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Abstract

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PARALLEL AND SERIAL PROCESSING OF VISUAL INFORMATION IN THE BRAIN: A REVIEW

A Thesis Presented to Pacific University College of Optometry For the Degree Master of Science in Clinical Optometry

by

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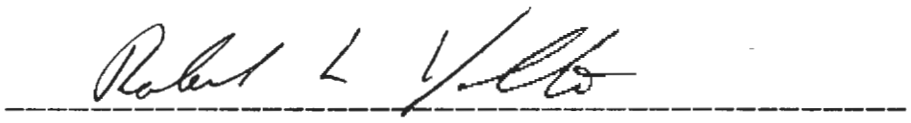

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ABSTRACT

Following the transduction of light by the photoreceptors in the retina, information about stimulus color and fine detail is separated from information about gross form and movement. Information regarding these stimulus characteristics is then carried via parallel pathways through the magno and parvo cellular layers of the geniculate to the cortex where it is analyzed in separate areas. This article reviews the parallel and serial analysis of visual information in the brain, and provides clinical examples illustrating failures in the analysis process.

KEY WORDS

Vision, visual system, information processing, retina, cortex, lateral geniculate nucleus, parallel processing, serial processing, M pathway, P pathway, magnocellular, parvocellular, motion, form, color, glaucoma, Alzheimer's disease, dyslexia, amblyopia, agnosia, transient, phasic, X, Y.

Vision is the sense that connects humans to the external world of light, form, and color. The concept of vision has undergone great changes from the early Greek theories of emanation through the eyes, to our present-day understanding of how visual information is processed in the brain to produce a perception. According to Polyak,[1] the early Greeks believed that substances emanating from the eyes reached out to objects and sensed them in a manner similar to palpation. About 100 AD, Galen described the optic nerve as a hollow tube that conveyed a "visual spirit" from the brain to the retina and then on to the lens which was the "principle receptor organ." The visual spirit then conveyed the information gathered by the lens back to the brain via the retina. This idea of vision prevailed, more or less intact, until the early half of the 17th century when Kepler and Descartes advanced the theory that light rays from each point on an object give rise to a point image on the retina.

Since the time of Kepler and Descartes, discoveries in optics, anatomy, and physiology have contributed greatly to the understanding of visual information processing. Within the last four decades, it has become clear that there are several parallel but interconnected pathways that carry visual information in the brain. Along these parallel pathways, information is processed and analyzed serially as it passes through different nuclei and cortical areas. At the end of the parallel visual pathways, information is recombined to create a unified perception, but the mechanisms for creating this perception are not yet well understood. At present, most of the research in this area is directed toward developing a

better understanding of the pathways themselves and their functions.

Early in evolution, the visual system developed a single pathway that conveyed information serially from the retina to an area called the optic tectum. In the tectum (which is analogous to the superior colliculus of mammals), sensory inputs elicited motor activity designed to facilitate capture of prey or avoidance of predators. This reflexive system is still present in humans and is designed primarily to direct the foveas toward peripheral visual, auditory, or tactile stimuli.

As evolution progressed and the cortex developed, new pathways were added to the older subcortical pathway. These new pathways conveyed information from the retina via the lateral geniculate to the visual cortex. At least two relatively separate cortical pathways evolved, perhaps at different times, which can be identified on the basis of response characteristics of the cells within them and the information they carry.

When discussing parallel processing in the visual system, care must be taken to specify which set of parallel pathways is being considered. Depending on the context, the term "parallel pathways" can refer to the subcortical (colliculus) and cortical pathways which in the older literature are sometimes called the ambient and focal pathways, respectively.[2-4] Alternatively, the term "parallel pathways" can refer to the two relatively separate channels that carry form and motion information to the cortex. In this article, the term will be used exclusively in reference to the pathways carrying information to the cortex.

PARALLEL PROCESSING IN THE CAT VISUAL SYSTEM

Extensive research on the visual system of cats in the late sixties and early seventies led to the original concept of parallel processing in the retino-geniculo-striate system. Three major cell types were identified in the cat and designated as the X, Y, and W types. Following the definition of these cells, it was theorized that the X and Y type cells carried different kinds of information along parallel pathways to the cortex.[5-13] Based on their response characteristics, the X cells were found to convey information on spatial form and pattern, whereas the Y cells convey information on temporal and spatial motion.[13,14] Along these pathways, visual information is carried serially from the retina to the lateral geniculate nucleus (LGN), and then on to various areas of the cortex.[15]

RETINA

Parallel visual pathways originate in the retina. In 1966 Brown and Major found two groups of retinal ganglion cells that differed on the basis of their dendritic field sizes.[16] Subsequently Leicester and Brown identified three major cell types which came to be known as the alpha, beta, and gamma cells.[17,18] At about the same time, Enroth-Cugell and Robson described two groups of cat ganglion cells with different physiological responses which they called X and Y cells.[19] Later a third class of retinal ganglion cells, called W cells was also identified.[20] The terms alpha, beta, and gamma are no longer in common use to describe ganglion cells; they have been replaced by the X, Y, and W nomenclature which probably describe the same populations of cells as alpha, beta, and gamma.[18]

RESPONSE CHARACTERISTICS OF X, Y AND W CELLS

The X cells constitute about 50% of the total retinal ganglion cell population, the Y cells account for about 20-30%, and the W cells account for the other 20-30%.[10,21] Much more information is available describing the X and Y cells than the somewhat more complicated W cells.

Both X and Y cells have concentric, circular receptive fields, the X cells have fields that are smaller than those of the Y cells by about a factor of two.[22,23] The receptive field size of X cells is typically about 1 degree, whereas the field of a Y cell can be even greater than 4 degrees.[24]

The Y cell axons are also bigger than the X cell axons and conduct neural impulses faster. Typical conduction rates for Y cell axons range between 35-45 m/sec, whereas X cell axons conduct at about 20-25 m/sec.[25] Within their receptive fields, the X cells exhibit linear spatial summation characteristics, as opposed to the nonlinear characteristics displayed by Y cells.[19,26]

INFORMATION CARRIED BY X AND Y CELLS

When a cat is presented with a light stimulus, the X and Y cells respond quite differently. The X cells give a prolonged or sustained response throughout the duration of stimulus presentation, and the response may even continue for a short period after the stimulus ends. For this reason the X cells are sometimes called tonic cells. Y cells typically give a brief transient response to stimulus onset and/or offset and therefore are called phasic cells.[27] Because of these response characteristics, the Y cells are better suited than the X cells for conveying information about rapidly moving or

flickering stimuli. Conversely, the smaller receptive fields of the X cells make them better suited for conveying information about fine spatial detail. X cells respond well to spatial frequencies in the range of 5-9 cpd, as compared to the 2-3 cpd maximum response range for Y cells.[22,23] In general, the X cells respond well to high spatial and low temporal frequencies, and the Y cells are relatively more sensitive to low spatial and high temporal frequencies.

