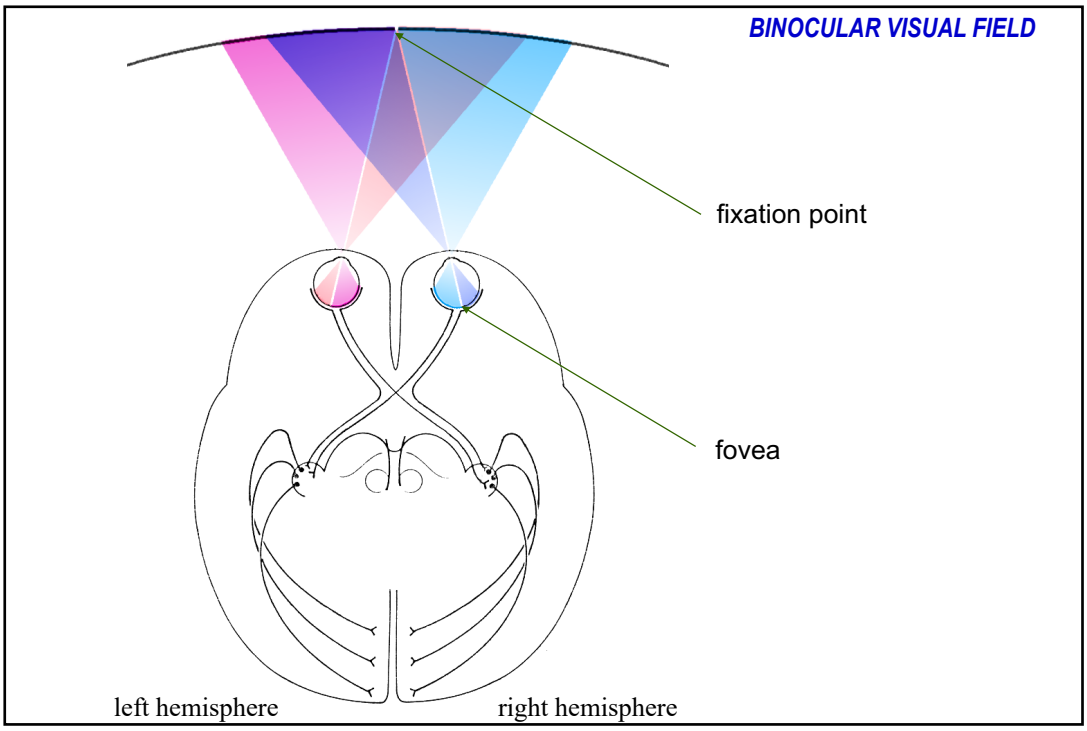
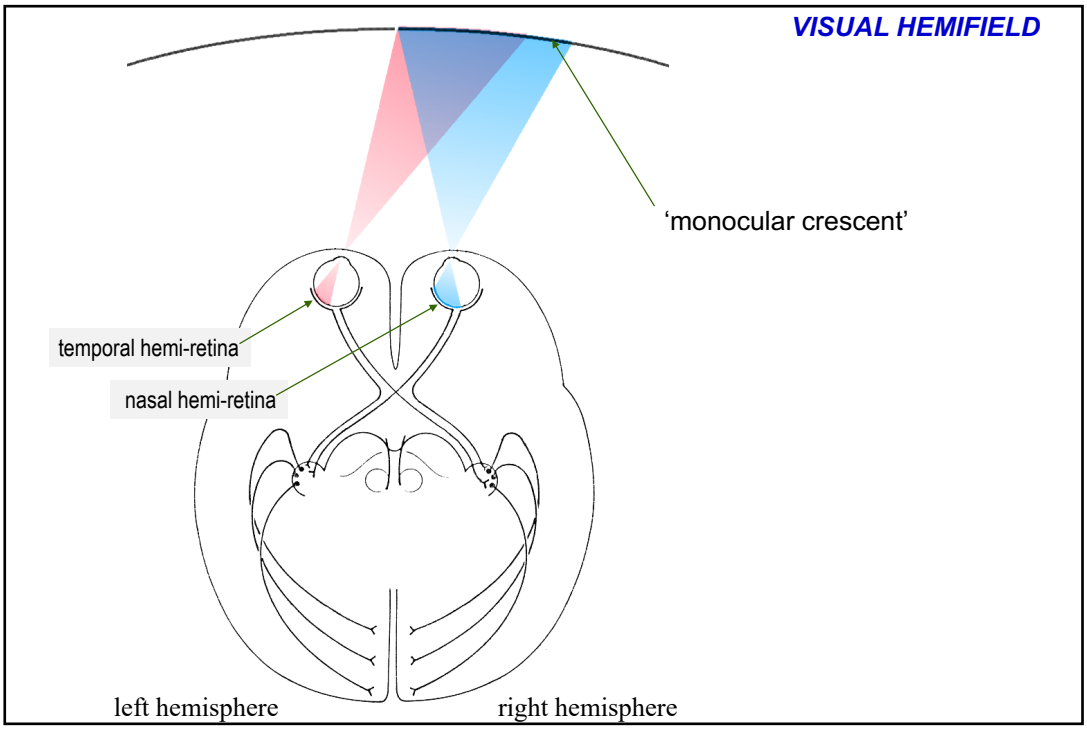
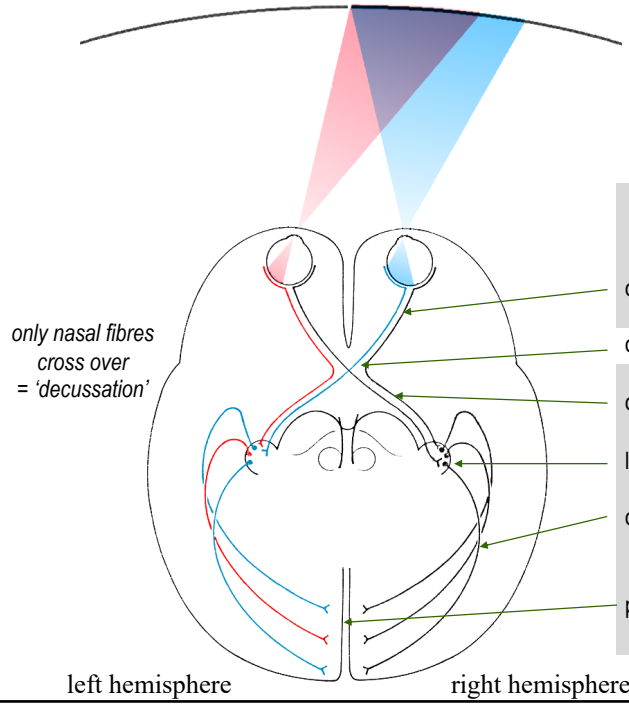

BINOCULAR VISUAL FIELD
fixation point
fovea
left hemisphere
right hemisphere

1


VISUAL HEMIFIELD
'monocular crescent'
temporal hemi-retina
nasal hemi-retina
left hemisphere
right hemisphere

2

VISUAL PATHWAYS
contralateral representation



PRE-CHIASMAL

optic nerve (= axons of retinal ganglion cells)

optic chiasm

POST-CHIASMAL

optic tract

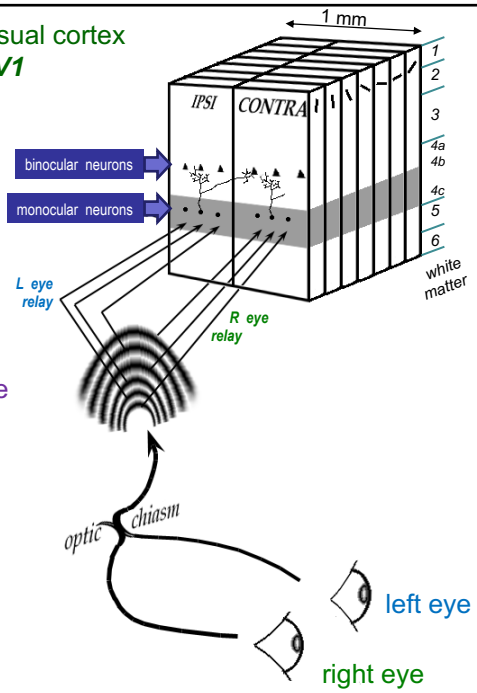
lateral geniculate nucleus (LGN)

optic radiation (axons of geniculate cells)
= cortical 'white matter'

primary visual cortex (V1)

3

primary visual cortex
= ***V1***



Lateral
Geniculate
Nucleus

FUNCTIONAL ARCHITECTURE OF PRIMARY VISUAL CORTEX

David **Hubel** & Torsten **Wiesel**

V1

two independent modular subsystems:
- orientation columns
- ocular dominance columns
(ipsilateral/contralateral = eye on the same/opposite side of the body)

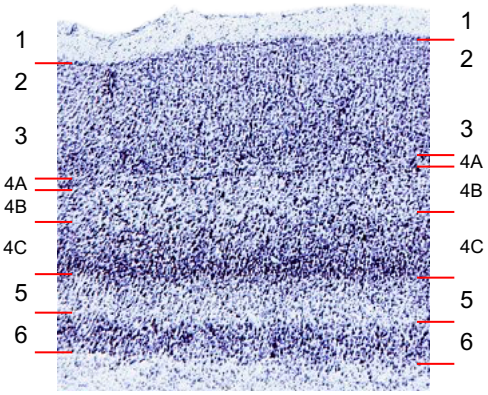
LGN

- 6 monocular layers;
- each layer has a map of a hemi-retina, alternating between the contralateral & ipsilateral eyes.

* *

4

PRIMARY VISUAL CORTEX (V1)
Laminar cytoarchitecture
as shown by *nissl* stain

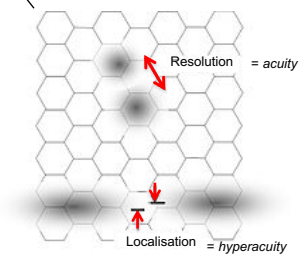


Layer 4C = the 'granular' layer

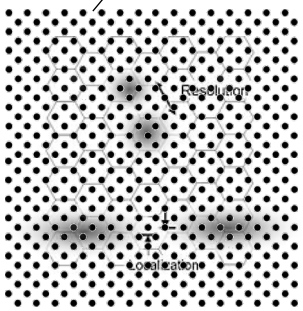
5

Acuity and Hyperacuity

Retinal
cone mosaic

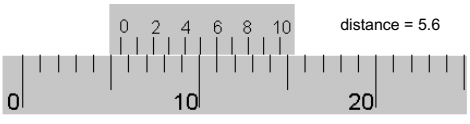


V1: layer 4C
'granule cell' mosaic



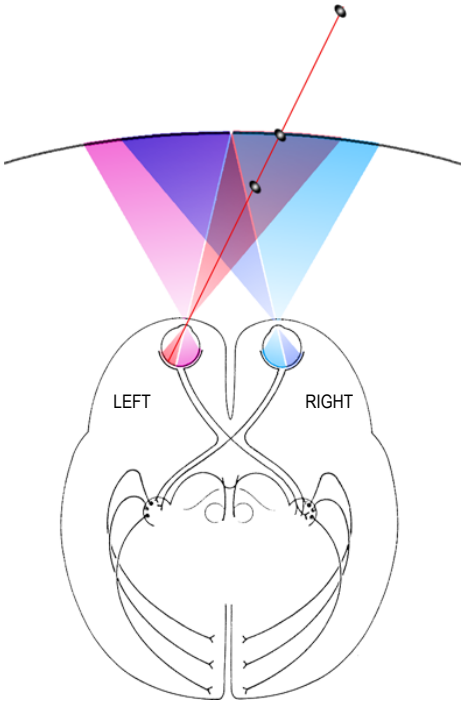
Snellen chart
to measure acuity

Vernier acuity, the judgment of co-linearity



6

BINOCULAR INTERACTION - OPTICS



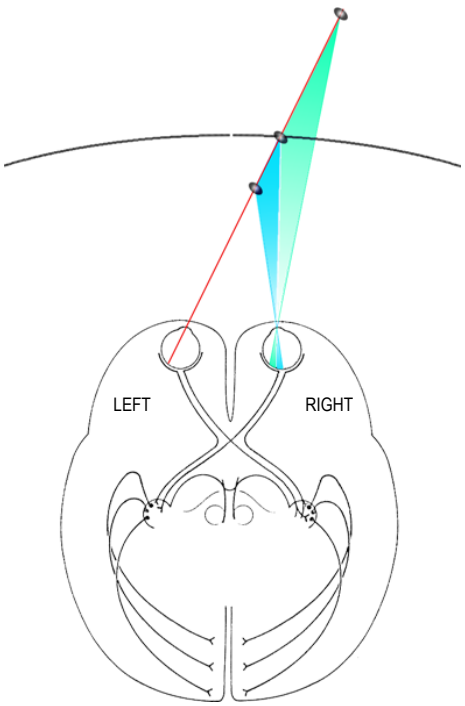
fixation plane - images of objects located on the plane of fixation fall at *corresponding locations* in each retina.
(i.e. in the nasal hemiretina of one eye, & in the temporal hemiretina of the other).

