Introduction to Neuroscience: Systems Neuroscience

Central visual processes

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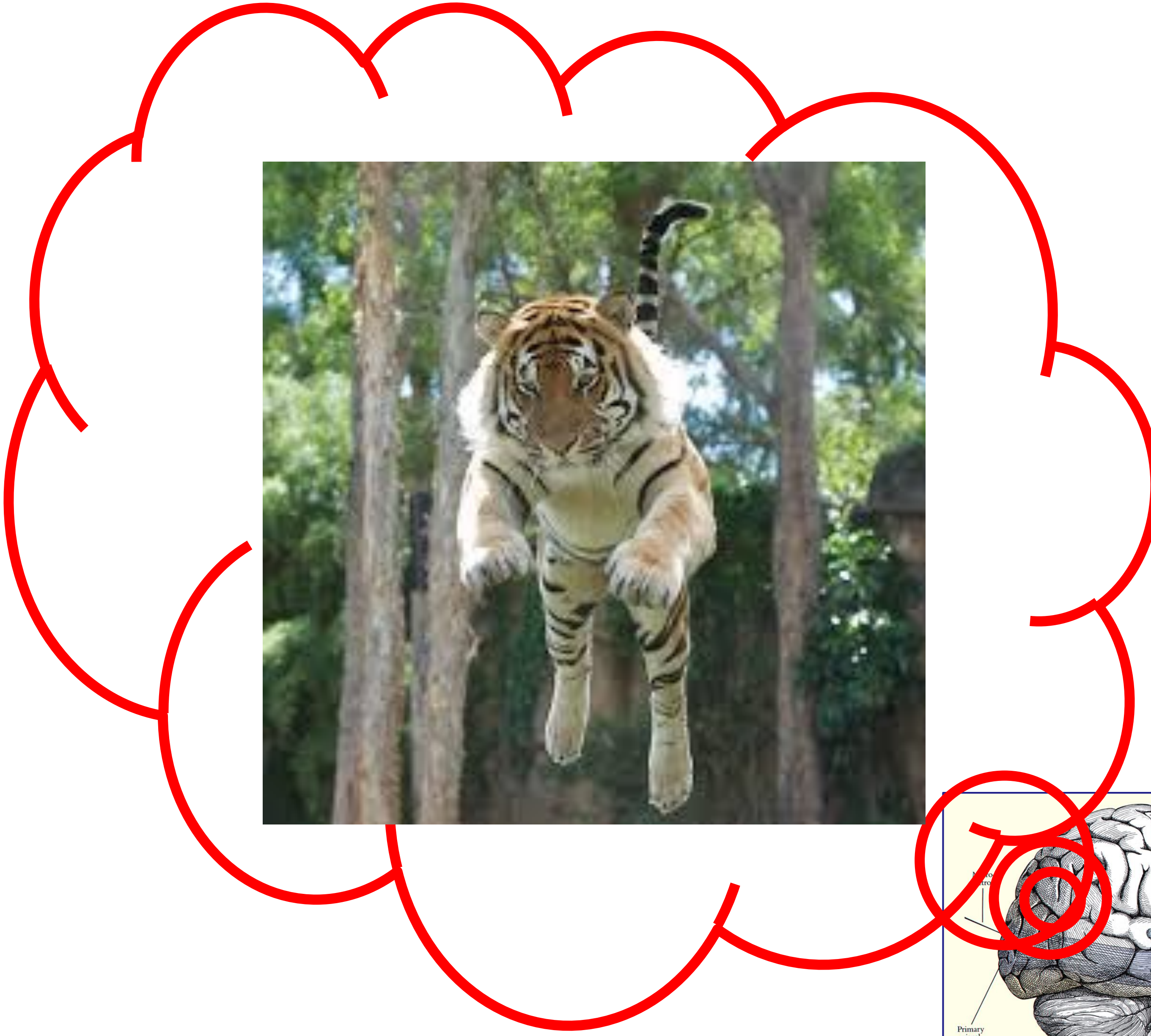
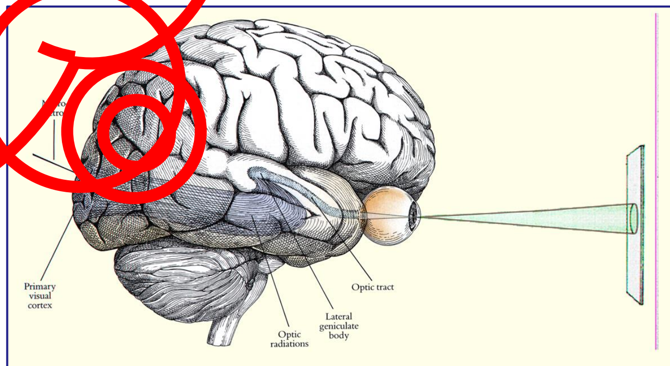
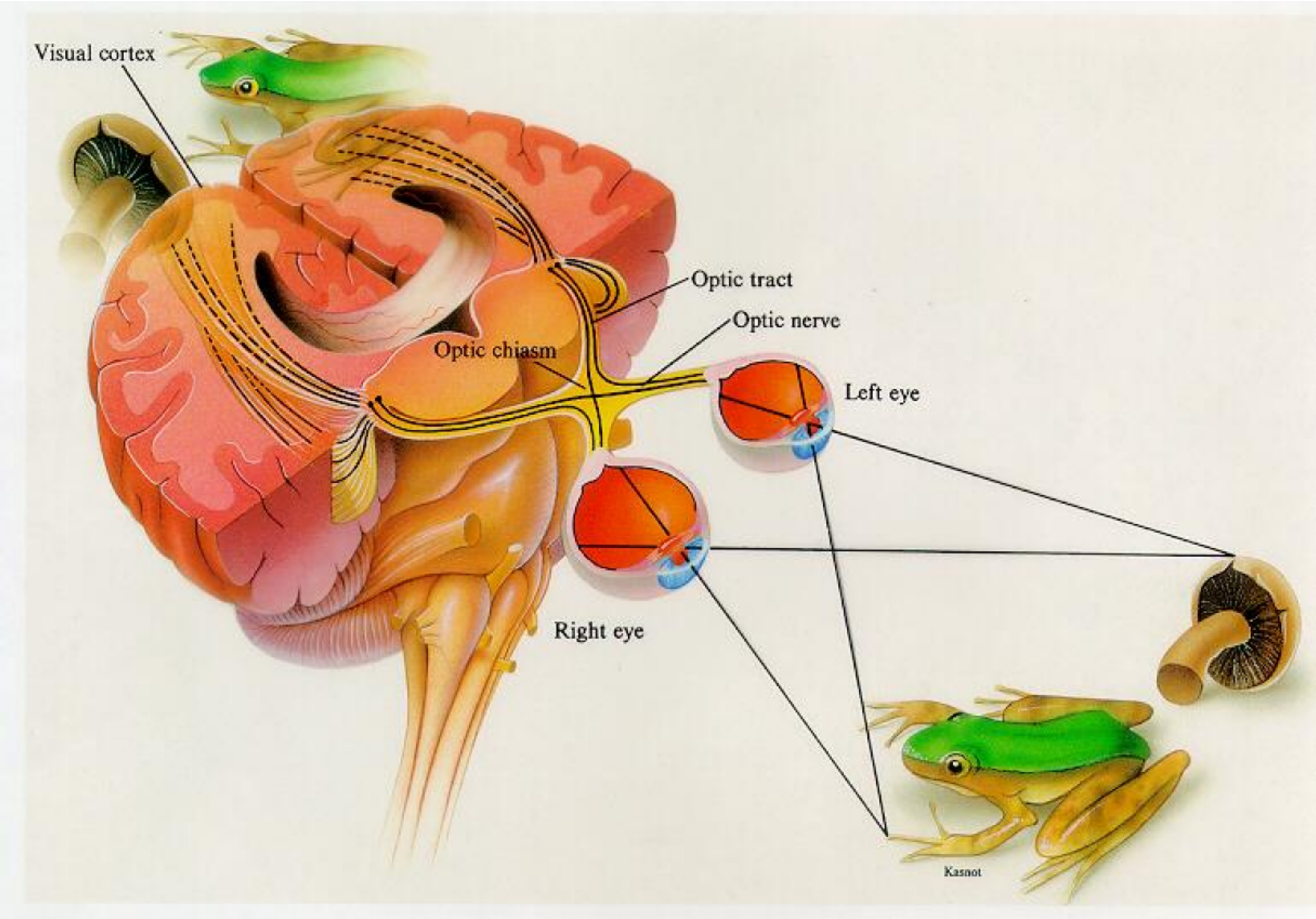
What is the function of the visual system?

Creating an adaptive model of the environment

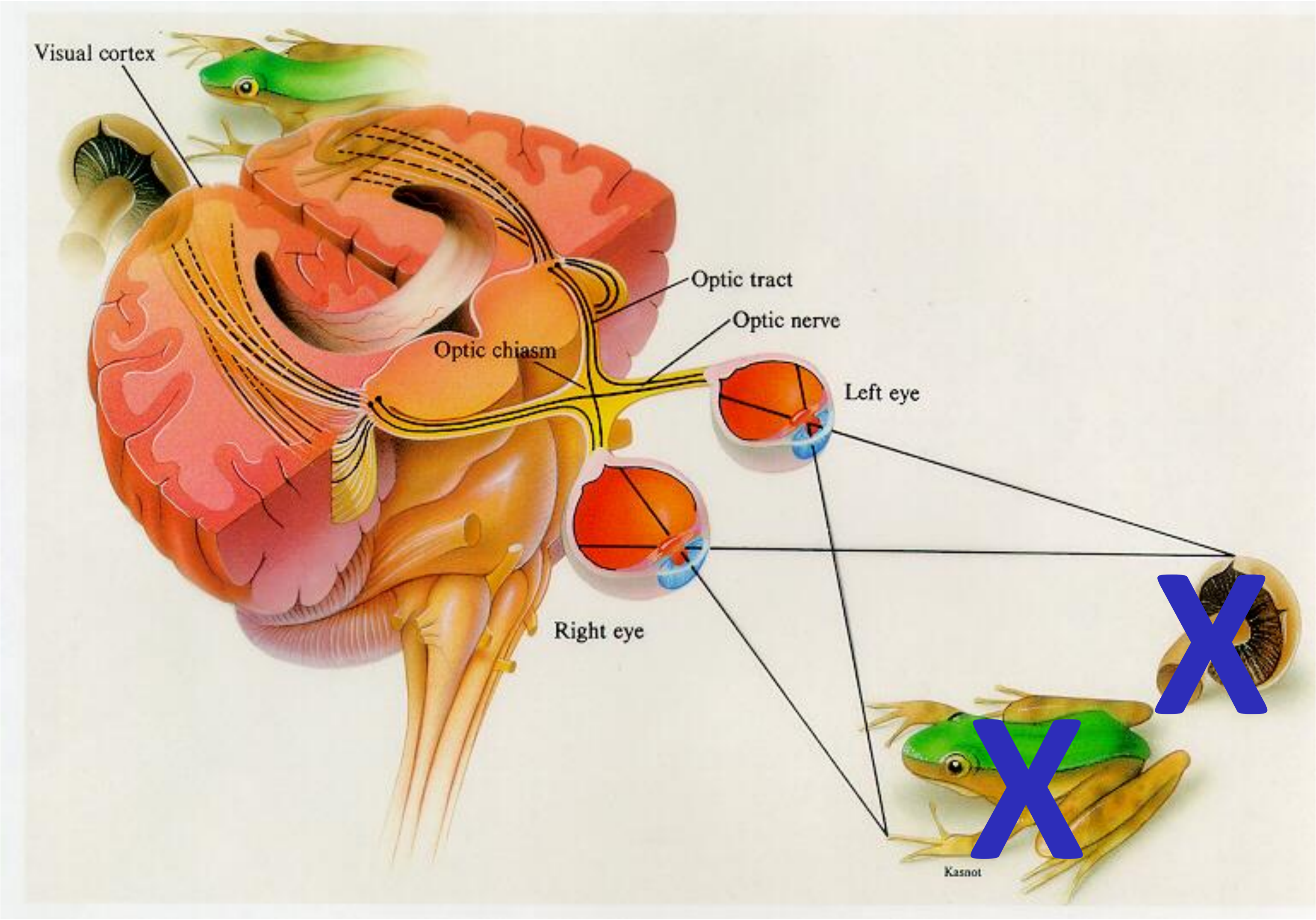




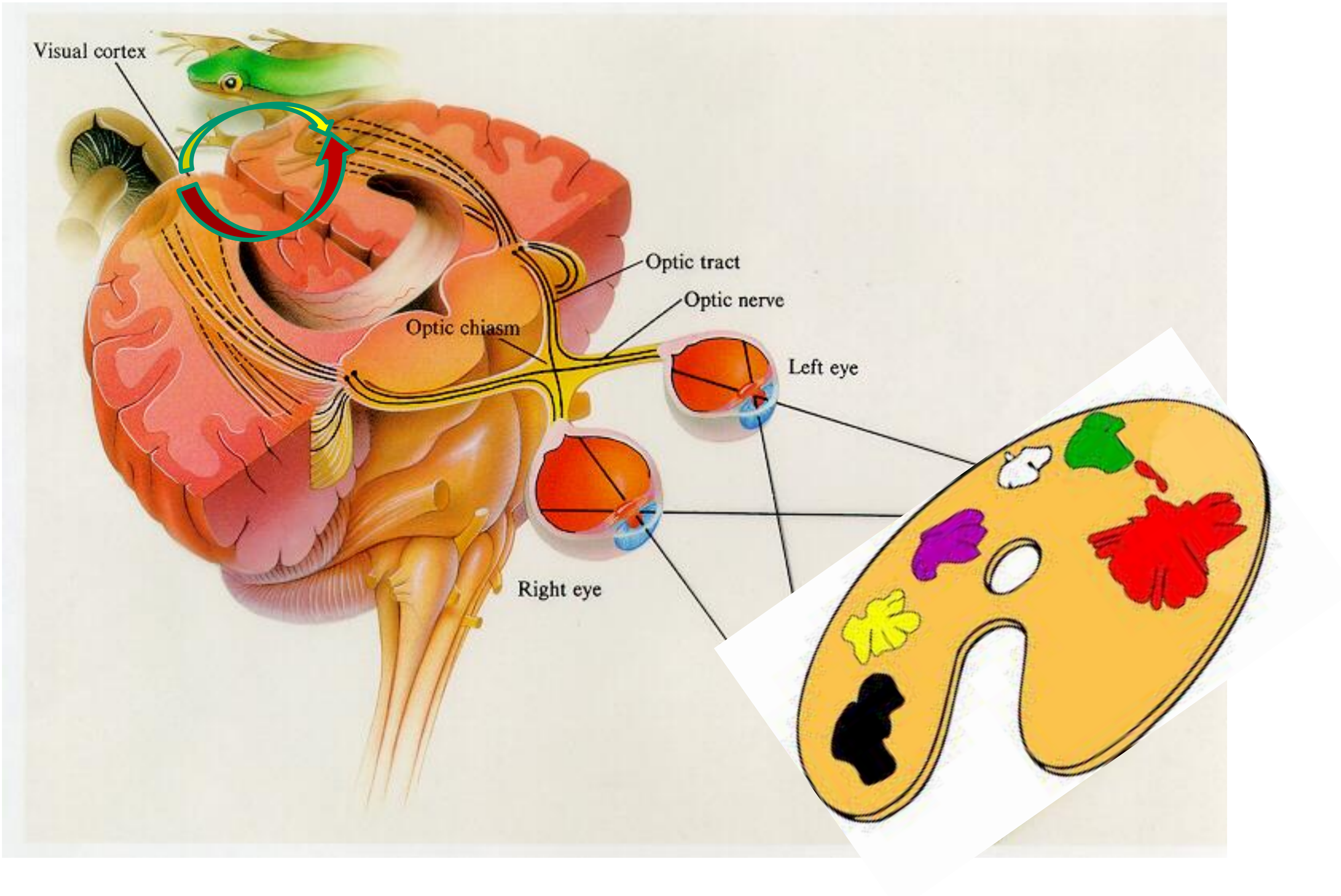
The representation model of visual perception



We do not see the external environment- only the model our visual system generates

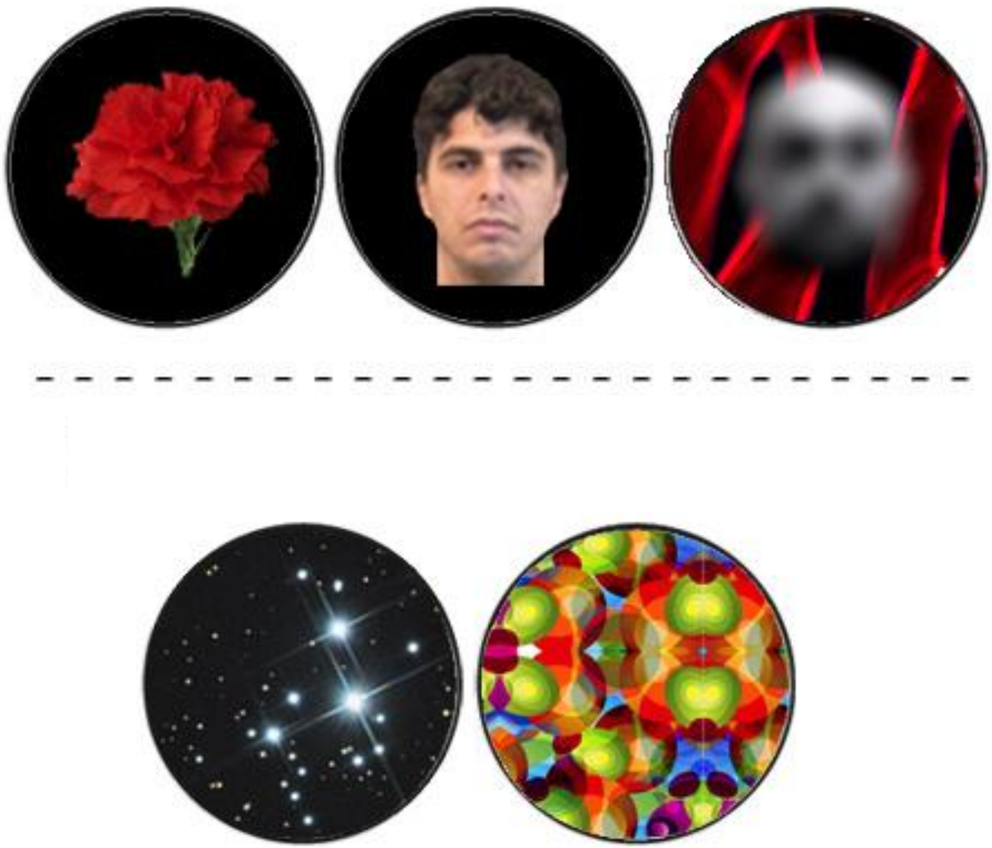


The external reality is infinite and incomprehensible- our vision selects from it materials with which it constructs its model



Totally blind individuals can see vivid visual images

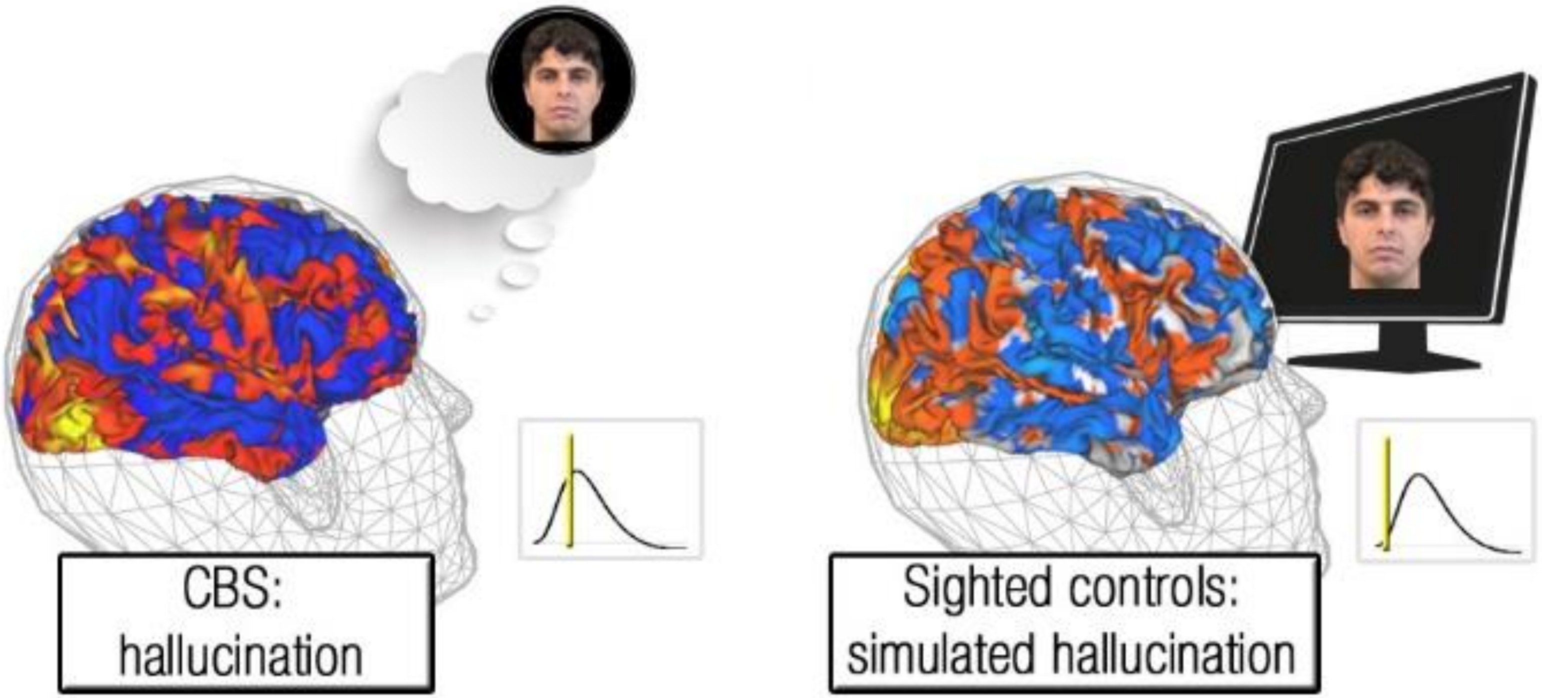
The Charles Bonnet Syndrome



Examples of visual hallucinations in late- blind individuals

Avital Hahamy, Marlene Behrmann

The visual system is activated during hallucinations similarly to normal vision



Avital Hahamy et. al.

Creating an adaptive model of the environment

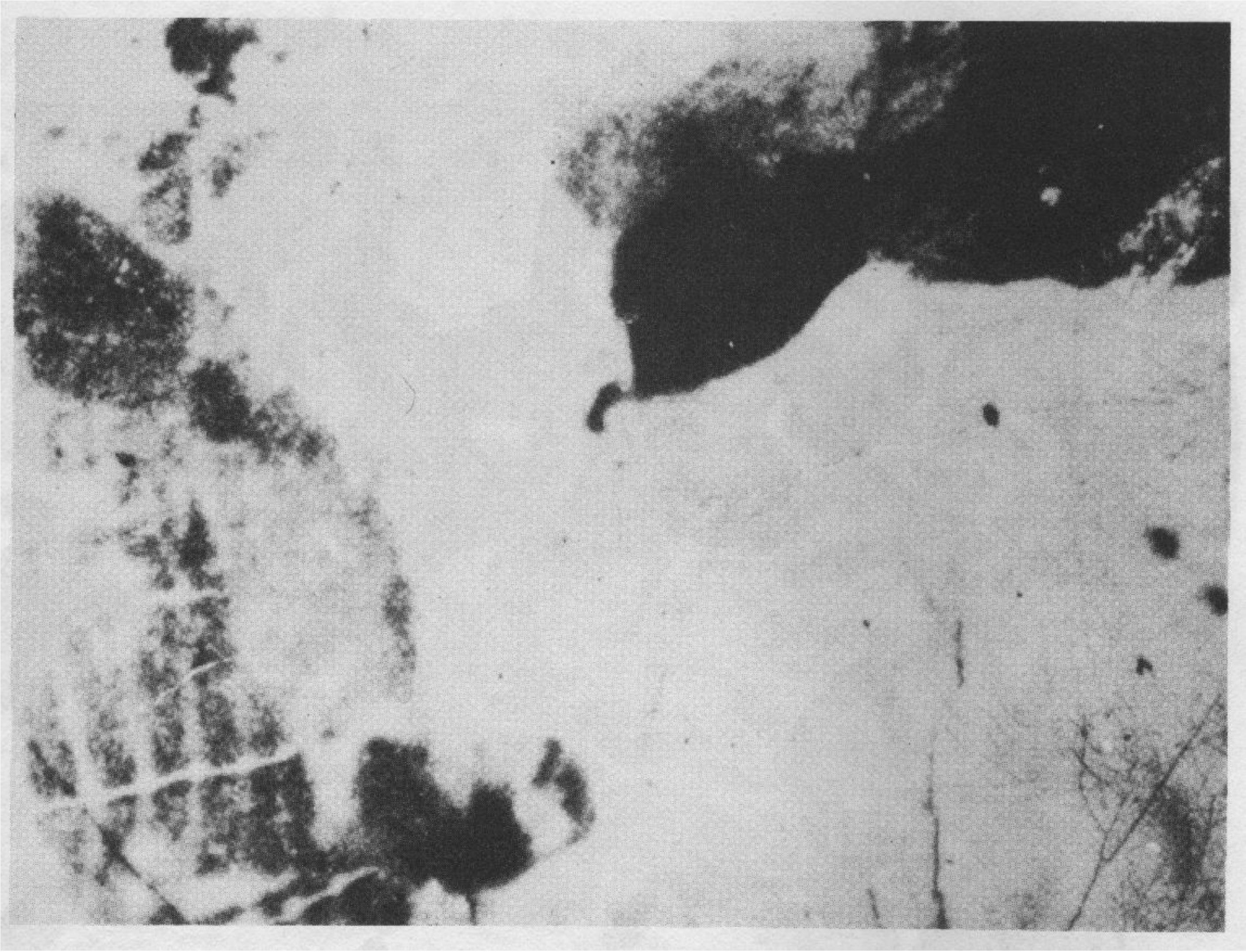
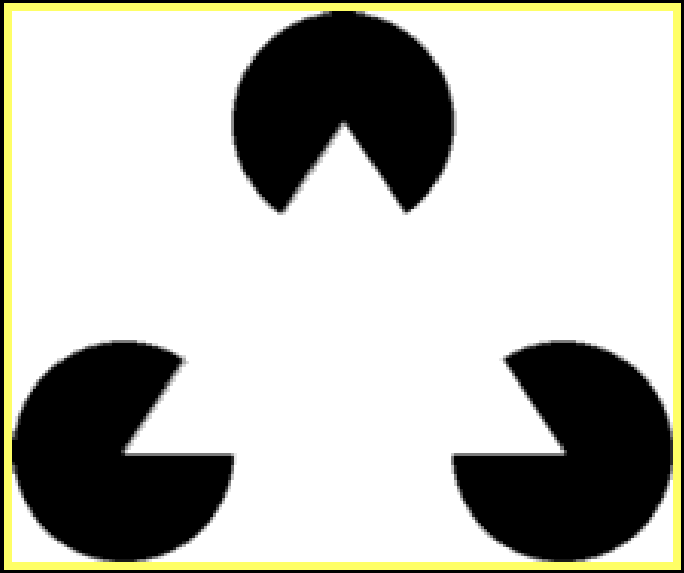


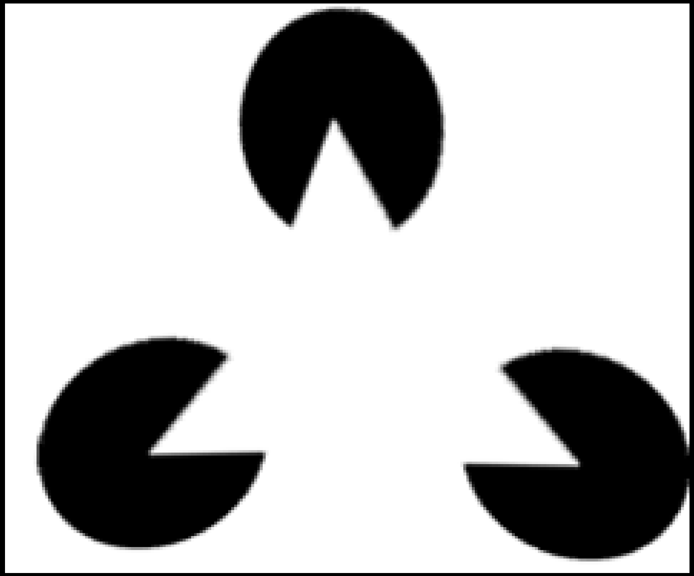
Illustration of the creative and adaptive nature of vision