DISTRIBUTION AND PROJECTION OF X AND Y CELLS

In the cat retina, X cells are distributed across the entire retina with their density peaking sharply within the area centralis. The Y cells are also distributed across the entire retina, but their density peaks just outside the area centralis. X cells project their axons mainly to the LGN, whereas the Y cells project equally to both the LGN and the superior colliculus.[22,25,28,29]

LATERAL GENICULATE NUCLEUS

Based on autoradiographic studies, the laminated portion of the cat lateral geniculate nucleus can be divided into six major subdivisions which are designated as A, A1, C, C1, C2 and C3.[30] A, C, and C2 receive their inputs predominately from the contra-lateral eye, and layers A1, and C1 receive predominately ipsi-lateral inputs.[30] Of the LGN layers, A and A1 have been studied in most detail with each having been found to contain a mixture of cells that receive their inputs from the X, Y and W type ganglion cells. Like ganglion cells, cat LGN cells are also designated as X, Y, and W types on the basis of the their response patterns and the types of ganglion cells that project to them.

In the cat LGN, X and Y pathways are not well segregated anatomically. Both lamina A and A1 contain a mixture of X and Y cells (40% X cells, 33% Y cells, and 25% interneurons) with the relative proportion of Y cells increasing mediolaterally in these laminae.[31] Layer C also contains a small proportion of X and Y cells, but most of the input to this layer comes from W type ganglion cells.[10,21]

The Y cells in the LGN are larger (493 um^2 average area) than the X cells (219 um^2 average area),[32] and have larger receptive fields (1.3-3 degrees) than the X cells (0.7-1.3 degrees).[33]

RESPONSE CHARACTERISTICS OF X AND Y TYPE LGN CELLS

Y cells in the LGN receive fast-conducting afferents from Y type retinal ganglion cells and send information to the visual cortex via large, fast conducting axons. Conversely, the LGN X cells receive slow-conducting afferents from X type retinal ganglion cells and send their information via slow conducting axons to the cortex.[5]

Like their retinal counterparts, the X cells respond well to higher spatial frequencies in the range of 5-8 cpd,[34,35] whereas the Y-cells respond best to lower frequencies of about 2 cpd.[5,34] With respect to moving stimuli, the Y cells respond well at temporal frequencies of 5-11 degrees/sec as compared to 1- 2 degrees/sec for X-cells.[5,34]

In the cat LGN, the information carried within the X and Y cell pathways is processed to some degree,[36] but the exact nature of this processing is not yet totally clear. Cells in the two pathways seem to be capable of exerting an inhibitory effect on one another,[5,37] and cortical feedback loops affect the cells in the two

pathways in yet to be understood ways. It is clear, however, that at the level of the LGN in cat, visual information is being carried by two relatively independent and parallel pathways.

VISUAL CORTEX

In the visual cortex of cat, the X and Y pathways remain relatively separate. From the LGN, the projections of the X cells go mainly to area 17, whereas projections from the Y cells go to both areas 17 and 18.[6-9,38] Within area 17, the projections of the X and Y cells remain separate with the X cells projecting to the lower half and below layer IV and the Y cells projecting to the upper half and above.[39,40,41] The cortical cells receiving X pathway inputs show a strong response selectivity to vertically or horizontally oriented stimuli, whereas the cells in the Y pathway are very weakly selective to stimulus orientation.[42]

Beyond the visual cortex in cat, X and Y visual information flow to the suprasylvian cortex for further processing.[43,44] This area receives direct input from the LGN as well as cortical input[45,46], and contains binocular cells with very large receptive fields.[43,47,48] Receptive fields in this area are selectively tuned for stimulus motion[47,48] and orientation, but it is unclear how the X and Y pathways converge to create the response characteristics of the suprasylvian cells.

SUMMARY OF PROCESSING IN CAT

As visual information leaves the retina, it is encoded by three major ganglion cell types: X, Y, and W. The W cells send a large proportion of their axons to the superior colliculus, whereas the X and Y cells mainly carry information to the cortex via the LGN.

Functionally, the X and Y pathways carry quite different kinds of information; the cells in the X pathway are specialized for detail vision and the Y pathway cells are specialized for motion detection. It is unclear why the visual system evolved these two pathways to carry information from retina to cortex. It is possible that they evolved at different times, with the movement sensitive Y cell pathway evolving first, but there is no clear evidence to support the sequential evolution theory.

PARALLEL PROCESSING IN THE PRIMATE VISUAL SYSTEM

If the cat visual system uses parallel pathways to carry visual information through sequential processing areas of the brain, it is reasonable to expect a similar design in the visual systems of primates. Indeed, primates have been found to have parallel pathways which have been designated the M and P pathways based on the fact that they pass through the magno, and parvocellular layers in the LGN.

Just as in cat, the visual system in primates, begins with separate information channels in the retina, continues with information carried via separate pathways serially through the LGN and primary visual cortex, and then, perhaps unlike the cat, terminates by distributing stimulus feature information to a large number of separate cortical areas for analysis.

RETINA

In the retina, two anatomically distinct populations of ganglion cells have been identified.[49-51] These populations are commonly referred to as the P and the M type retinal ganglion

cells[52,53] on the basis of the LGN parvo and magnocellular layers to which they project.[54] The P cells have also been called midget,[1] type B,[50] and P-beta[49] ganglion cells; and the M cells have been called parasol,[1] type A,[50] and P-alpha[49] cells. Currently, the names P an M seem to be the most popular, however.

Many researchers regard the primate P and the M cells to be the counterparts of the X and Y cells in cat,[49-51,54] but there are some significant differences between the primate and cat cells. A third class of retinal ganglion cell, with morphological characteristics similar to cat W cells have also been identified in primates,[50] but these cells will not be considered in this review.

RETINAL DISTRIBUTION

The M and P cells constitute approximately 10% and 80% of the total retinal ganglion cell population, respectively.[51,54] It is now believed that the density of both the M and P cells peak in the fovea,[51,55] but early reports suggested that the proportion of P to M cells was higher in the fovea with M cells being relatively rare.[55,56] A more recent report suggests that the 1 to 8 ratio of M to P cells holds across most of the retina including the foveal region.[54] The only area on the retina where the ratio does not hold is the peripheral nasal region where the M-cells constitute about 20% of the ganglion cells population.[54] This increase in density is consistent with speculation that the ability of the M cells to detect rapid peripheral movement would have survival and evolutionary value.

MORPHOLOGICAL CHARACTERISTICS

Physical sizes of the cell bodies, neuronal axons, and dendritic fields increase with retinal eccentricity for both M and P cells, but the M type ganglion cells are typically larger the P cells at all retinal eccentricities.[49-51] It is not correct to make the general statement that M cells are "big cells" and P cells are "small cells," because a peripheral P cell could be larger than a more centrally located M cell. It is reasonable to state, however, that for a given retinal eccentricity, M cells are bigger than P cells.