Objects at locations in front, or behind the fixation plane produce images at *non-corresponding* locations in each retina.

e.g. 3 items along the same line of sight in the left eye are imaged at 3 separate locations in the right eye.

7

BINOCULAR INTERACTION - OPTICS

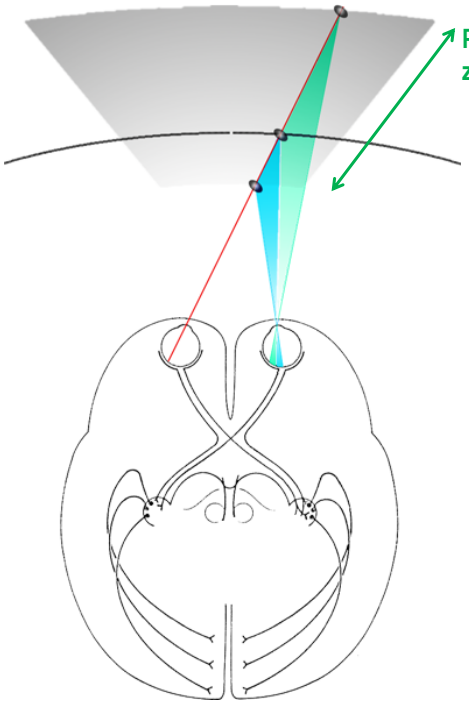


fixation plane

An object moving along the (red) line of sight remains at a fixed point in the left eye, but will traverse the visual field of the right eye;

*e.g. The image of an approaching object will move from the **'green'** to **'blue'** segments of the right retina.*

8



Panum's
zone of fusion

fixation plane

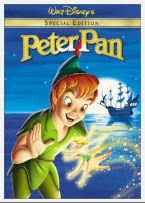
BINOCULAR INTERACTION
- PERCEPTION

There is a limited range of depths in front, and behind, of the fixation plane in which a single image is seen; outside this range there is double vision.

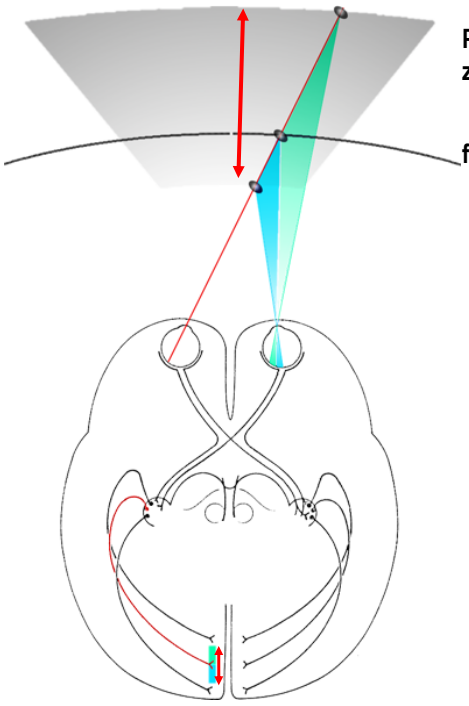
= Panum's zone of fusion (c. 1860)

Peter Panum

Professor of Physiology
University of Kiel 1853-1864



9



Panum's
zone of fusion

fixation plane

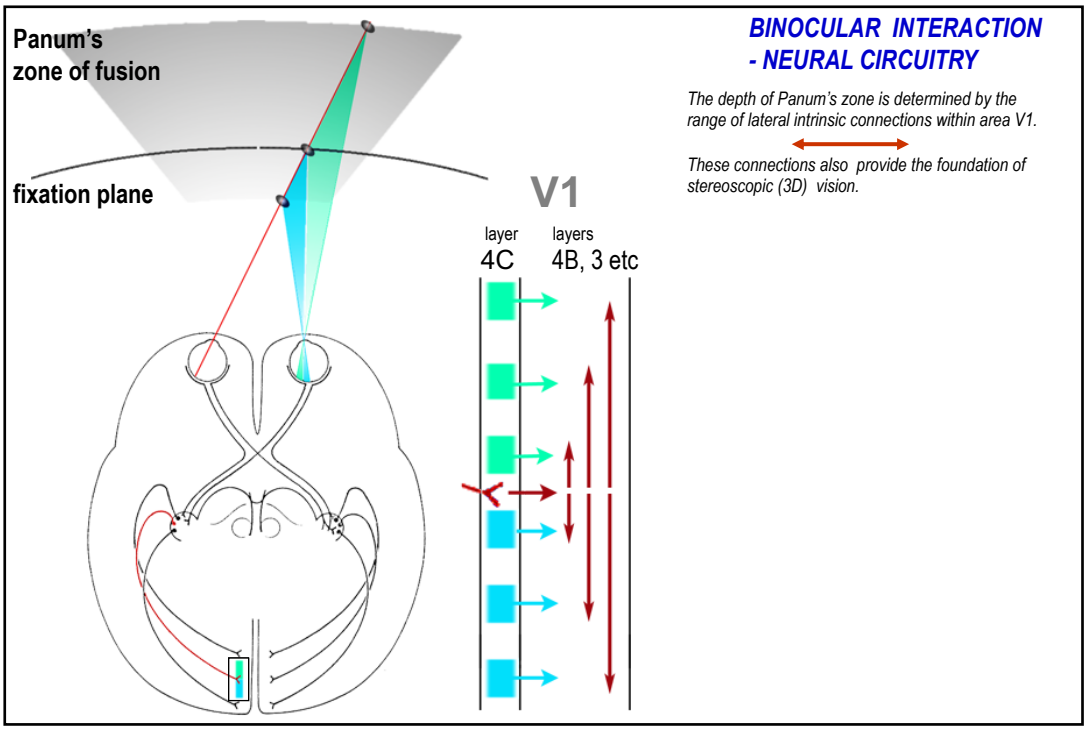
BINOCULAR INTERACTION
- NEURAL CIRCUITRY

Binocular single vision is achieved by creating binocular cells outside layer 4C of primary visual cortex (V1).

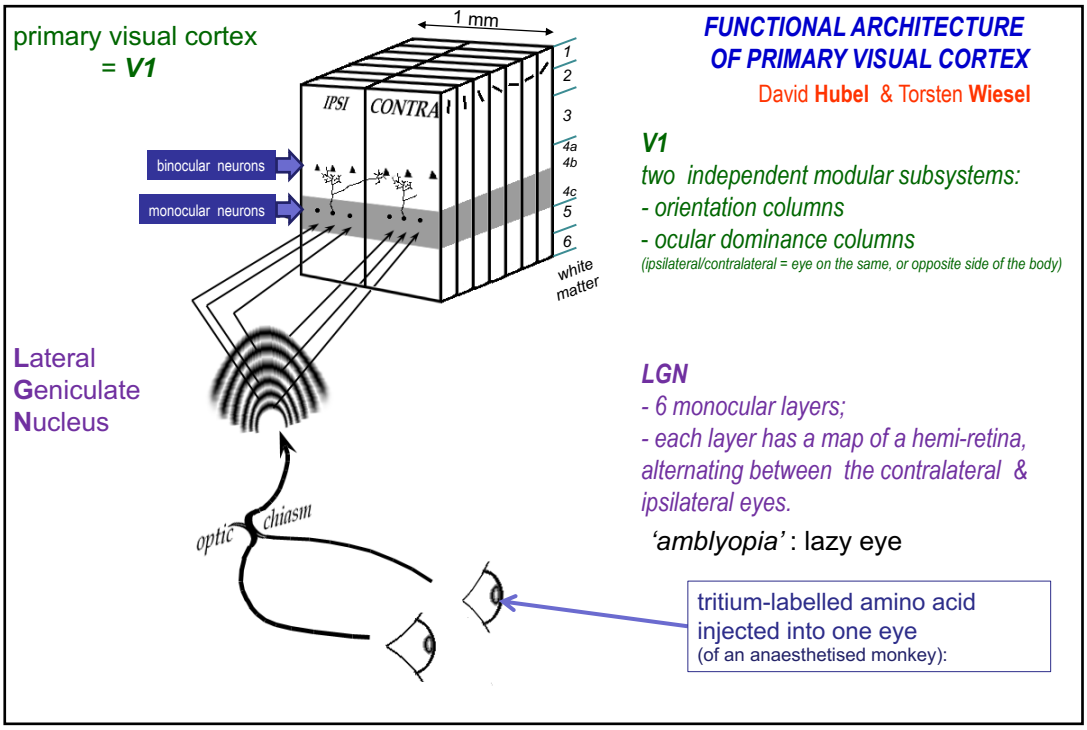
The depth of Panum's zone is determined by the range of intrinsic connections across the visual map of V1, that create binocular neurons - e.g. within layer 3 of area V1.

*

10

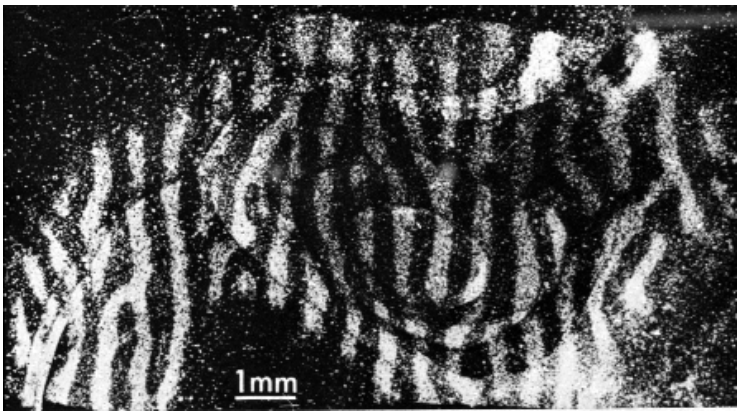

Panum's
zone of fusion
fixation plane
V1
layer
4C
layers
4B, 3 etc
BINOCULAR INTERACTION
- NEURAL CIRCUITRY
The depth of Panum's zone is determined by the range of lateral intrinsic connections within area V1.
These connections also provide the foundation of stereoscopic (3D) vision.

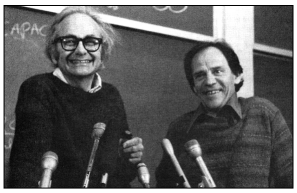
11


primary visual cortex
= V1
1 mm
IPSI
CONTRA
binocular neurons
monocular neurons
1
2
3
4a
4b
4c
5
6
white matter
Lateral
Geniculate
Nucleus
optic
chiasm
FUNCTIONAL ARCHITECTURE
OF PRIMARY VISUAL CORTEX
David Hubel & Torsten Wiesel
V1
two independent modular subsystems:
- orientation columns
- ocular dominance columns
(ipsilateral/contralateral = eye on the same, or opposite side of the body)
LGN
- 6 monocular layers;
- each layer has a map of a hemi-retina, alternating between the contralateral & ipsilateral eyes.
'amblyopia' : lazy eye
tritium-labelled amino acid
injected into one eye
(of an anaesthetised monkey):

12

Anatomical demonstration of ocular dominance columns in layer 4C of monkey visual cortex





David Hubel & Torsten Wiesel

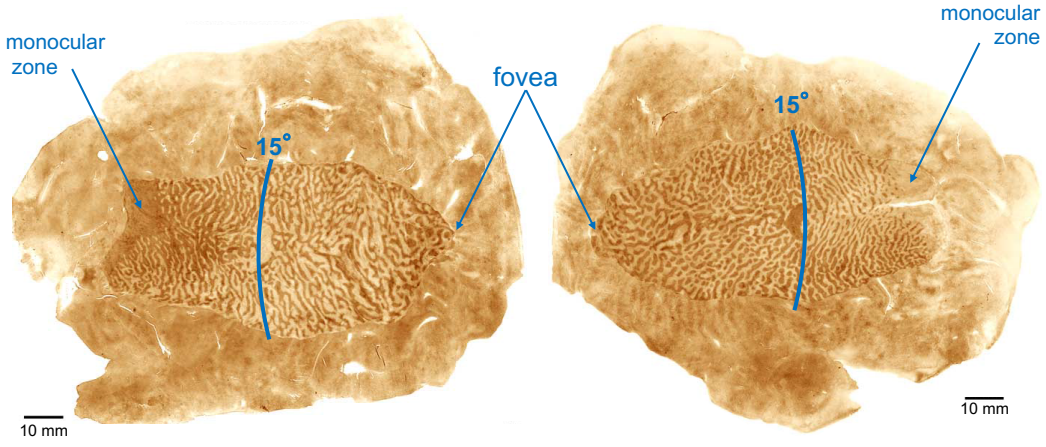
Nobel Prize winners 1981

This is a slice through cortical tissue parallel to layer 4C. The white stripes show the location of a neural tracer that was injected into one eye, taken up by retinal ganglion cell axons and transported across the LGN to reach V1.