Illusory Shapes contradict external information

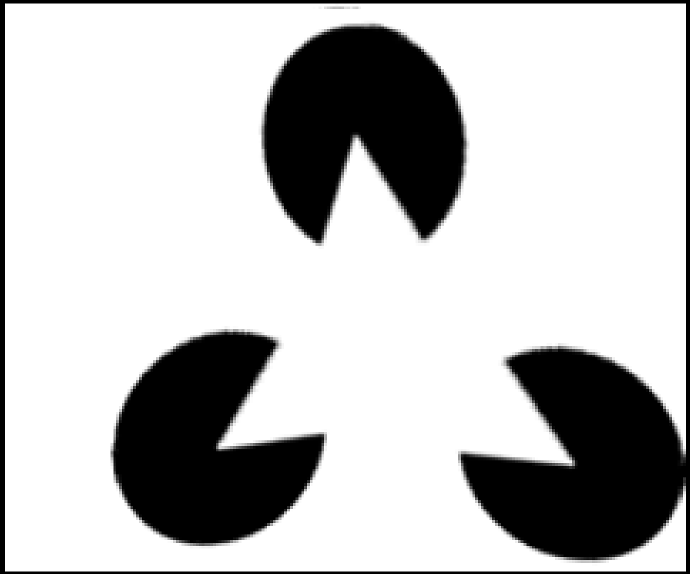


The Kanizsa Triangle

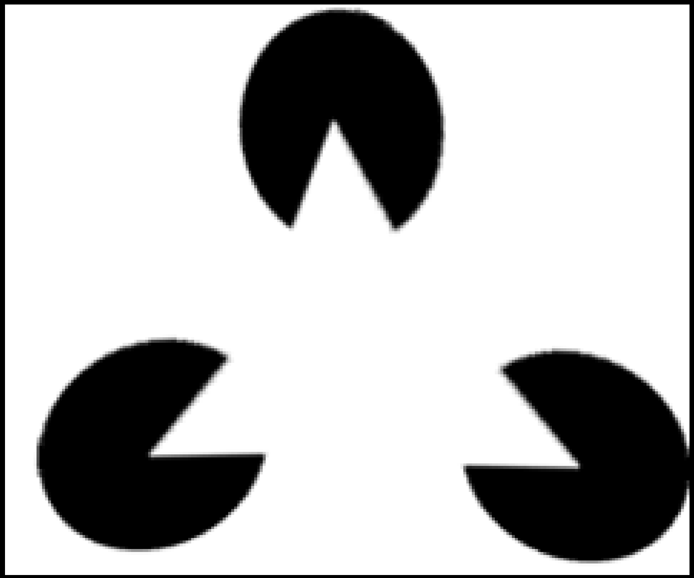
The motion illusion



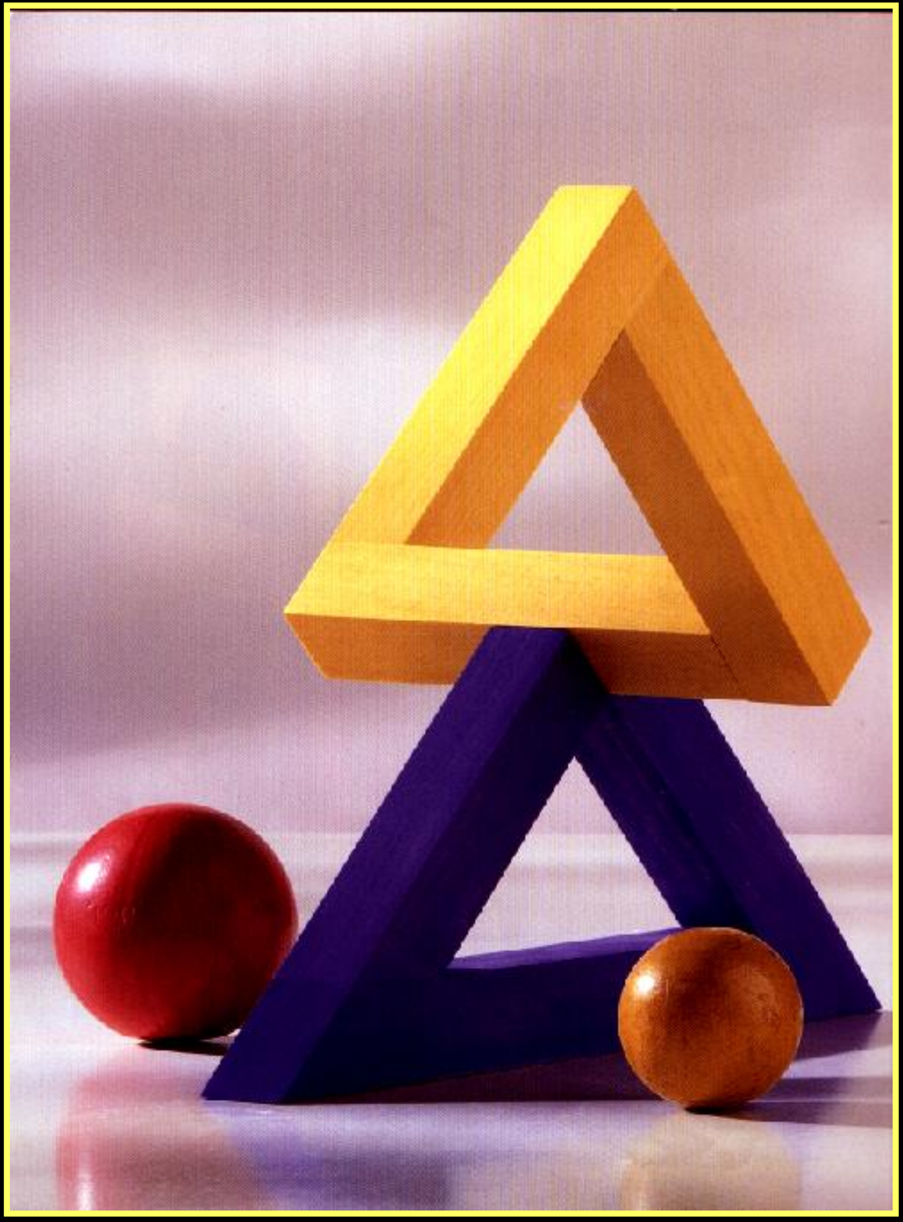
The motion illusion



The motion illusion



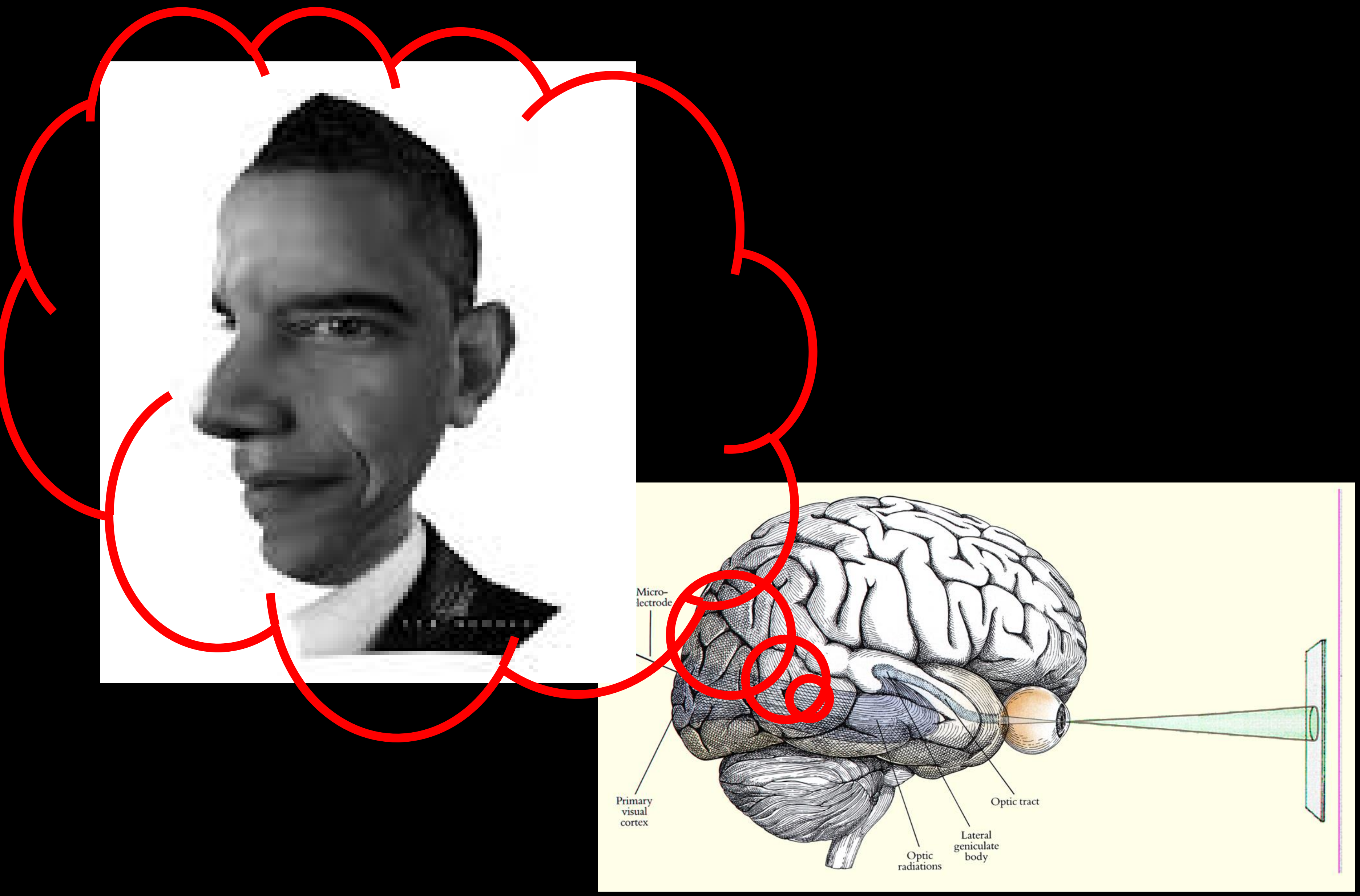
The visual system can create models of objects that can not possibly exist



Interim Summary

- Sensory perception is not the formation of a copy or representation of the external world
- The purpose of perception is to create a model of the world that helps us function effectively

The neuronal process underlying visual perception

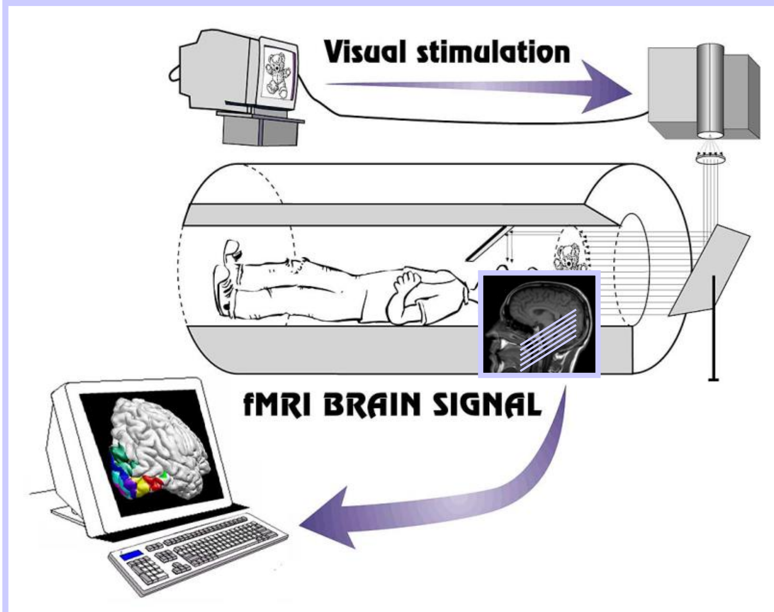


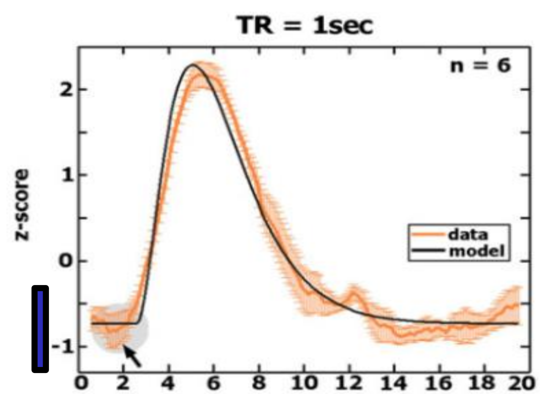
The Methods

Functional Magnetic Resonance Imaging

10^5-10^6 neurons

Hemodynamic Signal

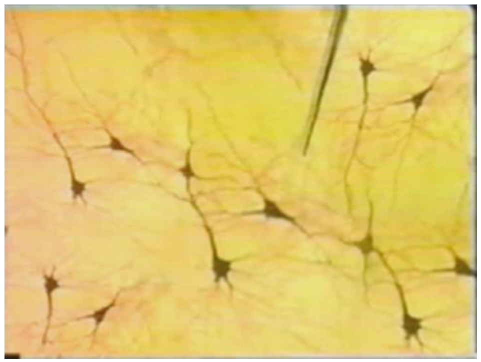


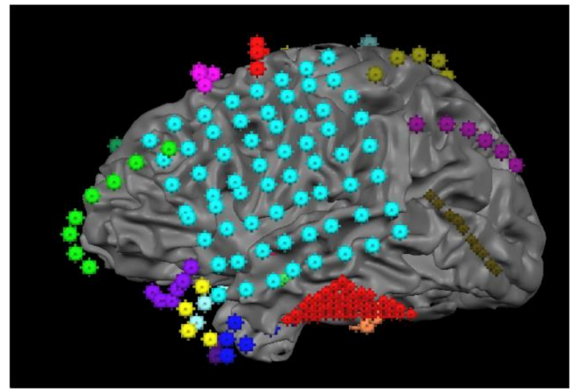


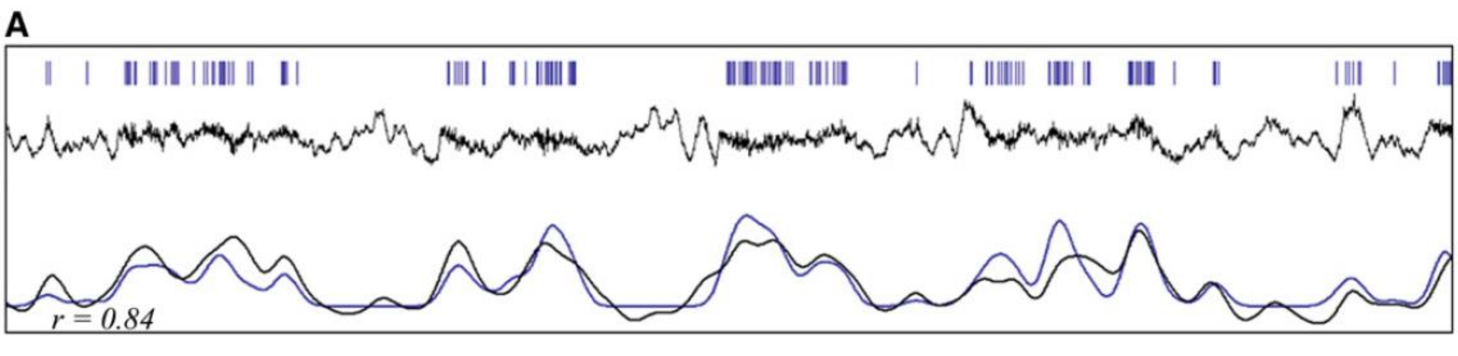
Electrophysiology

Micro-electrodes
1-10 neurons
Firing rate

Contacts
10^4-10^6 neurons
Broad band Gamma Power







Spikes

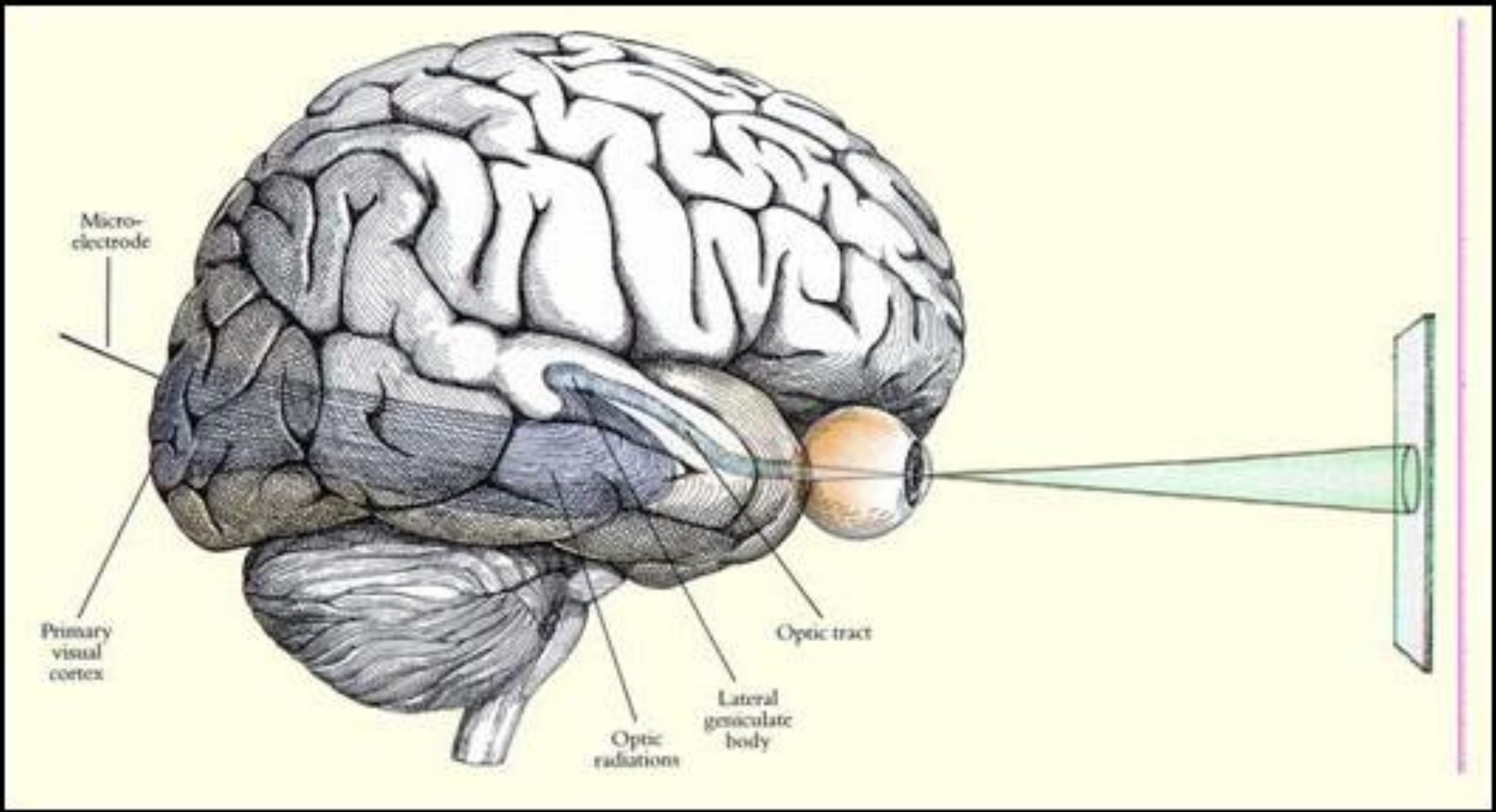
LFP

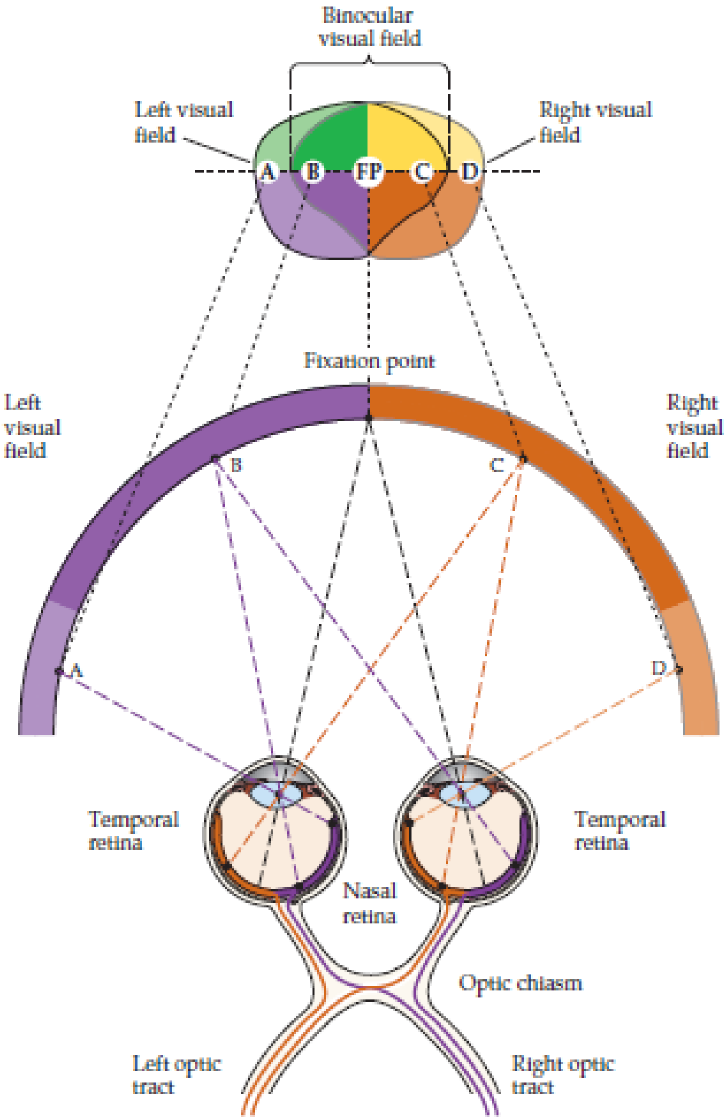
Spikes/
Gamma

Firing rate= amplitude of fast (Gamma) fluctuations

Nir et al.

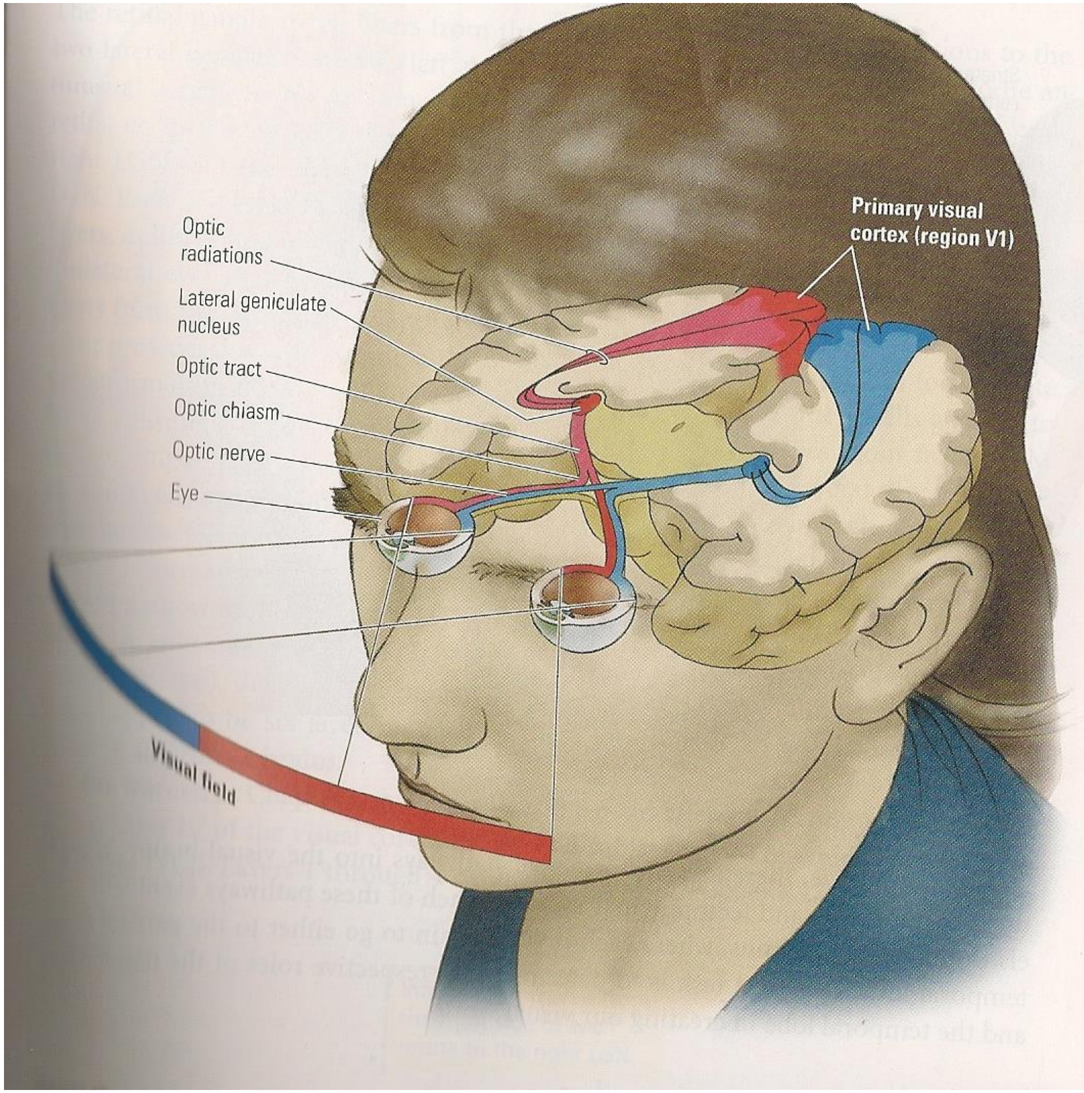
The flow of visual information in the human brain





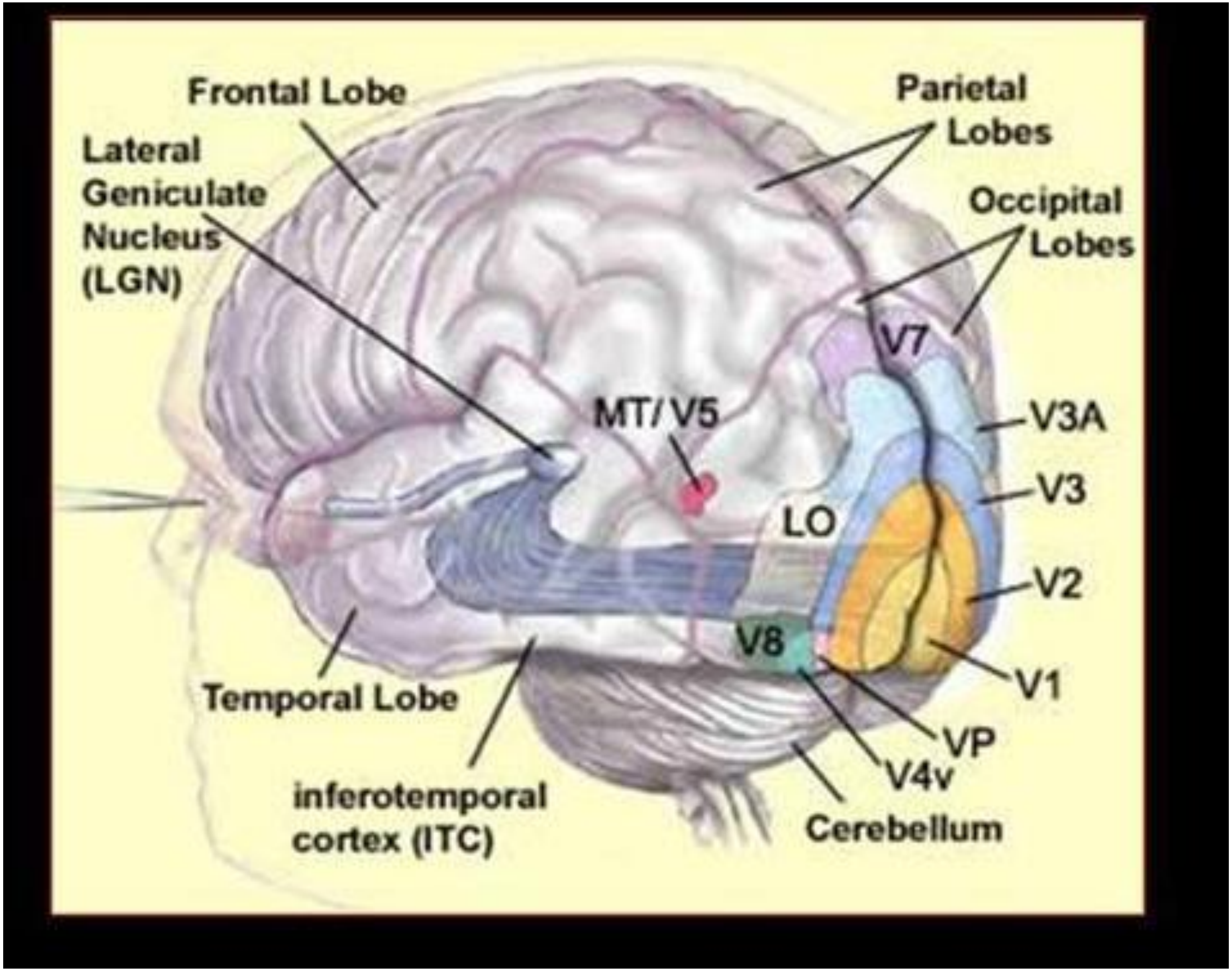
retinotopy, visual field, contra- ipsi, fixation point, vertical meridian
Horizontal meridian