RECEPTIVE FIELDS

The receptive fields of both the P and M cells are concentric, and organized in a center-surround fashion.[56,57] A very high proportion of the P cells show chromatic opponent responses, but a few show no evidence of color coding. Conversely, the M cells produce almost exclusively broad-band, non-chromatic opponent responses.[55,58] The broad-band cells generally have larger center sizes than the color opponent cells, with their receptive field sizes increasing considerably with retinal eccentricity.[56] It is usually assumed that the M cell pathway carries luminance information, and the P cell pathway carries the information required for color vision.[59,60]

RESPONSE CHARACTERISTICS

In general, the primate P cells, like the cat X cells, give a sustained response to visual stimuli, and the M cells, similar to the Y-cells, give a phasic or transient response.[55,61] The M cells respond to variations in contrast, and are very sensitive to flickering stimuli.[62] Because of their broad-band response

characteristics, the M cells are especially sensitive to achromatic luminance flicker, and respond best to contrast changes at temporal frequencies of around 10 Hz.[63] The high temporal frequency sensitivity of the M cells and the relatively reliable responses of these cells to temporal stimuli suggests that they are well suited for the detection of motion.[64]

Unlike the M cells, P cells respond strongly to chromatic flicker.[63] Single unit measurements of P cell chromatic flicker responses demonstrate that P cells can detect flicker at frequency modulations of 10 Hz or more, but the human sensitivity for the detection of chromatic flicker falls steeply for frequencies above 2 Hz. It has been speculated that even though P ganglion cells can detect rapid chromatic flicker, the high frequency signals in the chromatic pathway are not available for detection at higher centers on the P pathway.[63]

SELECTIVE DAMAGE TO THE P PATHWAY

Acrylamide monomer is a neurotoxic agent that selectively damages cells in the parvocellular pathway.[57,65-67] In animals treated with this agent, the only ganglion cells detected were M cells that responded to low spatial frequency signals of about 1 cpd, modulated at high temporal rates.[57] This study provides additional evidence to support the concept that the M cell pathway is responsible for detecting large, fast moving, achromatic stimuli, and the P pathway is responsible for detecting fine details in slow moving chromatic stimuli.

OPTIC NERVE AND TRACT

As the axons from the M and P ganglion cells leave the retina, they pass through the optic nerve and tract on their way to the LGN. The fibers of the P pathway are located more centrally in the optic nerve as opposed to the M pathway fibers which are located more peripherally.[68] In the optic tract, P cell degeneration resulting from acrylamide monomer administration indicates that the parvocellular pathway passes through the dorsolateral aspect of the tract.[65]

Ogden and Miller[69] have demonstrated that the optic nerve fibers vary in diameter from 0.4-0.6*u*m, and their conduction rates vary from 1.3 to 20 m/sec. They also showed that a linear relationship exists between the axonal diameter and conduction velocity. These size and conduction time ranges indicate the range of possible differences between P and M pathway axons.

It has been shown in developmental studies that the fibers from the central retina mature a little ahead of those from the peripheral retina and that the fibers of the M stream precede those of the P stream in development.[70] These differences raise the possibility of selective damage to the two pathways depending on when during development the damage occurred. They also suggest that the if damage does occur early in development, the M pathway might be more vulnerable.

LATERAL GENICULATE NUCLEUS

Axons from the ganglion cells pass into the LGN where they are segregated into the parvocellular and magnocellular portions of the nucleus. Because of this anatomical segregation, the physiological

characteristics of the M and P pathways have been studied most extensively at the level of the LGN.

The LGN is composed of six layers with the two ventral layers containing the large magnocellular cells; the remaining four layers contain the smaller parvocellular cells.[71,72] The nasal fibers from the contralateral eye terminate in layers one, three, and six, and temporal fibers from the ipsilateral eye terminate in layers two, four, and five (layers are numbered from dorsal to ventral).[73]

Based in part on their smaller size, the density of cells in the parvocellular layers is greater than the density in the magnocellular layers, and the density is also greater in the layers receiving input from the contralateral eye as compared to those receiving input from the ipsilateral eye.[74]

RESPONSE CHARACTERISTICS OF LGN CELLS

The response properties and conduction velocities of cells in the LGN are very similar to those of their retinal counterparts.[75] Both P and M geniculate cells have concentrically arranged receptive fields[76] with the M cells having larger receptive fields, by a factor of 1.6 or more.[77] The M cells also have shorter response latencies of about 1.6 msec, as compared to latencies of about 2.5 msec for the cells in the parvocellular layers.[58,78] Parvo cells receive input from axons with medium conduction velocities and they themselves conduct at medium velocities to the striate cortex. In contrast, M cells receive inputs from large, high velocity ganglion cell axons and send information to the cortex along their own large, high velocity axons.[75,78]

In general, cells in the magnocellular layers respond best to temporal frequency modulations of about 20 Hz, whereas the parvocellular response peaks at around 10 HZ, with a gradual loss of sensitivity toward lower temporal frequencies and much more rapid loss toward higher frequencies.[58,77]

With respect to spatial frequency sensitivity, cells in the parvocellular layers that receive inputs from the foveal ganglion cells are capable of detecting spatial frequencies of up to about 40 cpd,[77] but the spatial frequency response of these cells peaks at about 10 cpd. In distinction to the P cells, the M cells respond best to spatial frequencies of less than 2 cpd.[77, 79]

Cells in the parvocellular layers process both color-opponent and broad-band information, whereas cells in the magnocellular layers process broad-band information only.[58,75,78] Effects of lesions of the magno and parvocellular layers support the idea that the M pathway is responsible for high temporal and low spatial frequency information, whereas the P pathway is the mediator of color vision and high spatial frequency information.[67,80,81]

SUB-PATHWAYS IN THE MAGNOCELLULAR LAYERS

A clear consensus is not available among researchers on whether the magnocellular layers might contain sub-groups of cells. Kaplan and Shapley classified cells in the magno- and parvocellular layers as being equivalent to X or Y cat cells, mainly based on their spatial summation ability and the linearity or non-linearity of their responses.[79,82] Using these criteria, nearly all cells in the parvocellular layers, and 75% of the cells in the magnocellular layers were similar to X cells, with the remaining 25% of the cells

in the magnocellular layers being similar to Y cells. These results, along with work of Marrocco, et al.[58] suggest that is not accurate to equate all primate M cells with cat Y cells nor all P cells with X cells.

STRIATE AND EXTRASTRIATE VISUAL CORTEX

Most fibers from the LGN project to the primary visual cortex, known as Brodmann's area 17, area V1, or the striate cortex. The striate cortex consists of 6 layers, numbered from outside to inside as layers I to VI,[73] with a prominent band of LGN input fibers in layer IV. Layers III and IV are further divided into three subdivisions called a, b, and c, and layer IVc is further subdivided into IVc-alpha, IVc-beta, and IVc-gamma.

