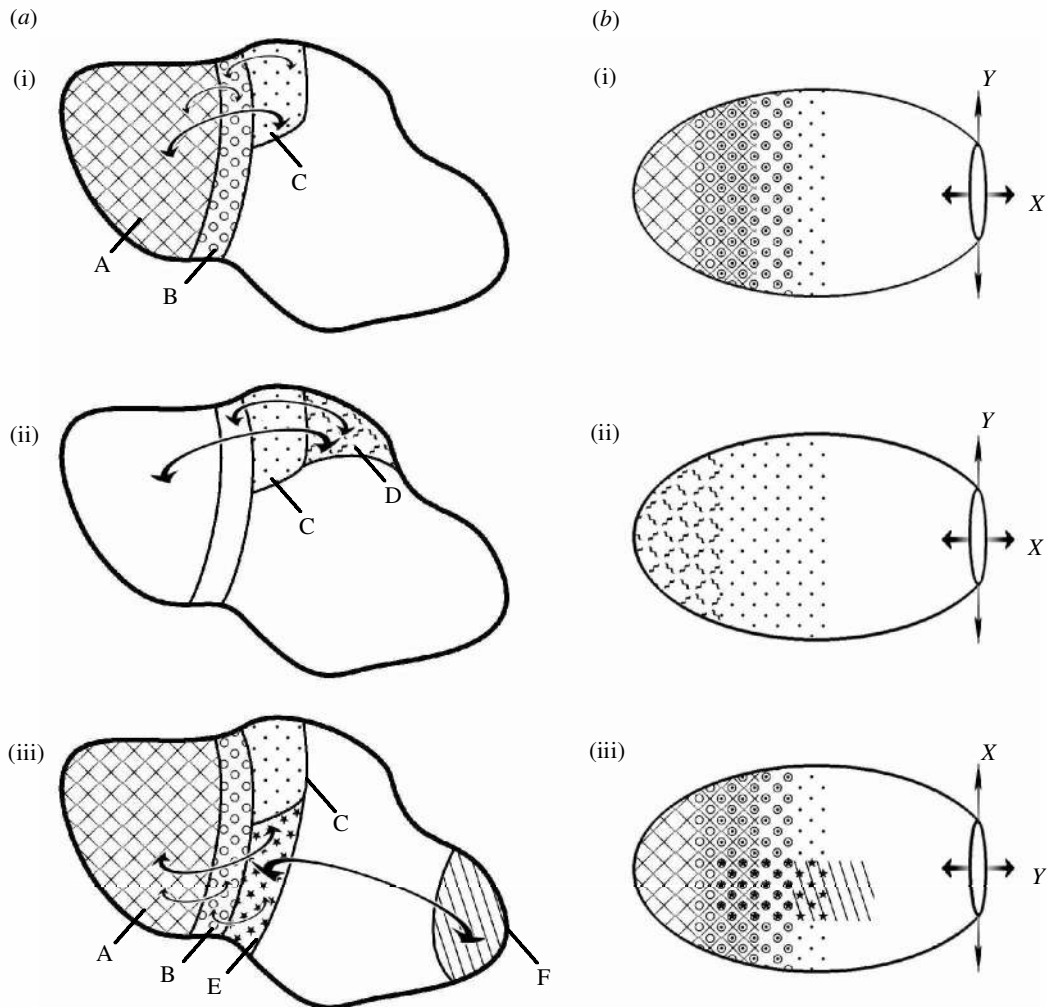


Figure 8. Schematic illustration of the replication principle, and its relationship to cortical topography in the pulvina. (a) A flattened sheet of cortex with areas A-F. The connectivity between areas is the same in all diagrams although, to avoid clutter, each interconnection is only shown once. (b) The pulvina is represented as a 3D ellipsoid, with arbitrary anatomical axes ( $X$  and  $Y$ ) defining the plane of a transverse section. The pulvina connection zone of any given cortical area is keyed by a common pattern of shading (cross-hatch, circles, dots, etc.). Each of the three parts shows a subset of connection zones, to highlight a specific feature of organization. (i) The serial cortical areas A-C are locally interconnected, and are represented by a smooth gradient of overlapping connectivity zones in the pulvina. Thus all direct cortico-cortical connections (i.e. A-B, B-C and A-C) can be 'replicated' by an indirect c-p-c pathway. If this pattern of organization were to obtain globally, a regular cortical topography must result. However, the global pattern is disrupted by various irregularities (shown in (ii) and (iii)). (ii) The neighbouring cortical areas C and D do not connect to each other, although both are connected to areas A and B. One way to replicate this system is for the pulvina connection zone of D to be dislocated from its lawful topographic location; here it has been extruded towards the opposite pole of the pulvina. (iii) Similarly, areas E and C are not connected with each other. Here, however, both areas adopt a topographically lawful pulvina zone, and the non-connection is replicated by a discontinuity in the third dimension. Note that the pulvina ellipse has been rotated through  $90^\circ$ , and the C and E connection zones are shown to be discontinuous (i.e. occupying discrete zones) in the  $X$ -axis. Finally, a distant area F is also shown to make a long-range connection with area E (but not with areas A, B or C); hence its connection zone overlaps discretely with zone E, but not zones A-C.