Flow of information form the eye to the brain



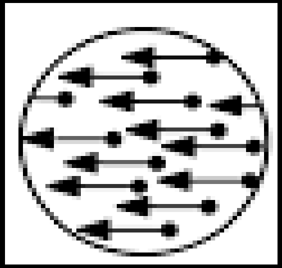
Optic nerve, chiasm, partial crossing, tract and radiation

Atlas of human visual areas

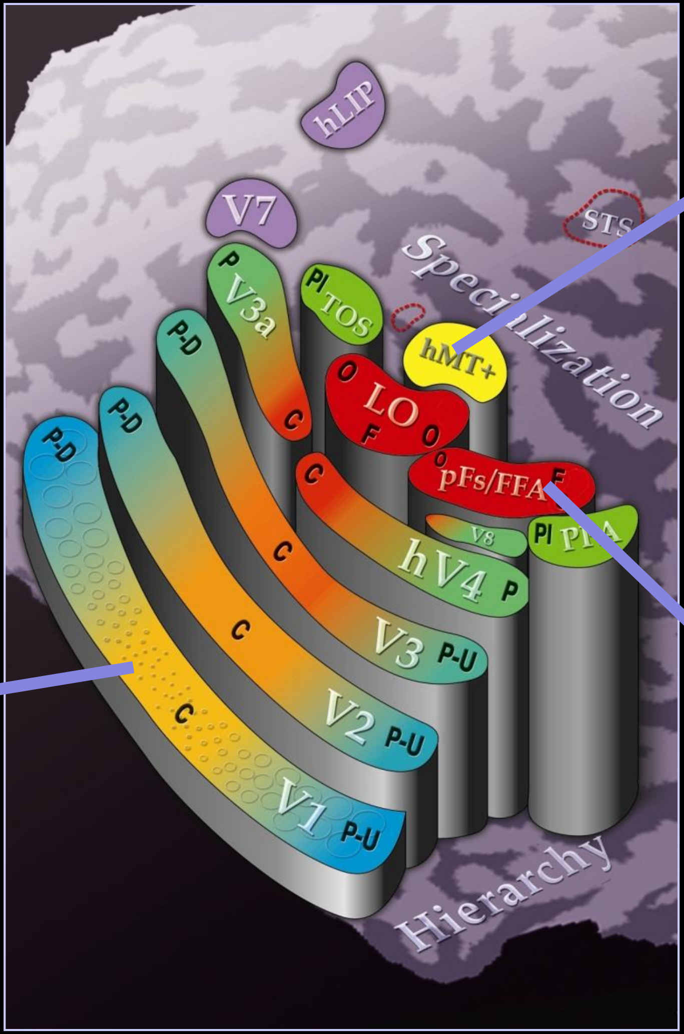


Functional Selectivity in the Human Visual Cortex

Dorsal-stream
(Action)

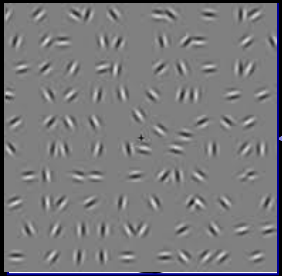


Motion
(MT/V5)



Ventral-stream
(Recognition)

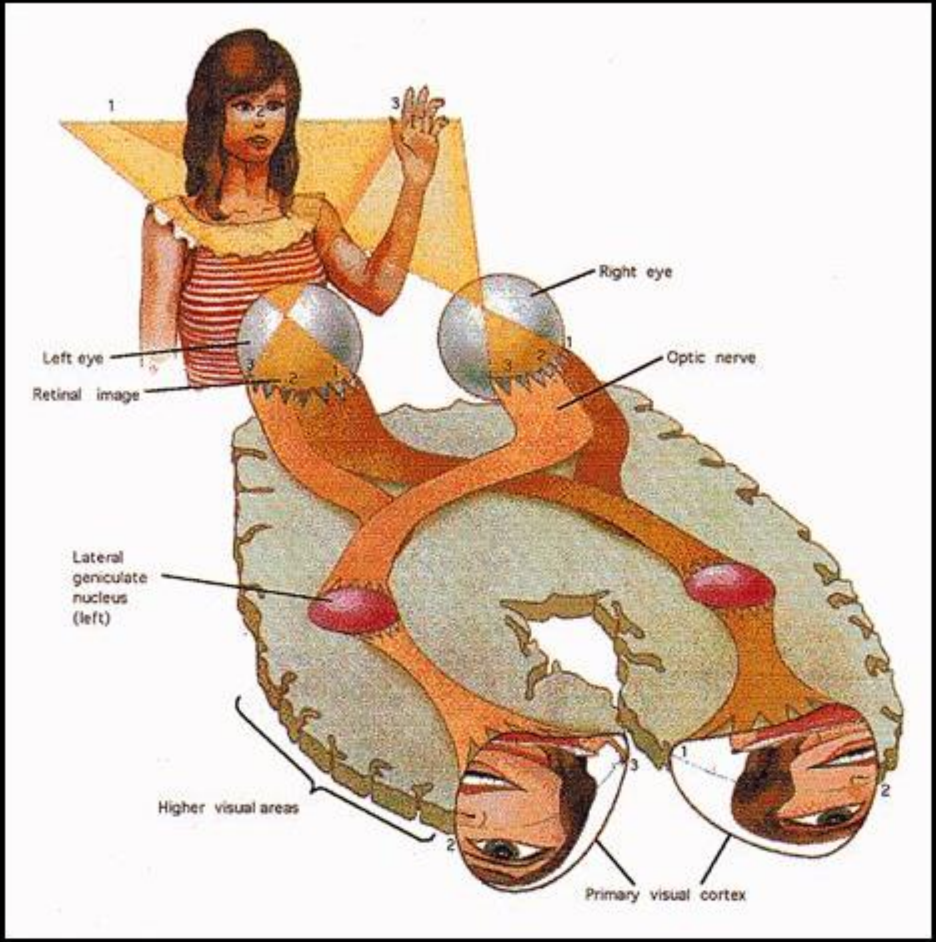
Gestalt
templates
IT/FFA



Local elements
V1

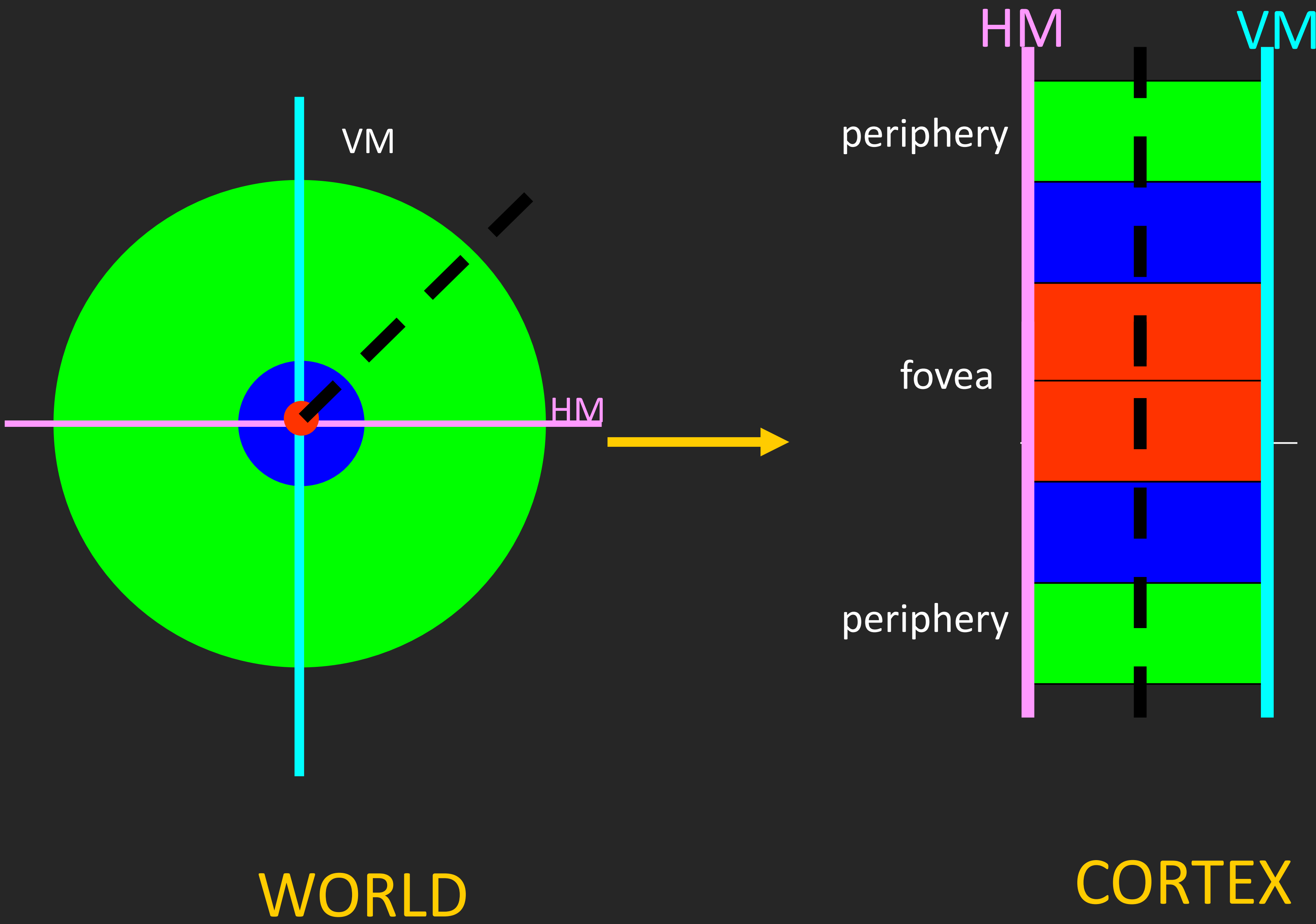
Large scale organizational principles of V1

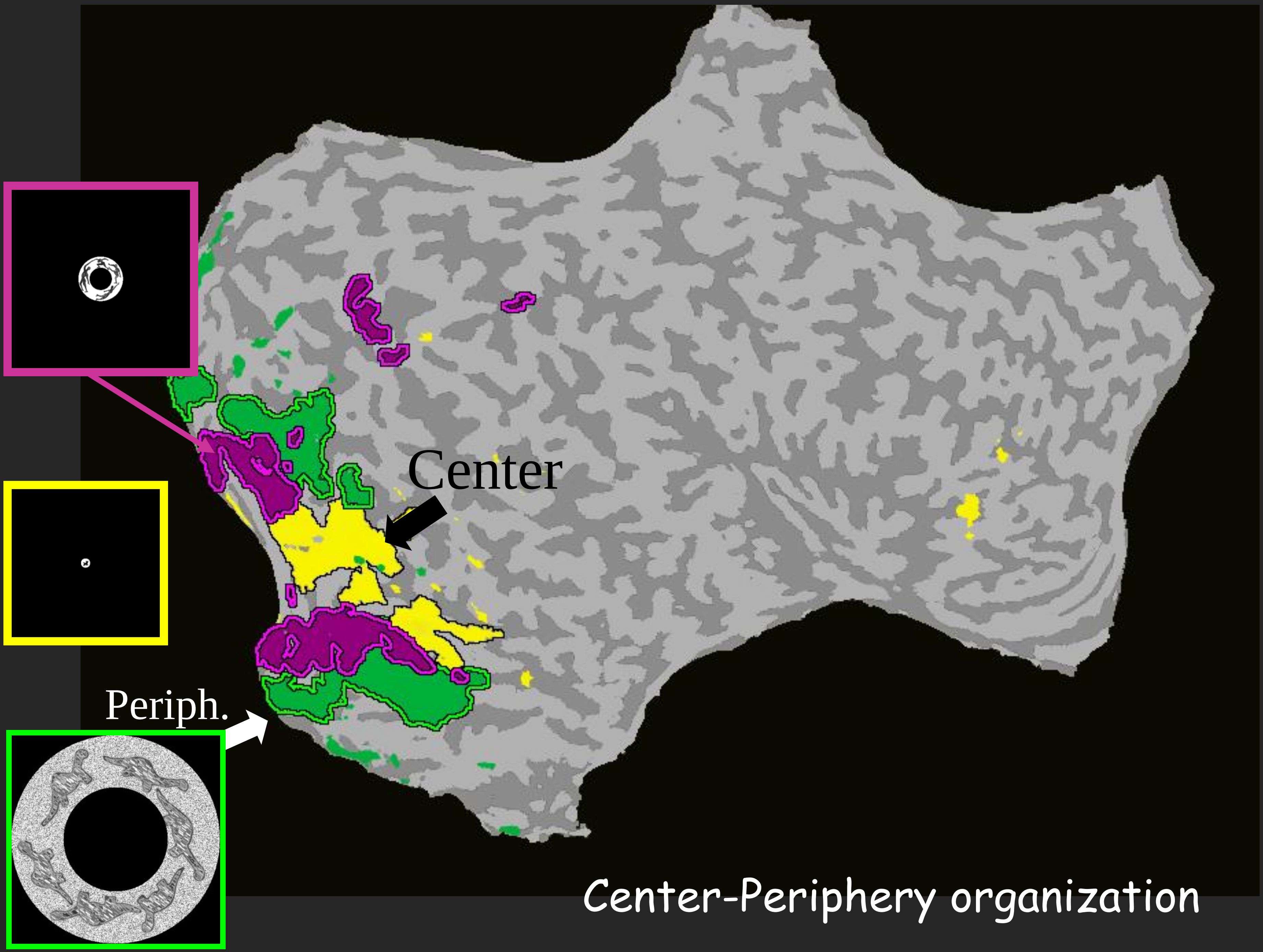
Retinotopy



Mmagnification factor- mm cortex/visual angle

Polar Retinotopic organization of visual cortex





Center-Periphery organization

Interim Summary

- The early, retinotopic, stages in the visual system consist of multiple representations of the visual field- organized as parallel bands on unfolded cortex

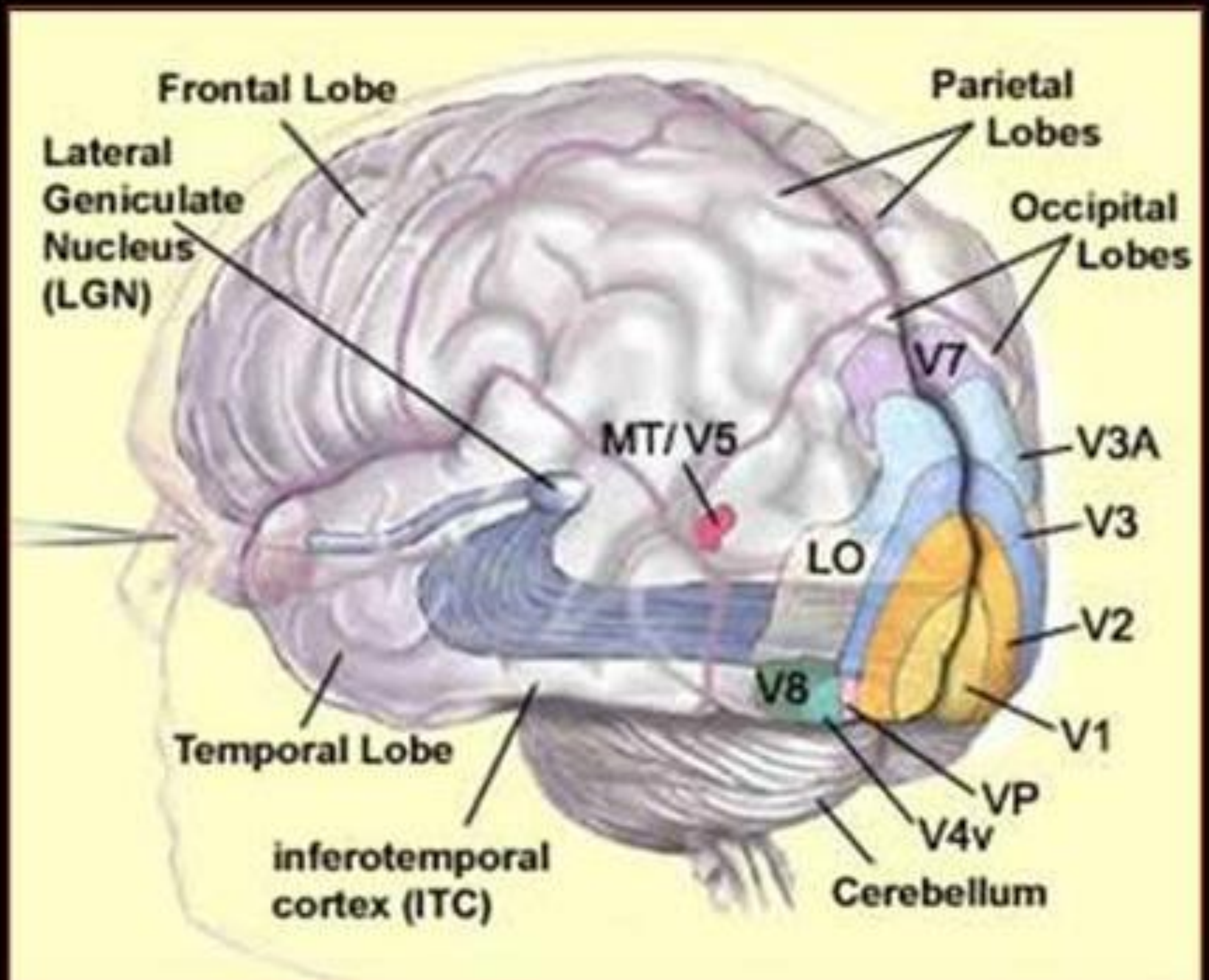
Three major principles of organization:

1) Magnification factor- the central visual field activates a larger number of neurons

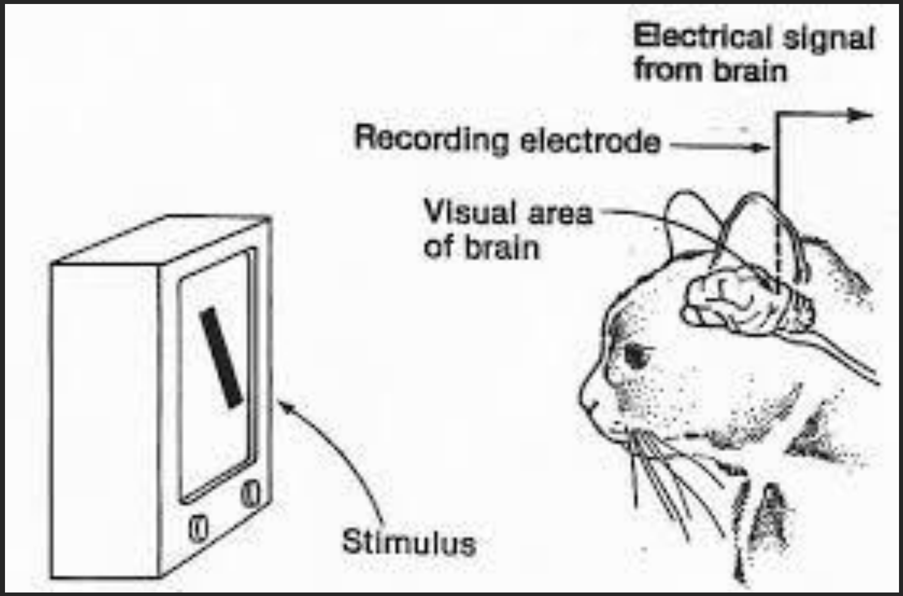
2) Center-periphery organization- central vision is in the center

3) Polar angle organization- right visual field in the left hemisphere, upper visual field – in ventral cortex

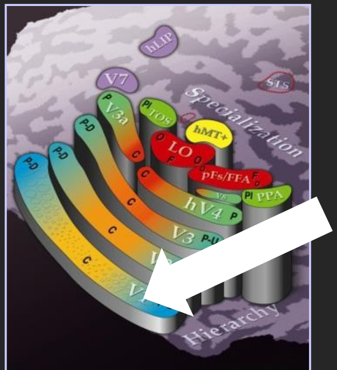
The functional transformations along the visual pathways



The transformation from the LGN to V1



The properties of single neurons in area V1



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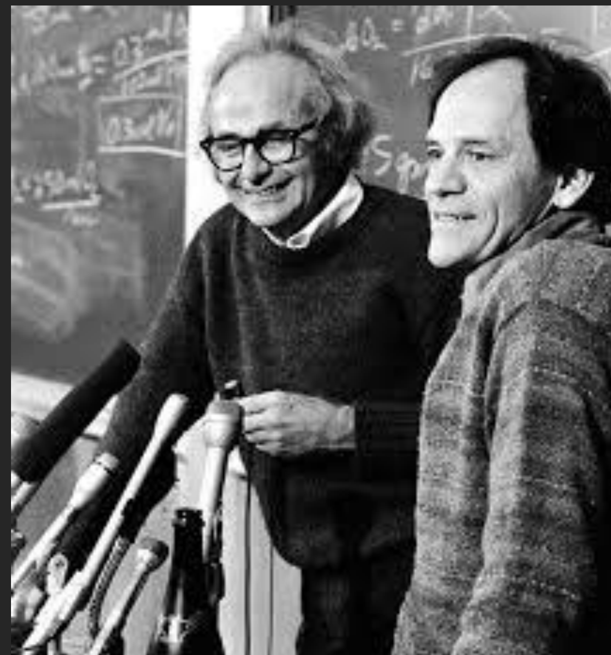
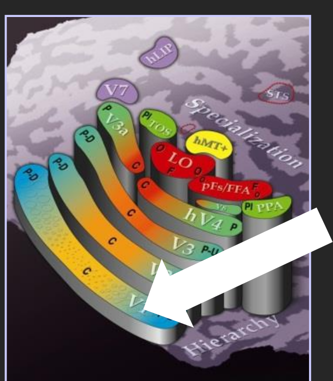


David Hubel and Torsten Wiesel



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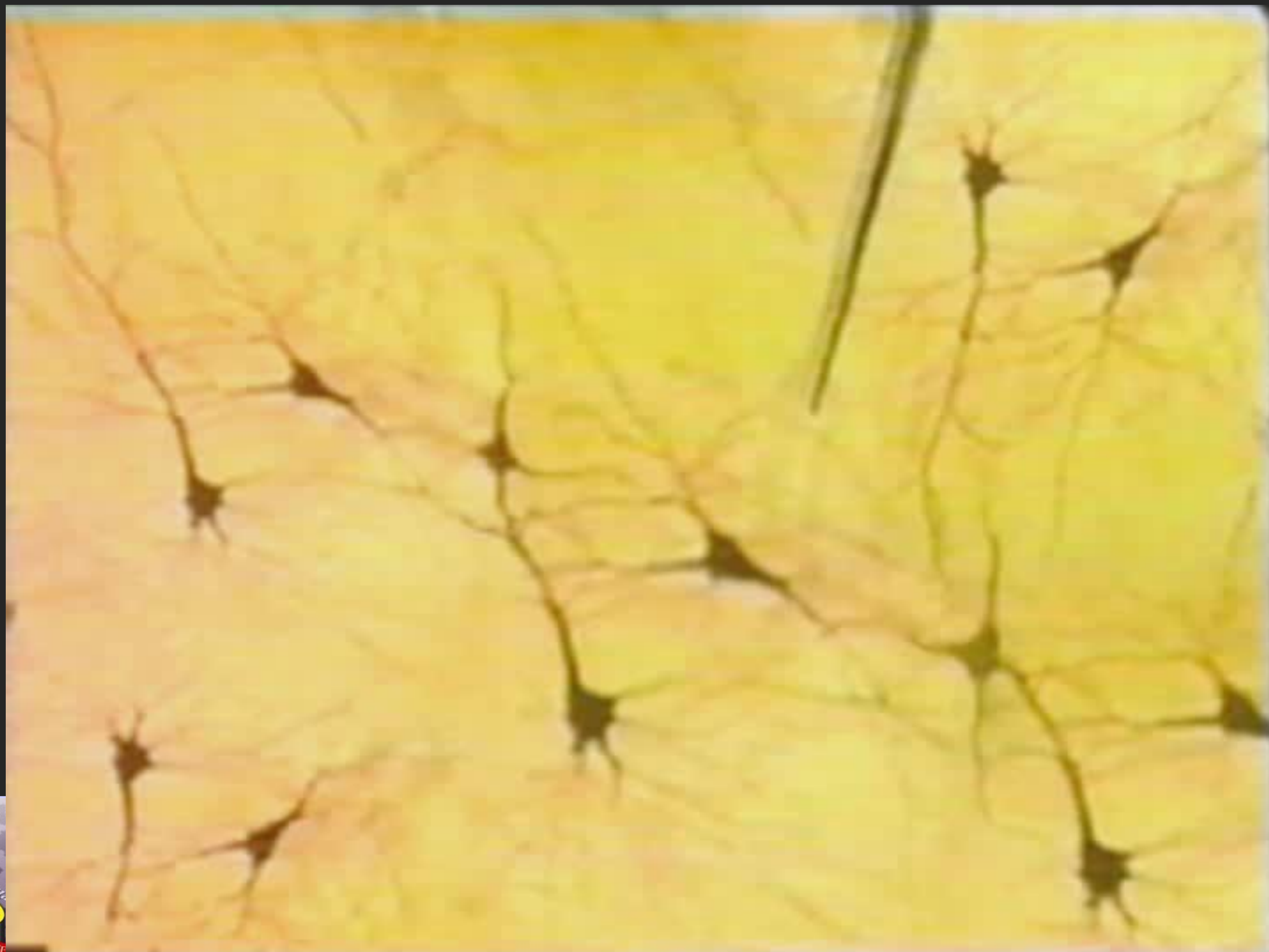
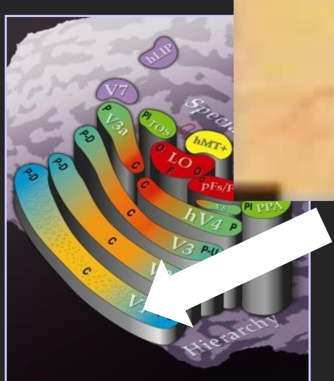
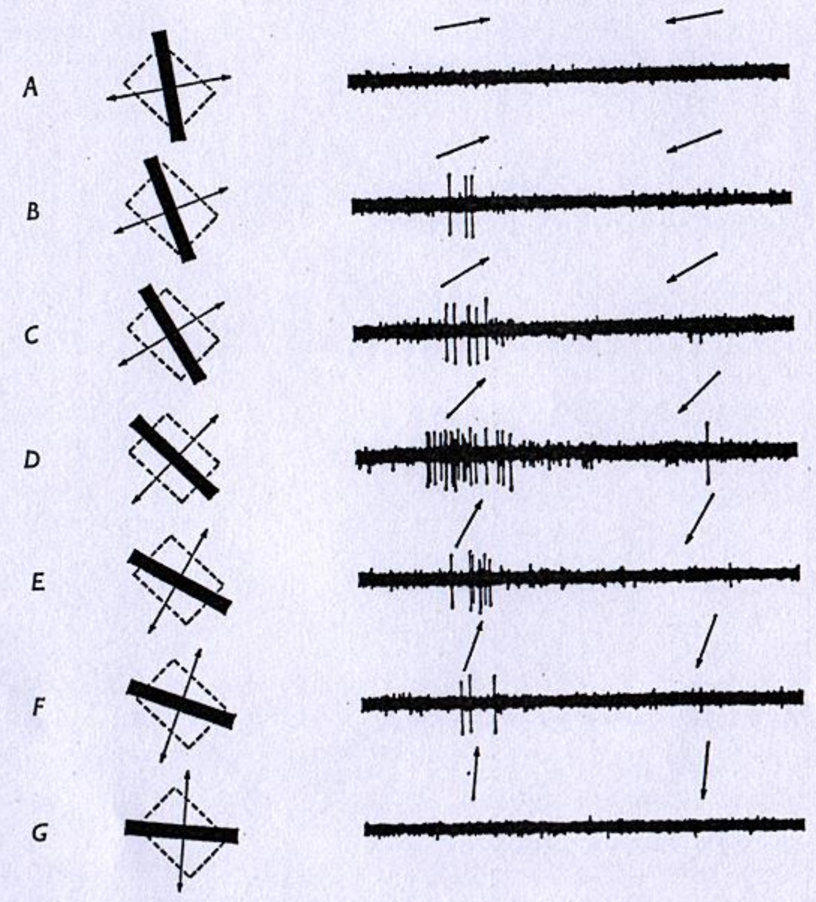




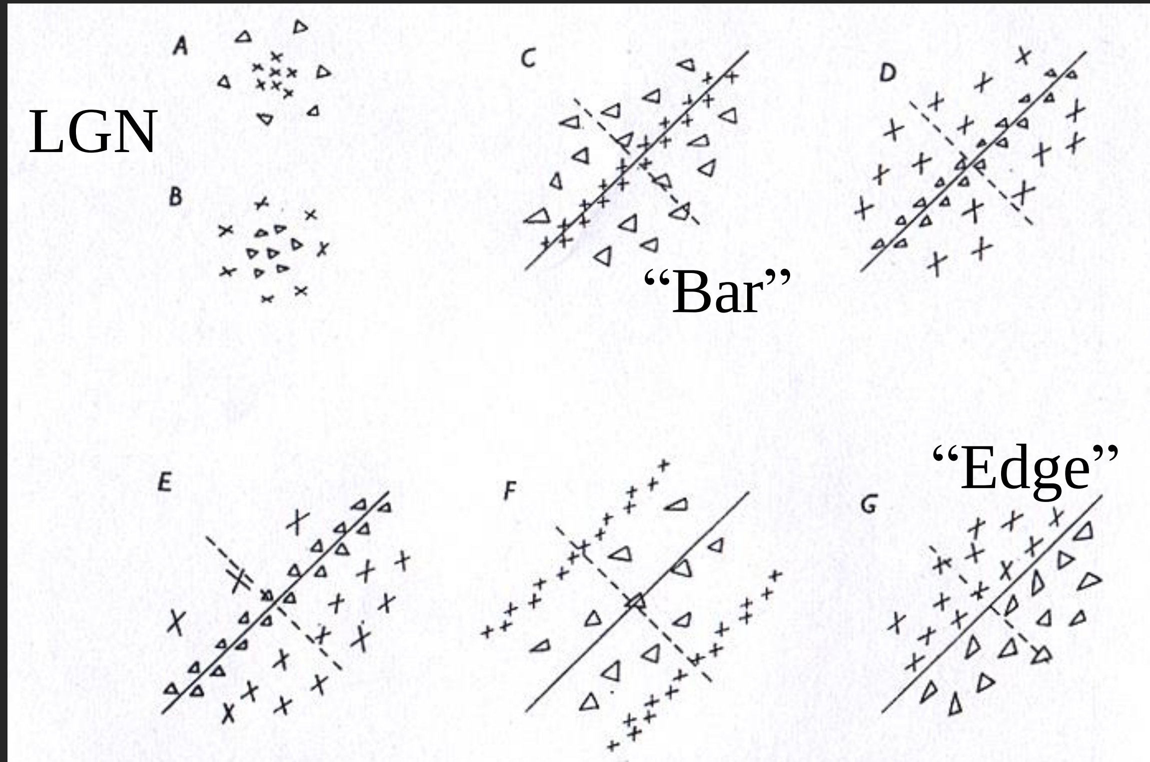
Receptive field of a visual neuron in area V1



Text-fig. 2. Responses of a complex cell in right striate cortex (layer IV A) to various orientations of a moving black bar. Receptive field in the left eye indicated by the interrupted rectangles; it was approximately $\frac{3}{8} \times \frac{3}{8}°$ in size, and was situated 4° below and to the left of the point of fixation. Ocular-dominance group 4. Duration of each record, 2 sec. Background intensity $1{\cdot}3\ \log_{10}\ cd/m^2$, dark bars $0{\cdot}0\ \log\ cd/m^2$.