ARCHITECTURE OF CORTICAL AREAS

Cytochrome oxidase studies of the striate cortex have revealed a prominent array of blob-like structures, located mainly in layers II, and III[83]. These blobs represent groups of cells that stain more densely than their neighboring cells in adjacent regions which are called inter-blob zones. A typical cytochrome oxidase staining pattern is also observed in visual area V2,[83]except that in this area the staining pattern takes the form of dark and pale stripes, with the dark stripes being classified as either wide or narrow.

Fibers from the LGN project to layer IV of the striate cortex,[73,83] and from there information is conveyed to the blobs and inter-blobs of layers II and III,[83-85] and to layers V and VI.[86]

Fibers from layers II and III exit from the striate cortex and project to the extra-striate areas.[83-85] Fibers from layer V

project to the superior colliculus, and those from layer VI project back to the LGN[86] to provide feedback for this nucleus.

Major extrastriate areas receiving direct visual input and/or fibers from area V1 include Brodmann's area 18 which consists of visual areas V2 and V3; Brodmann's area 19 which consists of visual areas V3a, V4, and V5; posterior parietal cortex; infero-temporal (IT) cortex; and the frontal eye fields.[87] Visual area V5 is now referred to as the middle temporal (MT) cortex, and area V5a is referred to as the medial superior temporal (MST) cortex.

SERIAL AND PARALLEL PROCESSING OF INFORMATION IN THE CORTEX

Most researchers now believe that the separation of information processing pathways represented by the M and P divisions of the LGN is continued in the cortex, however the separation is not as strict as it is in the geniculate. One of the more recent diagrams of parallel processing pathways in the cortex is shown as Figure 1. In this Figure, the P pathway from the LGN carries information to the cortex where it is divided for further processing of chromatic, form, and stereoscopic information. The outcome of processing in the form and color pathway (discussed below) results in a perception of what an object is, so this channel is often called the "what" channel. As information progresses serially through the channel, specific stimulus features, such as color, are distributed to a patchwork of cortical areas for detailed analysis.

Insert Figure 1 About Here

Information from the M geniculate pathway is also processed extensively in the cortex to produce a perception of where an object is in time and space. This processing pathway is often called the "where" or the motion pathway (discussed below).

THE FORM AND COLOR PATHWAY-ARCHITECTURE

Fibers from the parvocellular layers of the LGN project to layer IVc-beta in the striate cortex.[88] From there information travels via two routes with one set of fibers projecting to the inter-blob regions in layers II and III,[84] and another set projecting to the blobs.[84,86] The blobs also seem to receive some direct projections from the inter-laminar zone between the parvo and magnocellular layers of the LGN, but the function of this input is unknown.[88,89]

Outputs from the blob and inter-blob regions project to area V2,[83] with the inter-blobs projecting to the pale stripes, and the blobs projecting to the thick, dark stripes. Both of these areas then project to area V4[90, 91] where there is some evidence that color and form information are processed in separate and distinct sub-areas.[92] From here, fibers project to the inferior temporal cortex, and the inferior convexity of the temporal lobe.[93-96] There are further projections to the IT from the limbic structures, such as the amygdaloid complex,[97-100] and hippocampus[101].

THE FORM AND COLOR PATHWAY-RECEPTIVE FIELD CHARACTERISTICS

The cells in the IVc-beta layer of the striate cortex demonstrate either single-opponent color coding or broad-band characteristics, but they lack orientation specificity in their receptive fields.[102-104] These cells (and others) send information to the cells in the inter-blob region of V1 which demonstrate orientation specificity, and typically have broad-band center-surround characteristics.[104] Although the inter-blob regions receive input from single-opponent color coded cells, the cells in these regions respond best to selectively oriented contours regardless of the color and the relative brightness across the contour.[84,105,106]

Cells in the blob regions of V1 lack orientation selectivity in their receptive fields, but demonstrate either color-opponent or brightness selectivity. Their receptive fields have center-surround characteristics, and the color-coded cells demonstrate double-opponency characteristics.[104,107] It is hypothesized that the color coded blob cells receive their inputs from the color-opponent parvocellular LGN cells, and the non-color coded blob cells receive their inputs from the parvocellular and/or the magnocellular broad-band cells.[84,104,105]

In area V2, the pale stripes receive their inputs from cells in the inter-blob regions of V1 and show the same receptive field characteristics as V1 inter-blob cells, except that some or all of the cells in the V2 pale stripe areas are sensitive to the length of a stimulus (i.e., are end-stopped).[84,105] The thin dark stripes in area V2, like their counterparts in the V1 blobs, are not orientation

specific, but are mostly color coded, showing strong double-opponent characteristics.[84,105] These cells also have an optimum stimulus size to which they respond very actively when a stimulus is placed anywhere in the visual field.[108,109]

Less is known about the cells in area V4, but some cells in this area respond selectively to color,[110,111] stimulus orientation, and direction of motion.[111,112]

Beyond area V4, the information from the visual pathways is mixed with other information and the cortical areas loose their strictly visual nature. For example, the inferior temporal cortex plays a role in visual discrimination, learning, and retention, as can be demonstrated by ablating the IT cortex in laboratory animals.[113-115] The cells in the IT cortex are selective to certain visual parameters such as, shape, color, and texture, or a combination of these. It has been suggested that a single cell in the IT cortex can represent a fairly specific set of stimulus features and would respond only when these features were present (i.e., it might be triggered only by a specific stimulus).[116-118] Cells selectively responsive to a specific complex stimulus such as a hand or a face have been identified in this region.[117,119]

THE FORM AND COLOR PATHWAY-FUNCTION

Information about the color and high spatial frequency details of a stimulus are separated from information about low spatial frequency and motion at the level of the retina. This high frequency and color information is carried largely by the P type ganglion cells to the parvocellular layers of the LGN, and then by the axons of these cells to cortical area V1. In V1, the color information is kept

separate by sending it to the blob regions and the form information is processed in the inter-blobs. This separation is also maintained in area V2, but, as information processing becomes more sophisticated at higher cortical levels, it begins to break-down and areas that have cells specifically responsive to combinations of stimulus features are found. Currently, it is believed that there may be over 30 of these specific areas with each having its own map of the visual world and being responsible for analysis of some general or specific stimulus characteristic.[120,121] Evidence to support the concept that specific stimulus features are processed in different cortical areas will be presented in the section below on agnosias.