13

Ocular dominance columns in human V1
Adams *et al* (2007) [ref 1]

Unfolded, flattened human cortex stained for cytochrome oxidase activity.
This is post-mortem tissue from a subject who was blind in the left eye.

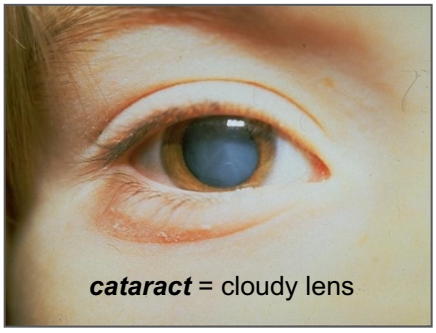


14

Hubel & Wiesel set out to investigate the neural consequences of congenital cataract.

The standard ophthalmological treatment at that time was not to remove the cataract immediately after birth, but to wait for a year or so, when the infant would be better able to tolerate eye surgery. Although this resulted in perfectly clear optical media, the operated eye did not regain full visual function. It gave a blurred image and poor binocular fusion.

This is the condition termed amblyopia, or colloquially 'lazy eye'.



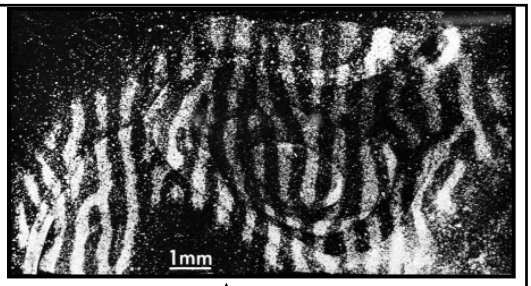
'amblyopia' : lazy eye

15

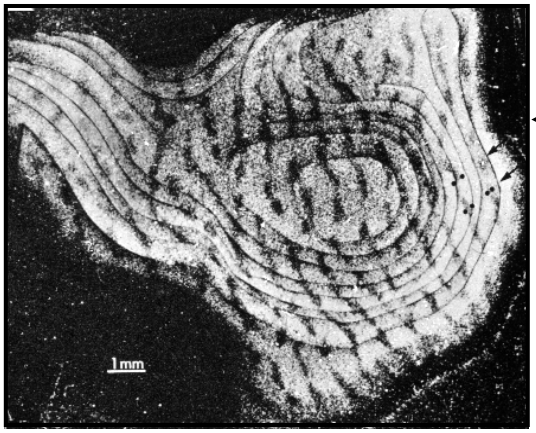
The effect of monocular deprivation on ocular dominance patterns in primate layer 4C
Hubel *et al (1977)* [ref 2]

One eyelid of a newborn animal is sutured to remain shut - this is an experimental 'model' of congenital cataract.

What is found when the eye is re-opened 18 months later ?



Normal pattern of ocular sharing in layer 4C

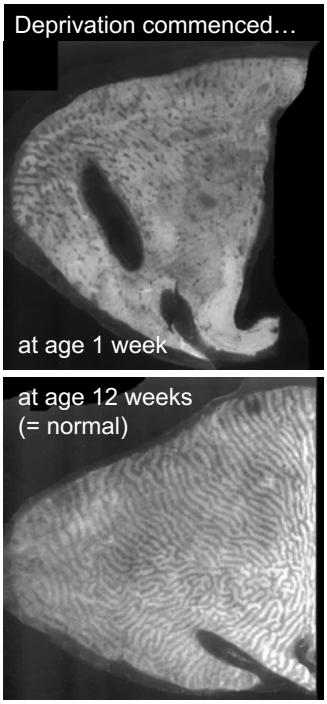


Effect of monocular deprivation
from age 2 weeks – 18 months;
(tracer placed in non-deprived eye).

- *contraction of territory in layer 4C receiving LGN axons fed by the deprived eye;*

- *expansion of territory in layer 4C receiving LGN axons fed by the 'good' eye.*

16



The effect of monocular deprivation: duration of the 'critical period'
Horton & Hocking 1997 [ref 3]

Monocular deprivation by eyelid suture for a period of 8 months.

Deprivation commenced later after birth has progressively less effect.

The *critical period* for neural wiring in layer 4C is from birth to age 3 months (in monkeys).

17

Some important concepts…

PLASTICITY
The ability of the nervous system to adapt its structure (or 'wiring') in response to changing patterns of input and neural activity.

CRITICAL PERIOD
A phase during development in which the 'wiring' of the nervous system is critically dependent on *experience* i.e. upon the pattern of neural activity induced by behavioural interaction with the animal's environment.
- Different neural systems mature at different times; hence there are many different, overlapping critical periods during childhood; the adult brain is much less plastic.

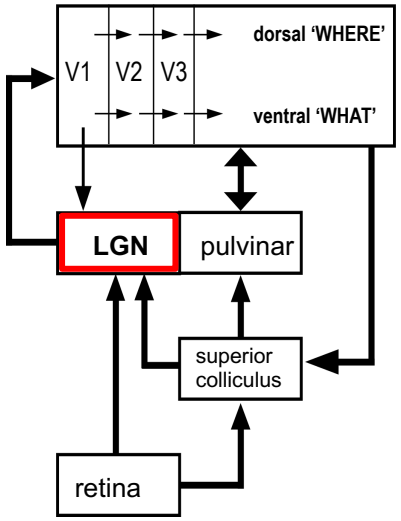
What governs plasticity ? HEBB'S POSTULATE (1949)
If presynaptic activity frequently coincides with postsynaptic depolarisation, and spiking, the potency of the synapse will increase;
But, if presynaptic activity rarely coincides with postsynaptic activity, the potency of the synapse will diminish.

'Cells that fire together wire together' : Hebb's Law

Donald Hebb 1904-1985

18

THE PRIMATE VISUAL SYSTEM



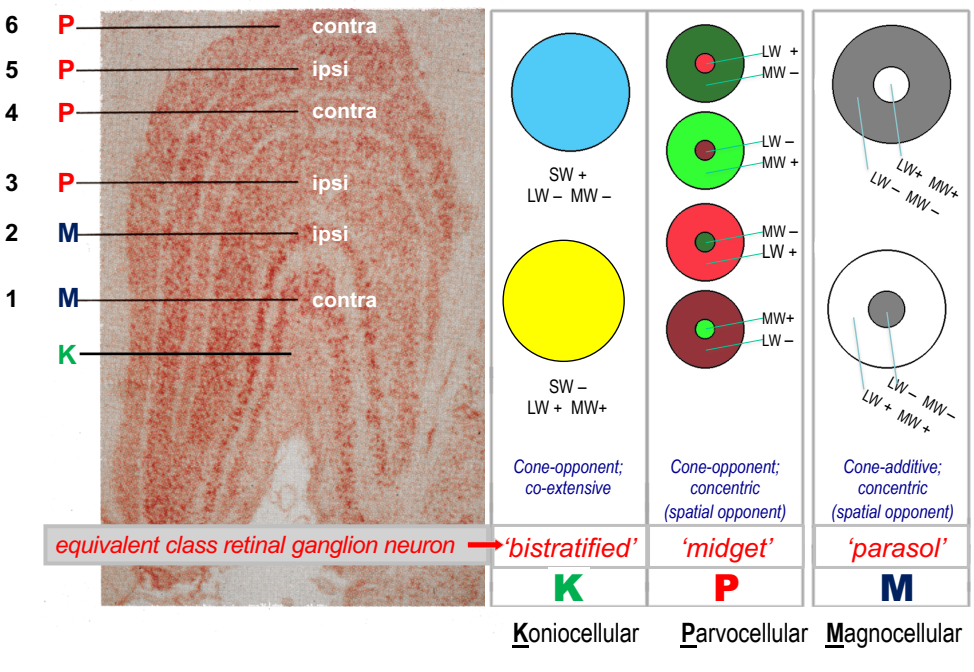
forebrain cortex

forebrain thalamus

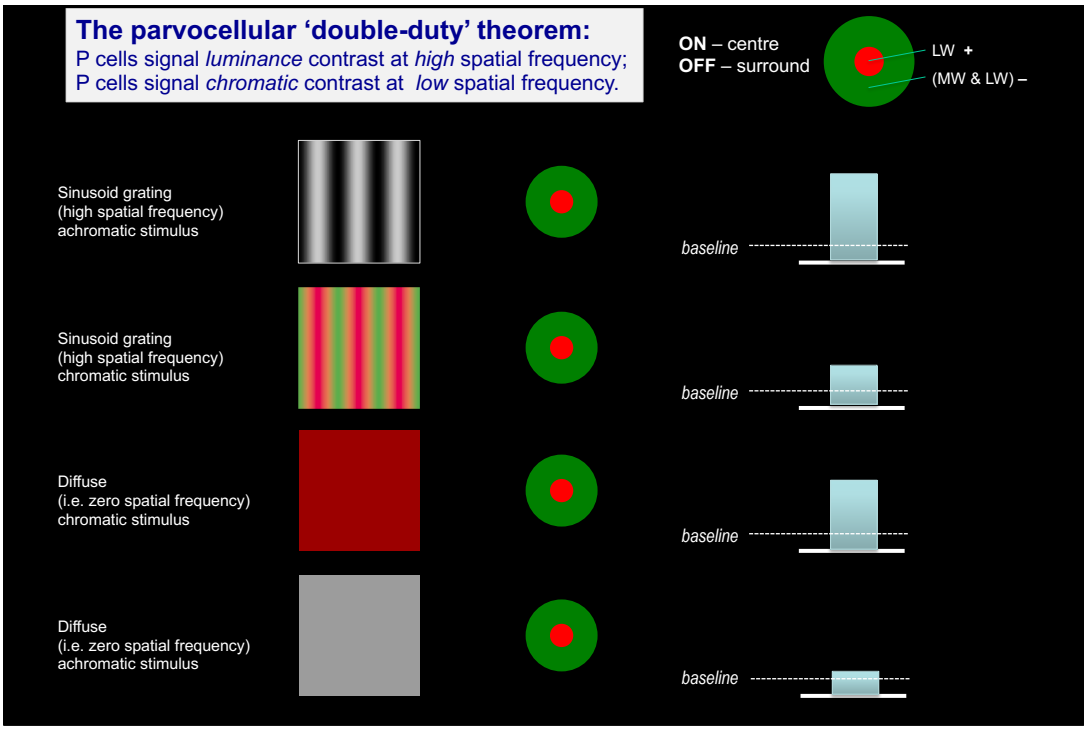
midbrain (optic tectum)