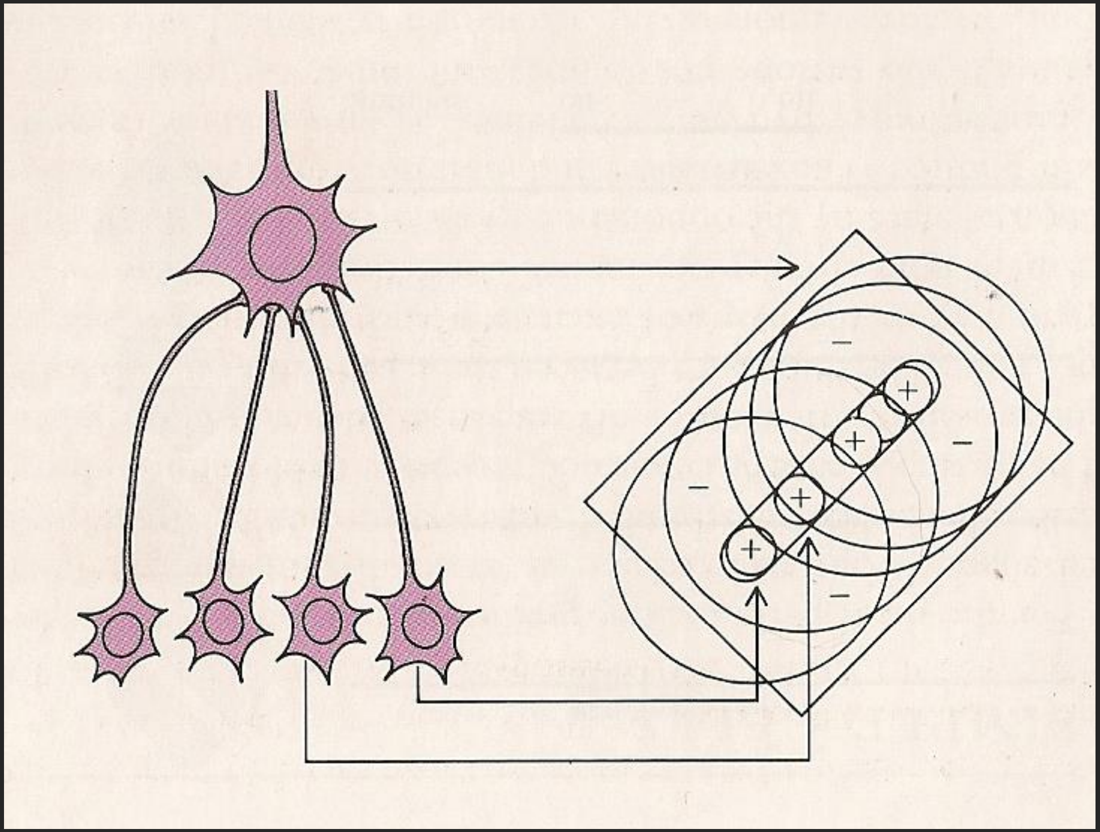
Stimulus selectivity of receptive fields

Receptive field of a "Simple" cell in area V1



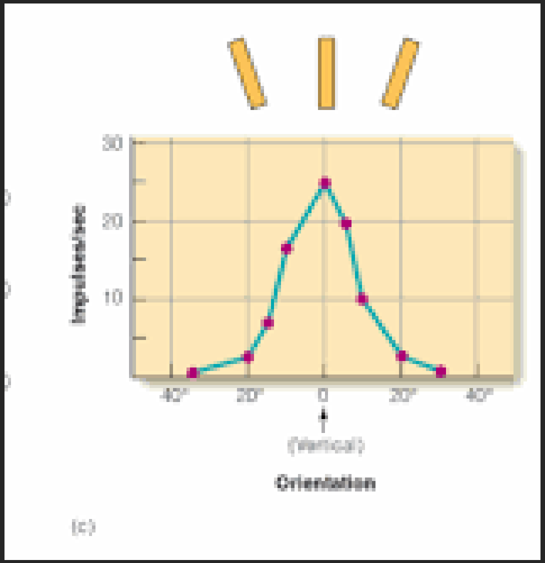
Text-fig. 2. Common arrangements of lateral geniculate and cortical receptive fields. *A*. 'On'-centre geniculate receptive field. *B*. 'Off'-centre geniculate receptive field. *C–G*. Various arrangements of simple cortical receptive fields. ×, areas giving excitatory responses ('on' responses); △, areas giving inhibitory responses ('off' responses). Receptive-field axes are shown by continuous lines through field centres; in the figure these are all oblique, but each arrangement occurs in all orientations.

The simple cell model

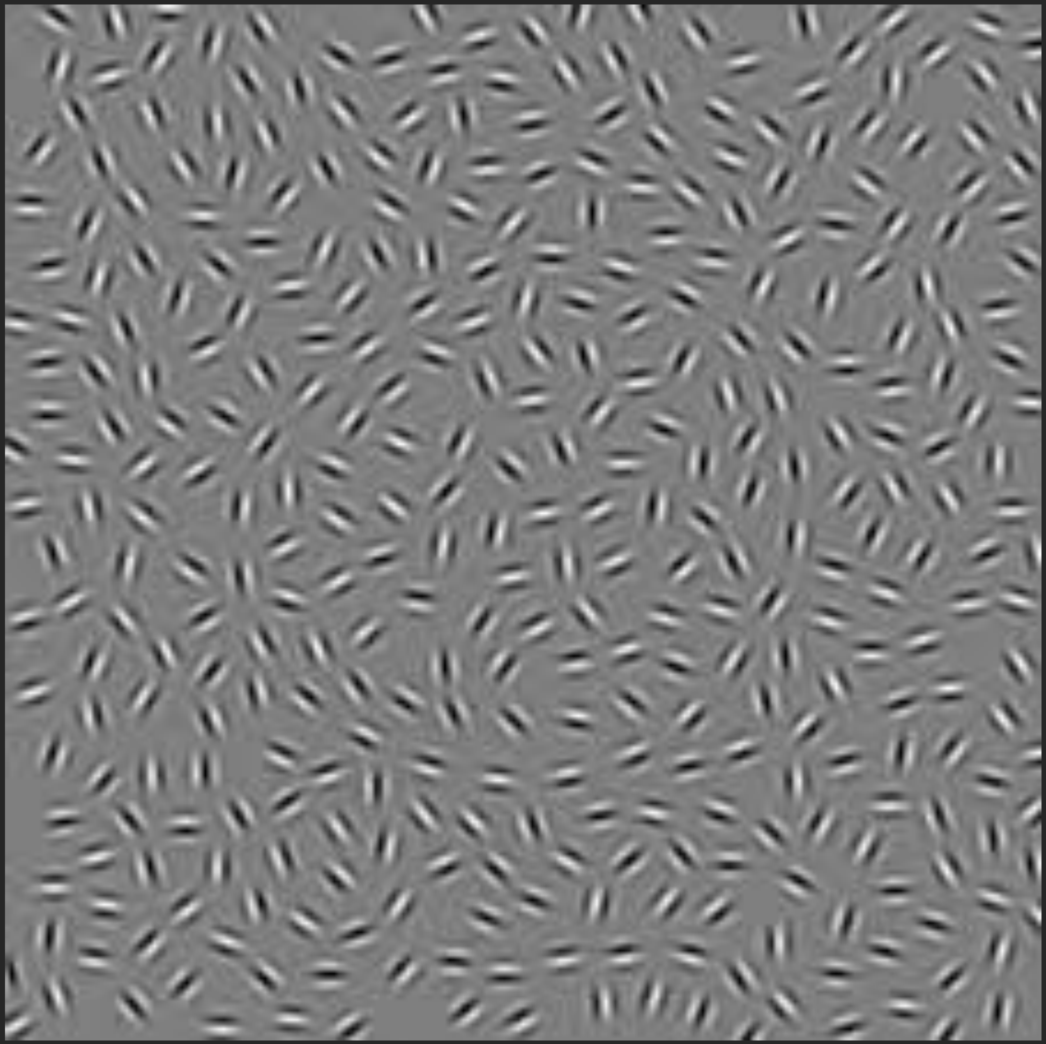


Convergence, threshold, synchrony
an “and” function

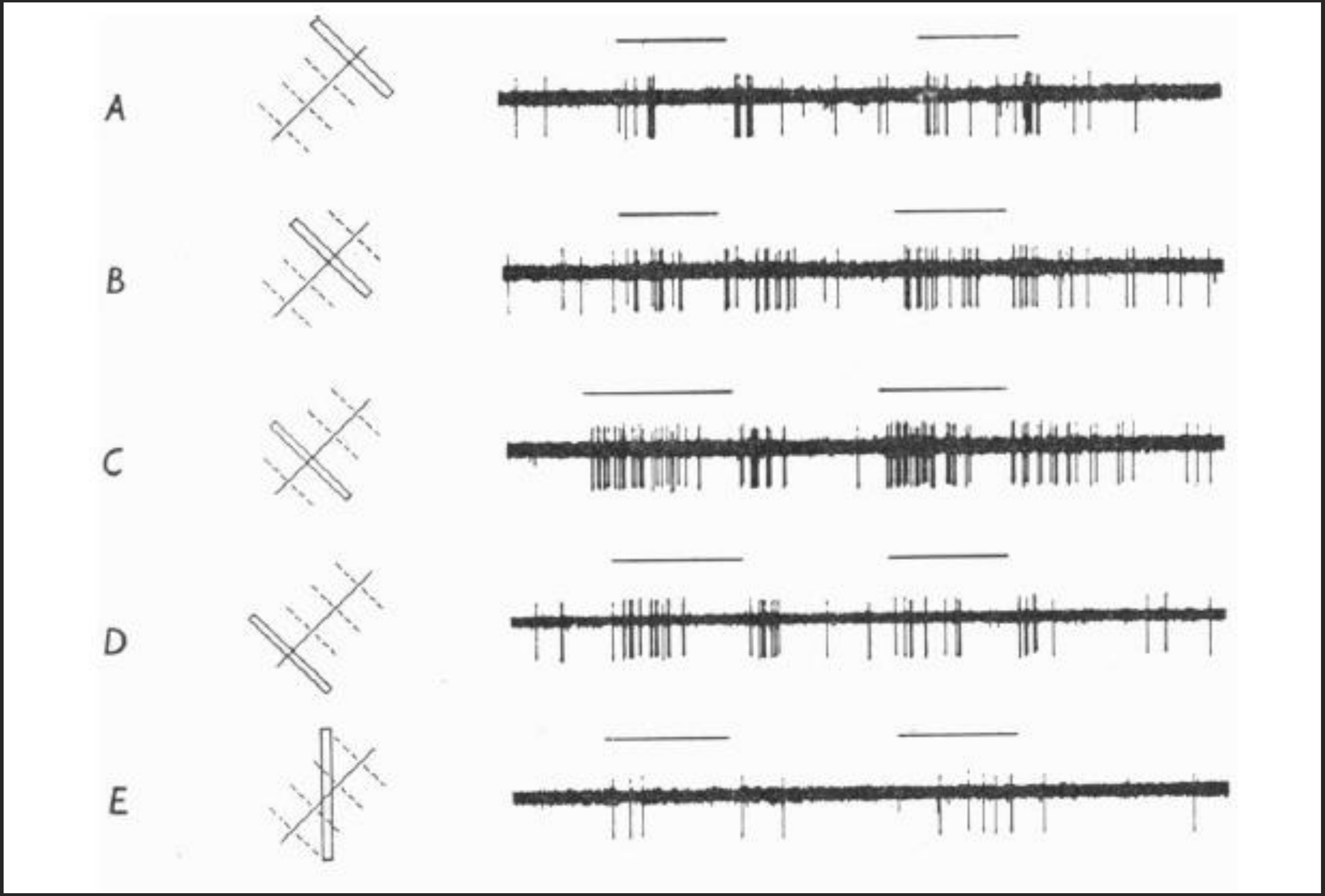
What is the function of the oriented line detectors?



Perceptual saliency of line detection



Functional Hierarchy within V1

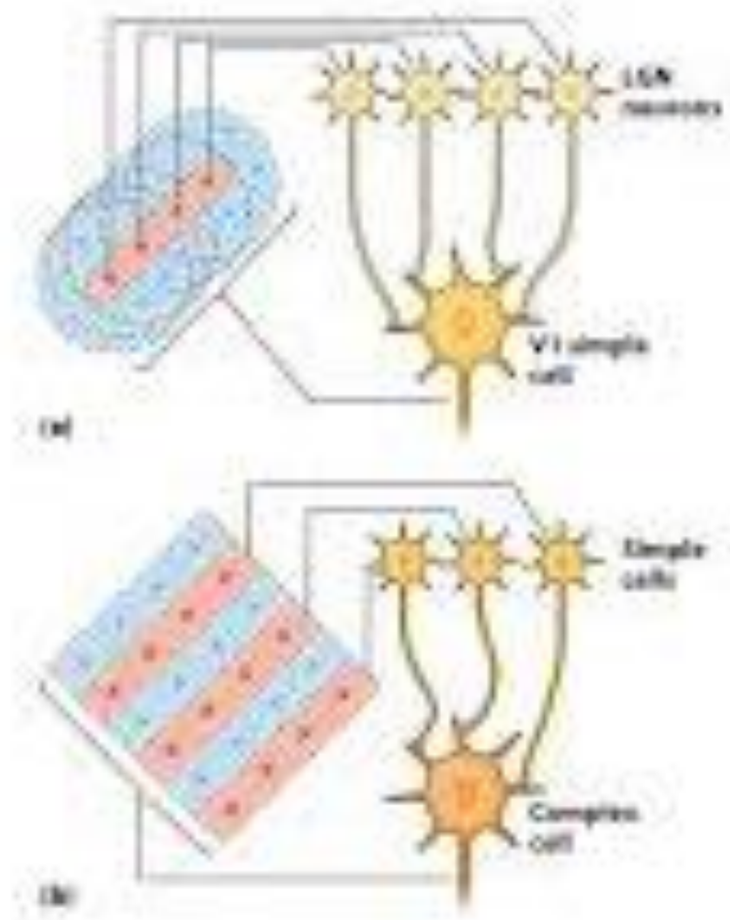


complex cells

Functional hierarchy within V1

Simple cells

"And" function

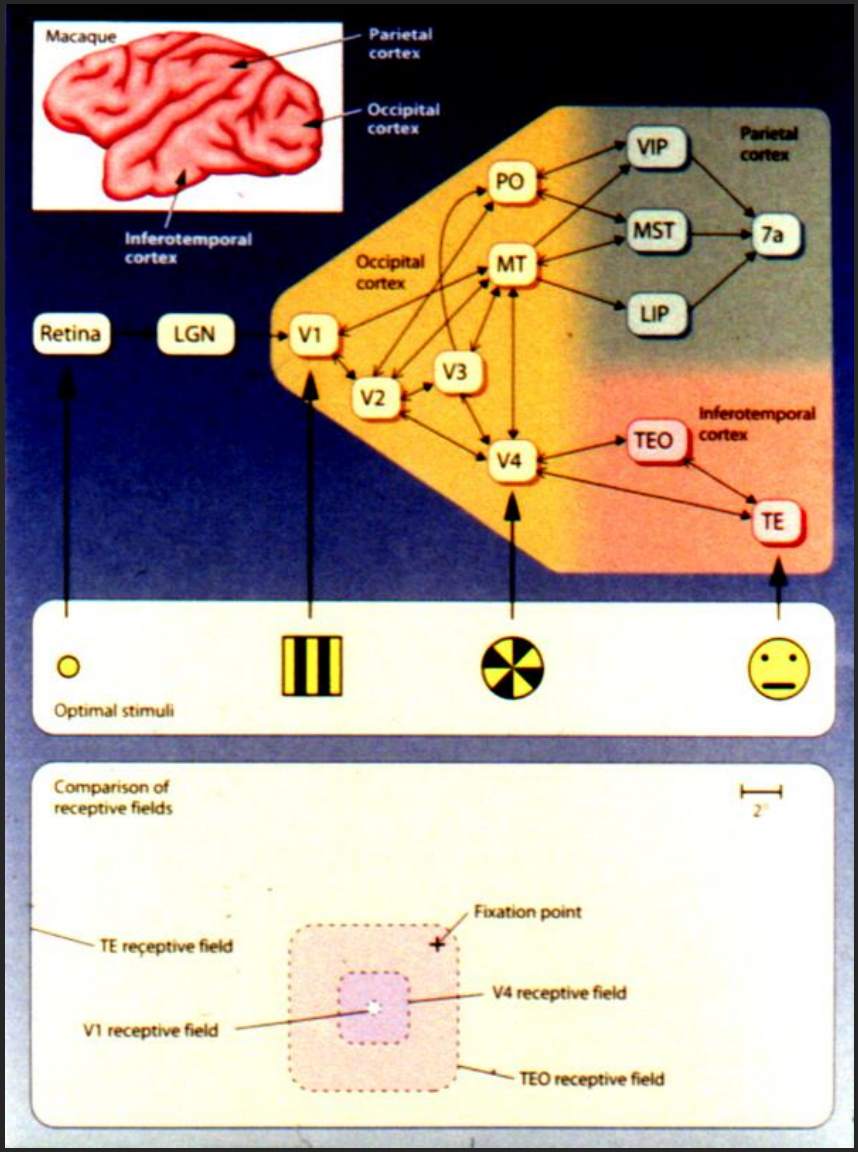


Complex cells

"Or" function

The transformation from simple to complex cells

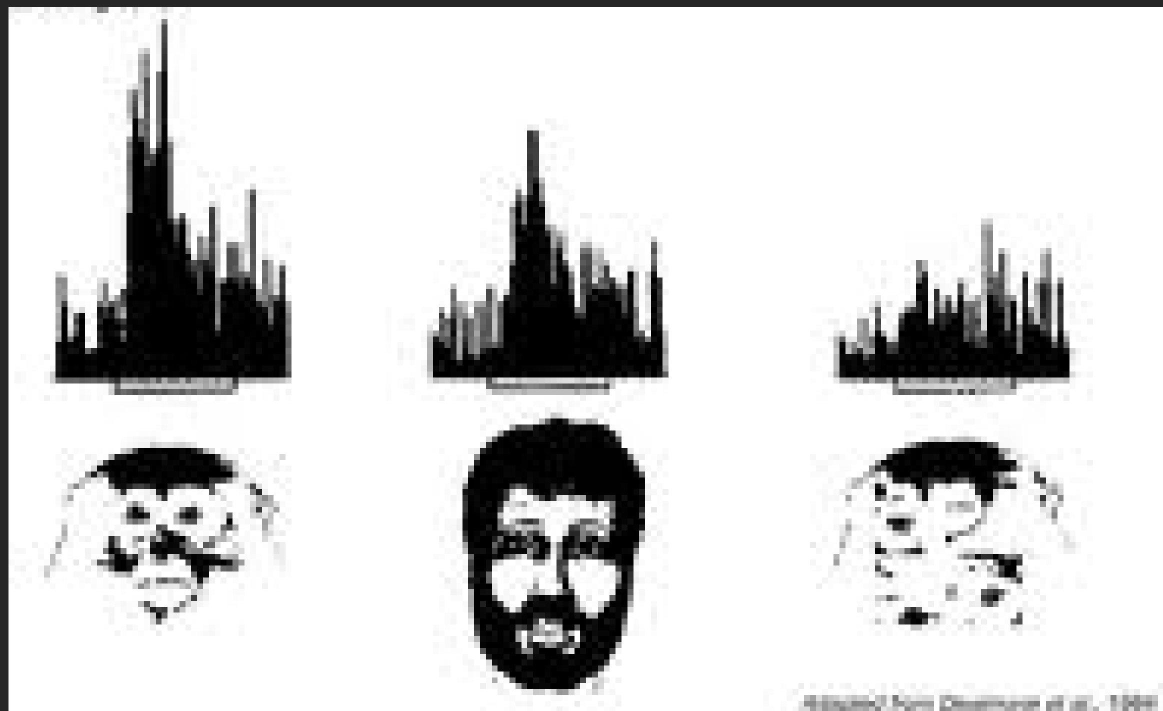
Growing "abstraction" along the visual hierarchy