Although it is reasonably clear that stimulus details and color are processed via the P pathway, the pathway responsible for stereopsis is not that obvious. It was once thought that information carried through the magnocellular pathways played a chief role in determining stereoscopic depth.[84,105] However, it is now suspected that stereopsis is not a unitary function and that both the magno- and parvocellular pathways are involved in the processing of information regarding depth.[122-124] Information about fine stereopsis (up to about 20 min disparity) is now believed to be carried by the P pathway to the inter-blob system,[122-124] and information about coarse stereopsis and stereo-movement is processed by the magnocellular, broad-band channel.[122]

THE MOTION PATHWAY-ARCHITECTURE

Cells in the magnocellular layers of the LGN project to layer IVc-alpha in the striate cortex,[88] and information then flows to layers IVb and VI.[86,125] Fibers from layer VI project back to the

LGN[86,125] to provide a feedback loop to the geniculate. There is also some evidence that the fibers from layer IVc-alpha of V1 may serve as inputs to the blob cells in layers II and III of this area.[83-85,89,105]

Fibers from layer IVb exit from the striate cortex and project to the medial temporal cortex, which is a small area on the posterior bank of the superior temporal sulcus.[125-127] Fibers from layer IVb also project to MT[90,91] via the thick, dark stripes in area V2.[83] From the MT, there are separate projections to other extrastriate areas such as the medial portion of the superior temporal sulcus (MST), and the ventral intraparietal cortex (VIP).[128] Separate connections have also been identified from the MST to the frontal eye fields which are associated with eye movements,[128,129] and to the posterior parietal cortex[130,131] which has been implicated in certain forms of complex behavior, including attention.[131,132]

THE MOTION PATHWAY-RECEPTIVE FIELD CHARACTERISTICS

In general, cells in the M pathway respond best to low spatial and high temporal frequencies. In the retina and LGN, M pathway cells encode information on moving targets by detecting any change in contrast over time. In layer IVc-alpha of the striate cortex, M pathway cells are predominantly broad-band,[103] and show a preference for specific stimulus orientations.[104] Cells in area V2 respond selectively to stimulus distance, and, to some degree, are sensitive to the direction of motion.[133]

At the level of the MT cortex, cells are selectively tuned to respond to stimulus orientation, direction,[134-138] depth, and

speed.[137,139] MT cells respond over a range of speeds from 2-256 degrees/sec[137,138,140] with best responses at about 32 degrees/sec. The cells in the MT are not capable of differentiating a retinal image shift caused by movement of the target from movement of the eye itself, however, the cells in the MST can make this discrimination and respond differently under the two conditions.[141]

The cells in the MT and MST show other difference in their receptive field characteristics.[141] Cells in the foveal MT (MTf) prefer small moving spots of light, whereas those in the dorsal-medial MST (MSTd) prefer large, moving stimuli such as patterns of random dots; cells in the lateral anterior MST (MSTl) show mixed responses.

THE MOTION PATHWAY-FUNCTION

As its name implies, the motion pathway processes information about stimulus motion, and it probably also has a role in guiding the motion of the eyes and body. Following initial processing in the retina, LGN, and visual cortex, the M pathway passes information on to higher cortical areas and to subcortical areas responsible for moving the eyes. In these areas, the direction and velocity of a stimulus are analyzed, and the relative location of the stimulus with respect to the body and other objects is determined. The processing required to accomplish these tasks is quite complex, as is illustrated by considering the means by which the visual system is able to foveate or pursue a moving target.

The generation and control of eye movements involves projections from the MT and superior temporal areas to the superior

colliculus,[128,142] and to the pons[128,143,144] which serves to guide pursuit and tracking eye movements.[145,146] In turn, the pons is connected to the cerebellum[147-150] which contains a map related to eye movements,[151] as well as neurons that signal eye movement and retinal image slip velocities.[152] The cerebellum plays a role in the regulation of pursuit eye movements[152-155] by exerting control over the oculo-motor nuclei in the brain stem.

To track a target in motion, the eyes have to execute a smooth pursuit movement matching the velocity of the target so that the image is held stable on the retina. To accomplish this, cells in the MTf and MSTl areas of the motion processing channel initiate the pursuit eye movement. Then, in reaction to the motion of the target to be pursued, another group of cells in the MSTd and MSTl indicate the perceptual consequences of the pursuit movement and provide feedback to guide the pursuit movement.[156,157] It is this group of cells that detects a slip of the retinal image from the fovea during tracking and initiates a refixation movement to refoveate the moving target. Behavioral studies on monkeys show that lesions in the MT, MST and the pontine areas lead to defective pursuit eye movements.[145,158,159] Animals with these lesions try to make refixation movements during pursuits but are unsuccessful. The eyes of these animals always lag behind the actual position of the object, thus illustrating the importance of these motion pathway nuclei for control of eye movements.

CLINICAL PROBLEMS ILLUSTRATING SERIAL AND PARALLEL PROCESSING WITHIN THE VISUAL SYSTEM

In humans, visual information is carried via separate, parallel pathways through a series of separate nuclei and cortical areas. Analysis of this configuration suggests that failures in the visual system could involve either an entire pathway or one of the analysis sites along a pathway. It appears that both types of failures do occur in humans; pathway failures have been associated with problems including glaucoma, Alzheimer's disease, dyslexia, and amblyopia, whereas specific processing site failures in the cortex are probably best illustrated by the agnosias.

GLAUCOMA

The major signs and symptoms associated with glaucoma include elevated intraocular pressure, optic disc changes, and visual field loss resulting from death of ganglion cells. One of the most commonly proposed causes of ganglion cell death is disruption of axon nutriture and/or metabolic transport[160] at or near the optic disc. Histological studies of retinal tissue from glaucoma patients have shown that there is a significant tendency for cells with larger sizes to die first as a result of the disease. This has lead to the conclusion that glaucoma affects cells in the M pathway prior to affecting the smaller cells of the P pathway.[161-164] It would also account for the fact that a significant proportion of ganglion cells die before any effect is found using the conventional perimetry techniques that are best suited for detecting loss of P cell function.[161,165]

Further evidence of large cell death in glaucoma patients comes from psychophysical tests that specifically evaluate magnocellular system function. Contrast sensitivity to low spatial frequency patterns (less than 2 cpd) modulated at high temporal frequencies (8 Hz) is impaired in patients with glaucoma,[166,-170] which definitely indicates an M cell problem. Further, in glaucoma patients who have had early intervention and return of their pressures to the normal range, responses to flicker contrast sensitivity testing show significant improvement.[171]

These results illustrate a failure in one of the parallel visual pathways, and suggest better methods for assessing this type of failure. For example, a recent pilot study has demonstrated that flicker perimetry is more effective than conventional static perimetry in detecting glaucoma caused visual field defects.[172] Monitoring flicker contrast sensitivity in patients with elevated intraocular pressure might, therefore, help separate those who are experiencing cell death and must be treated, from those who only have ocular hypertension.

ALZHEIMER'S DISEASE

Alzheimer's disease has been described as "A condition of gradual onset, which leads to impairment of recent memory, disorientation, confabulations, and retrogressive loss of remote memories."[173] Pathologically the disease is characterized by neuronal loss, neurofibrillar tangles, and neuritic plaques occurring mainly in subcortical areas[174] such as the hippocampus, amygdala, locus ceruleus,[175,176] and the neocortical association areas.

Primary neocortical areas such as the motor and visual cortices are relatively spared in Alzheimer's disease.[177]

The vague visual symptoms reported by Alzheimer's disease patients have typically been attributed to psychogenic causes because it is not unusual for these patients to have 20/20 visual acuity and full fields. Such patients are often told that there is nothing wrong with their vision. Recently, however, changes in retinal ganglion cells[178,179] and optic nerve fibers[180] have been detected in patients and these signs must now be added to the constellation of neuropathological findings present in patients with Alzheimer's.