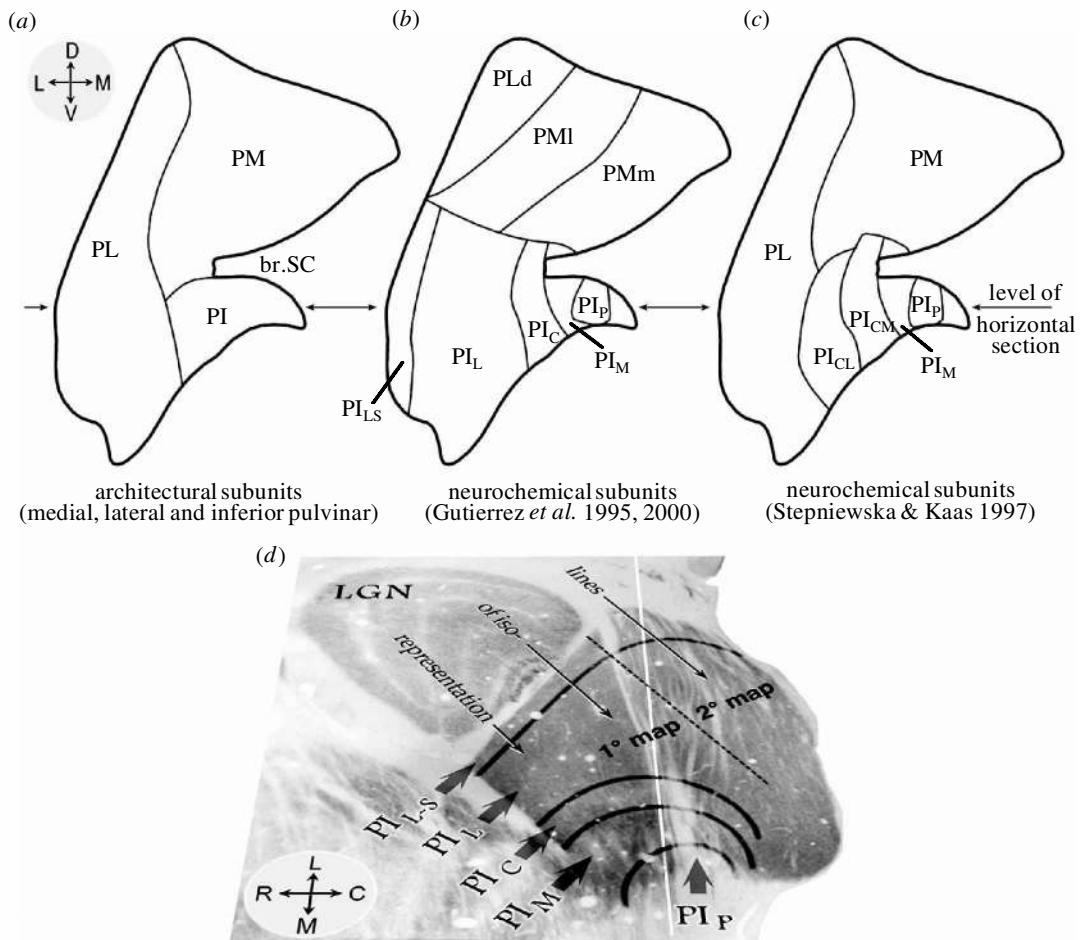


Figure 9. Correlation of connective domains and neurochemical zones. (a–c) The outline of the traditional pulvinar nuclei in coronal section (a), and two more recent neurochemical schemes of parcellation (b,c). Scheme (c) (Lin & Kaas 1979, 1980; Stepniewska & Kaas 1997) retains the traditional PL and PM (with minor modifications) while dividing PI into four subunits. Scheme (b) has an expanded PI (incorporating the ventral half of PL) divided into five subunits, and a dorsal pulvinar that is PM merged with the dorsal half of PL (Cusick *et al.* 1993; Gutierrez *et al.* 1995; Gray *et al.* 1999). The subunits PI<sub>C</sub> of scheme (b) and PI<sub>CM</sub> of scheme (c) correspond quite closely, whereas PI<sub>P</sub> and PI<sub>M</sub> of the two schemes are virtually identical. The lower diagram (d) shows the approximate configuration of the subunits of scheme (b) within a horizontal section, taken at the level of the arrows between the upper, coronal sections and shown in perspective view. The neurochemical subunits of the ventral pulvinar are arranged like concentric shells around the core zone, PI<sub>P</sub>. The white line through the horizontal section indicates, roughly, the position of the coronal sections within the horizontal plane; this line also provides a fair indication of the ‘neurochemical axis’ (i.e. an axis intersecting the shells perpendicularly). The lower diagram also gives an indication of visual topography, showing the course of lines of iso-representation and the border of the 1° and 2° maps. Abbreviations: br.SC, brachium of superior colliculus; PI, PL, PM, inferior, lateral and medial pulvinar nucleus; (b) PLd, dorsal division of lateral pulvinar; PMI and PMm, lateral and medial divisions of medial pulvinar; PI<sub>P</sub>, PI<sub>M</sub>, PI<sub>C</sub>, PI<sub>L</sub> and PI<sub>LS</sub>, posterior, medial, central, lateral and lateral-shell subunits of a revised and enlarged inferior pulvinar; (c) PI<sub>CL</sub> and PI<sub>CM</sub>, centrolateral and centromedial subunits of classical inferior pulvinar. ((a,b) Redrawn from Gutierrez *et al.* (1995, 2000) with permission from Wiley-Liss Inc; (c) Stepniewska & Kaas (1997), with permission from Cambridge University Press.)

and less well tuned for orientation, at least among layer 5 cells projecting to the superior colliculus (Finlay *et al.* 1976; Schiller *et al.* 1976).

- (ii) Even if the output from layer 5 cortico-thalamic neurons was as orientation selective as that from layer 4B, there would be no guarantee that orientation specificity is retained by the c-p-c circuitry, because precise terminal connections are needed to avoid convergence between differently tuned afferents; there is no sign of a fine-grained patchiness in cortico-pulvinar, or pulvino-cortical, terminations that is often characteristic of forward cortical projections.