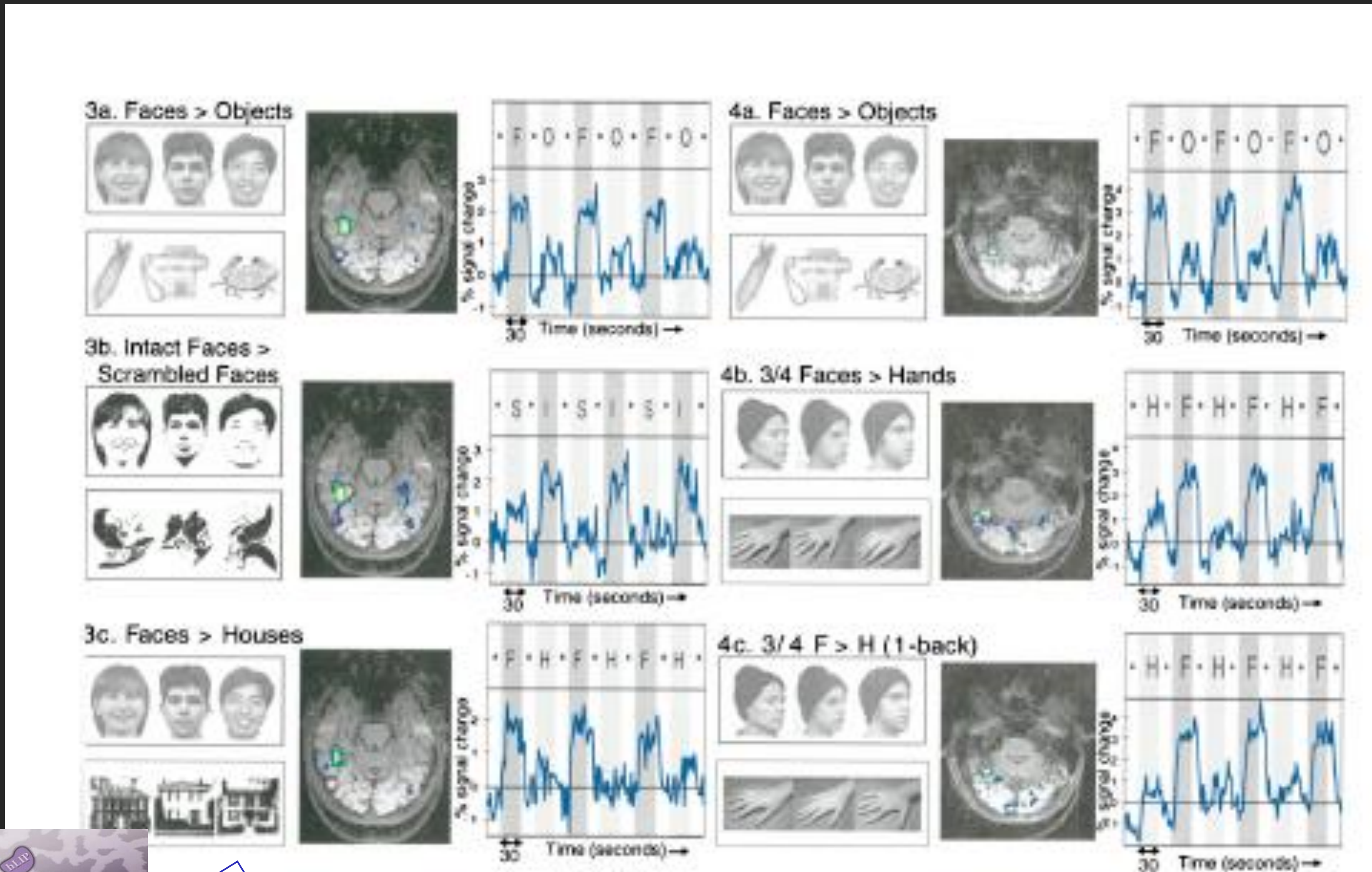
Increased complexity

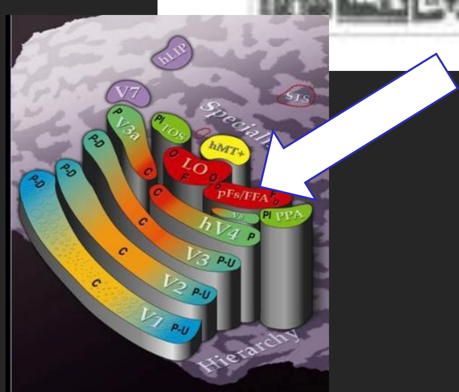
Increased RF size

Complex templates at the top of the VENTRAL stream



"Face" neurons

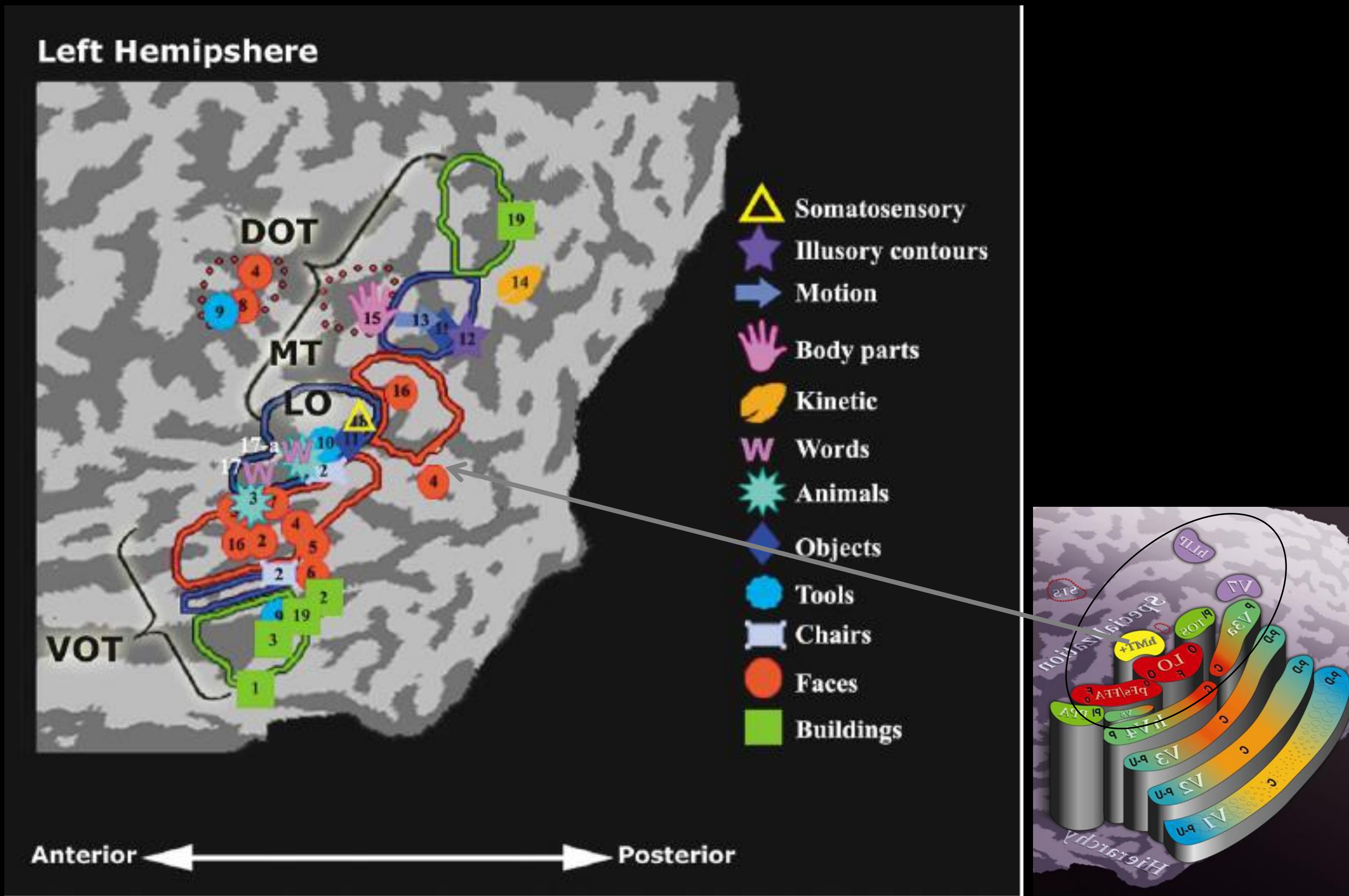




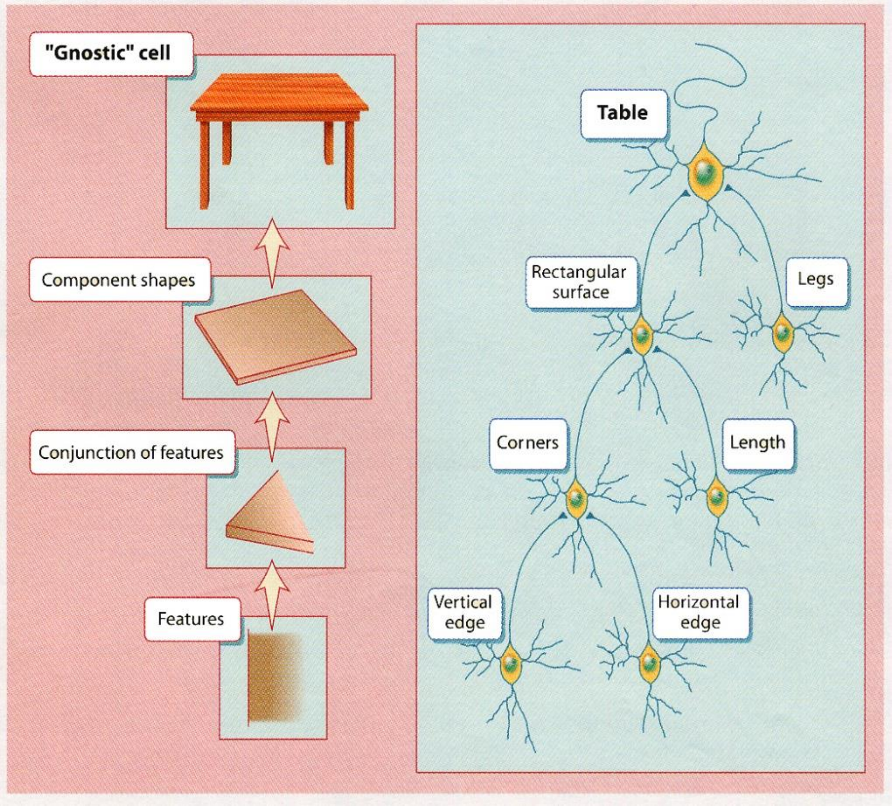
Fusiform “Face” Area

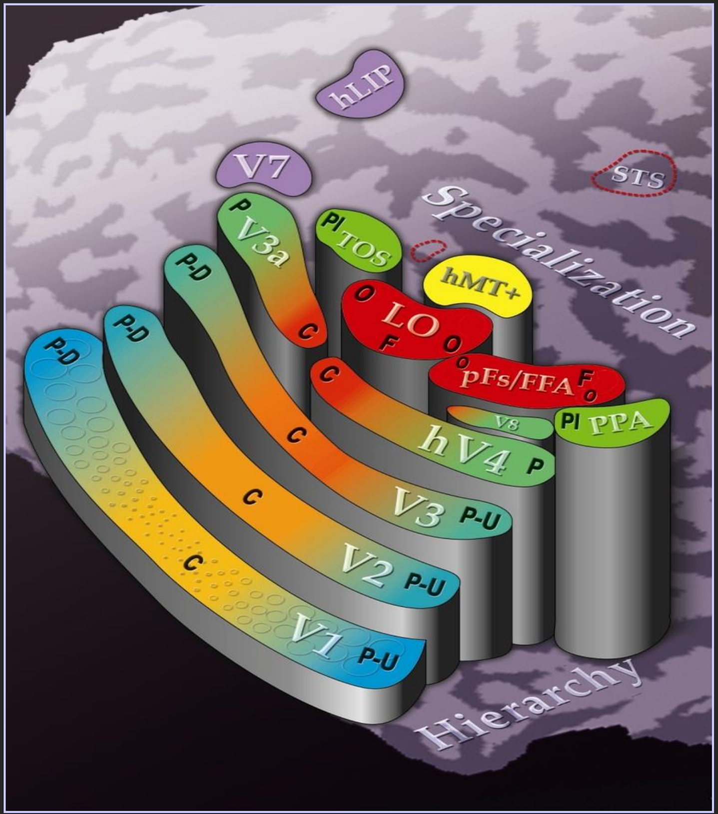
Electrical stimulation of the fusiform face area

Mosaic of category-selective cortical regions



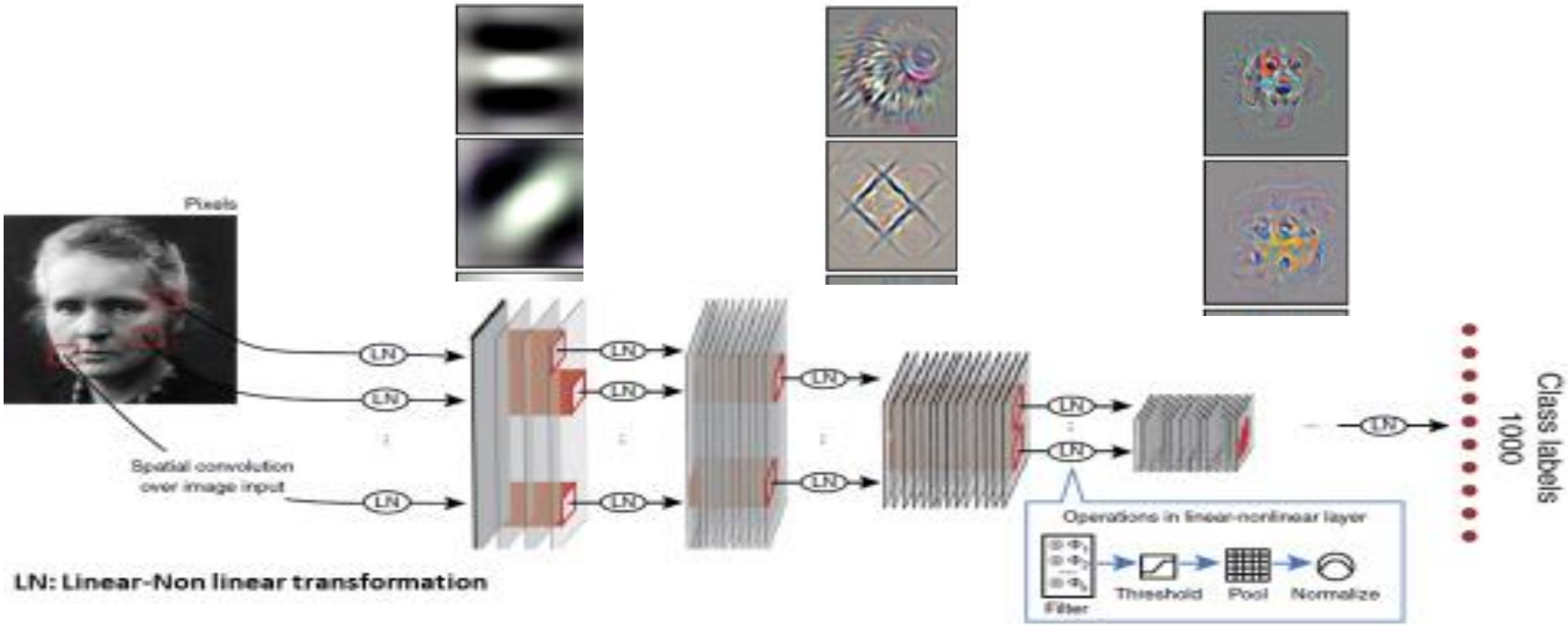
How are the functional transformations implemented?





Repeating the feed-forward simple cell model along the hierarchy

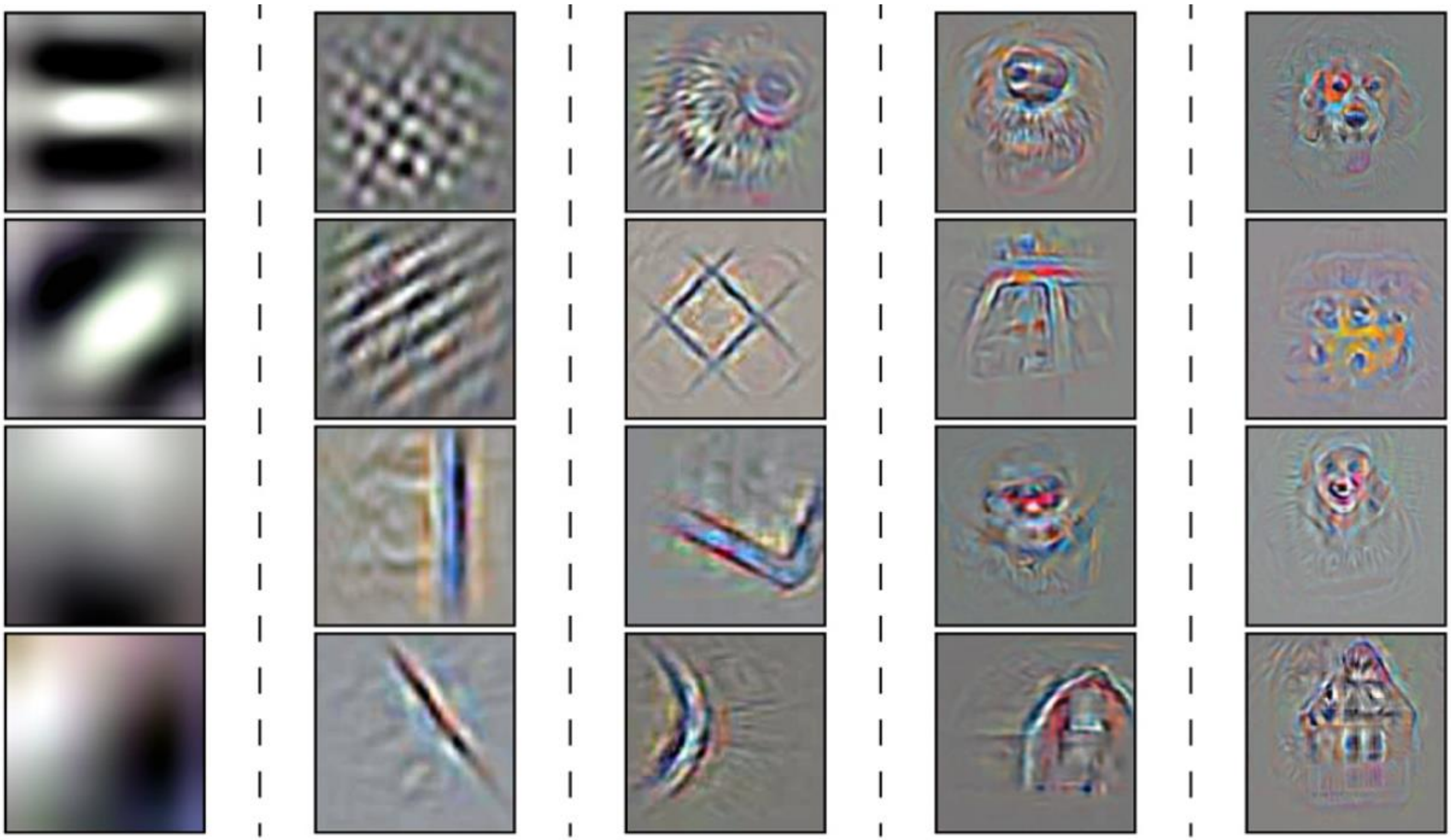
Deep Convolutional Neural Network:
A successful hierarchical model of human visual performance



Yamin and DiCarlo, 2016
Guculu and Van Gerven, 2015

Artificial networks now out-perform human visual recognition capabilities

Receptive fields of artificial neurons along the hierarchy



Interim Summary

- The visual pathway consists of a series of functional transformations

Characteristics of the transformation:

1) Increasingly holistic – from picture elements to entire percepts organized in categories

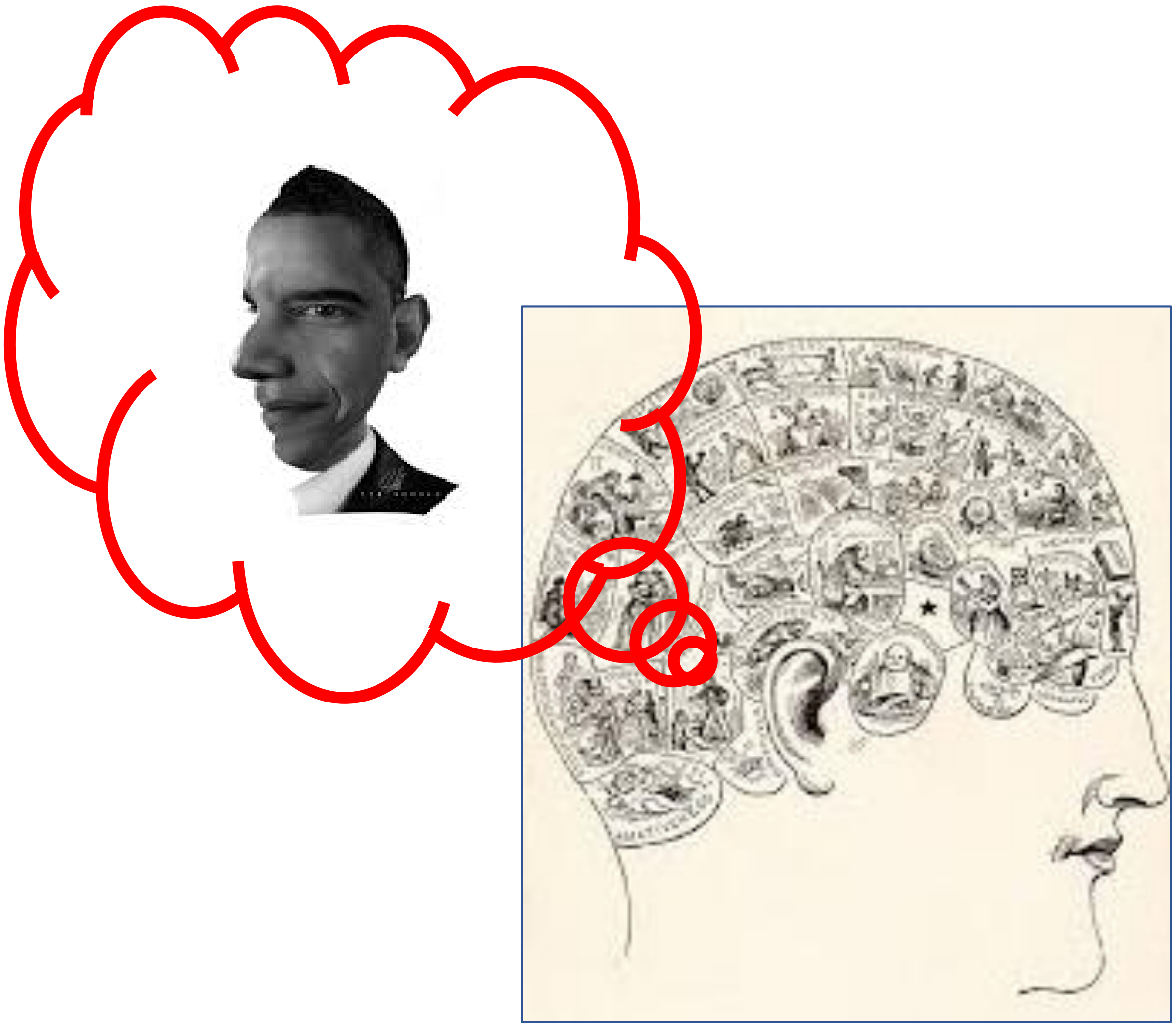
2) Increasingly invariant- reduced sensitivity to position in the visual field

3) The transformation is implemented through selective convergence of inputs combined with a decision non-linearity (e.g. the LGN- to simple cell transformation)

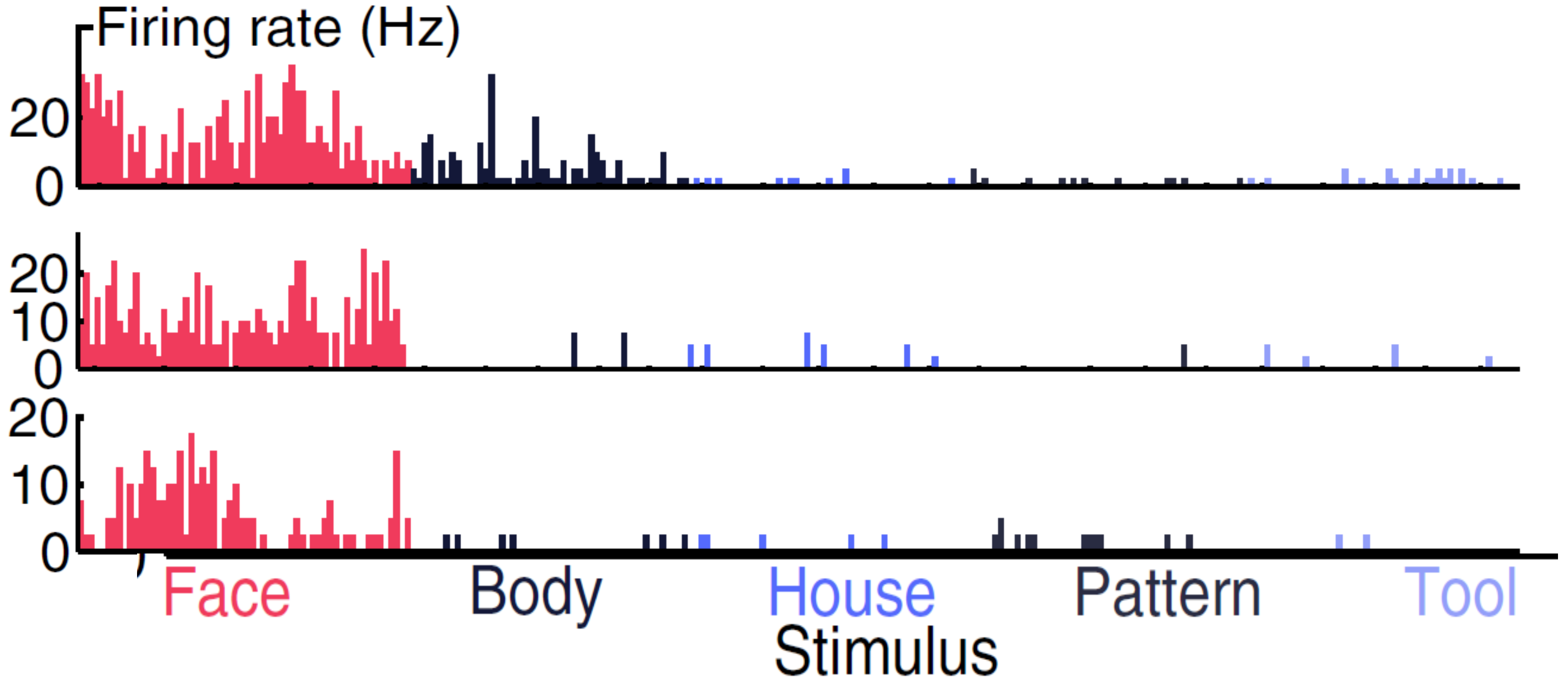
4) Extending the principle can account for functional properties along the visual hierarchy

5) Supported by artificial networks

What is the neuronal code underlying the images in the visual system?



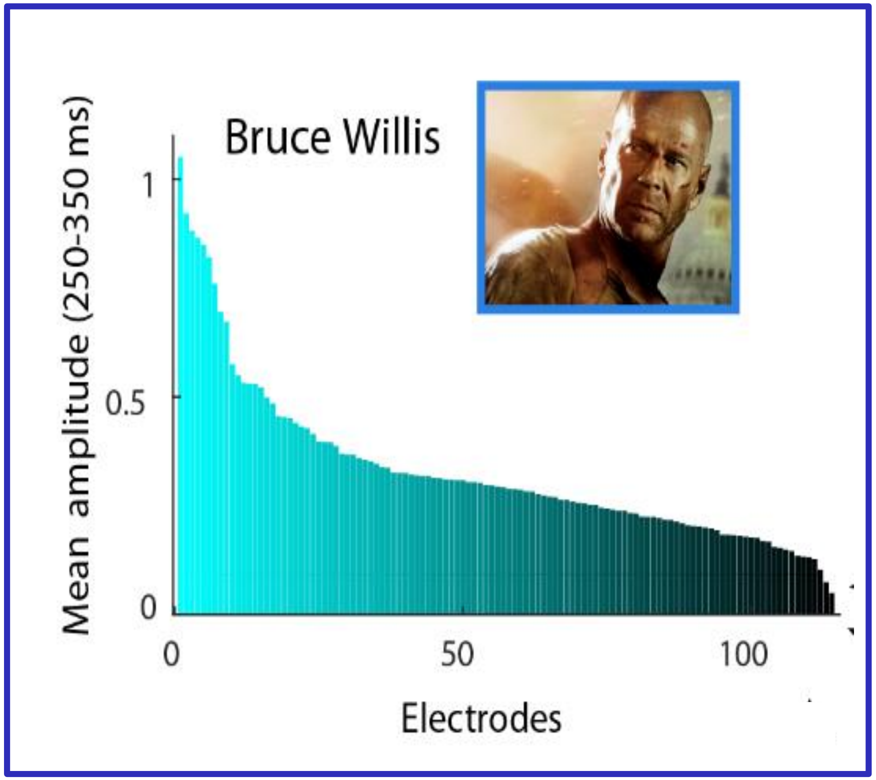
First code: tuning of single neurons



Widely distributed responses
Unique face tuning of each neuron

Simon Khouvis

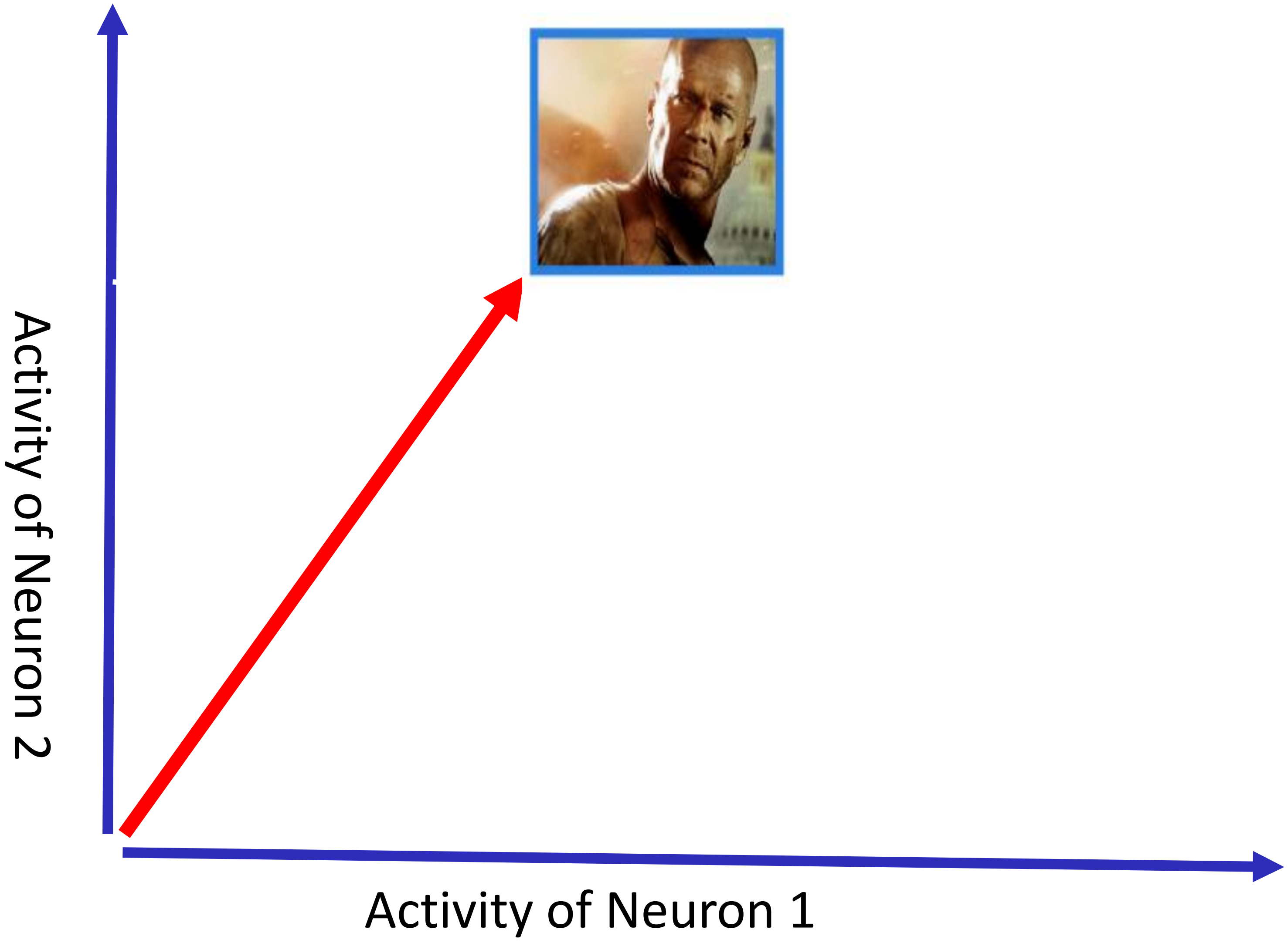
Second code: population vector



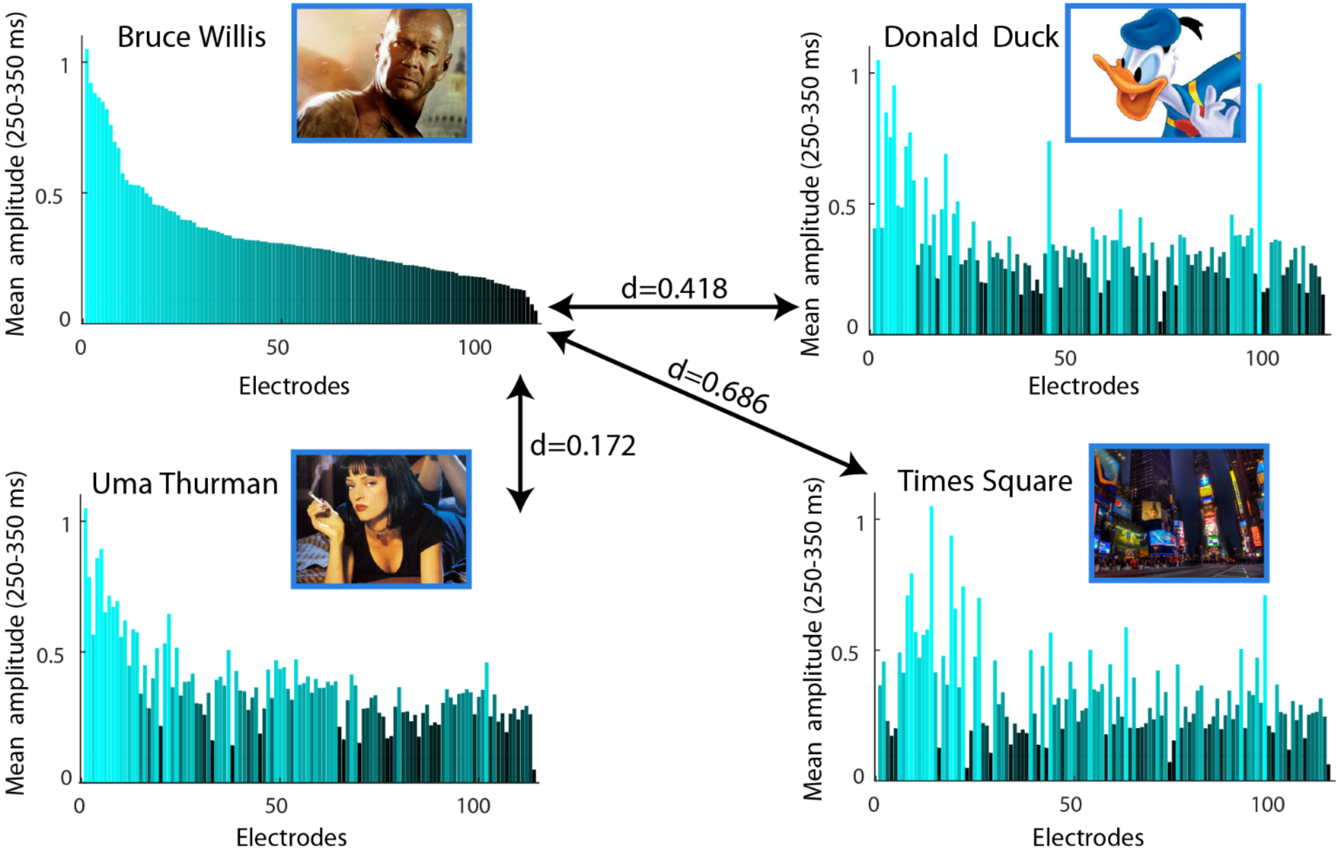
Multi-unit activation pattern to each visual image