19

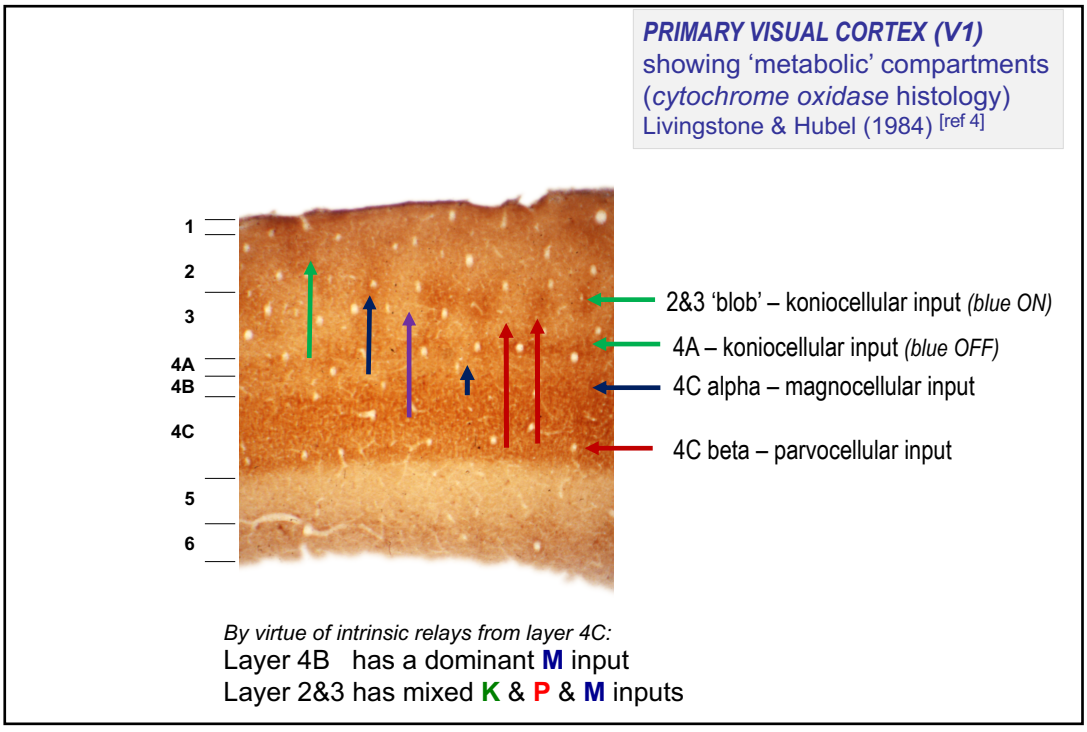
LGN – receptive field properties of 3 different channels



20

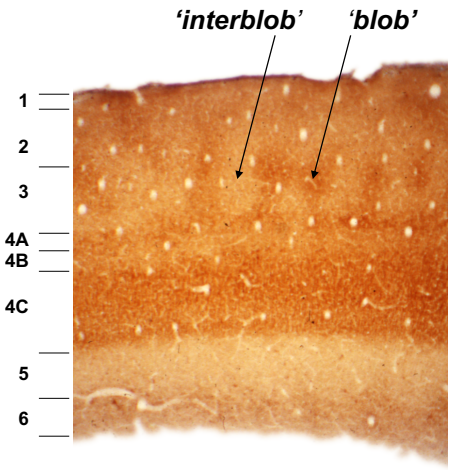

The parvocellular 'double-duty' theorem:
P cells signal luminance contrast at high spatial frequency;
P cells signal chromatic contrast at low spatial frequency.
ON – centre
OFF – surround
LW +
(MW & LW) –
Sinusoid grating
(high spatial frequency)
achromatic stimulus
Sinusoid grating
(high spatial frequency)
chromatic stimulus
Diffuse
(i.e. zero spatial frequency)
chromatic stimulus
Diffuse
(i.e. zero spatial frequency)
achromatic stimulus
baseline
baseline
baseline
baseline

21


PRIMARY VISUAL CORTEX (V1)
showing 'metabolic' compartments
(cytochrome oxidase histology)
Livingstone & Hubel (1984) [ref 4]
1
2
3
4A
4B
4C
5
6
2&3 'blob' – koniocellular input (blue ON)
4A – koniocellular input (blue OFF)
4C alpha – magnocellular input
4C beta – parvocellular input
By virtue of intrinsic relays from layer 4C:
Layer 4B has a dominant M input
Layer 2&3 has mixed K & P & M inputs

22

PRIMARY VISUAL CORTEX (V1)
showing 'metabolic' compartments
(*cytochrome oxidase* histology)
Livingstone & Hubel (1984) [ref 4]

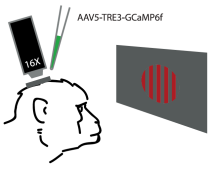


'blob' compartments are specialised for colour processing;
'interblob' compartments are specialised for high resolution form processing (i.e. orientation selective cells).

*

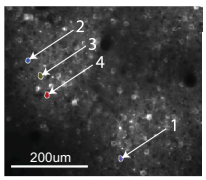
23

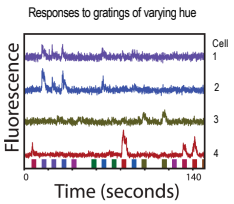
Two-photon imaging of monkey V1 blobs v interblobs
Garg *et al.* (2019) [ref 7]



viral vector **AAV-TRE-GCaMP6f:**
AAV = adeno-associated virus; **TRE** = promoter sequence, to induce transcription of viral genome;
GCaMP6f = a genetically encoded, artificial calcium indicator; in the presence of Ca^{++} ions, the GCaMP protein undergoes a change in conformation, becoming a potent fluorescent intracellular indicator of neuronal spiking activity.

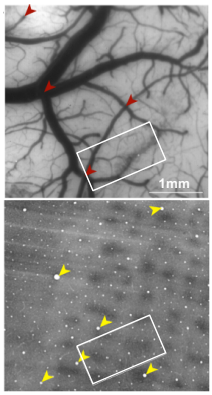
Visual stimuli: squarewave gratings, isoluminant with grey background, of varying hue & orientation; or achromatic, high contrast equivalent.

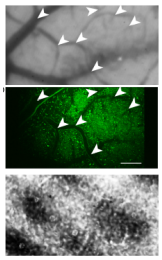




Determine each cell's stimulus selectivity by it's relative response to gratings of varied hue, orientation and direction of drift; also to achromatic gratings.

4351 cells were characterised !



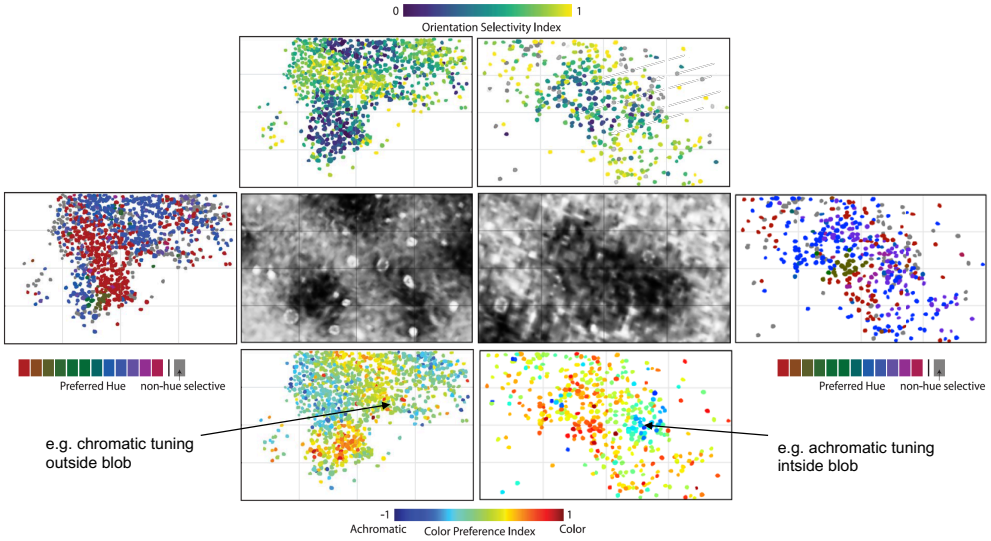


The pattern of cytochrome oxidase blobs is revealed by post-mortem histology.

Cell position with respect to blobs is determined by co-registration with pial-surface vasculature, and blood vessels seen in histological sections

24

Two-photon imaging of monkey V1 blobs v interblobs Garg *et al.* (2019) [ref 7]



NB. there is probably some residual, minor inaccuracy in the registration of the imaging data with the cytochrome oxidase staining (not commented on by authors).

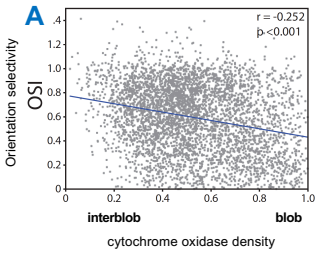
25

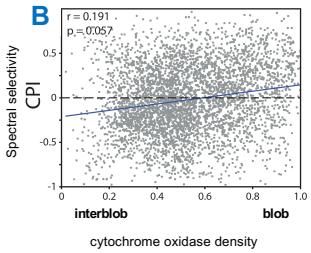
Two-photon imaging of monkey V1 blobs v interblobs Garg *et al.* (2019)[ref 7]

Conclusions:

1: Statistically, interblobs (i.e. the matrix of low cytochrome oxidase density) have higher levels of orientation selectivity (**A**), and lower levels spectral selectivity* (**B**), than blobs (focal regions of high cytochrome oxidae density); but

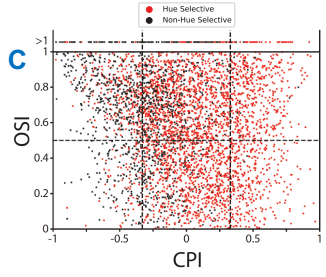
2: Cells that are both orientation and wavelength selective are numerous (**C**), and common in the interblobs.





OSI = orientation selectivity index
CPI = colour preference index

*** NB.**
'Spectral selectivity' is a better description than '*colour selectivity'*, as V1 cells respond to the spectral composition of light within their receptive fields, irrespective of the spectral reflectance (colour) of the surface from which that light is reflected *[recall videos shown in class !]*



The study uses two measures of spectral selectivity:

- *CPI ('colour preference index')* compares the cell's response to its preferred hue with its response to an achromatic stimulus ;
- '*Hue selectivity*' *(red data points above)* refers to the level of preference for one hue over other hues.

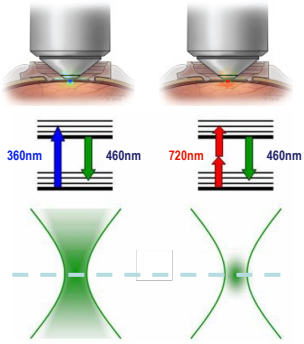
26

Two-photon excitation fluorescence microscopy

The two-photon microscope emits light at the excitatory wavelength, focused at a certain depth within the tissue, and images fluorescent light collected from this focal plane.

Single-photon elicited fluorescence:

- uses more energetic, short wavelength excitation (e.g. 360nm);
- undergoes more scatter within tissue;
- causes more photobleaching;
- less image resolution & contrast.



Two-photon elicited fluorescence:

- uses less energetic, longer wavelength excitation (e.g 720nm);
- undergoes less scatter within tissue, hence penetrates deeper;
- causes less photobleaching;
- higher image resolution & contrast;
- can examine greater depths within tissue.

The green shading signifies the vertical zone of tissue emitting fluorescence.
Single-photon fluorescence is proportional to the intensity of the illumination. Two-photon excitation depends upon the simultaneous absorption of two photons, so the resultant fluorescence emission intensity depends on the *square* of the illumination intensity; this property means that the fluorescent signals diminish at shorter distances above and below the focal plane, where the illumination intensity is greatest. Hence the image is more sharply focused in depth.