- (iii) Orientation tuning is a documented property of pulvinar neurons, but the proportions of these cells and their tightness of tuning fall below cortical levels (Bender 1982; Petersen *et al.* 1985). It is an important point in the analogy with the retina-LGN-VI circuit that orientation selective cells in the cortex can synchronize their activity by interacting with non-oriented thalamic neurons (Sillito *et al.* 1994). In this view, therefore, the broader the stimulus specificity of a pulvinar neuron, the broader the range of its capability for feature binding.
- (iv) In a similar vein, pulvinar units may show unrelated specificities in different submodalities; the caudal

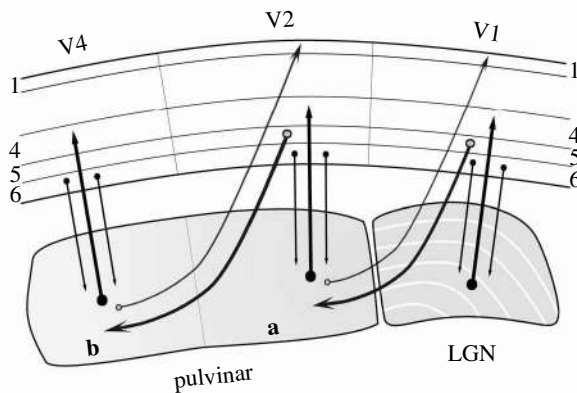


Figure 10. An integrated thalamo-cortical hierarchy? The diagram models the micro-circuitry predicted by the hypothesis that primary (driving) and non-primary cortical input to the pulvinar (putatively R- and E-type axonal terminations; Rockland (1996, 1998)) is coordinated with the well-known cortical hierarchy, as if the pulvinar, too, has an internal hierarchical order. Consideration of the known micro-circuitry between V1 and the thalamus helps to specify the model. Most geniculate afferents (i.e. magno- and parvo-, but not konio-cellular) terminate in V1 layer 4, with side branches in layer 6 (Hubel & Wiesel 1972; Blasdel & Lund 1983; Ding & Casagrande 1997), and layer 6 is also the source of the return projection to the LGN (Lund *et al.* 1975). Cortico-pulvinar output arises from layer 5B of V1 (Lund *et al.* 1975; Levitt *et al.* 1995) and pulvino-cortical feedback to V1 terminates in superficial layers, mainly layer 1 (Benevento & Rezak 1976; Ogren & Hendrickson 1977; Rezak & Benevento 1979). The anatomical distinction between forward/driving and backward/modulatory pulvino-cortical inputs is thus mooted to be differential termination in layer 4 and layer 1, respectively, similar to the pattern of cortico-cortical circuitry (Felleman & Van Essen 1991; Crick & Koch 1998). There is a further correlation with neurochemical characteristics of the pulvinar projection neurons, because cells positive for parvalbumin project to cortical layer 4, and cells positive for calbindin project mainly to cortical layer 1 (Jones 1998, 2001). The model shows that site 'a' in the pulvinar is driven by input from layer 5 of V1, and in turn sends driving input to area V2. It sends feedback to layer 1 of V1, and receives feedback (modulatory) influences from layer 6 of V2. Driving cortico-pulvinar output from V2 targets a higher-ranking site 'b', in the pulvinar (which might, for instance, be reciprocally linked with V4). Therefore, a site in the pulvinar such as **b** should connect to two distinct fields within the occipito-temporal cortical hierarchy. The low-ranking (relatively occipital) field should display pulvino-cortical terminals in layer 1, and cortico-pulvinar efferent cells in layer 5; the high-ranking (relatively temporal) field should display pulvino-cortical terminals in layer 3/4, and cortico-pulvinar efferent cells in layer 6. Given that real experiments involve imperfectly focal locations in pulvinar, possibly involving a range of rank, rather than a single rank, the prediction could tolerate some considerable overlap between these two cortical fields. However, even with this allowance, the observational data do not accord well with these predictions (see text for details).

pole of VP, for instance, has neurons jointly sensitive to movement in depth, to movement in the fronto-parallel plane, and to intensity of light flux, but lacking any predictable cross-modal relationship in these

responses (Benevento & Miller 1981). And the DP (in the neighbourhood of the PL/PM junction) has neurons combining pattern or colour selectivity with spatially selective peri-saccadic activity (Benevento & Port 1995).

Hence, the verdict here is that the innate rhythmicity of thalamic neurons enables the c-p-c link to facilitate long-range synchronization of cortical activity, but is less important in specifying the sensory tuning of that activity. This is in keeping with the generally diffuse nature of c-p-c circuitry at a local level: anatomically, it seems quite plausible that a pulvinar neuron mediating the interaction between V1 and V3 might, in a different sensory context, intermediate between (for example) V2 and V4. Because the effect of synchronization is to strengthen neural communication, there is also a clear parallel with theories of the thalamus providing a more secure, indirect pathway for long range cortical communication (Miller 1996, 2002). This view originates from the idea that local intrinsic connections from highly active layer 5 neurons may exert a 'priming' effect over communication between relatively inert layer 2/3 neurons, although the layer 5 neurons are not critical in defining the information content, which is carried by the specific network of superficial layer activity (Miller 2002). Cortico-thalamic output from layer 5 would then act to spread this priming effect over c-p-c circuitry to a wider cortical territory, beyond the boundaries of a single area (Miller 2002).

### (c) *Relationship to theories of attention*

Although the specific proposals differ, a role in visual attention has been a recurrent theme in hypotheses regarding pulvinar function (e.g. Chalupa *et al.* 1976; Crick 1984; LaBerge & Buchsbaum 1990; Robinson & Petersen 1992; Olshausen *et al.* 1993; Shipp 2000). Recent work finds that attentional modulation of activity is pervasive within the pulvinar, and as significant as any area of the cortex (Bender & Youakim 2001). The present model also has a natural extension to the question of attention. The logic of the above discussion supposes that any pulvinar element can act to facilitate large-scale synchronization across several distinct transcortical networks, each formed of specific modules/columns in several cortical areas and representing different object qualities. It is then but a short step towards supposing that incipient object networks compete with each other to recruit the same pulvinar circuits (when there are rival objects for attention in the field of view). If rival object networks tend to synchronize at different phases, it is necessary for one network to entrain a disproportionate share of thalamic elements to dominate, and maintain its long-term activity, corresponding to selective attention to that object. The broad and diffuse connectivity of the pulvinar would then be (one) anatomical analogue of the switchable, but limited capacity processing machinery that cognitive (Broadbent 1958; Neisser 1967), computational (Tsotsos 1990) and neural (Desimone & Duncan 1995; Duncan *et al.* 1997) accounts of attention all envisage.