Yitzhak Norman, Rotem Broday-Dvir

The population vector

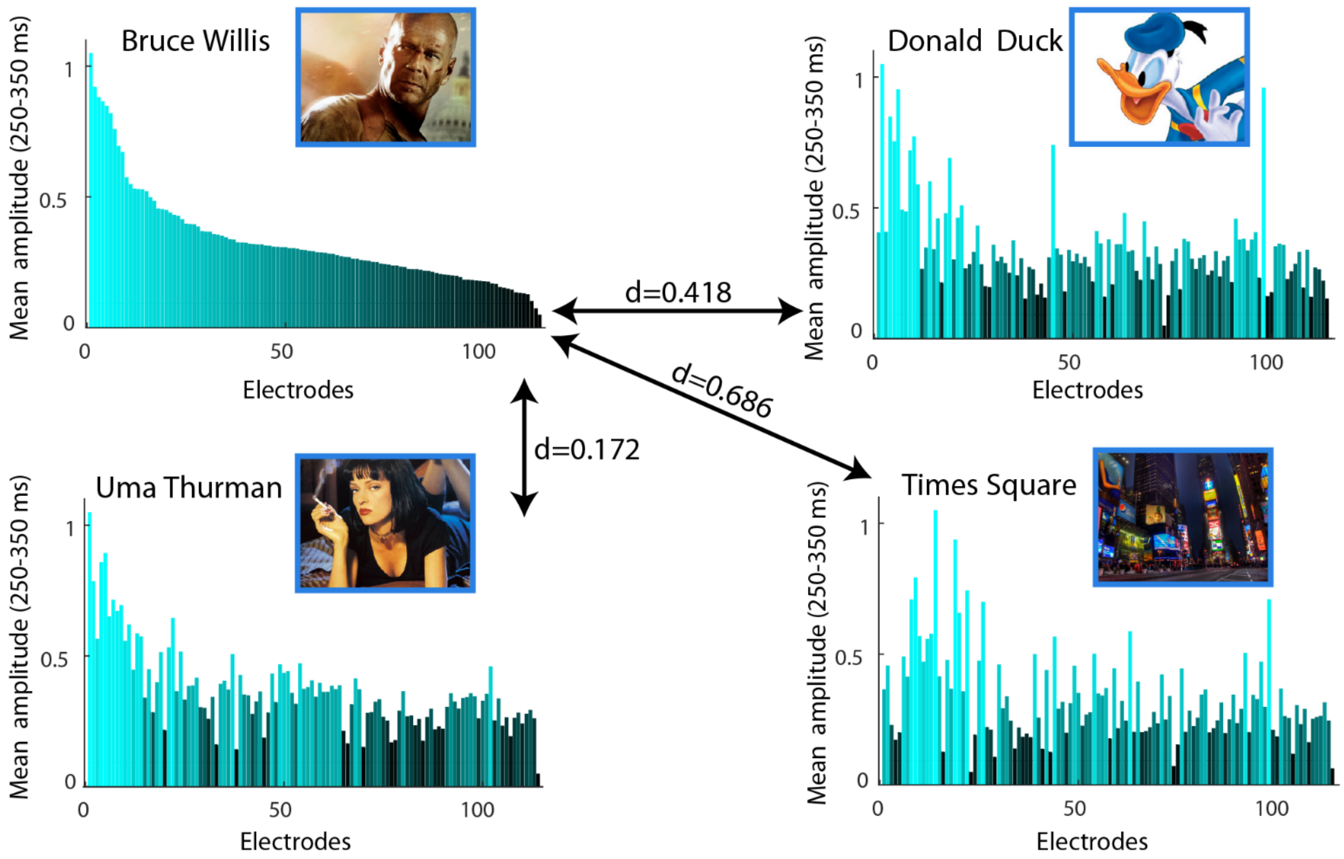


Second code: population vector



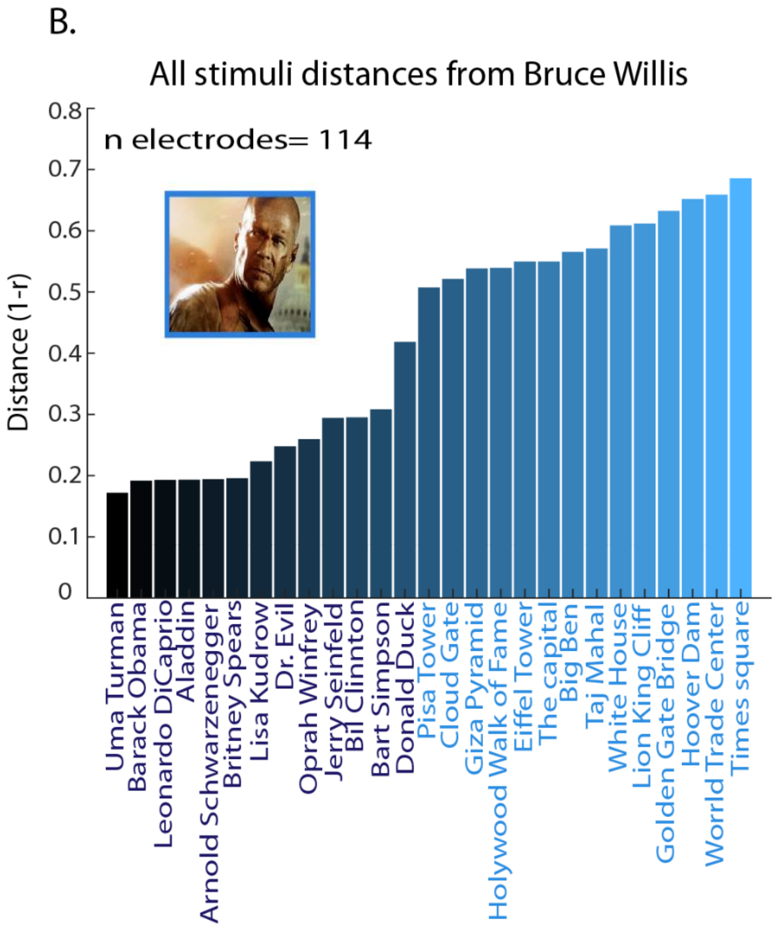
Multi-unit activation pattern to each visual image

Third code: relational coding



The image is coded by the similarity of its activation pattern to other patterns

Third code: relational coding



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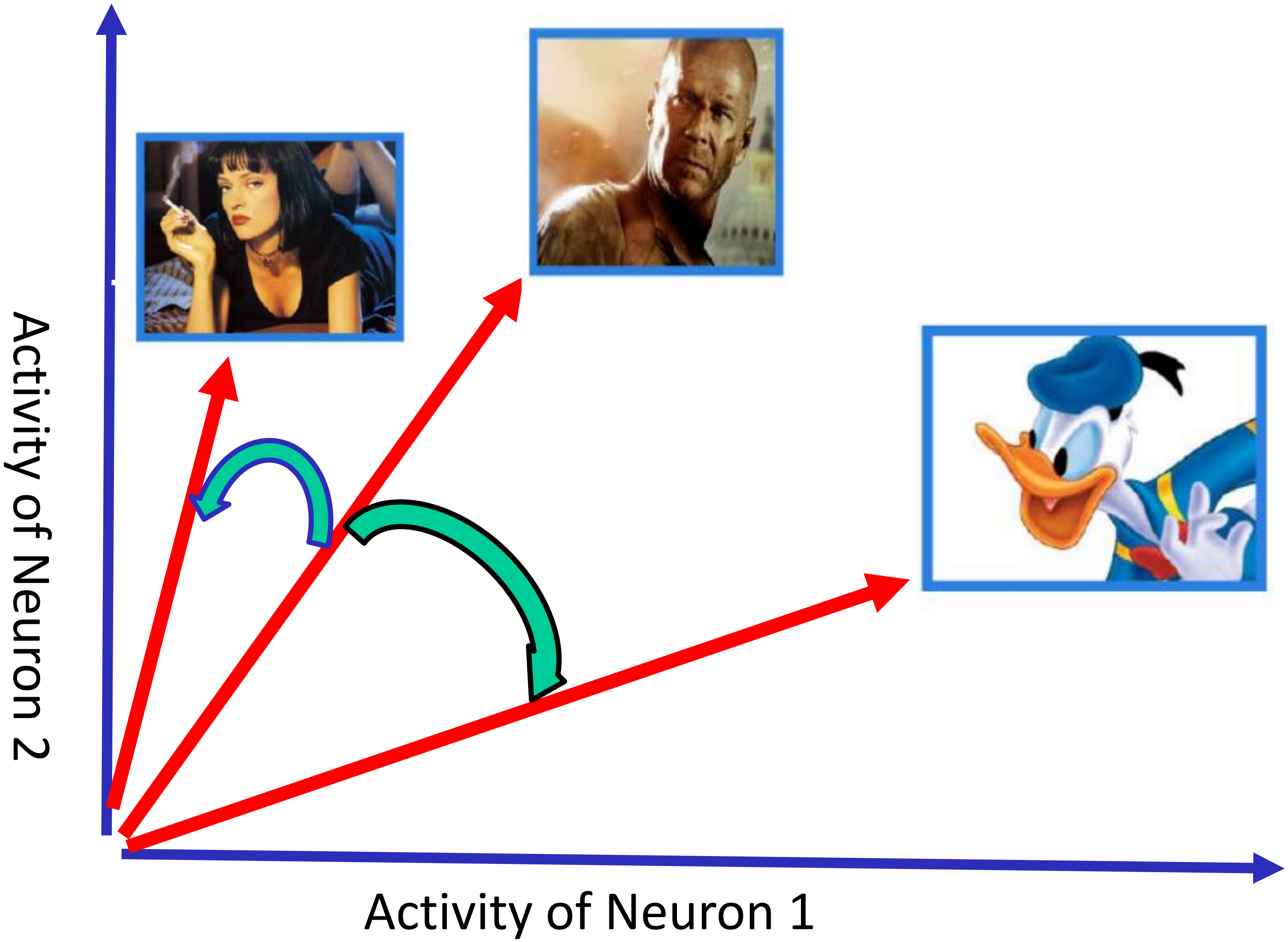
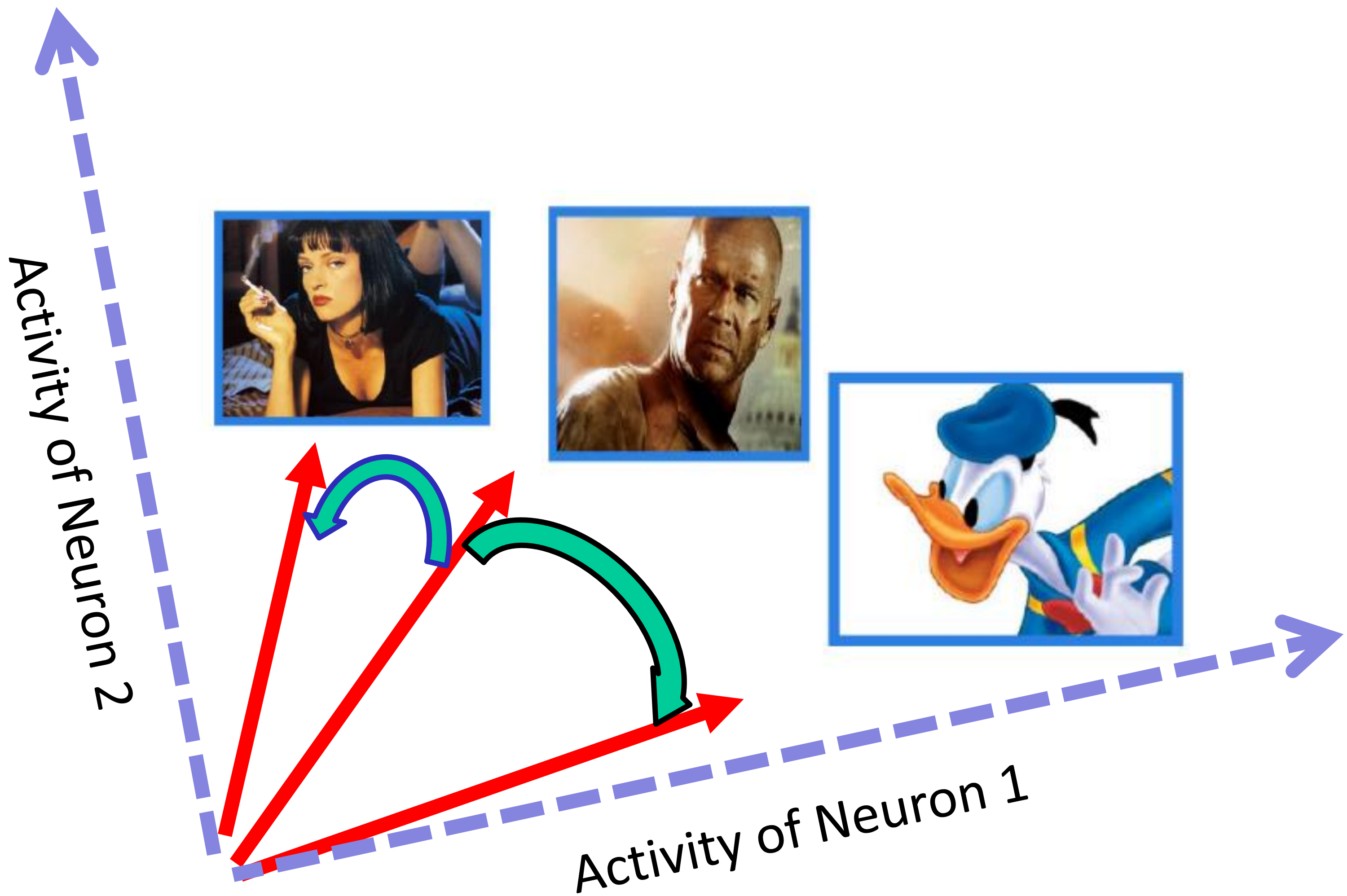


The image is coded by the angles formed between the population vectors

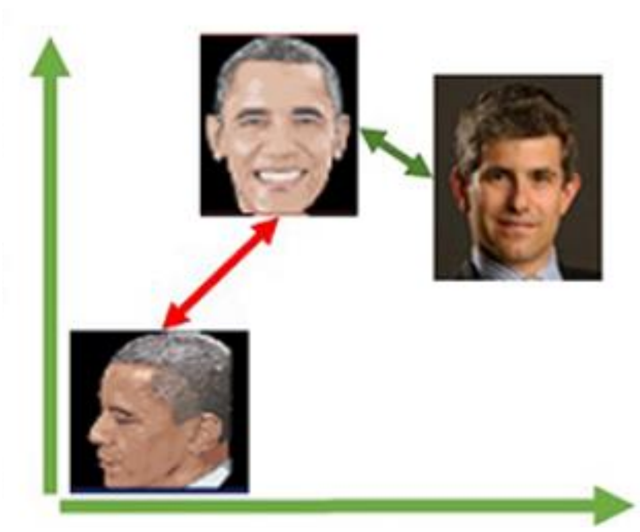
Third Code: Relational coding



Relational coding is not dependent on the single neuron tuning or magnitude

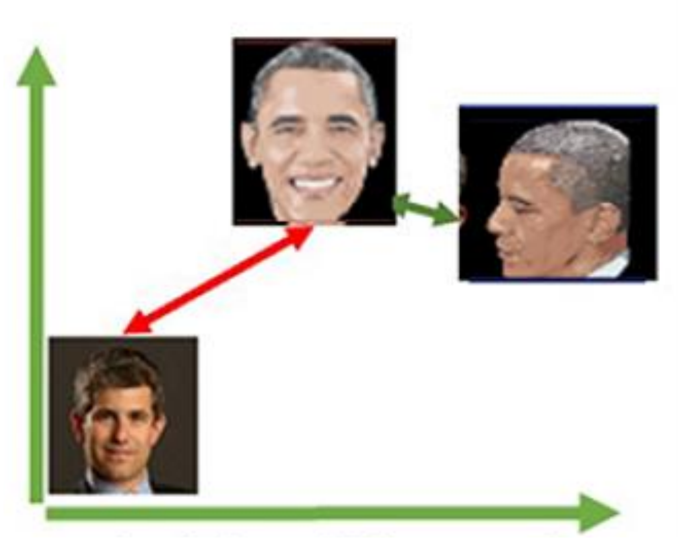
Different relational synaptic structures are associated with different categories of conscious experiences

Pictorial experience
How the face looks



View-point sensitivity

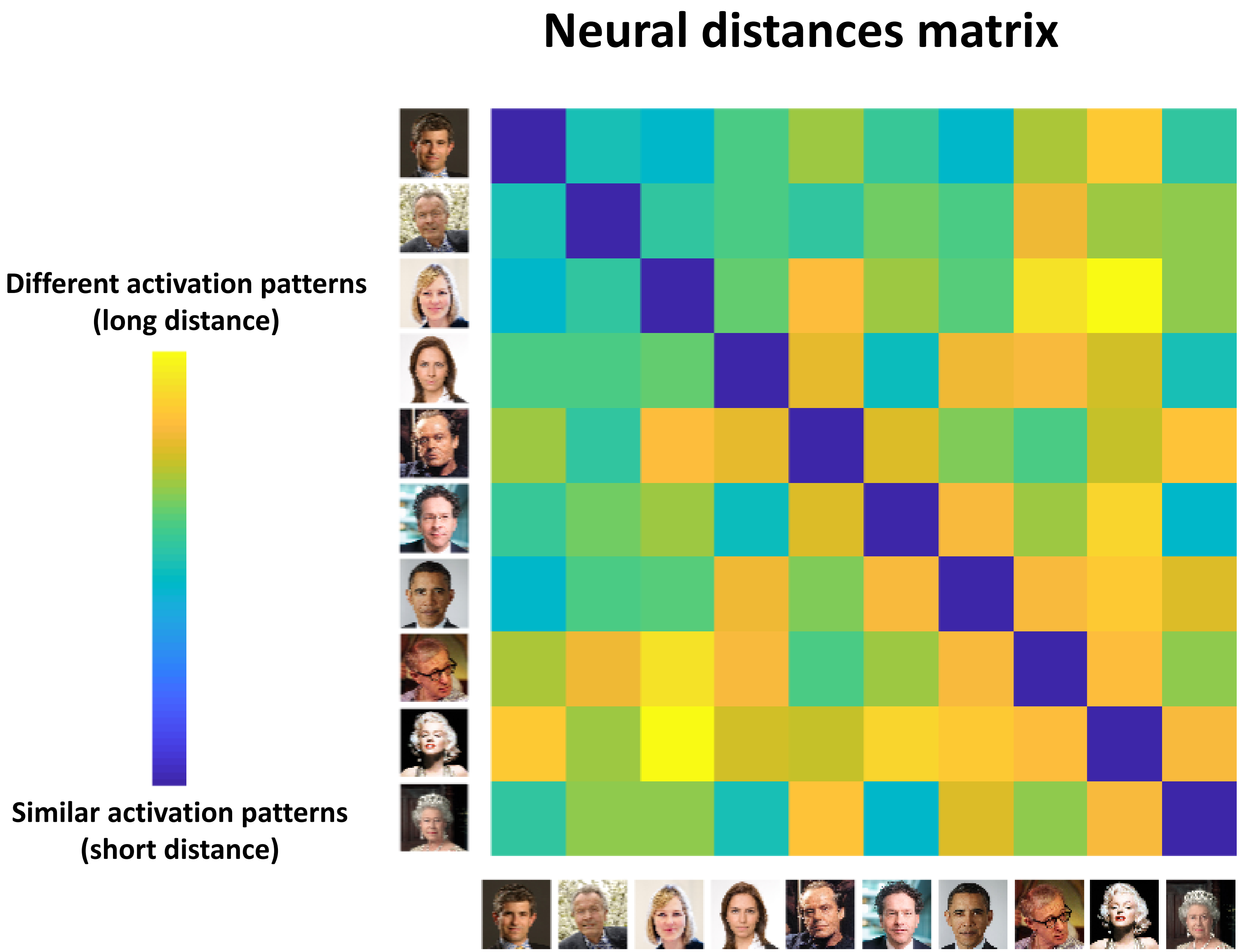
Identity experience
Who is this person



View-point invariance

Measuring relational coding in the brain

Representational Similarity Analysis (RSA)



Interim Summary

- Three possible coding schemes of of visual images

:

1) Single neurons- information coded in the magnitude of single neuron response to different images

Pro: most simple and straightforward coding scheme

Con: Unrealistic given large number of possible images, “grand-mother” neuron never found

2) Population vector- information coded by the activation patterns of neuronal groups

Pro: solves the combinatorial explosion problem

Con: Sensitive to large scale noise, adaptation and input disruptions

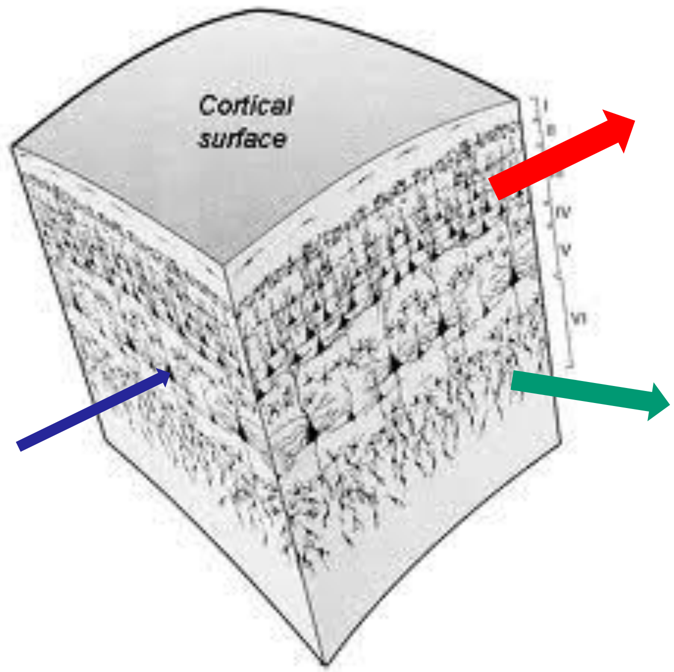
3) Relational coding- information is coded by the correlations between patterns