27

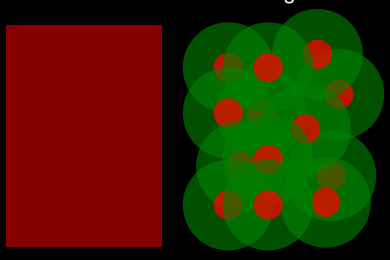
The parvocellular 'double-duty' theorem:

P cells signal chromatic contrast at low spatial frequency.
Extraction of chromatic contrast by cortex (V1)

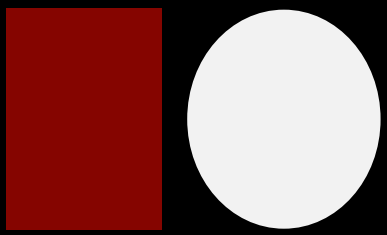
Hypothetical scheme for combination of parvo geniculate afferents

geniculate afferents

Diffuse
(i.e. zero spatial frequency)
chromatic stimulus

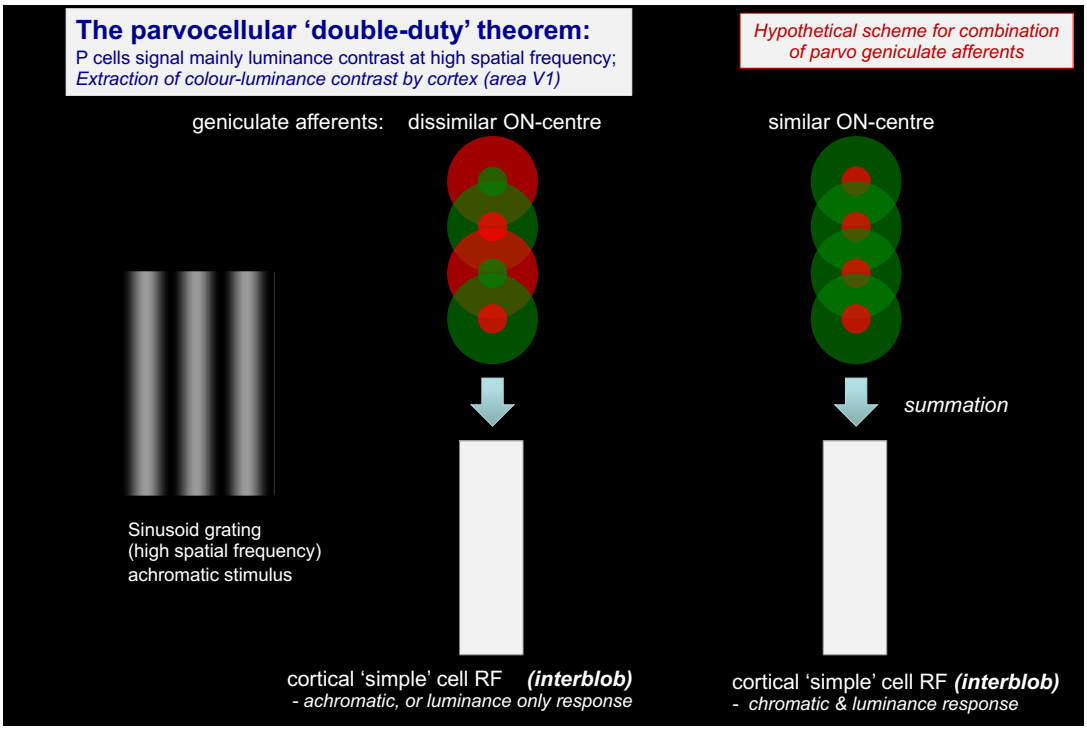


summation

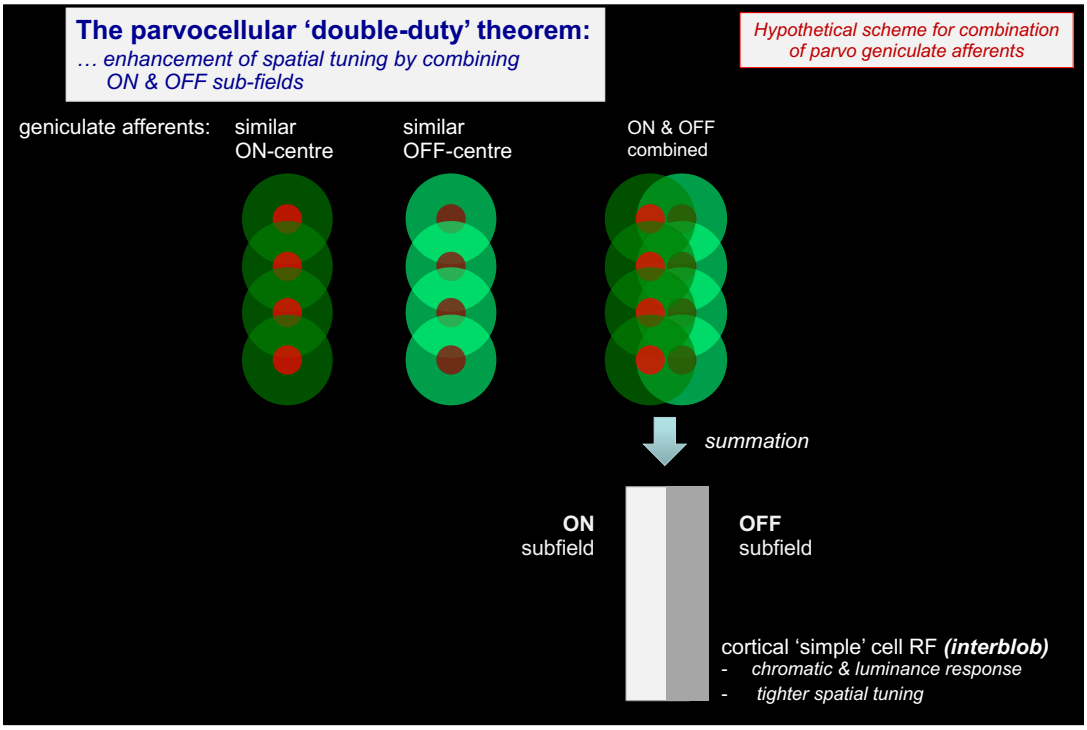


cortical colour ('single opponent') cell ***(blob)***

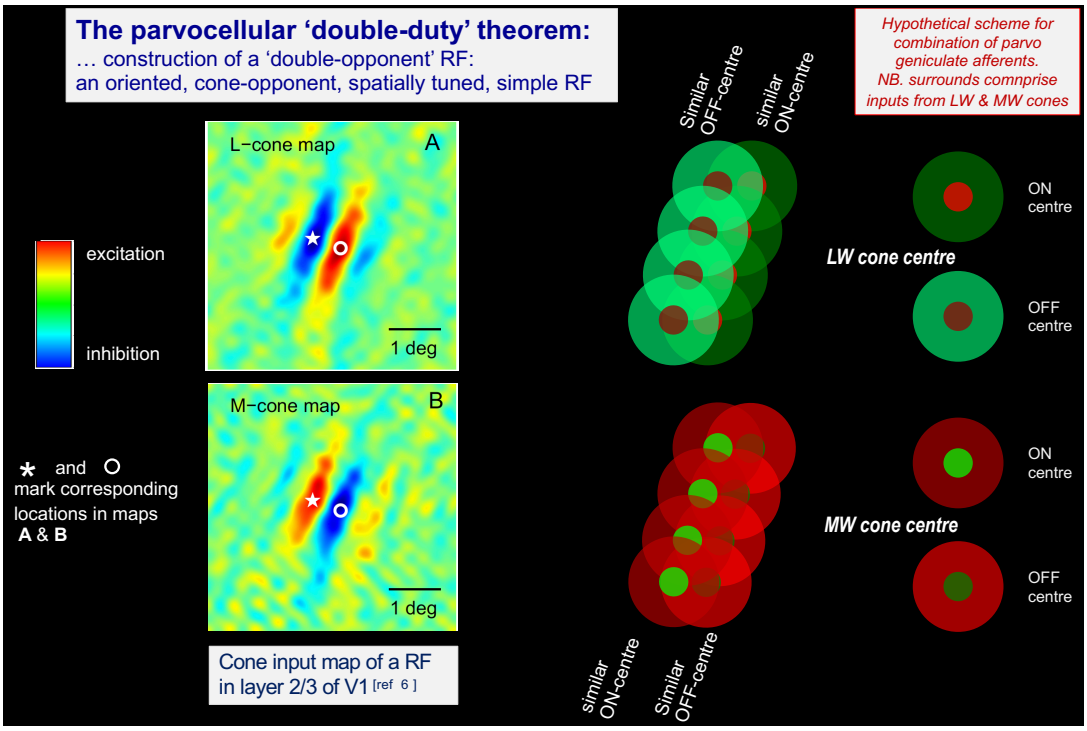
28


The parvocellular 'double-duty' theorem:
P cells signal mainly luminance contrast at high spatial frequency;
Extraction of colour-luminance contrast by cortex (area V1)
Hypothetical scheme for combination of parvo geniculate afferents
geniculate afferents:
dissimilar ON-centre
similar ON-centre
summation
Sinusoid grating
(high spatial frequency)
achromatic stimulus
cortical 'simple' cell RF (interblob)
- achromatic, or luminance only response
cortical 'simple' cell RF (interblob)
- chromatic & luminance response

29


The parvocellular 'double-duty' theorem:
… enhancement of spatial tuning by combining ON & OFF sub-fields
Hypothetical scheme for combination of parvo geniculate afferents
geniculate afferents:
similar ON-centre
similar OFF-centre
ON & OFF combined
summation
ON subfield
OFF subfield
cortical 'simple' cell RF (interblob)
- chromatic & luminance response
- tighter spatial tuning

30


The parvocellular 'double-duty' theorem:
… construction of a 'double-opponent' RF:
an oriented, cone-opponent, spatially tuned, simple RF
Hypothetical scheme for combination of parvo geniculate afferents. NB. surrounds comnprise inputs from LW & MW cones
L−cone map
A
excitation
inhibition
1 deg
M−cone map
B
1 deg
* and O mark corresponding locations in maps A & B
Cone input map of a RF in layer 2/3 of V1 [ref 6]
Similar OFF-centre
similar ON-centre
ON centre
LW cone centre
OFF centre
ON centre
MW cone centre
OFF centre
similar ON-centre
Similar OFF-centre

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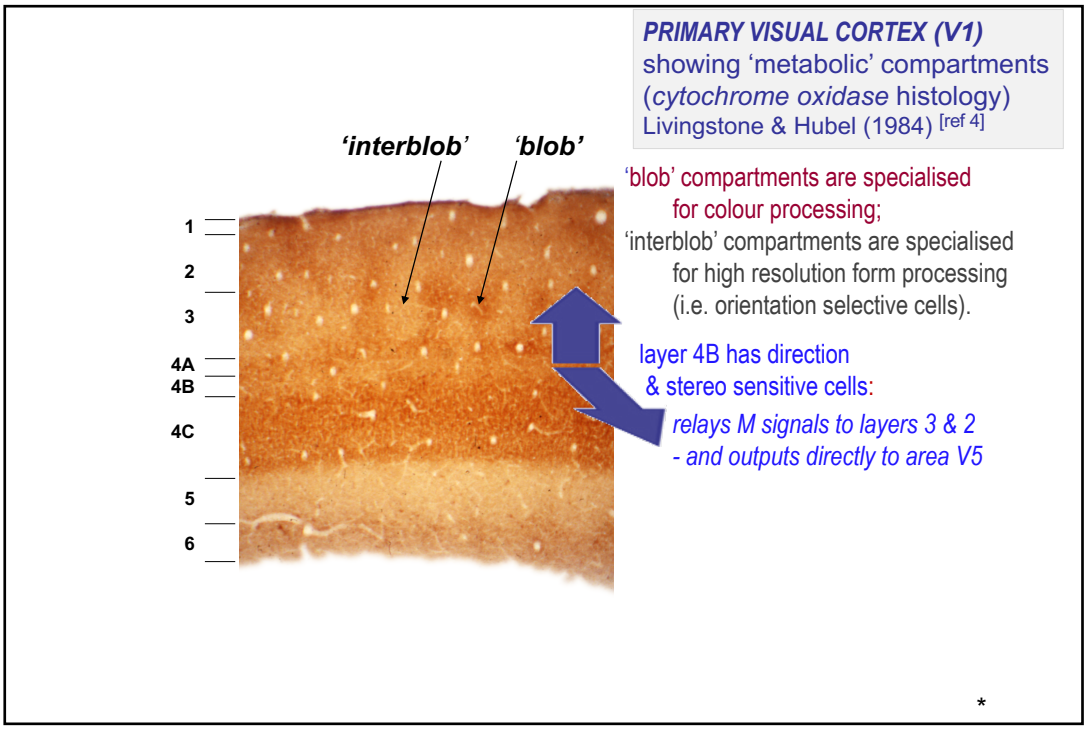
PRIMARY VISUAL CORTEX (V1)
showing 'metabolic' compartments
(cytochrome oxidase histology)
Livingstone & Hubel (1984) [ref 4]
'interblob'
'blob'
1
2
3
4A
4B
4C
5
6
'blob' compartments are specialised for colour processing;
'interblob' compartments are specialised for high resolution form processing (i.e. orientation selective cells).
layer 4B has direction & stereo sensitive cells:
relays M signals to layers 3 & 2 - and outputs directly to area V5
*

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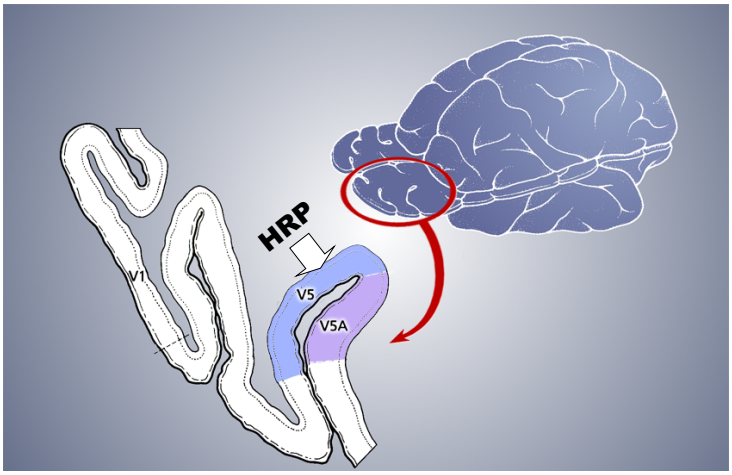
What is the source of input to area V5 ?