Ultimately, the synchronized neural assembly is proposed to mediate the perceptual binding of different object features (von der Malsburg & Schneider 1986; Tononi *et al.* 1992; Eckhorn 1994; Singer & Gray 1995). If the



pulvinar is a key element of the assembly, damage to the pulvinar should have a noticeable effect on feature binding. There is already some preliminary evidence in favour of this prediction, documenting one patient's report of illusory conjunctions of colour and letter form (i.e. 'misbinding') in the visual hemifield contralateral to a pulvinar lesion (Ward *et al.* 2002).

#### (d) *Beyond the replication principle*

The functional diagnosis above assumes that the connectional domains operate similarly and in parallel, each in conjunction with semi-independent swathes of cortex. The similarity of cortical connectivity across VP1 and VP2 then becomes something of a puzzle, as it implies a corresponding duplication of function. There is no obvious hierarchical relationship between VP1 and VP2 (akin to cortical areas V1 and V2), since they are not reciprocally connected to each other (Trojanowski & Jacobson 1975). The only recorded difference is that VP1 receives a more widespread input from the superior colliculus (Harting *et al.* 1980; Benevento & Standage 1983; Stepniewska *et al.* 2000). Yet, the overriding rule of brain anatomy is that segregation of structure implies separation of function, so the search for the separate functions of VP1 and VP2 must go on.

## 8. SUMMARY

The organization of connections between the cortex and the pulvinar nucleus of the thalamus is surveyed for analogues of the parallel and serial elements characteristic of transcortical connections. Examination of the topography of connectivity reveals four connectional 'domains' that disrespect the traditional morphological subdivisions, while corresponding in part to thalamic chemoarchitecture. However, in ventral pulvinar there is a pair of domains (VP1 and VP2) with topologically inverted topographies conforming to mirror-image visual maps, which have no architectural correlate. There is a regular cortical topography within each domain, but it is sufficiently blurred to allow cortical areas to communicate indirectly via non-reciprocal cortico-pulvinar circuitry. Thus c-p-c circuits tend to mirror direct local cortical connections between areas (the 'replication principle'). This principle also applies to irregularities in the cortical topography that may 'replicate' the presence of longer-range cortico-cortical connections, or the absence of specific short-range connections. Possibly, the domain pairs VP1/VP2 and VP3/DP may be analogues of the parallel (dorsal and ventral) visual cortical pathways. The cortical topography of VP1 (and VP2) mimics the ventral pathway, a serial chain of areas culminating in inferotemporal cortex; however, the micro-circuitry of the connections bears no simple correspondence to the predictions of a hierarchical scheme for cortico-pulvinar interactions. Ultimately, the organization of the pulvinar's connectional domains must govern the operation of specific, resonant cortico-thalamo-cortical circuits. Although the indirect thalamic circuitry seems to replicate the direct cortical circuits, the discussion of its function centres on a role in coordinating, rather than duplicating, transcortical information processing.

This work was supported by a grant to Professor S. Zeki from the Wellcome Trust.

## REFERENCES

- Adams, M. M., Hof, P. R., Gattass, R., Webster, M. J. & Ungerleider, L. G. 2000 Visual cortical projections and chemoarchitecture of macaque monkey pulvinar. *J. Comp. Neurol.* **419**, 377–393.
- Adams, N. C., Lozsadi, D. A. & Guillery, R. W. 1997 Complexities in the thalamocortical and corticothalamic pathways. *Eur. J. Neurosci.* **9**, 204–209.
- Allman, J. M. & Kaas, J. H. 1974 The organization of the second visual area (V II) in the owl monkey: a second order transformation of the visual hemifield. *Brain Res.* **76**, 247–265.
- Allman, J. M., Kaas, J. H., Lane, R. H. & Miezin, F. M. 1972 A representation of the visual field in the inferior nucleus of the pulvinar in the owl monkey (*Aotus trivirgatus*). *Brain Res.* **40**, 291–302.
- Asanuma, A., Andersen, A. & Cowan, W. M. 1985 The thalamic relations of the caudal inferior parietal lobule and the lateral prefrontal cortex in monkeys: divergent cortical projections from cell clusters in the medial pulvinar nucleus. *J. Comp. Neurol.* **241**, 357–381.
- Baizer, J. S., Desimone, R. & Ungerleider, L. G. 1991 Organization of visual inputs to the inferior temporal and posterior parietal cortex in macaques. *J. Neurosci.* **11**, 168–190.
- Baizer, J. S., Desimone, R. & Ungerleider, L. G. 1993 Comparison of subcortical connections of inferior temporal and posterior parietal cortex in monkeys. *Vis. Neurosci.* **10**, 59–72.
- Baleydier, C. & Mauguier, F. 1987 Network organization of the connectivity between parietal area 7, posterior cingulate cortex and medial pulvinar nucleus: a double fluorescent tracer study in monkey. *Exp. Brain Res.* **66**, 385–393.
- Baleydier, C. & Morel, A. 1992 Segregated thalamocortical pathways to inferior parietal and inferotemporal cortex in macaque monkey. *Vis. Neurosci.* **8**, 391–405.
- Barbas, H., Haswell Henion, T. H. & Dermon, C. R. 1991 Diverse thalamic projections to the prefrontal cortex in the rhesus monkey. *J. Comp. Neurol.* **313**, 65–94.
- Beck, P. D. & Kaas, J. H. 1998 Thalamic connections of the dorsomedial visual area in primates. *J. Comp. Neurol.* **396**, 381–398.
- Bender, D. B. 1981 Retinotopic organization of macaque pulvinar. *J. Neurophysiol.* **46**, 672–693.
- Bender, D. B. 1982 Receptive field properties of neurons in the inferior pulvinar. *J. Neurophysiol.* **48**, 1–17.
- Bender, D. B. & Youakim, M. 2001 Effect of attentive fixation in macaque thalamus and cortex. *J. Neurophysiol.* **85**, 219–234.
- Benevento, L. A. & Davis, P. 1977 Topographical projections of the prestriate cortex to the pulvinar nuclei in the macaque monkey: an autoradiographic study. *Exp. Brain Res.* **30**, 405–424.
- Benevento, L. A. & Miller, J. 1981 Visual responses of single neurons in the caudal lateral pulvinar of the macaque monkey. *J. Neurosci.* **1**, 1268–1278.
- Benevento, L. A. & Port, J. D. 1995 Single neurons with both form/color differential responses and saccade-related responses in the nonretinotopic pulvinar of the behaving macaque monkey. *Vis. Neurosci.* **12**, 523–544.
- Benevento, L. A. & Rezak, M. 1976 The cortical projections of the inferior pulvinar and adjacent lateral pulvinar in the rhesus monkey (*Macaca mulatta*): an autoradiographic study. *Brain Res.* **108**, 1–24.
- Benevento, L. A. & Standage, G. P. 1983 The organization of projections of the retinorecipient and nonretinorecipient nuclei of the pretectal complex and layers of the superior colliculus to the lateral pulvinar and medial pulvinar in the macaque monkey. *J. Comp. Neurol.* **217**, 307–336.