The retina and the optic nerve of Alzheimer's patients show damage predominantly to the large retinal ganglion cells and their axons,[180,181] which suggests a problem in the M pathway. Psychophysical tests on Alzheimer's patients also suggest damage to the M pathway.[182-185] Pattern electroretinographic studies show the dysfunction of the fast-conducting retinal ganglion cells and their cortical counterparts that would be expected if the M pathway was compromised.[182,183] Alzheimer's patients also show a decrease in contrast sensitivity for low spatial frequency gratings (0.5-2 cpd) alternated at a temporal frequency of 7.5 Hz, and this is consistent with an M pathway defect.[184,185]

DYSLEXIA

The term dyslexia has many definitions ranging from an almost complete loss of the ability to understand word meanings to a simple reading difficulty. Suggested etiologies for dyslexia are equally wide ranging, with one group of researchers and clinicians

sure that the visual system is involved in the problem and another group equally sure that it is not. Some have argued that dyslexia is an auditory-linguistic problem arising from a poor understanding of the phonological structure of words.[186,187] This notion has been supported by anatomical studies that have demonstrated an atypical language area (the planum temporale) in the left hemisphere of disabled readers.[188,189]

More recently, it has been suggested that dyslexia need not be secondary to a linguistic problem, but could involve a defect in the M cell or transient visual pathway.[190-200] In addition, it has been suggested that the transient pathways in other sensory systems,[201-203] such as audition, could also be compromised in dyslexia, and this would result in a problem in processing any high temporal frequency information.[201,204]

If such a defect does exist, its etiology is unclear. It is possible that neuronal input to higher centers can be affected by genetic defects or other extrinsic factors at different stages during early development. This, in turn, could affect development of the cortex, thereby creating an abnormal cytoarchitecture.[205,206] On this basis, it has been hypothesized that the planum temporale might receive defective inputs from transient components of the auditory system. This could result in the previously described abnormality in this area.[204]

INTERACTION OF PARALLEL PATHWAYS DURING READING

The clinical signs and symptoms caused by a transient or M pathway, failure in dyslexia can best be understood by considering the theoretical model of reading proposed by Breithmeyer and

Ganz.[207,208] According to this model, normal reading consists of a series of repetitive fixations and saccades.[209] During each fixation, which lasts approximately 500 msec,[210] the image of a small section of print is placed on the fovea and information about it is transmitted from the retina via the LGN to the cortex by the sustained pathway. When the fixation ceases, information still persists in the sustained pathway until it either fades or is erased.

Following the fixation, a saccade takes place to position a new section of print on the fovea. The ability to detect stimulus features is greatly attenuated during this saccade,[211-213] as well as during a short period slightly before and after it.[214] One of the functions of this suppression is to reduce the perception of stimulus blur that would be produced by the eye movement; this phenomenon is commonly referred to as saccadic suppression.[211-213]

During a saccade, the fast movement of contours across the retina activates the transient visual pathway which inhibits the sustained or P cell pathway. This causes the persistent image of the previous fixation held in the P pathway to be erased, thus making room for the information from the subsequent fixation.[207,208] If the persistent image if not erased, the new image will be superimposed on the old image and confusion and/or poor reading will result. The process of erasing the image of a previous fixation during a saccade is commonly referred to as transient-on-sustained inhibition, and it forms a major theme in Breithmeyer's theoretical model of reading.

EFFECTS OF A DEFECT IN THE TRANSIENT PATHWAY ON READING

Many studies have identified a transient system deficit in subjects with reading problems. Differences in visually evoked potential recordings,[191] contrast sensitivity,[190,192,199,215] duration of persistence,[190,197-200] flicker contrast sensitivity,[190,195] and flicker masking effects[193,194] have all been found between disabled readers and controls, and in each case the difference is in the direction predicted by a deficit in the transient system.

According to Breitmeyer's model, if the transient system is not working properly, it would fail to inhibit the sustained system, and thus fail to erase the image of a previous fixation before information from the next fixation was available. This would result in superimposition of the images and confusion. The reader faced with this problem might deal with it by increasing fixation durations (to allow persistent images of previous fixations to fade without saccadic suppression), by decreasing the number of letters per fixation, and/or by making extra saccades to build up more saccadic suppression. Such strategies might explain the increased number of fixations,[217] saccades,[218] and regressions[219] commonly observed in dyslexic individuals.

Though pursuit movements are usually not directly involved in reading, it has been found that pursuits are often abnormal in reading disabled individuals.[219] This is also consistent with a M cell or transient pathway problem because there is a link between the motion processing centers in the brain which receive their

inputs from the M pathway, and the brain areas responsible for the generation and control of pursuit eye movements.

MORPHOLOGICAL DIFFERENCES IN M CELLS OF DYSLEXICS

If dyslexics have a problem in their M cell pathway, it might be possible to identify this problem by observing cells in the magnocellular layers of the LGN. Recently Livingstone, et al. have confirmed this possibility by identifying morphological abnormalities in the magnocellular LGN layers of a group of dyslexic individuals.[204] They found the cells in the dyslexic's magnocellular layers to be much smaller than those of matched controls. The physiological consequence of this reduction in cell body and axon sizes would be a change in the M cell's transmission times which could result in a loss of synchronization of the fixation-suppression pattern in reading.

THERAPY FOR DYSLEXIA BASED ON TRANSIENT PATHWAY DEFECTS

If the balance between the M cell or transient pathway and the P cell or sustained pathway is defective in dyslexia, it should be possible to develop therapies or reading aids to re-balance the pathways. Disabled readers have shown improvement in visual search and reading performance when passages were presented with blurred images and with reduced the contrast.[196,220] Both of these stimulus changes would provide a relative advantage to the M cells that are more responsive to lower spatial frequencies than the P cells. It has also been suggested that a reduction in contrast could serve to decrease the amplitude of the sustained component of the visual response and re-establish normal temporal interactions with the poorly functioning transient system.[196]

It has also been suggested[221] that the use of colored overlays in reading could re-balance the transient and sustained pathways, but it is unclear whether any effects of these filters are due to their color or to the changes in luminance contrast that the filters create.

AMBLYOPIA

Glaucoma, Alzheimer's disease, and dyslexia all illustrate problems primarily in the M or transient pathway. The problems in amblyopia might also involve the M pathway, but more commonly they involve a portion of the P or sustained pathway. Functional amblyopia is defined as a loss of visual acuity for which no organic cause can be detected by the physical examination of the eye. It is considered to be a result of form deprivation and/or abnormal binocular interaction usually associated with strabismus, anisometropia, or stimulus deprivation occurring during critical development periods.