HRP (horseradish peroxidase) is a bidirectional tracer of connections: it is taken up by axonal terminals and transported retrogradely to cell bodies; it is also taken up by cell bodies, and transported anterogradely to axonal terminals.

HRP is an enzyme (extracted from the horseradish plant) that catalyses chemical reactions of peroxide.

Procedure: inject tracer, & allow 2-3 days survival for axon transport, prior to histology (incubate brain sections with substrate & peroxide)

HISTOLOGY: substrate + hydrogen peroxide $\xrightarrow[\text{CATALYST}]{\text{HRP}}$ deep blue reaction product

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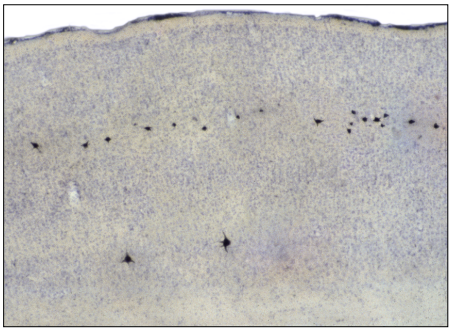
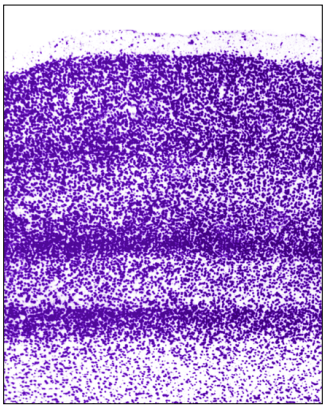
V1 – laminar source of projections to V5
Shipp & Zeki 1989 [ref 8]



4B

6

Retrogradely-labelled cells in layers 4B & 6 of area V1;
- axons of these cells project to area V5.



1
2
3
4A
4B
4C
5
6

Cytoarchitecture of V1 to show layers.

This is a demonstration of retrograde connections using the neural tracer 'HRP' (horseradish peroxidase).

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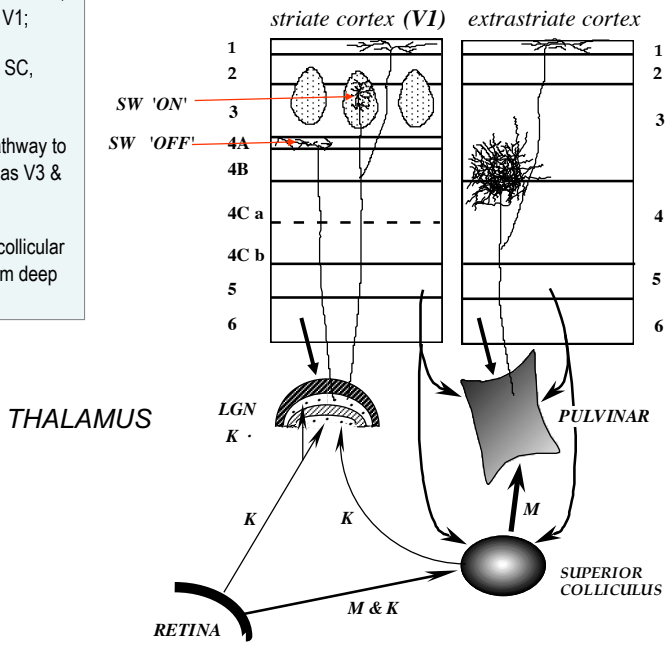
NB:

- Konio pathway from retina, to LGN, to blobs & layers 1 & 4A of V1;
- Konio pathway to LGN, via SC, lacks SW (blue) sensitivity;
- 'LGN/V1 bypass' magno pathway to extrastriate cortex (i.e. areas V3 & V5) via SC & pulvinar;
- Cortico-thalamic & cortico-collicular feedback loops, issuing from deep layers (5 & 6).

Some other retino-thalamo-cortical pathways



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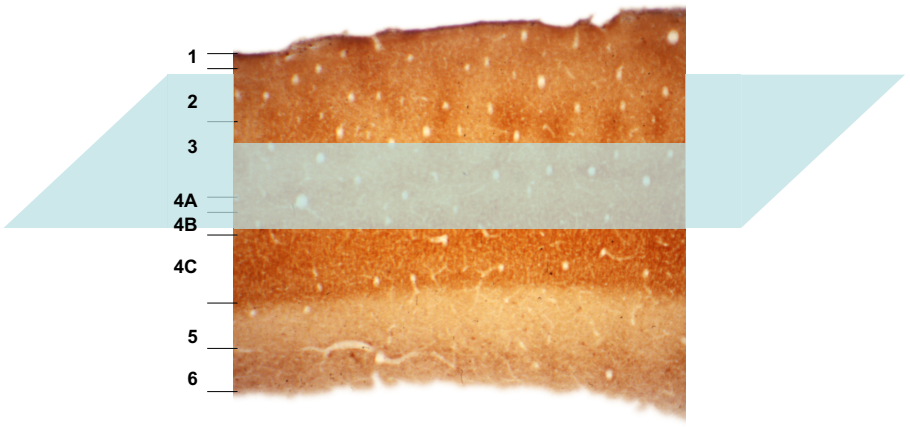
PRIMARY VISUAL CORTEX (V1)
showing metabolic compartments
(cytochrome oxidase histology)



Tangential plane of section
(parallel to cortical layering)
- as shown in next slide

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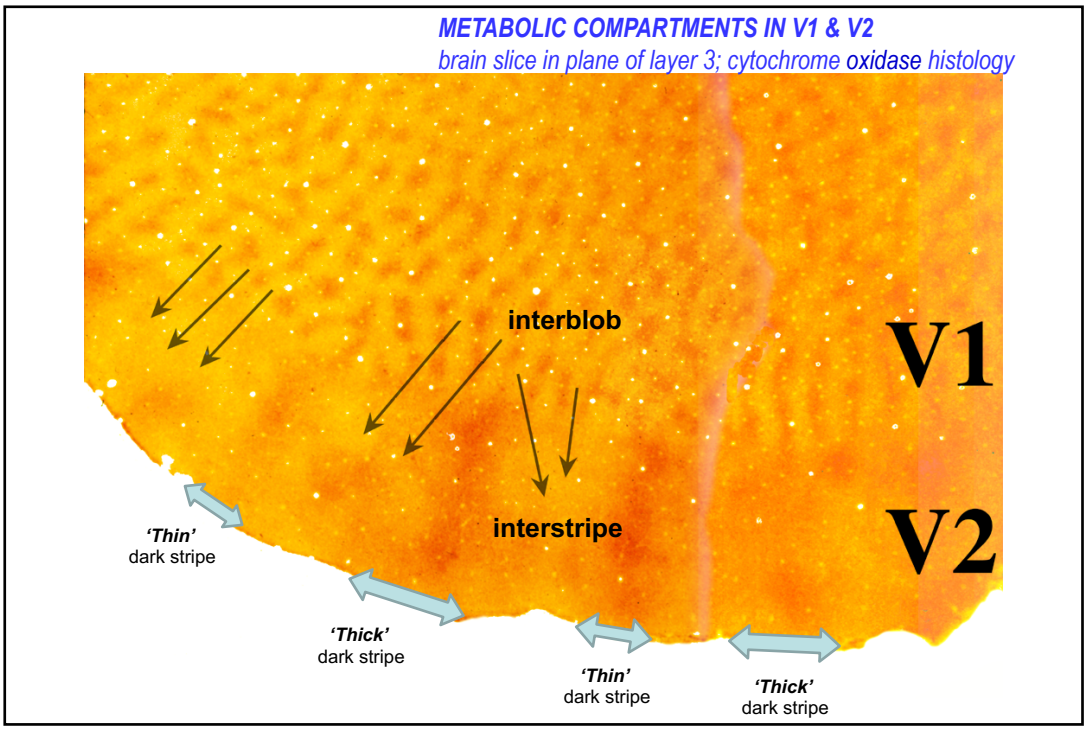
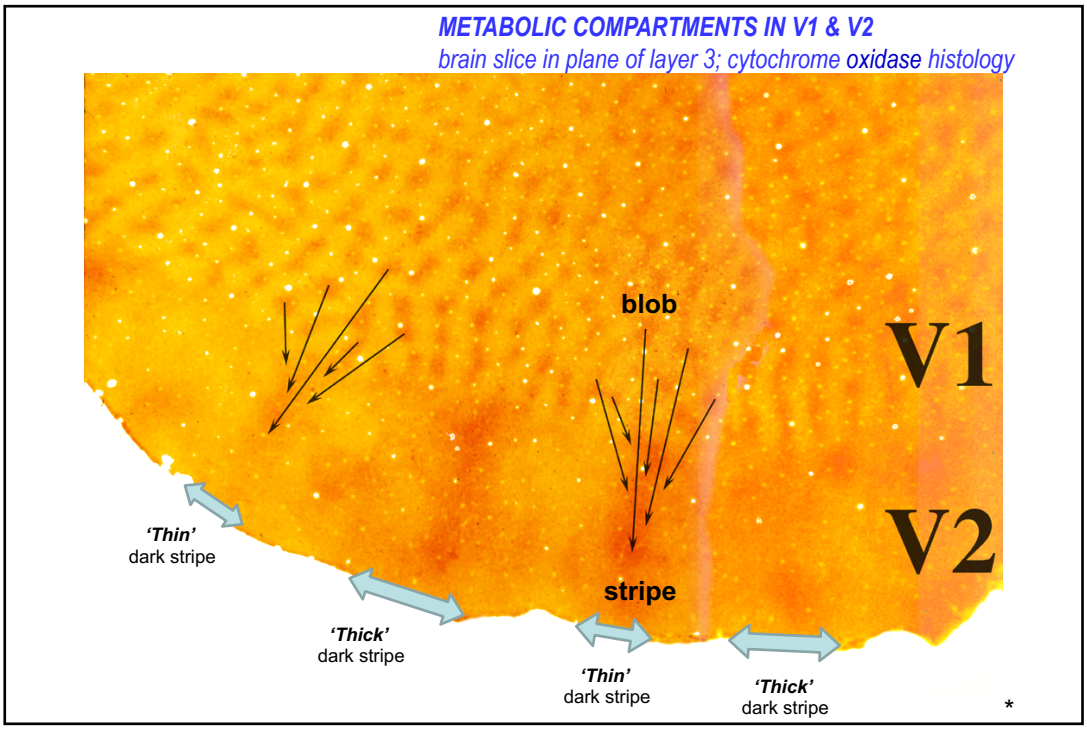
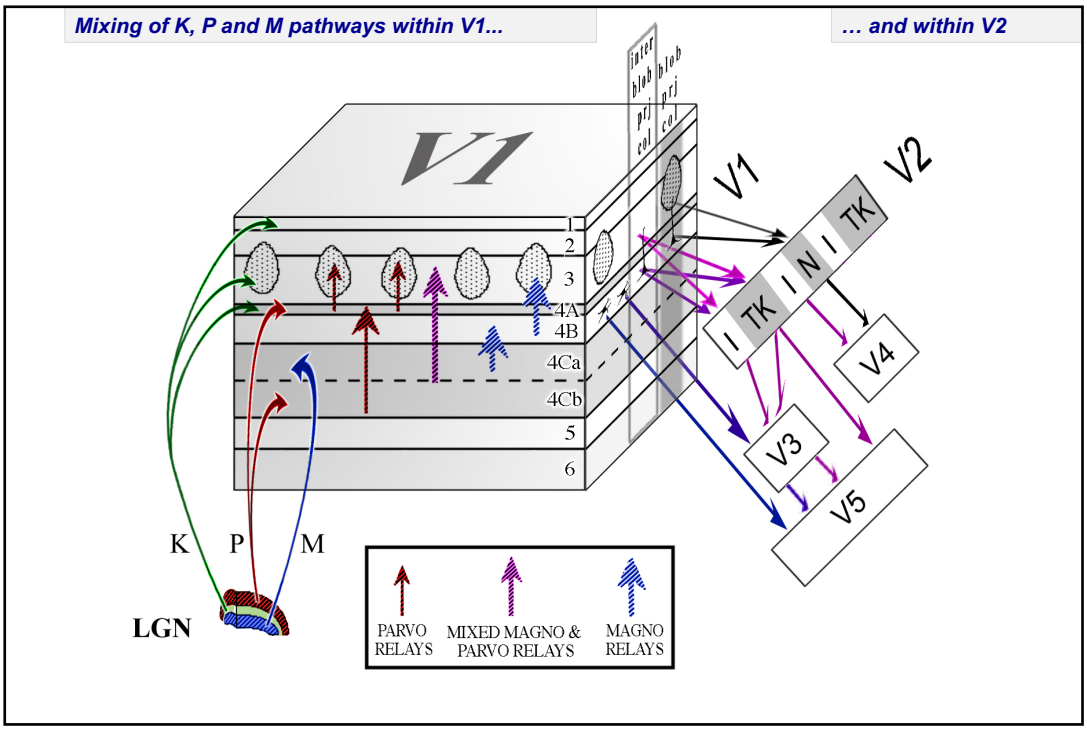