- Billock, V. A. 1997 Very short-term visual memory via reverberation: a role for the cortico-thalamic excitatory circuit in temporal filling-in during blinks and saccades? *Vision Res.* **37**, 949–953.
- Blasdel, G. G. & Lund, J. S. 1983 Termination of afferent axons in macaque striate cortex. *J. Neurosci.* **3**, 1389–1413.
- Boussaoud, D., Desimone, R. & Ungerleider, L. G. 1991 Visual topography of area TEO in the macaque. *J. Comp. Neurol.* **306**, 554–575.
- Boussaoud, D., Desimone, R. & Ungerleider, R. 1992 Subcortical connections of visual areas MST and FST in macaques. *Vis. Neurosci.* **9**, 291–302.
- Broadbent, D. E. 1958 *Perception and communication*. London: Pergamon.
- Bruce, C., Desimone, R. & Gross, C. G. 1981 Visual properties of neurons in a polysensory area in superior temporal sulcus of the macaque. *J. Neurophysiol.* **46**, 369–384.
- Cavada, C., Company, T., Hernandez-Gonzalez, A. & Reinoso-Suarez, F. 1995 Acetylcholinesterase histochemistry in the macaque thalamus reveals territories selectively connected to frontal, parietal and temporal association cortices. *J. Chem. Neuroanat.* **8**, 245–257.
- Chalupa, L. M., Coyle, R. S. & Lindsley, D. B. 1976 Effect of pulvinar lesions on visual pattern discrimination in monkeys. *J. Neurophysiol.* **39**, 354–369.
- Crick, F. C. 1984 Function of the thalamic reticular complex: the searchlight hypothesis. *Proc. Natl Acad. Sci. USA* **81**, 4586–4590.
- Crick, F. & Koch, C. 1998 Constraints on cortical and thalamic projections: the no-strong-loops hypothesis. *Nature* **391**, 245–250.
- Cusick, C. G., Scriptor, J. L., Darensbourg, J. G. & Weber, J. T. 1993 Chemoarchitectonic subdivisions of the visual pulvinar in monkeys and their connections with the middle temporal and rostral dorsolateral visual areas, MT and DLr. *J. Comp. Neurol.* **336**, 1–30.
- Darian-Smith, C., Tan, A. & Edwards, S. 1999 Comparing thalamocortical and corticothalamic microstructure and spatial reciprocity in the macaque ventral posterolateral nucleus (VPLc) and medial pulvinar. *J. Comp. Neurol.* **410**, 211–234.
- Desimone, R. & Duncan, J. 1995 Neural mechanisms of selective visual attention. *A. Rev. Neurosci.* **18**, 193–222.
- Ding, Y. & Casagrande, V. A. 1997 The distribution and morphology of LGN K pathway axons within the layers and CO blobs of owl monkey V1. *Vis. Neurosci.* **14**, 691–704.
- Dow, B. M. 1974 Functional classes of cells and their laminar distribution in monkey visual cortex. *J. Neurophysiol.* **37**, 927–946.
- Duncan, J., Humphreys, G. & Ward, R. 1997 Competitive brain activity in visual attention. *Curr. Opin. Neurobiol.* **7**, 255–261.
- Eckhorn, R. 1994 Oscillatory and non-oscillatory synchronizations in the visual cortex and their possible roles in associations of visual features. *Prog. Brain Res.* **102**, 405–426.
- Engel, K., Fries, P. & Singer, W. 2001 Dynamic predictions: oscillations and synchrony in top-down processing. *Nature Rev. Neurosci.* **2**, 704–716.
- Felleman, D. J. & Van Essen, D. C. 1987 Receptive field properties of neurons in area V3 of macaque monkey extrastriate cortex. *J. Neurophysiol.* **57**, 889–920.
- Felleman, D. J. & Van Essen, D. C. 1991 Distributed hierarchical processing in the primate cerebral cortex. *Cereb. Cortex* **1**, 1–47.
- Felleman, D. J., Burkhalter, A. & Van Essen, D. C. 1997 Cortical connections of areas V3 and VP of macaque monkey extrastriate visual cortex. *J. Comp. Neurol.* **379**, 21–47.
- Finlay, B. L., Schiller, P. H. & Volman, S. F. 1976 Quantitative studies of single-cell properties in monkey striate cortex. IV. Corticotectal cells. *J. Neurophysiol.* **39**, 1352–1361.