Pro: Robust to noise, intrinsic in nature, explains cortical specializations

Con: limited experimental support

Functional organization of the cortex

Vertical organization: 6 layers



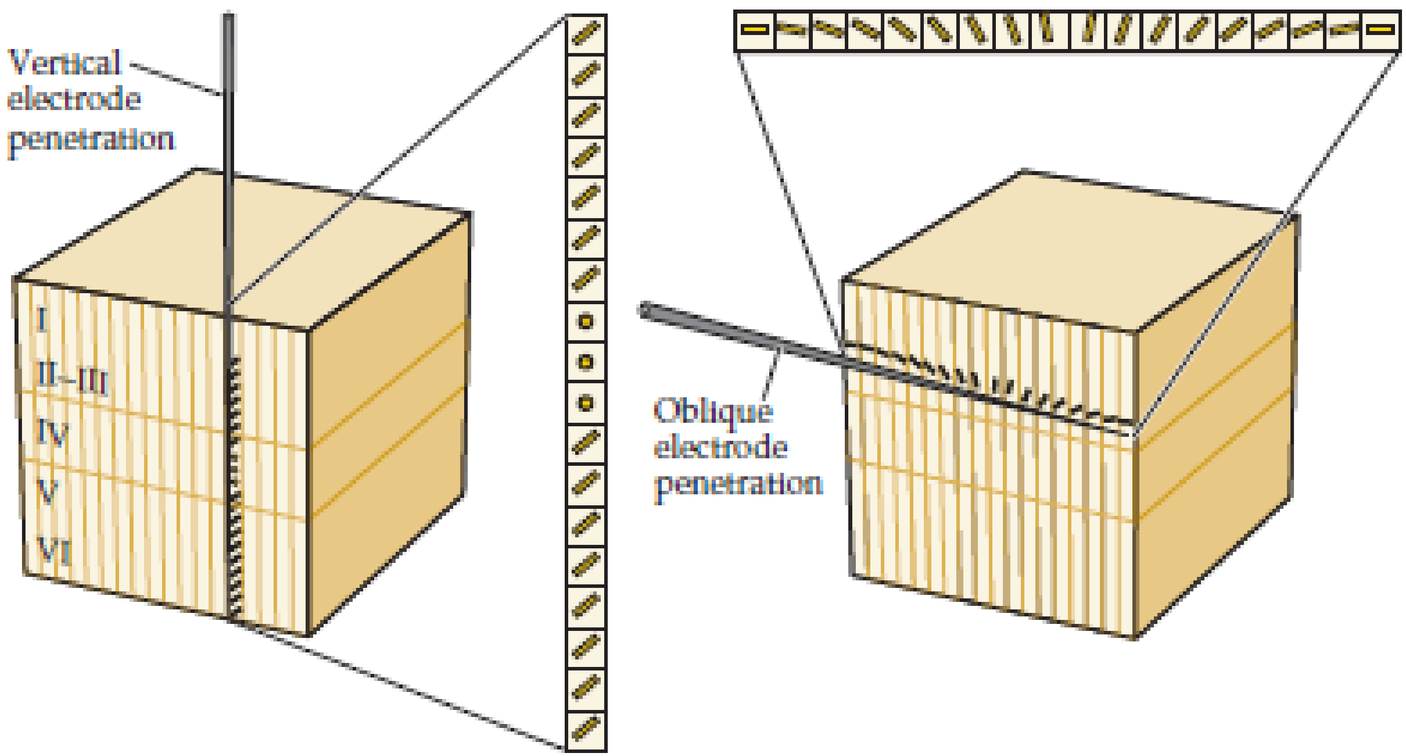
Outputs to higher cortical areas

Outputs to other brain systems

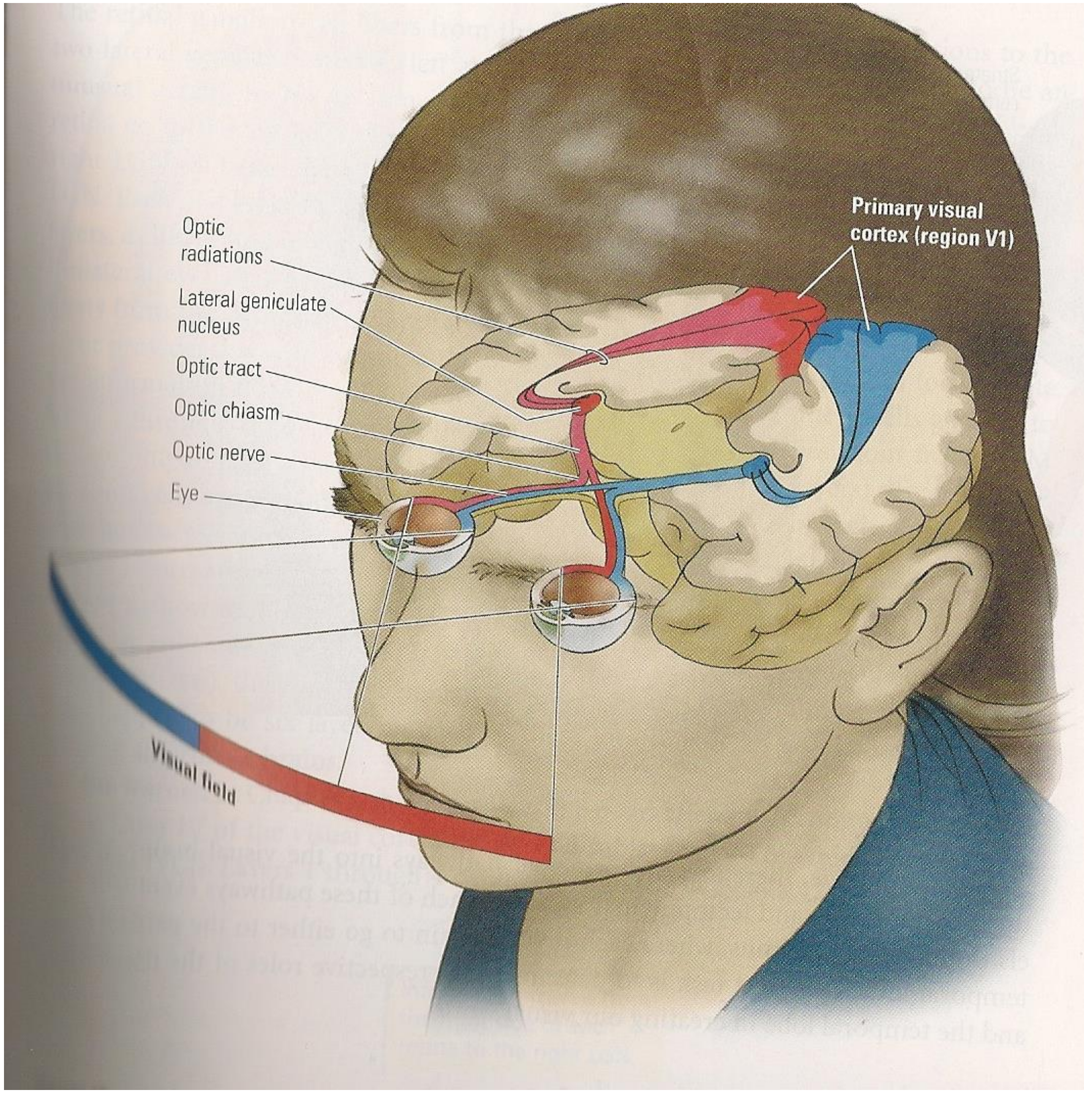
Inputs from Lower cortical areas

Functional organization of Area V1

Horizontal organization: “Orientation columns”

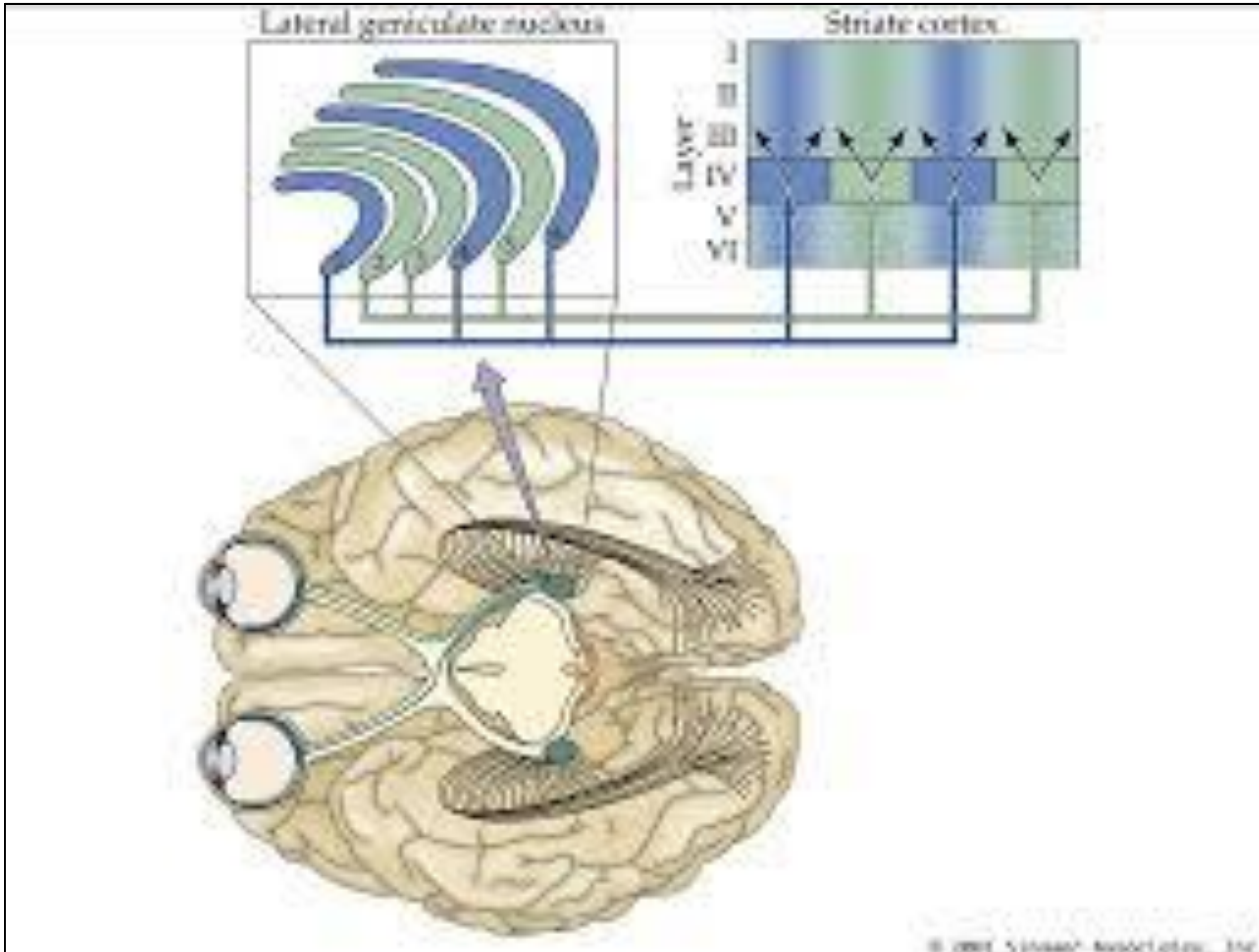


How is the information from the two eyes combined?



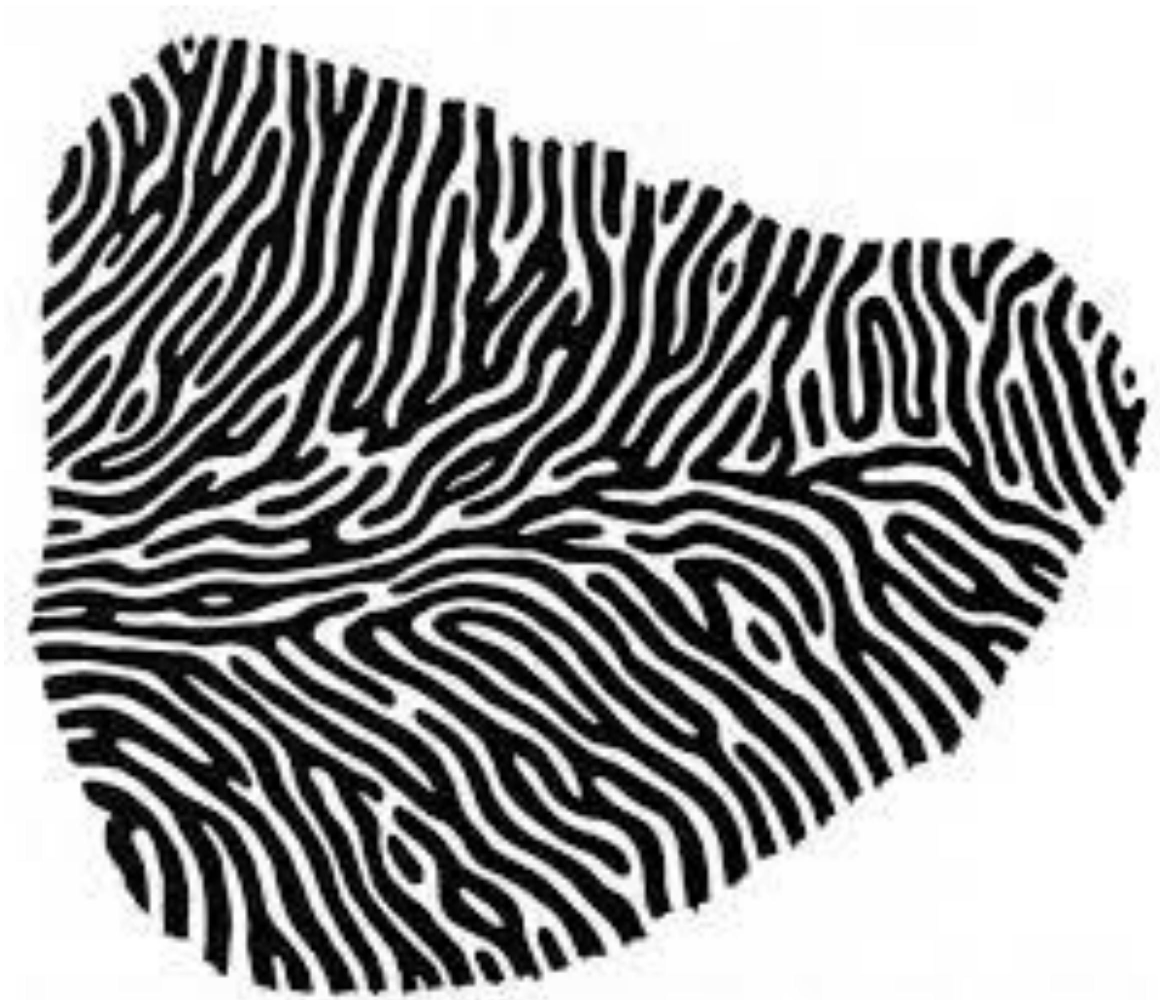
Right and left eyes outputs converge in the LGN

LGN: Ocular outputs are segregated in layers
Cortex: Ocular outputs are segregated in columns



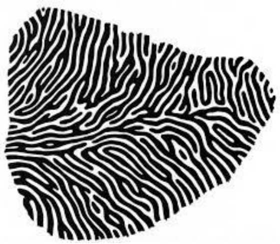
Ocular Dominance Columns

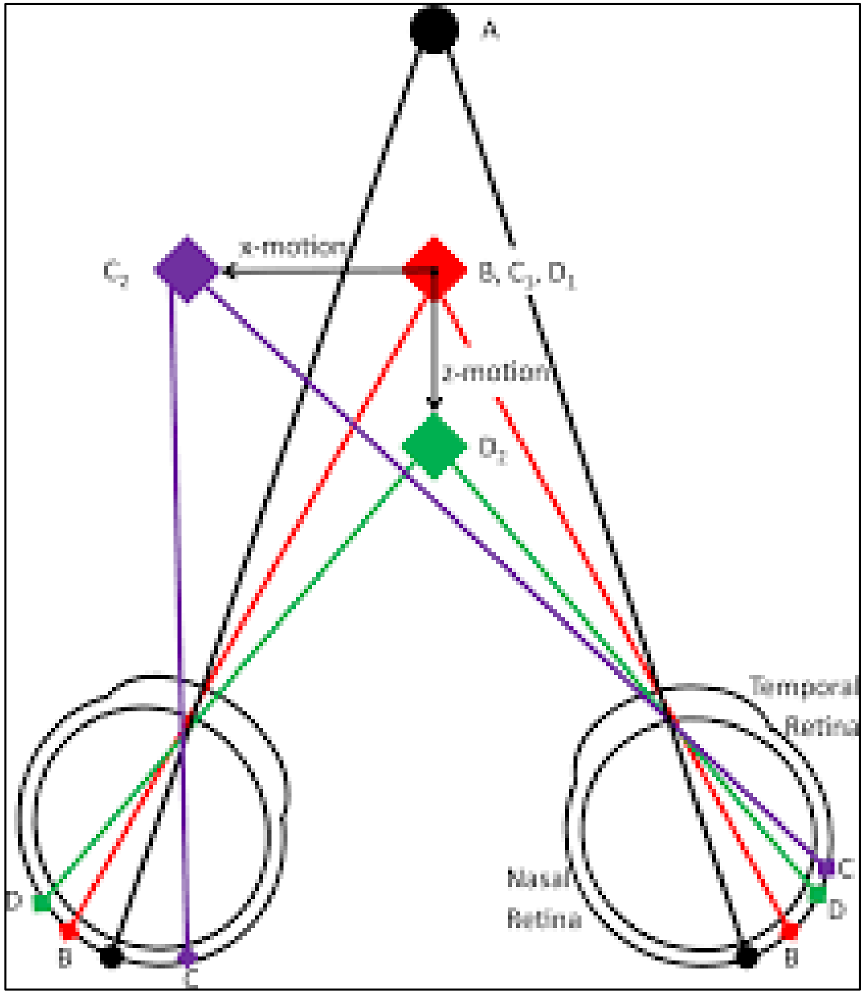
Monkey Ocular Dominance Columns- top view



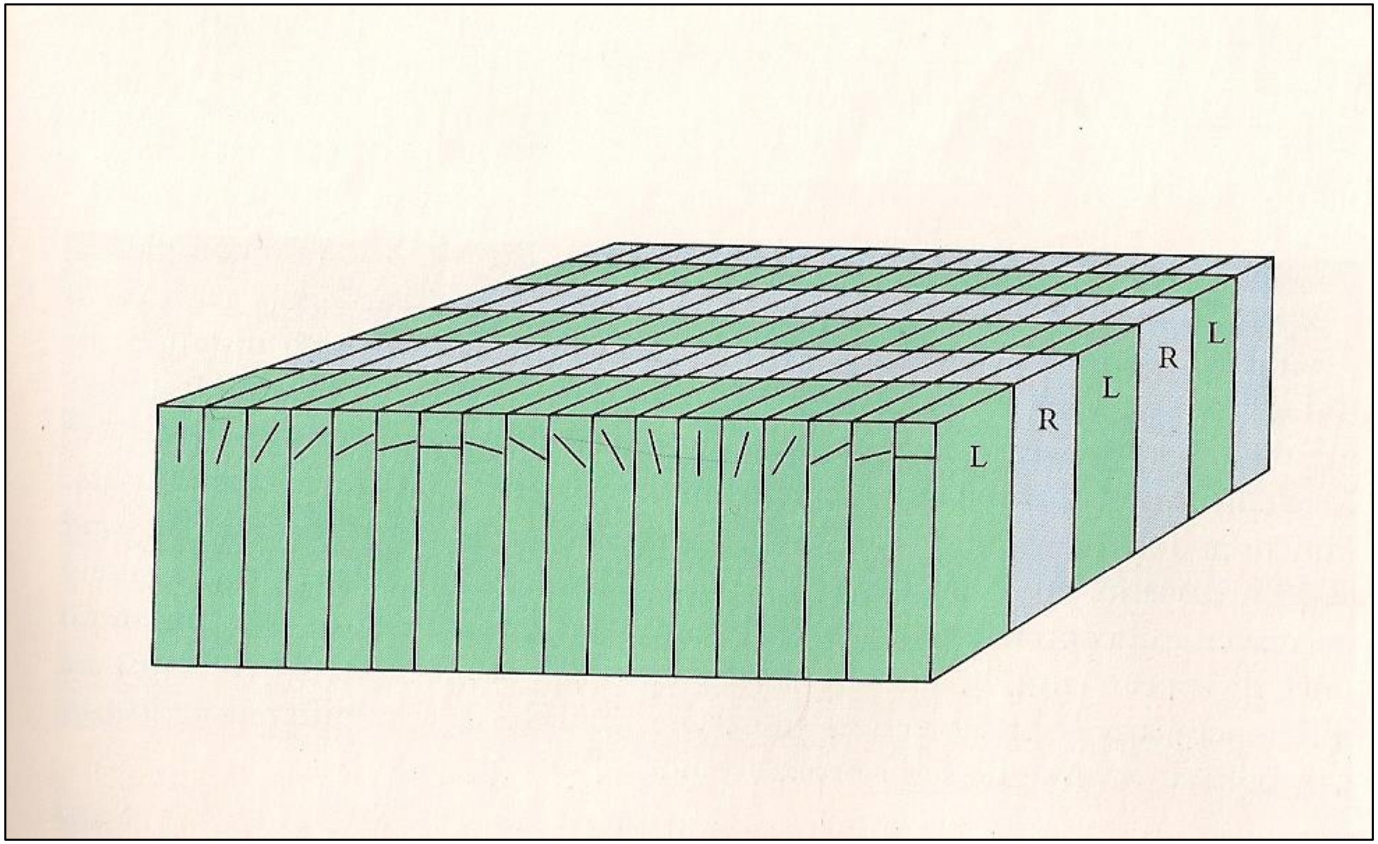
Area V1

What is the function of the ocular selectivity?





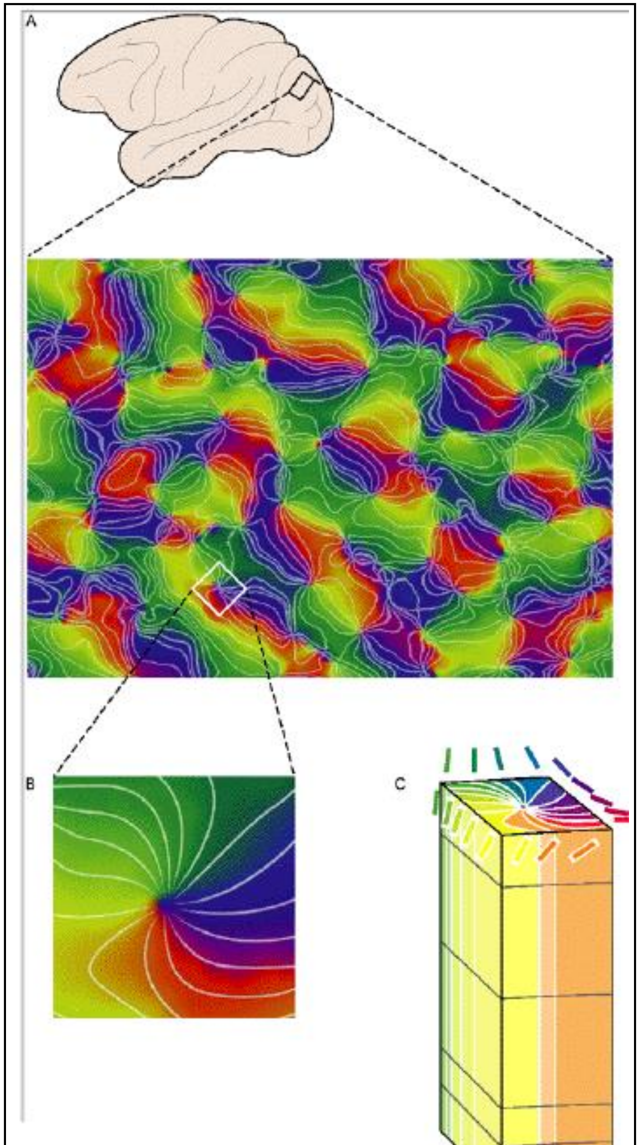
How are the ocular dominance and orientation columns combined?



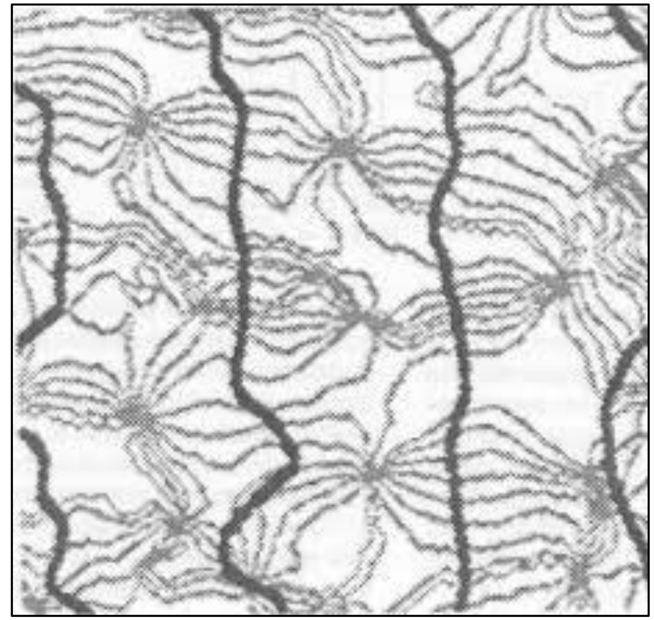
The idealized "hyper-column" model

How are the ocular dominance and orientation columns combined?

Orientation map of V1



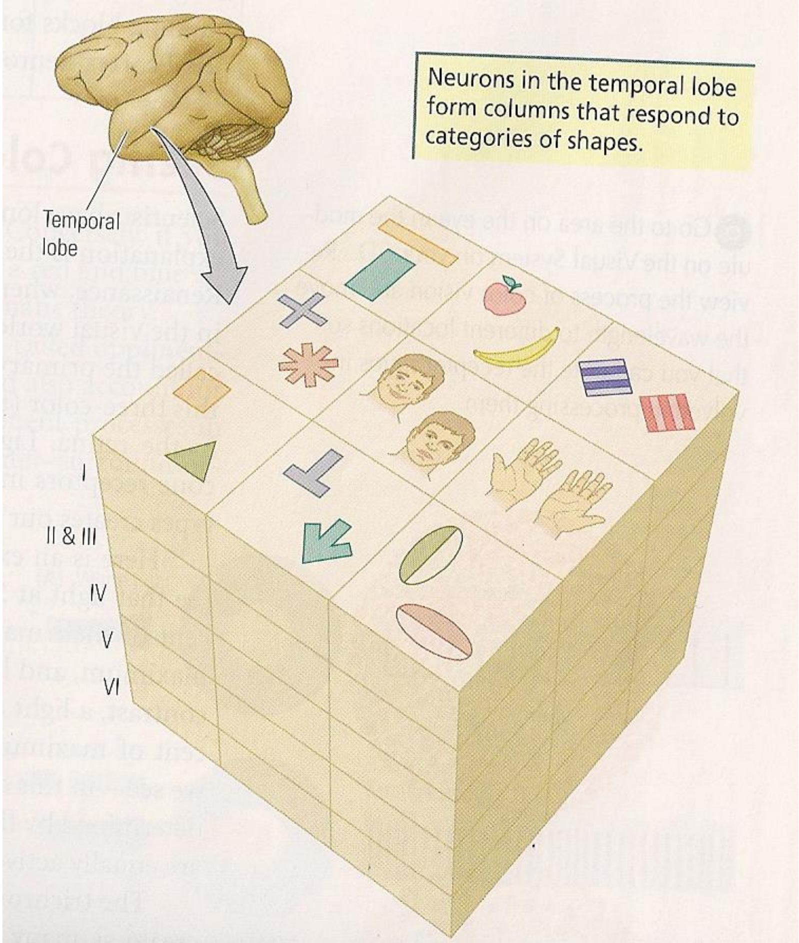
Orientation vs. Ocular Dominance



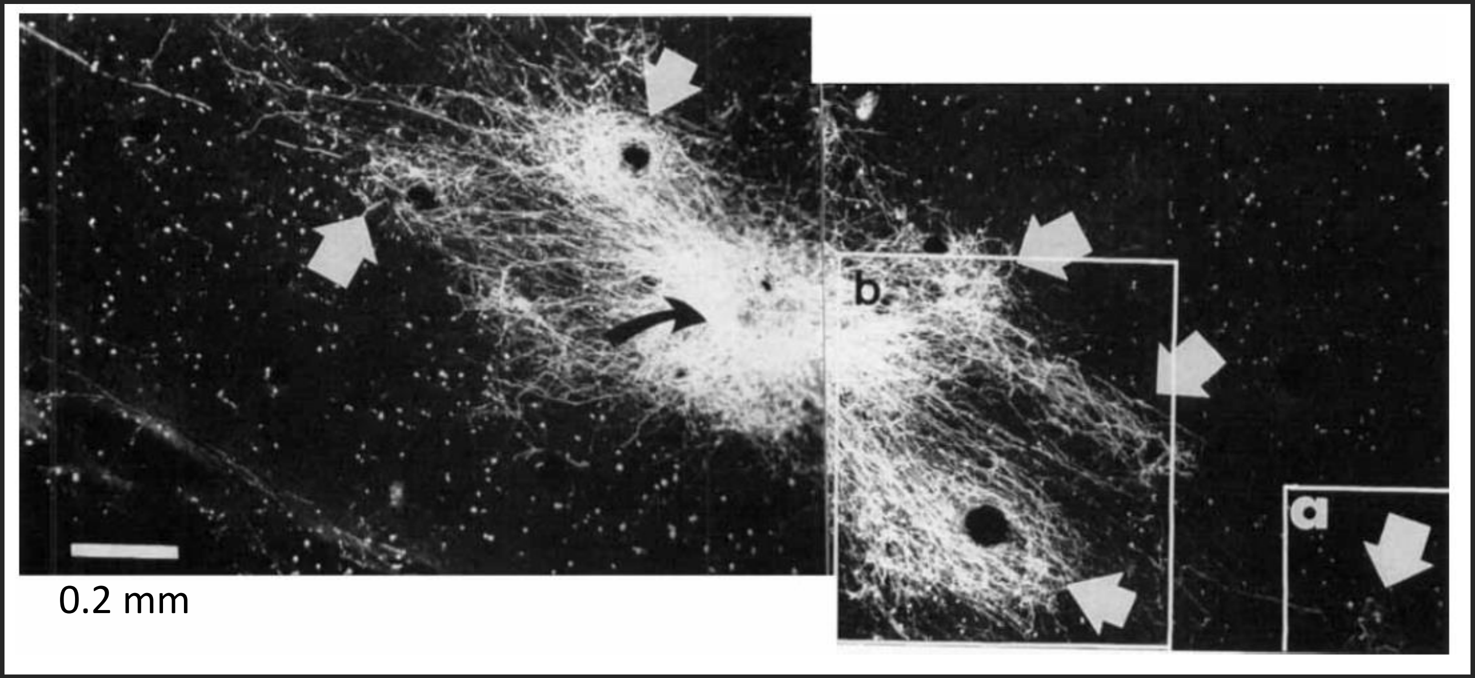
Orientation (thin lines)
Ocular-Dominance (thick lines)