It has long been known that amblyopic patients have problems performing tasks involving fine visual discrimination.[222-228] Similar results have also been obtained in animal studies.[229-237] Based on the definition of amblyopia, all patients have reduced acuities and impaired performance with high spatial frequency stimuli (greater than 2 cpd). This strongly suggests a problem in the P or sustained pathway which is responsible for processing this type of information. Some patients, however, also have a contrast sensitivity reduction at lower spatial frequencies, and this is consistent with a problem in the M pathway.

Although amblyopia primarily involves a spatial vision deficit, opinions are divided as to whether there is an associated temporal processing deficit. Several studies suggest that temporal information carried by the transient channel is essentially normal in amblyopia,[223,224] but others report a deficit in temporal resolution[238,239] which could be secondary to a defect in the spatial vision channels.[239] Since the high spatial frequency P or sustained channel is also responsible for processing low velocity movement, it would make sense that a loss of this information would create problems in analyzing the motion of a stimulus.

Studies at the level of the LGN in cats reared with strabismus, and visual deprivation have identified defective responses from both X,[35,240] and Y cell populations.[241] Monocular deprivation studies in primates have demonstrated that cells in the parvocellular layers of the LGN,[242,243] and IVc-beta layers of the striate cortex[242] are preferentially affected. This is consistent with the concept that these cells are part of the pathway that carries information about high spatial frequencies, and that damage to them will result in the reduced acuity seen in amblyopia. However, there are other animal studies which suggest that both M and P pathways are affected in the same general manner.[244]

To resolve these differences, many researchers now believe that there are several different types of amblyopia, each with different etiologies and different effects on the visual pathways. For example, Sherman[234] suggests that complete visual form deprivation, as would be produced by lid suturing of laboratory cats affects the input to cells in both the X and Y pathways, however

defocussing the retinal image, as would occur in anisometropia, could affect the X pathway more than the Y pathway.

In summary, it seems certain that the X or P pathway is affected in most or all cases of amblyopia, and, in some cases, there is M pathway involvement also. It is important to remember, however, that the entire P pathway is not affected in amblyopia. A major proportion of this pathway is responsible for conveying information about stimulus color, and defective color vision is not a symptom of amblyopia. This suggests that either amblyopia exerts a preferential effect on the form component of the P pathway at subcortical levels, or that it manifests in the cortex at levels where color and form information are analyzed in anatomically separate areas.

AGNOSIAS

As illustrated by the conditions discussed above, visual information is carried to the cortex along parallel pathways which are vulnerable to damage at many points. Beyond the primary visual cortex, the pathways fractionate into many individual areas which are responsible for analysis of specific stimulus components. Selective damage to these individual areas can produce strange perceptual impairments called agnosias. Depending on the actual site of the damage, the nature of the perceptual impairment in agnosia can vary.[245]

Agnosias provide remarkable evidence for functional localization at higher visual centers. Consider, for example, the infero-temporal (IT) cortex in which some 10% of the cells have been found to respond only to specific stimuli such as a hand or

face.[117,119] A lesion in the IT that involves these cells can lead to a selective inability to recognize faces, while the ability to recognize other objects remains intact. This clinically observed condition is known as prosopagnosia.[246-249] There are also reports of cases in which a patient can recognize an object when it is in motion, and fails to recognize the same object when it is static.[250] In another movement related agnosia, bilateral damage in the medial temporal or medial superior temporal cortical areas can manifest as a selective loss of movement perception without loss of any other perceptual capabilities.[87]

Other agnosias can affect the ability to recognize multiple objects simultaneously, or to perceive the color of objects. For example, strokes involving the posterior inferior occipital lobe can lead to the selective impairment of color perception known as achromatopsia.[87,105]

In laboratory experiments, functional losses can be demonstrated very clearly by creating lesions with great precision and accuracy.[113-115] In humans, however, visual agnosias very rarely occur in pure forms. This is because they are usually caused by vascular accidents or traumas that do not restrict damage to functionally discrete regions. Nevertheless, the clinical findings with human agnosia patients are consistent with the theory that at higher cortical centers visual information is processed by decomposing the stimulus into component parts and analyzing these components separately in discrete cortical areas.

SUMMARY

During evolution, nature obviously decided that it was expedient to keep information on fine detail and color separate from information on gross form and motion. It is not clear whether this separation occurred because these pathways evolved at different times, or because there are processing advantages to such a separation, but parallel pathways flowing through a series of brain areas seems to be a universal design for the visual systems of primates.

In the processing areas beyond the primary visual cortex, the strict separation of pathways begins to change somewhat, and a new pattern emerges. In the patch-work of areas beyond V4, specific stimulus features are extracted and analyzed individually. It seems almost as though nature developed these individual areas one at a time when it became desirable to analyze a new stimulus feature such a face, or multiple objects presented simultaneously.

The complexity of the nuclei and cortical areas that together make up the P pathway is at least matched by the complexity of the areas responsible for visually guided movements of the eyes and body. Added to the complexity of the individual pathways are interactions such as the over 300 connections diagrammed by Van Essen, Anderson, and Felleman that are shown in Figure 2.[121] This degree of complexity makes it clear that the study of the visual system will keep researchers busy for many years to come.

Insert Figure 2 About Here

From a clinical perspective, many disease entities are now beginning to make more sense based on an increased understanding of the ways in which the visual system conveys and analyzes information. In particular, the vulnerability of the larger cells in the M pathway helps to explain the problems associated with conditions like glaucoma, Alzheimer's disease, and dyslexia; but, it is not yet clear why the M pathway seems so vulnerable to damage. Is it because it develops ahead of the P pathway? Are there specific pathophysiologic process that affect it? Or, is there a special biochemical problem that renders cells in the M pathway less capable of repairing damage that they sustain? Answers to these questions will have major clinical implications for the millions of patients who suffer diseases associated with failures in the visual pathways.