- Gattass, R. & Gross, C. G. 1981 Visual topography of striate projection zone (MT) in posterior superior temporal sulcus of the macaque. *J. Neurophysiol.* **46**, 621–638.
- Gegenfurtner, K. R., Kiper, D. C. & Levitt, J. B. 1997 Functional properties of neurons in macaque area V3. *J. Neurophysiol.* **77**, 1906–1923.
- Gray, C. M. 1999 The temporal correlation hypothesis of visual feature integration: still alive and well. *Neuron* **24**, 31–47, 111–125.
- Gray, D., Gutierrez, C. & Cusick, C. G. 1999 Neurochemical organization of inferior pulvinar complex in squirrel monkeys and macaques revealed by acetylcholinesterase histochemistry, calbindin and Cat-301 immunostaining, and *Wisteria floribunda* agglutinin binding. *J. Comp. Neurol.* **409**, 452–468.
- Guillery, R. W. 1995 Anatomical evidence concerning the role of the thalamus in cortico-cortical communication: a brief review. *J. Anat.* **187**, 583–592.
- Gutierrez, C. & Cusick, C. 1997 Area V1 in macaque monkeys projects to multiple histochemically defined subdivisions of the inferior pulvinar complex. *Brain Res.* **765**, 349–356.
- Gutierrez, C., Yaun, A. & Cusick, C. 1995 Neurochemical subdivisions of the inferior pulvinar in macaque monkeys. *J. Comp. Neurol.* **363**, 545–562.
- Gutierrez, C., Cola, M. G., Seltzer, B. & Cusick, C. 2000 Neurochemical and connectional organization of the dorsal pulvinar complex in monkeys. *J. Comp. Neurol.* **419**, 61–86.
- Hackett, T. A., Stepniewska, I. & Kaas, J. H. 1998 Thalamo-cortical connections of the parabelt auditory cortex in macaque monkeys. *J. Comp. Neurol.* **400**, 271–286.
- Hardy, S. G. P. & Lynch, J. C. 1992 The spatial distribution of pulvinar neurons that project to two subregions of the inferior parietal lobule in the macaque. *Cereb. Cortex* **2**, 217–230.
- Harting, J. K., Huerta, M. F., Frankfurter, A. J., Strominger, N. L. & Royce, G. J. 1980 Ascending pathways from the monkey superior colliculus: an autoradiographic study. *J. Comp. Neurol.* **192**, 853–882.
- Hikosaka, K., Iwai, E., Saito, H. & Tanaka, K. 1988 Polysensory properties of neurons in the anterior bank of the caudal superior temporal sulcus of the macaque monkey. *J. Neurophysiol.* **60**, 1615–1637.
- Hilgetag, C. C., O'Neill, M. A. & Young, M. P. 1996 Indeterminate organization of the visual system. *Science* **271**, 776–777.
- Hilgetag, C. C., O'Neill, M. A. & Young, M. P. 2000 Hierarchical organization of macaque and cat cortical sensory systems explored with a novel network processor. *Phil. Trans. R. Soc. Lond. B* **355**, 71–89. (DOI 10.1098/rstb.2000.0550.)
- Hohl-Abraham, J. C. & Creutzfeldt, O. D. 1991 Topographical mapping of the thalamocortical projections in rodents and comparisons with that in primates. *Exp. Brain Res.* **87**, 283–294.
- Hubel, D. H. & Livingstone, M. S. 1990 Color and contrast sensitivity in the lateral geniculate body and primary visual cortex of the macaque monkey. *J. Neurosci.* **10**, 2223–2237.
- Hubel, D. H. & Wiesel, T. N. 1972 Laminar and columnar distribution of geniculate-cortical fibers in the macaque monkey. *J. Comp. Neurol.* **146**, 421–450.
- Itaya, S. K. & Van Hoesen, G. W. 1983 Retinal projections to the inferior and medial pulvinar in the Old-World monkey. *Brain Res.* **269**, 223–230.
- Iwai, E. & Yukie, M. 1987 Amygdalofugal and amygdalopetal connections with modality-specific visual cortical areas in macaques (*Macaca fuscata*, *M. mulatta*, and *M. fascicularis*). *J. Comp. Neurol.* **261**, 362–387.
- Jones, E. G. 1998 Viewpoint: the core and matrix of thalamic organization. *Neuroscience* **85**, 331–345.