METABOLIC COMPARTMENTS IN V1 & V2
brain slice in plane of layer 3; cytochrome oxidase histology
interblob
interstripe
V1
V2
'Thin'
dark stripe
'Thick'
dark stripe
'Thin'
dark stripe
'Thick'
dark stripe

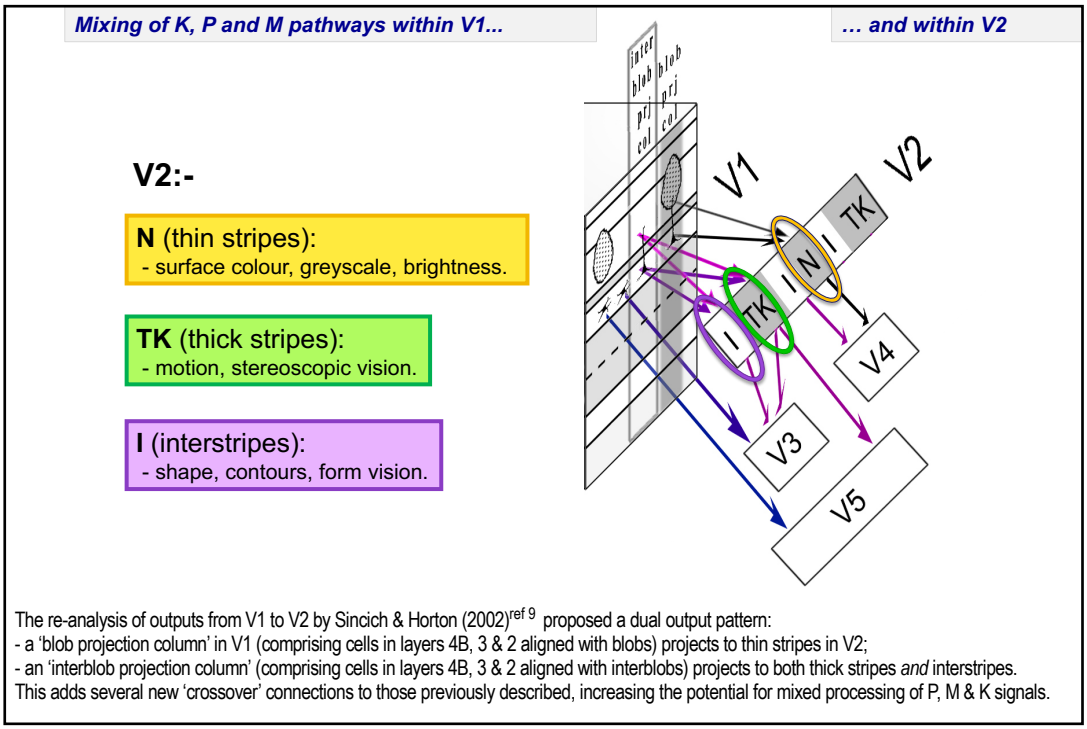
37


METABOLIC COMPARTMENTS IN V1 & V2
brain slice in plane of layer 3; cytochrome oxidase histology
blob
stripe
V1
V2
'Thin'
dark stripe
'Thick'
dark stripe
'Thin'
dark stripe
'Thick'
dark stripe
*

38



39



The re-analysis of outputs from V1 to V2 by Sincich & Horton (2002)[ref 9] proposed a dual output pattern:
- a 'blob projection column' in V1 (comprising cells in layers 4B, 3 & 2 aligned with blobs) projects to thin stripes in V2;
- an 'interblob projection column' (comprising cells in layers 4B, 3 & 2 aligned with interblobs) projects to both thick stripes *and* interstripes.
This adds several new 'crossover' connections to those previously described, increasing the potential for mixed processing of P, M & K signals.

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RECEPTIVE FIELD PROPERTIES OF MODULES IN V1 & V2

TUNING	BLOBS (V1) THIN STRIPES (V2)	INTERBLOBS (V1) INTERSTRIPES (V2)	LAYER 4B (V1) THICK STRIPES (V2)
Spectral	prevalent	some	negligible
Orientation	negligible	prevalent	prevalent
Direction	negligible	negligible	substantial
Stereo	negligible	negligible	prevalent
Spatial	low frequency	high frequency	mixed

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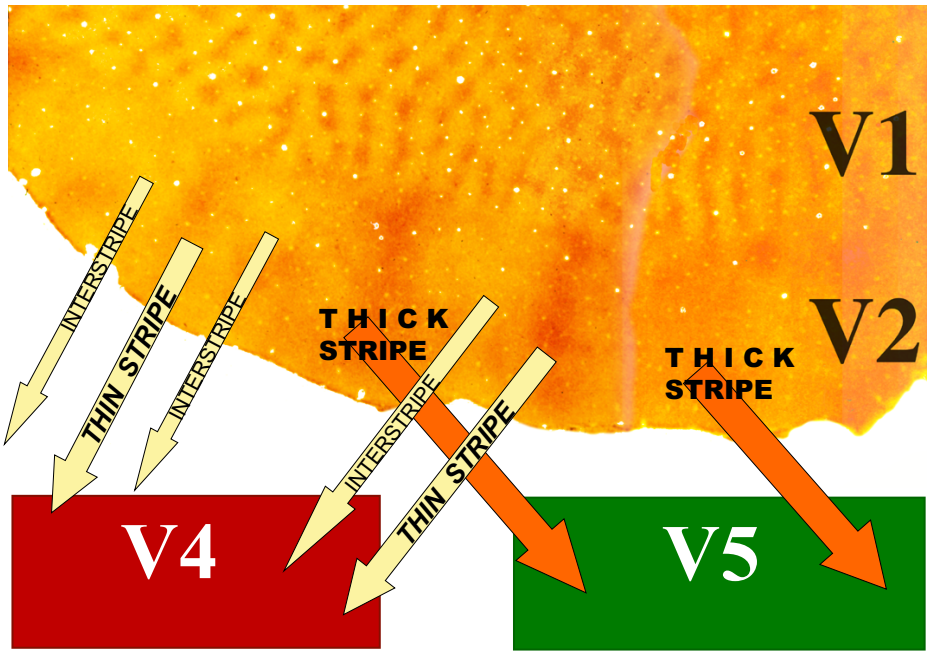
SPECIFIC OUTPUTS FROM V2 STRIPES



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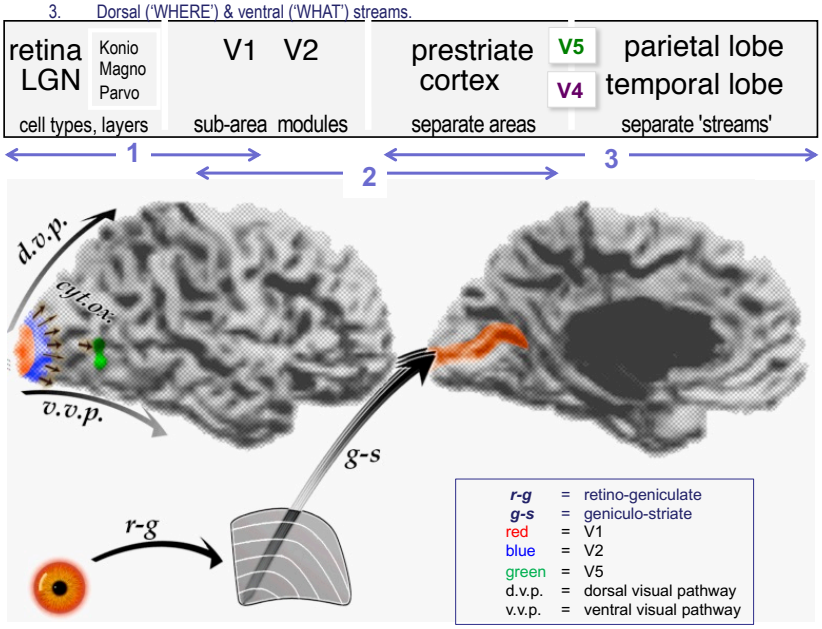
Three separate levels of organisation in parallel visual pathways:

1. Magno, Parvo & Konio retino-geniculo-cortical pathways;
2. Cytochrome oxidase modules in areas V1 & V2;
3. Dorsal ('WHERE') & ventral ('WHAT') streams.



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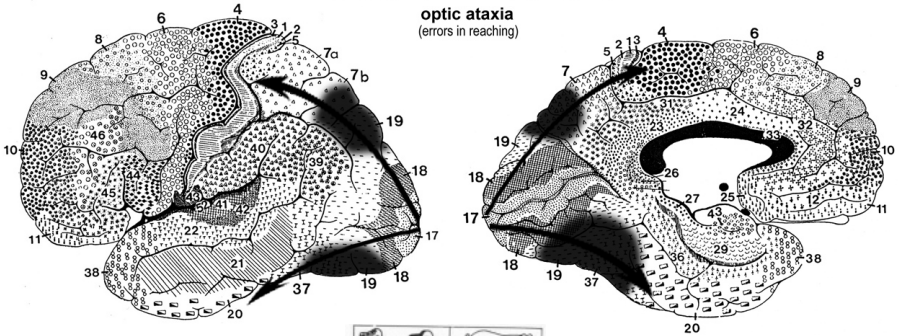
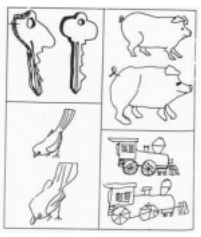
THE TWO VISUAL PATHWAYS DOGMA

Dorsal 'WHERE' pathway

optic ataxia
(errors in reaching)



"I don't know"



"Could be a dog or any other animal"

Ventral 'WHAT' pathway

"Could be a branch stump" ?

"A wagon, or a car of some sort" ?