FIGURE 1

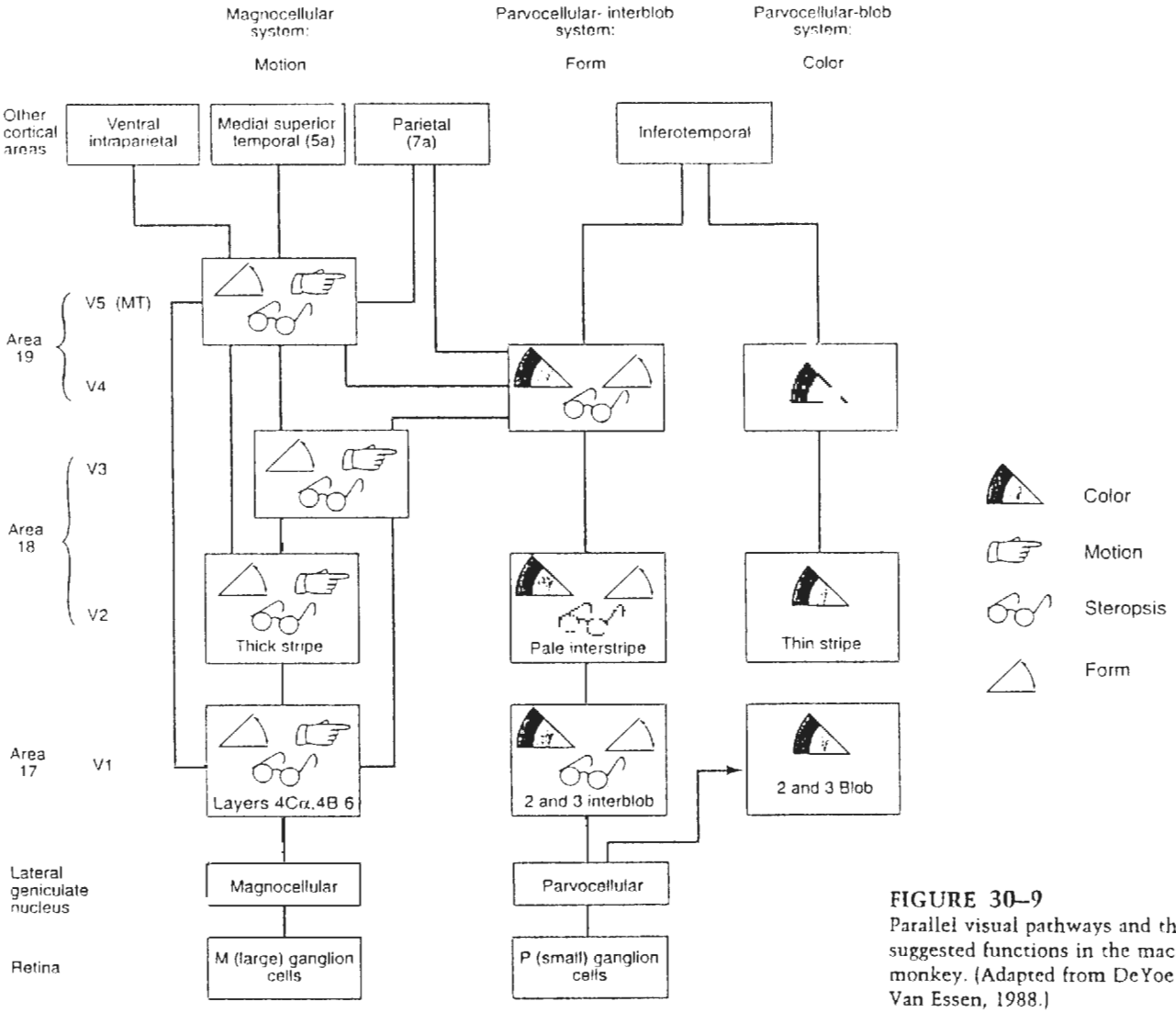

FIGURE 30–9
Parallel visual pathways and their suggested functions in the macaque monkey. (Adapted from DeYoe and Van Essen, 1988.)

FIGURE 2

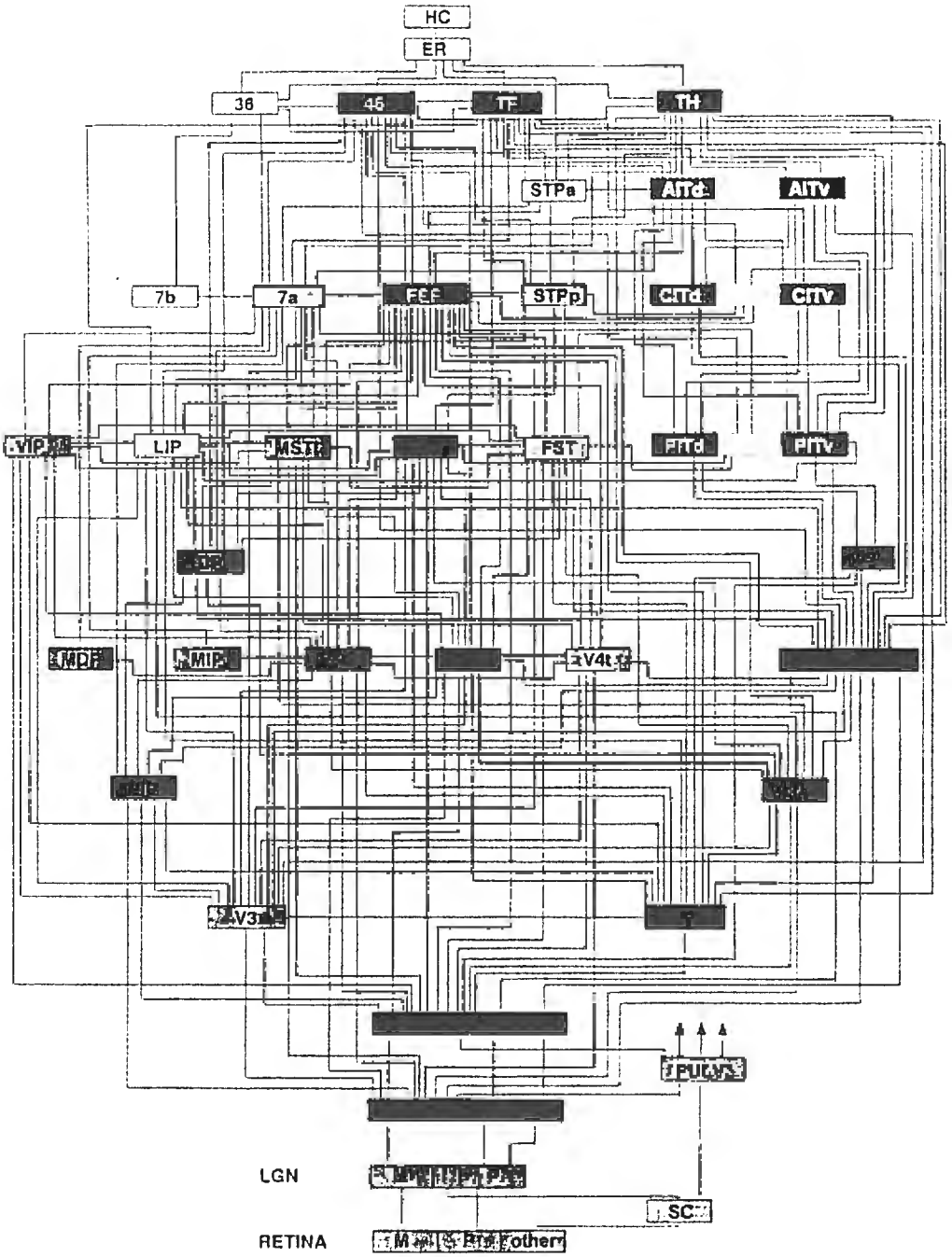

Fig. 2. A hierarchy of visual areas in the macaque, based on laminar patterns of anatomical connections. About 90% of the known pathways are consistent with this hierarchical scheme; the exceptions may reflect either inaccuracies in the reported anatomical data or genuine deviations from a rigid hierarchical scheme. [Modified, with permission, from (*1*), with subcortical connections based on (*37*)]

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