- Jones, E. G. 2001 The thalamic matrix and thalamocortical synchrony. *Trends Neurosci.* **24**, 595–601.
- Kennedy, H. & Bullier, J. 1985 A double-labelling investigation of the afferent connectivity to cortical areas V1 and V2 of the macaque monkey. *J. Neurosci.* **5**, 2815–2830.
- LaBerge, D. & Buchsbaum, M. S. 1990 Positron emission tomography of pulvinar activity during an attention task. *J. Neurosci.* **10**, 613–619.
- Levitt, J. B., Yoshioka, T. & Lund, J. S. 1995 Connections between the pulvinar complex and cytochrome oxidase-defined compartments in visual area V2 of macaque monkey. *Exp. Brain Res.* **104**, 419–430.
- Lin, C. S. & Kaas, J. H. 1979 The inferior pulvinar complex in owl monkeys: architectonic subdivisions and patterns of input from the superior colliculus and subdivisions of visual cortex. *J. Comp. Neurol.* **187**, 655–678.
- Lin, C. S. & Kaas, J. H. 1980 Projections from the medial nucleus of the inferior pulvinar complex to the middle temporal area of the visual cortex. *Neuroscience* **5**, 2219–2228.
- Llinas, R., Ribary, U., Contreras, D. & Pedroarena, C. 1998 The neuronal basis for consciousness. *Phil. Trans. R. Soc. Lond. B* **353**, 1841–1849. (DOI 10.1098/rstb.1998.0336.)
- Lund, J. S., Lund, R. D., Hendrickson, A. E., Bunt, A. M. & Fuchs, A. F. 1975 The origin of efferent pathways from the primary visual cortex, (area 17), of the macaque monkey as shown by retrograde transport of horseradish peroxidase. *J. Comp. Neurol.* **164**, 287–304.
- Lysakowski, A., Standage, G. P. & Benevento, L. A. 1988 An investigation of collateral projections of the dorsal lateral geniculate nucleus and other subcortical structures to cortical areas V1 and V4 in the macaque monkey: a double label retrograde tracer study. *Exp. Brain Res.* **69**, 651–661.
- Miller, R. 1996 Cortico-thalamic interplay and the security of operation of neural assemblies and temporal chains in the cerebral cortex. *Biol. Cybernet.* **75**, 263–275.
- Miller, R. 2002 Wheels within wheels: circuits for integration of neural assemblies on small and large scales. In *Cortical areas: unity and diversity* (ed. A. Schüz & R. Miller), pp. 423–458. London: Taylor & Francis.
- Morel, A. & Bullier, J. 1990 Anatomical segregation of two cortical visual pathways. *Vis. Neurosci.* **4**, 555–578.
- Mumford, D. 1991 On the computational architecture of the neocortex. I. The role of the thalamo-cortical loop. *Biol. Cybernet.* **65**, 135–145.
- Nakagawa, S. & Tanaka, S. 1984 Retinal projections to the pulvinar nucleus of the macaque monkey: a re-investigation using autoradiography. *Exp. Brain Res.* **57**, 151–157.
- Neisser, U. 1967 *Cognitive psychology*. New York: Appleton.
- O'Brien, B. J., Abel, P. L. & Olavarria, J. F. 2001 The retinal input to calbindin-D28k-defined subdivisions in macaque inferior pulvinar. *Neurosci. Lett.* **312**, 145–148.
- Ogren, M. P. & Hendrickson, A. E. 1977 The distribution of pulvinar terminals in visual areas 17 and 18 of the monkey. *Brain Res.* **137**, 343–350.
- Ogren, M. P. & Hendrickson, A. E. 1979a The morphology and distribution of striate cortex terminals in the inferior and lateral subdivisions of the *Macaca* monkey pulvinar. *J. Comp. Neurol.* **188**, 179–200.
- Ogren, M. P. & Hendrickson, A. E. 1979b The structural organization of the inferior and lateral subdivisions of the *Macaca* monkey pulvinar. *J. Comp. Neurol.* **188**, 147–178.
- Olshausen, B. A., Anderson, C. H. & Van Essen, D. C. 1993 A neurobiological model of visual attention and invariant pattern recognition based on dynamic routing of information. *J. Neurosci.* **13**, 4700–4719.
- Orban, G. A., Kennedy, H. & Bullier, J. 1986 Velocity and direction selectivity of neurons in areas V1 and V2 of the monkey: influence of eccentricity. *J. Neurophysiol.* **56**, 462–480.
- Pandya, D. N., Rosene, D. L. & Doolittle, A. M. 1994 Corticothalamic connections of auditory-related areas of the temporal lobe in the rhesus monkey. *J. Comp. Neurol.* **345**, 447–471.
- Petersen, S. E., Robinson, D. L. & Keys, W. 1985 Pulvinar nuclei of the behaving monkey: visual responses and their modulation. *J. Neurophysiol.* **54**, 867–886.
- Rezak, M. & Benevento, L. A. 1979 A comparison of the projections of the dorsal lateral geniculate nucleus, the inferior pulvinar and adjacent lateral pulvinar to primary visual cortex (area 17) in the macaque monkey. *Brain Res.* **167**, 19–40.
- Robinson, D. L. & Petersen, S. E. 1992 The pulvinar and visual salience. *Trends Neurosci.* **15**, 127–132.
- Rockland, K. 1996 Two types of cortico-pulvinar terminations: round (type 2) and elongate (type 1). *J. Comp. Neurol.* **368**, 57–87.
- Rockland, K. S. 1998 Convergence and branching patterns of round, type 2 cortico-pulvinar axons. *J. Comp. Neurol.* **390**, 515–536.
- Rockland, K. S., Andresen, J., Cowie, R. J. & Robinson, D. L. 1999 Single axon analysis of pulvinocortical connections to several visual areas in the macaque. *J. Comp. Neurol.* **406**, 221–250.
- Romanski, L. M., Giguere, M., Bates, J. F. & Goldman-Rakic, P. S. 1997 Topographic organization of medial pulvinar connections with the prefrontal cortex in the rhesus monkey. *J. Comp. Neurol.* **379**, 313–332.
- Schiller, P. H., Finlay, B. L. & Volman, S. F. 1976 Quantitative studies of single-cell properties in monkey striate cortex. I. Spatio-temporal organization of receptive fields. *J. Neurophysiol.* **39**, 1288–1319.
- Schmahmann, J. D. & Pandya, D. N. 1990 Anatomical investigation of projections from thalamus to posterior parietal cortex in the rhesus monkey: a WGA-HRP and fluorescent tracer study. *J. Comp. Neurol.* **237**, 408–426.
- Selemon, L. D. & Goldman-Rakic, P. S. 1988 Common cortical and subcortical targets of the dorsolateral prefrontal and posterior parietal cortices in the rhesus monkey: evidence for a distributed neural network subserving spatially guided behaviour. *J. Neurosci.* **8**, 4049–4068.
- Sherman, S. M. & Guillery, R. W. 1996 Functional organization of thalamocortical relays. *J. Neurophysiol.* **76**, 1367–1395.
- Sherman, S. M. & Guillery, R. W. 1998 On the actions that one nerve cell can have on another: distinguishing 'drivers' from 'modulators'. *Proc. Natl Acad. Sci. USA* **95**, 7121–7126.
- Shipp, S. 2000 A new anatomical basis for 'spotlight' metaphors of attention. *Eur. J. Neurosci.* **12**(Suppl. 11), 196.
- Shipp, S. 2001 Corticopulvinar connections of areas V5, V4 and V3 in the macaque monkey: a dual model of retinal and cortical topographies. *J. Comp. Neurol.* **439**, 469–490.
- Shipp, S. 2002 Fundamentals of association cortex. In *Cortical areas: unity and diversity* (ed. A. Schüz & R. Miller), pp. 387–422. London: Taylor & Francis.
- Shipp, S. & Zeki, S. 1995 Segregation and convergence of specialised pathways in macaque monkey visual cortex. *J. Anat.* **187**, 547–562.
- Shipp, S., Blanton, M. & Zeki, S. 1998 A visuo-somatomotor pathway through superior parietal cortex in the macaque monkey: cortical connections of areas V6 and V6A. *Eur. J. Neurosci.* **10**, 3171–3193.
- Sillito, A. M., Jones, H. E., Gerstein, G. L. & West, D. C. 1994 Feature-linked synchronization of thalamic relay cell firing induced by feedback from the visual cortex. *Nature* **369**, 479–482.
- Singer, W. 1999 Neuronal synchrony: a versatile code for the definition of relations? *Neuron* **24**, 49–65, 111–125.