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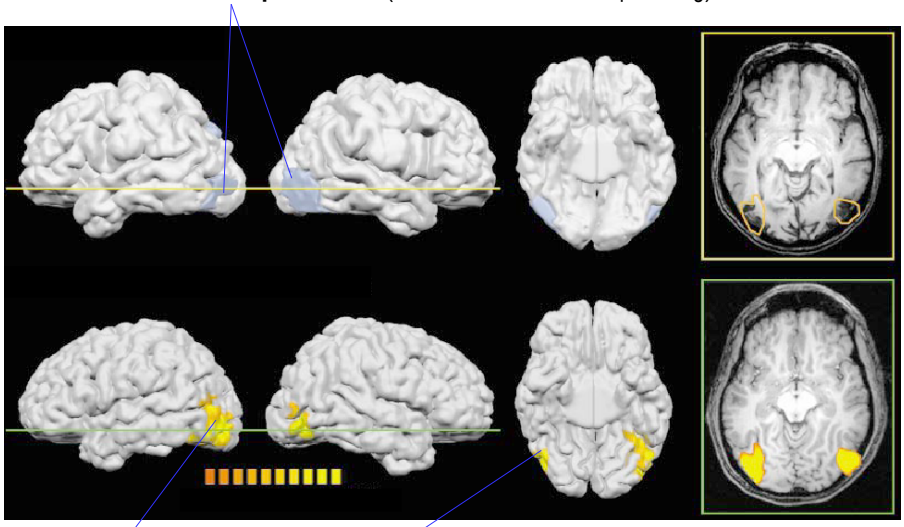
Ventral occipital lesions impair object recognition but not object-directed grasping: an fMRI study.
James et al. (2003) [ref 11]

Area LO and agnosia

brain lesions in **patient DF** (case of carbon monoxide poisoning)



area LO in a normal subject

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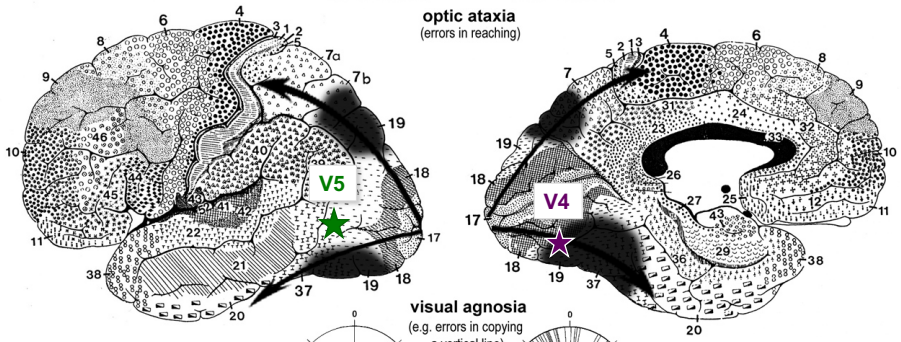
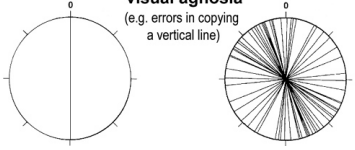
THE TWO VISUAL PATHWAYS DOGMA

Dorsal 'WHERE' pathway
*or **vision for action***

optic ataxia
(errors in reaching)



visual agnosia
(e.g. errors in copying a vertical line)



(patient DF)

Ventral 'WHAT' pathway
*or **vision for perception***

David Milner &
Melvyn Goodale

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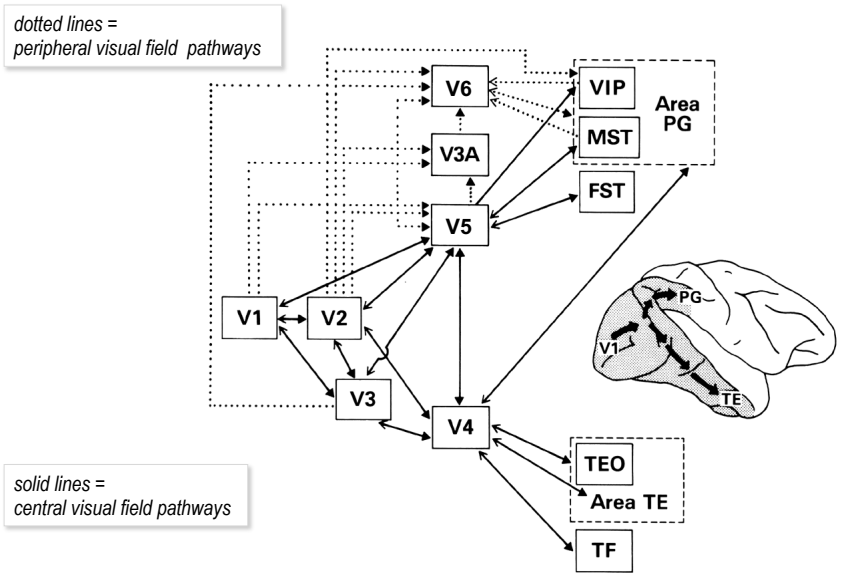
Two Visual Pathways Dogma: Leslie Ungerleider & Mortimer Mishkin



Ungerleider et al: *two visual pathways, circa 1986* [ref 12]

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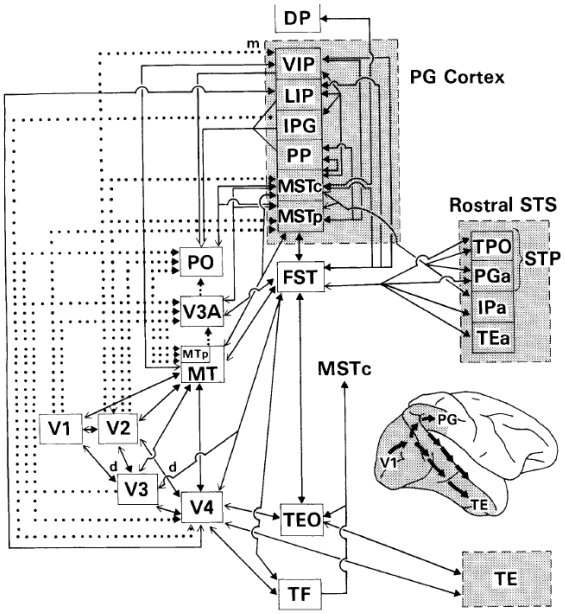
Ungerleider et al:

two visual pathways, circa 1990 [ref 13]

Introduces a 'third processing stream' leading to rostral superior temporal lobe.



solid arrowheads = *forward* connections
open arrowheads = *backward* connections
reciprocal solid arrowheads = *intermediate* or *lateral* connections

solid lines = central visual field pathways
dotted lines = peripheral visual field pathways
shaded areas = terminal stations

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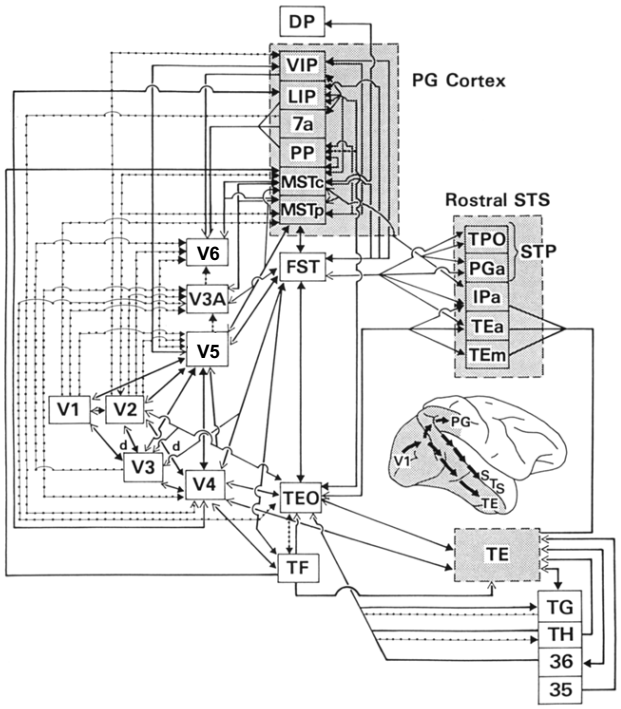
Ungerleider et al:

two visual pathways, circa 1993 [ref 14]

Maintaining & extending the territory of the third pathway



solid arrowheads = *forward* connections
open arrowheads = *backward* connections
reciprocal solid arrowheads = *intermediate* or *lateral* connections

solid lines = central visual field pathways
dotted lines = peripheral visual field pathways
shaded areas = terminal stations

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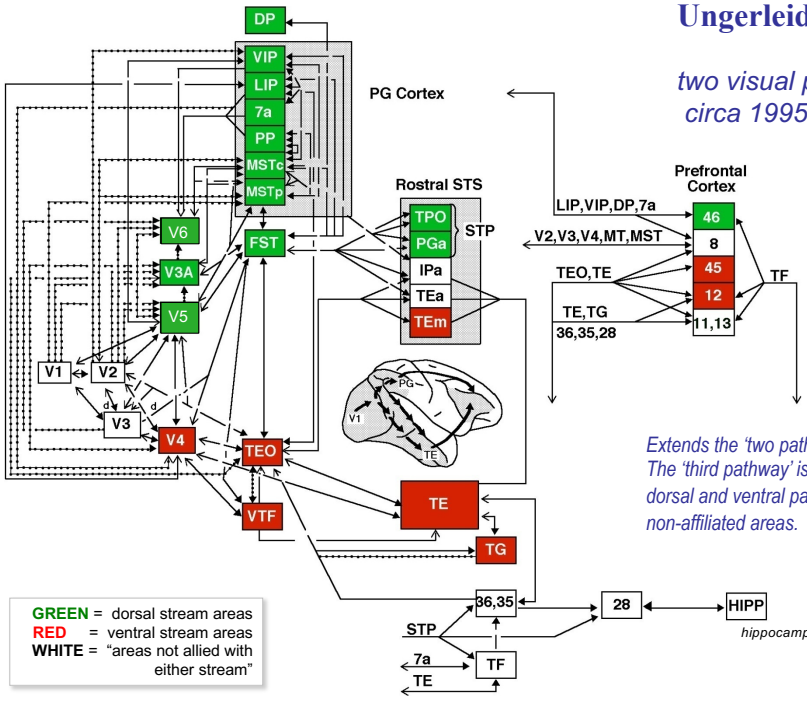
Ungerleider et al:

two visual pathways, circa 1995 [ref 15]



Extends the 'two pathways' to the frontal lobe. The 'third pathway' is now absorbed into the dorsal and ventral pathways, but leaving two non-affiliated areas.

GREEN = dorsal stream areas
RED = ventral stream areas
WHITE = "areas not allied with either stream"

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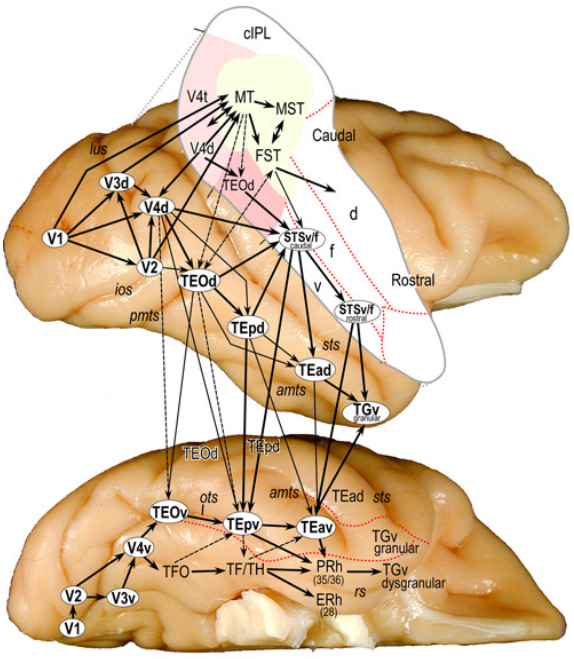
Ungerleider et al:

the ventral visual pathway, circa 2013 [ref 16]



areas MT/V5, MST & FST now shown as constituents of the ventral pathway.

Kravitz DJ… Ungerleider LG & Mishkin M (2013)
The ventral visual pathway: an expanded neural framework for the processing of object quality
Trends in Cognitive Sciences 17: 26-49.

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