- Singer, W. & Gray, C. M. 1995 Visual feature integration and the temporal correlation hypothesis. *A. Rev. Neurosci.* **18**, 555–586.
- Soares, J. G., Gattass, R., Souza, A. P., Rosa, M. G., Fiorani, M. & Brandao, B. L. 2001 Connectional and neurochemical subdivisions of the pulvinar in *Cebus* monkeys. *Vis. Neurosci.* **18**, 25–41.
- Standage, G. P. & Benevento, L. A. 1983 The organization of connections between the pulvinar and visual area MT in the macaque monkey. *Brain Res.* **262**, 288–294.
- Stanton, G. B., Goldberg, M. E. & Bruce, C. J. 1988 Frontal eye field efferents in the macaque monkey: I. Subcortical pathways and topography of striatal and thalamic terminal fields. *J. Comp. Neurol.* **271**, 473–492.
- Stepniewska, I. & Kaas, J. H. 1997 Architectonic subdivisions of the inferior pulvinar in New World and Old World monkeys. *Vis. Neurosci.* **14**, 1043–1060.
- Stepniewska, I., Qi, H. & Kaas, J. H. 1999 Do superior colliculus projection zones in the inferior pulvinar project to MT in primates? *Eur. J. Neurosci.* **11**, 469–480.
- Stepniewska, I., Qi, H. & Kaas, J. H. 2000 Projections of the superior colliculus to subdivisions of the inferior pulvinar in New World and Old World monkeys. *Vis. Neurosci.* **17**, 529–549.
- Steriade, M. 1997 Synchronized activities of coupled oscillators in the cerebral cortex and thalamus at different levels of vigilance. *Cereb. Cortex* **7**, 583–604.
- Steriade, M. 2000 Corticothalamic resonance, states of vigilance and mentation. *Neuroscience* **101**, 243–276.
- Steriade, M., Amzica, F. & Contreras, D. 1996a Synchronization of fast (30–40 Hz) spontaneous cortical rhythms during brain activation. *J. Neurosci.* **16**, 392–417.
- Steriade, M., Contreras, D., Amzica, F. & Timofeev, I. 1996b Synchronization of fast (30–40 Hz) spontaneous oscillations in intrathalamic and thalamocortical networks. *J. Neurosci.* **16**, 2788–2808.
- Tononi, G., Sporns, O. & Edelman, G. M. 1992 Re-entry and the problem of integrating multiple cortical areas: simulation of dynamic integration in the visual system. *Cereb. Cortex* **2**, 310–335.
- Trojanowski, J. Q. & Jacobson, S. 1975 Peroxidase labeled subcortical afferents to pulvinar in rhesus monkey. *Brain Res.* **97**, 144–150.
- Tsotsos, J. K. 1990 Analyzing vision at the complexity level. *Behav. Brain Sci.* **13**, 423–469.
- Ungerleider, L. G., Galkin, T. W. & Mishkin, M. 1983 Visuo-topographic organization of projections from striate cortex to inferior and lateral pulvinar in rhesus monkey. *J. Comp. Neurol.* **217**, 137–157.
- Ungerleider, L. G., Desimone, R., Galkin, T. W. & Mishkin, M. 1984 Subcortical projections of area MT in the macaque. *J. Comp. Neurol.* **222**, 368–386.
- Van Essen, D. C. & Drury, H. A. 1997 Structural and functional analyses of human cerebral cortex using a surface based atlas. *J. Neurosci.* **17**, 7079–7102.
- von der Malsburg, C. & Schneider, W. 1986 A neural cocktail-party processor. *Biol. Cybern.* **54**, 29–40.
- Ward, R., Danziger, S., Owen, V. & Rafal, R. 2002 Deficits in spatial coding and feature binding following damage to spatiotopic maps in the human pulvinar. *Nature Neurosci.* **5**, 99–100.
- Webster, M. J., Bachevalier, J. & Ungerleider, L. G. 1993 Subcortical connections of inferior temporal areas TE and TEO in macaque monkeys. *J. Comp. Neurol.* **335**, 73–91.
- Wong-Riley, M. T. T. 1972 Neuronal and synaptic organization of the normal dorsal lateral geniculate nucleus of the squirrel monkey, *Saimiri sciureus*. *J. Comp. Neurol.* **144**, 25–59.
- Yeterian, E. H. & Pandya, D. N. 1985 Corticothalamic connections of the posterior parietal cortex in the rhesus monkey. *J. Comp. Neurol.* **237**, 408–426.
- Yeterian, E. H. & Pandya, D. N. 1989 Thalamic connections of the cortex of the superior temporal sulcus in the rhesus monkey. *J. Comp. Neurol.* **282**, 80–97.
- Yeterian, E. H. & Pandya, D. N. 1991 Corticothalamic connections of the superior temporal sulcus in rhesus monkeys. *Exp. Brain Res.* **83**, 268–284.
- Yeterian, E. H. & Pandya, D. N. 1997 Corticothalamic connections of extrastriate visual areas in rhesus monkeys. *J. Comp. Neurol.* **378**, 562–585.
- Young, M. P. 1992 Objective analysis of the topological organization of the primate visual system. *Nature* **358**, 152–154.
- Zeki, S. M. 1978 Uniformity and diversity of structure and function in rhesus monkey prestriate visual cortex. *J. Physiol. Lond.* **277**, 273–290.