The hyper-column as revealed by optical imaging

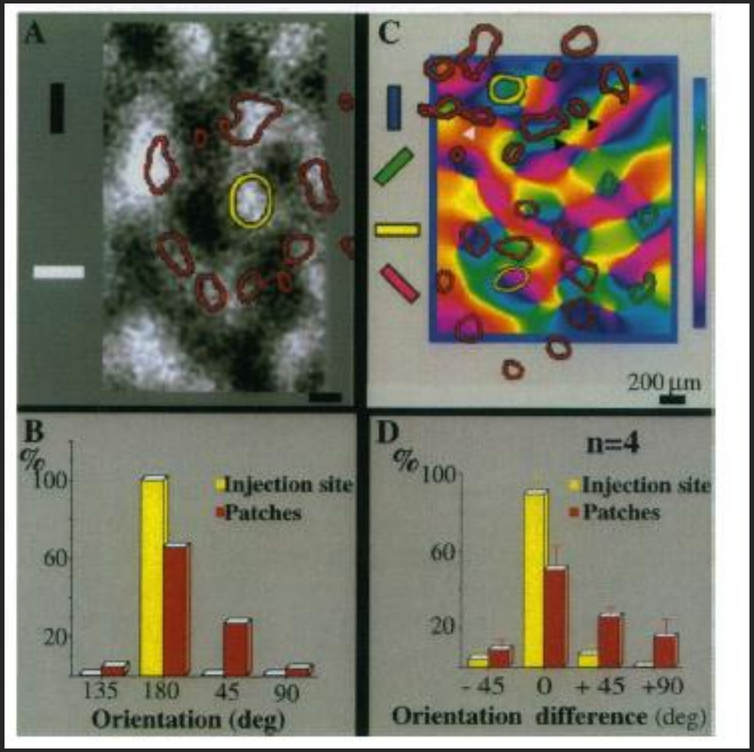
Columnar organization of complex templates in high order Ventral Stream

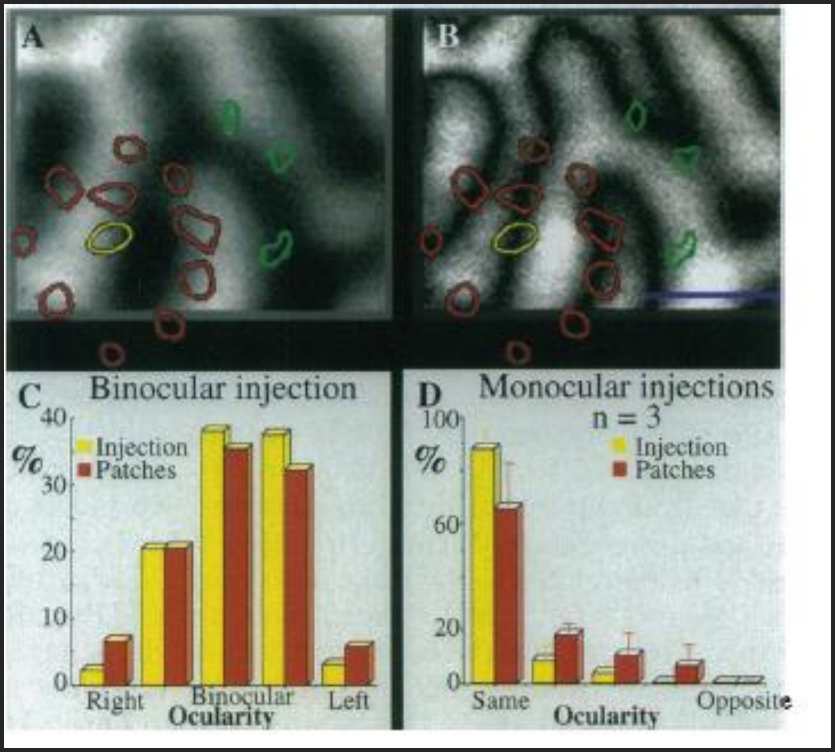


Lateral Connectivity: massive, local, reciprocal interactions



Lateral Connectivity connects similar-function columns





Interim Summary

- The functional organization of local cortical sites

Along the vertical dimension:

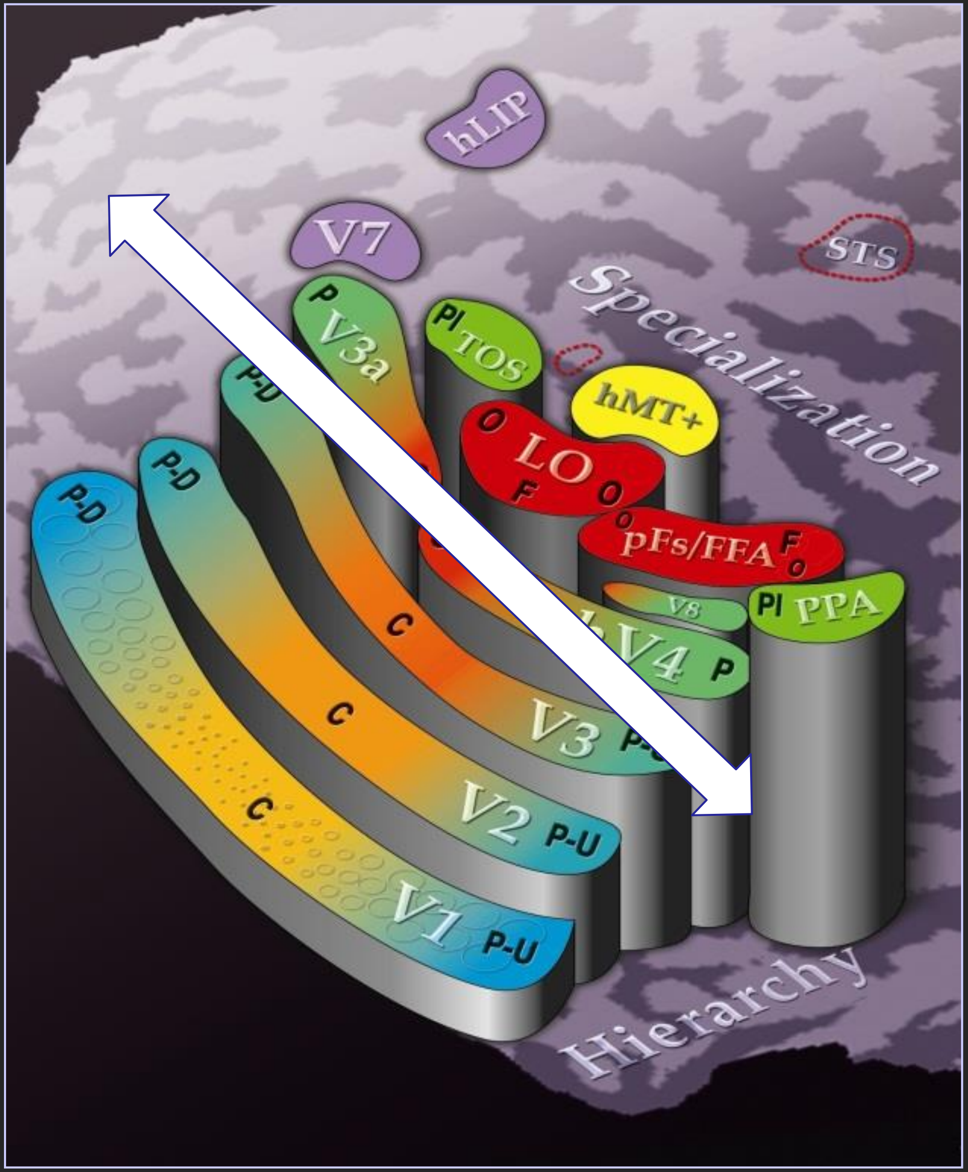
Similar functional selectivities (orientation, ocular dominance)
Six different layers- inputs arrive in middle layers, output leave of outer layers

Along the horizontal dimension
Local transition in orientation and ocular dominance
Global transition along retinotopic positions

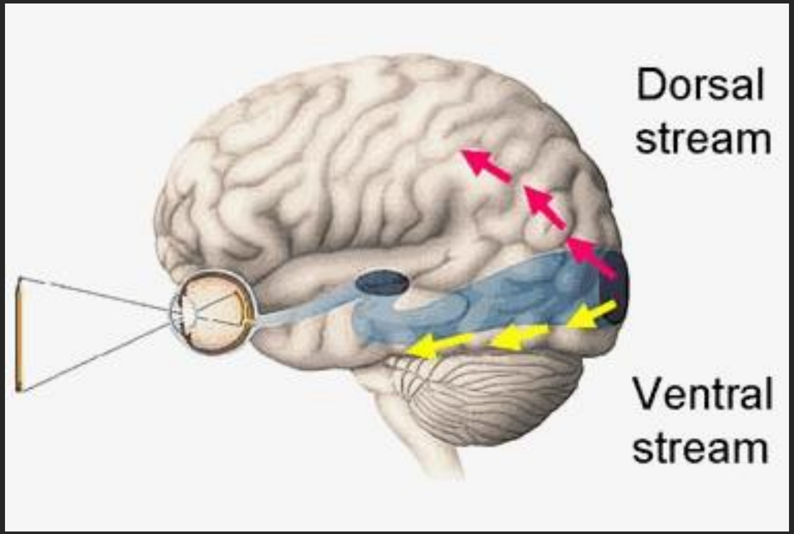
Same organization in higher areas but for complex shapes

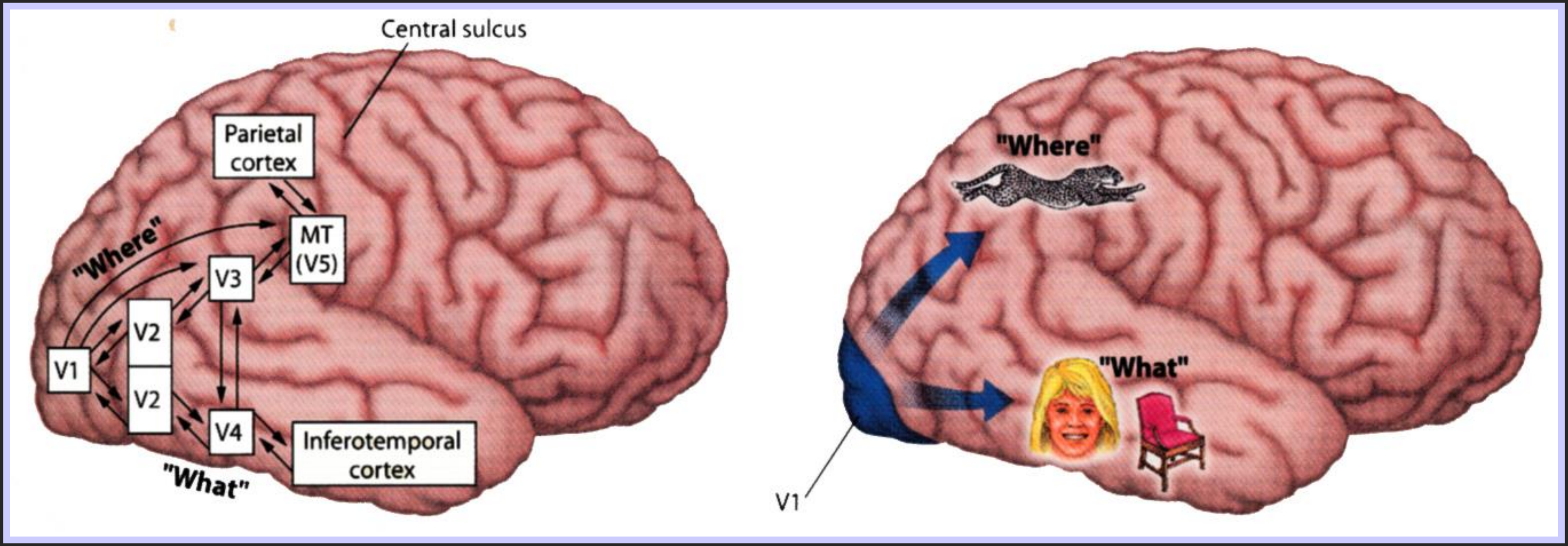
Inter-columnar communication through massive lateral connections

Large scale specialization in the visual system

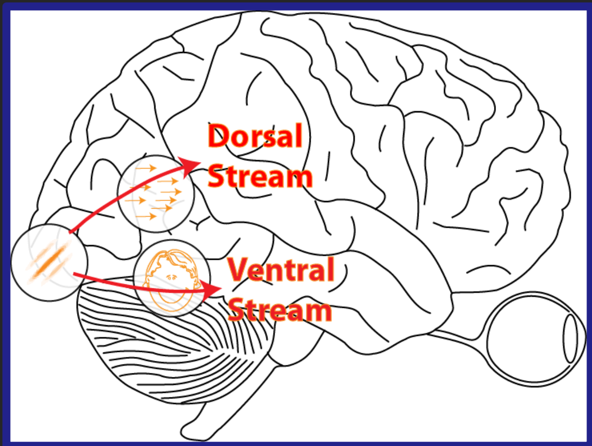


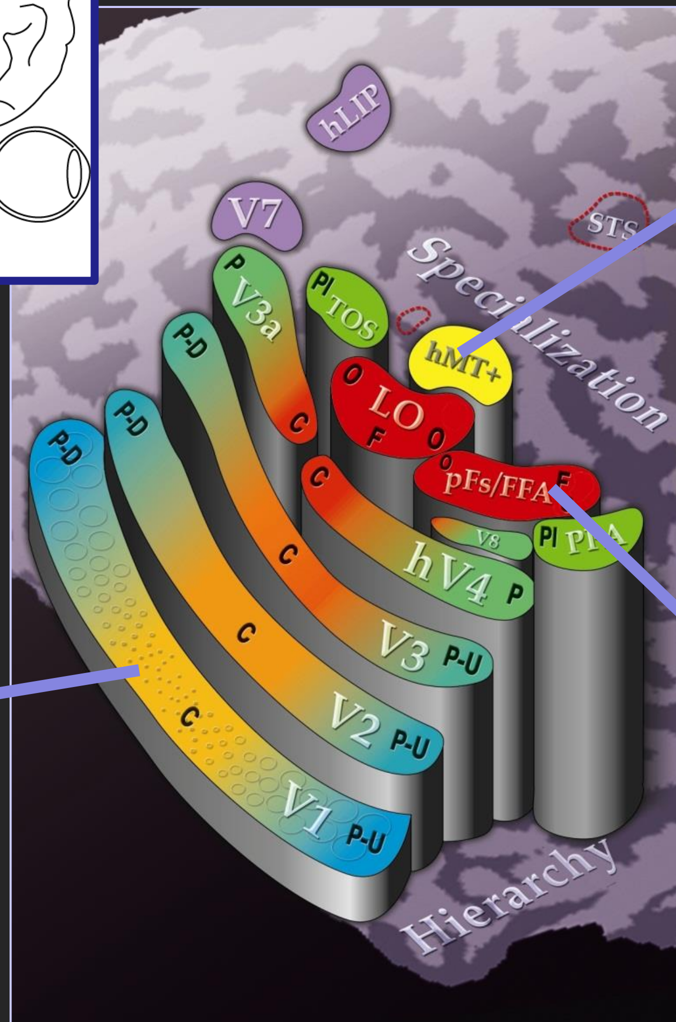
Two streams in the visual system



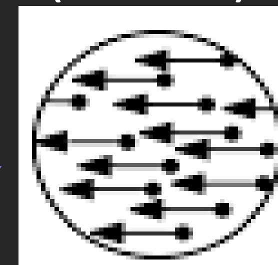


Content-Selectivity in human visual cortex



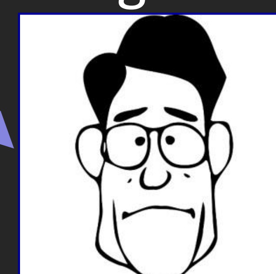


Dorsal-stream
(Action)

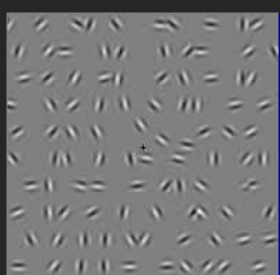


Motion
(MT/V5)

Ventral-stream
(Recognition)

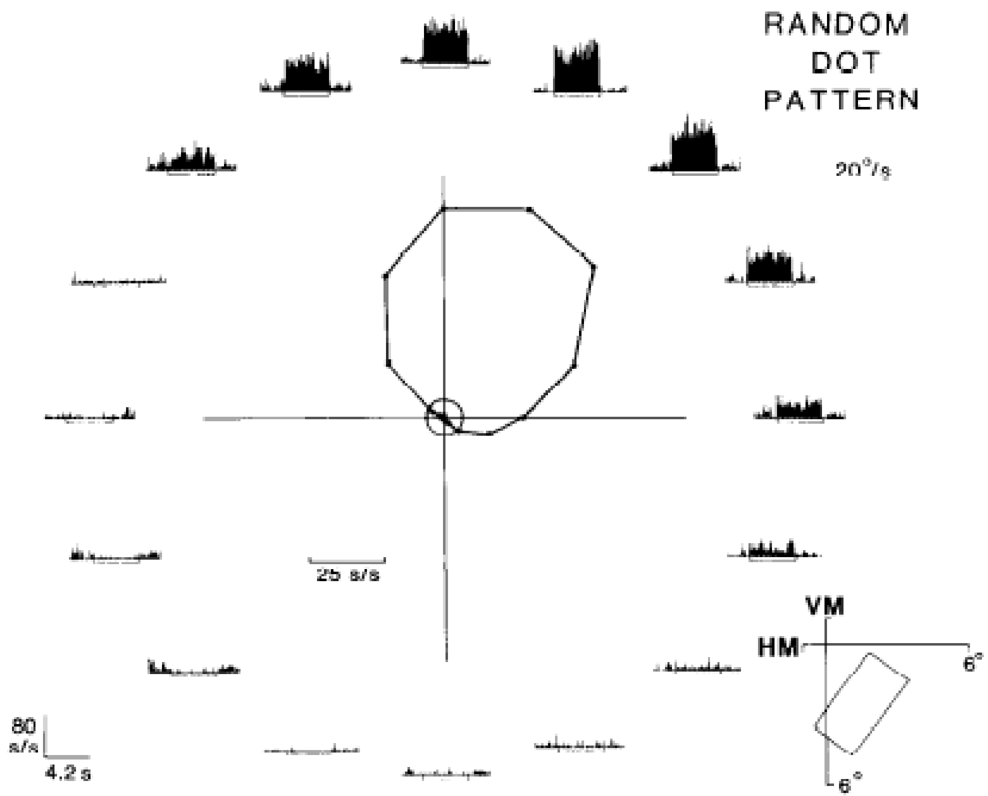


Gestalt
templates
IT/FFA



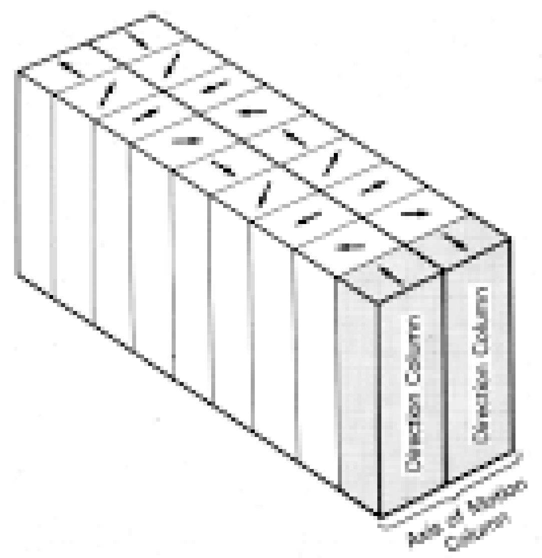
Local elements
V1

Direction selectivity in area MT- Dorsal stream



Columnar organization for direction and orientation in area MT

Columnar architecture in MT



Motion blindness following dorsal stream lesion

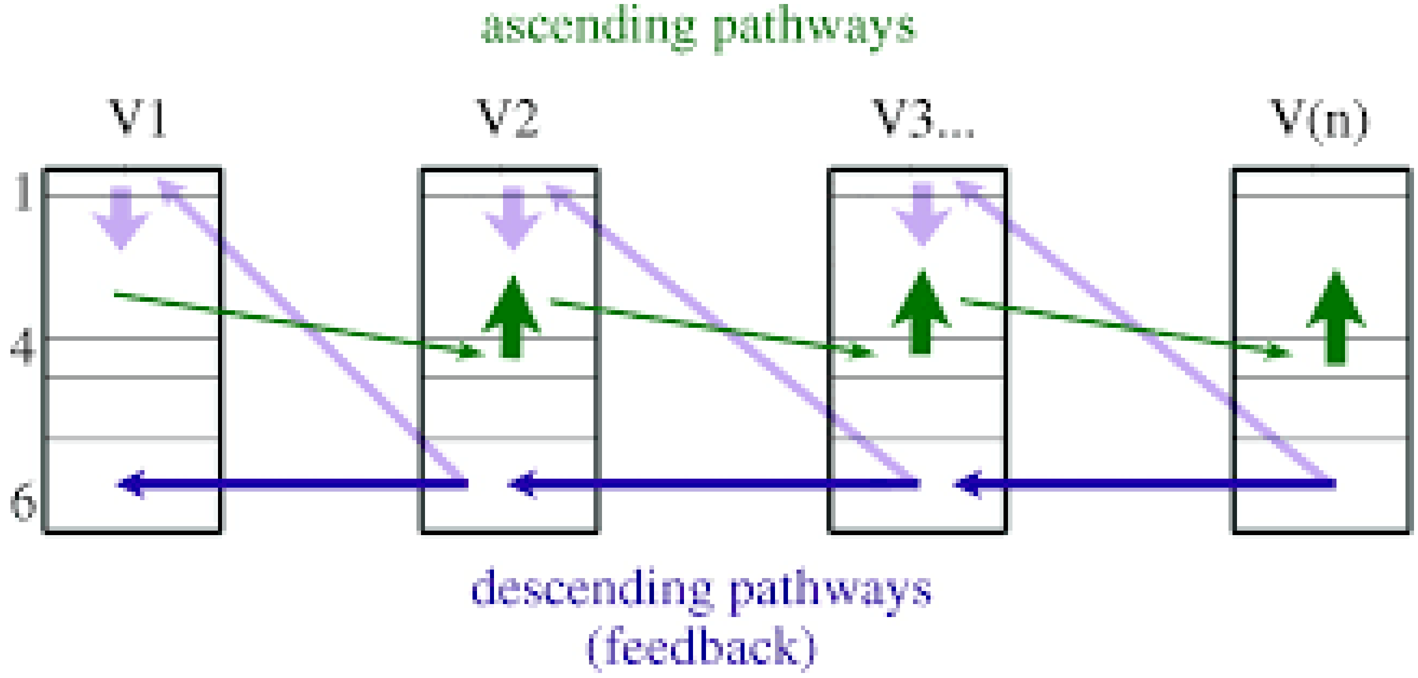
Interim Summary

- On a large scale we find a specialization of the visual system into two streams

The ventral stream specializes in form perception and recognition
Contains neurons sensitive to static templates of objects insensitive to location

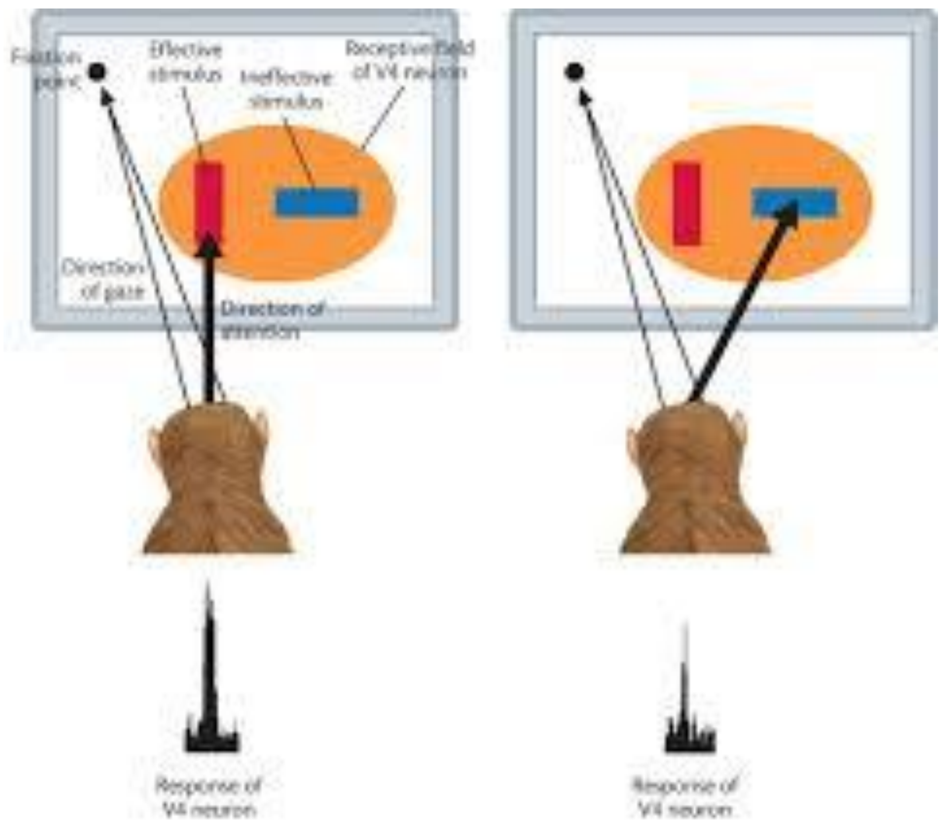
The dorsal stream specializes in motion and action
Contains neurons sensitive to motion direction and speed

Massive "Top-Down" connections along the visual hierarchy



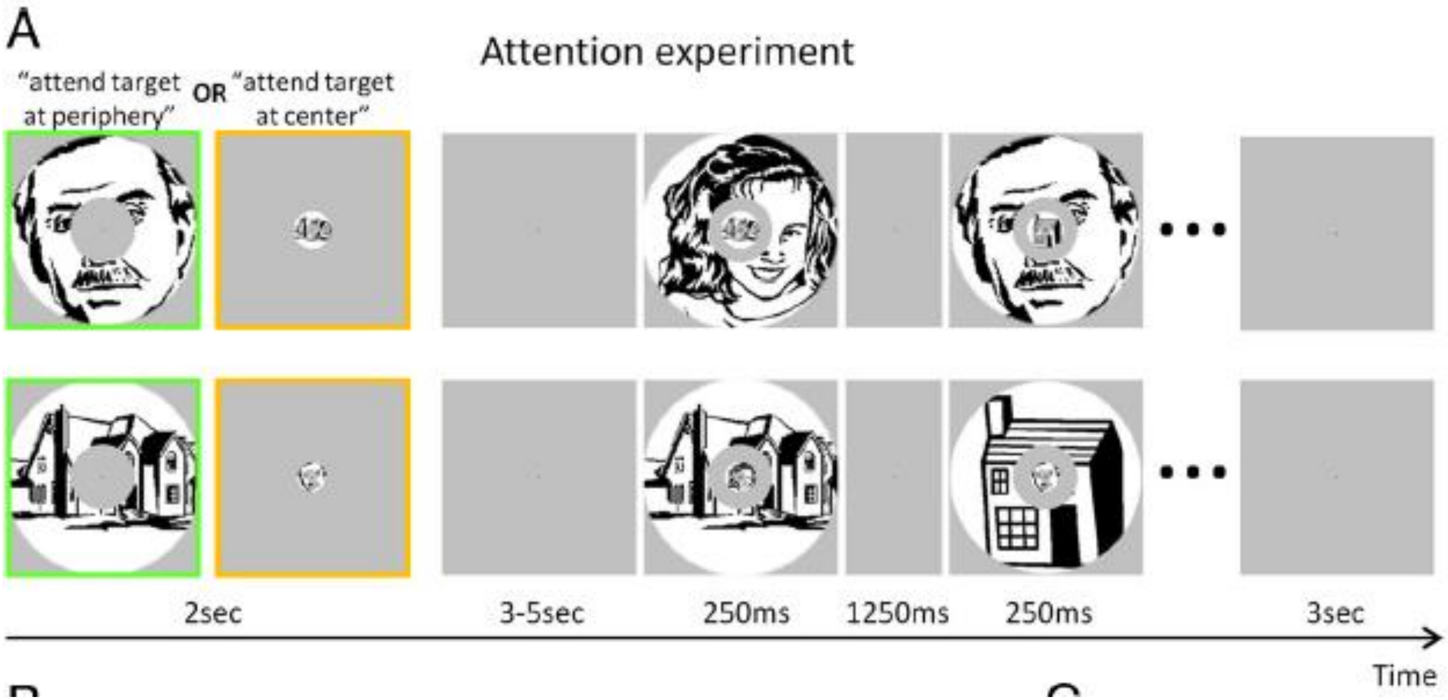
Illustrating the role of attention in visual model creation

Attention mediated by top-down connections

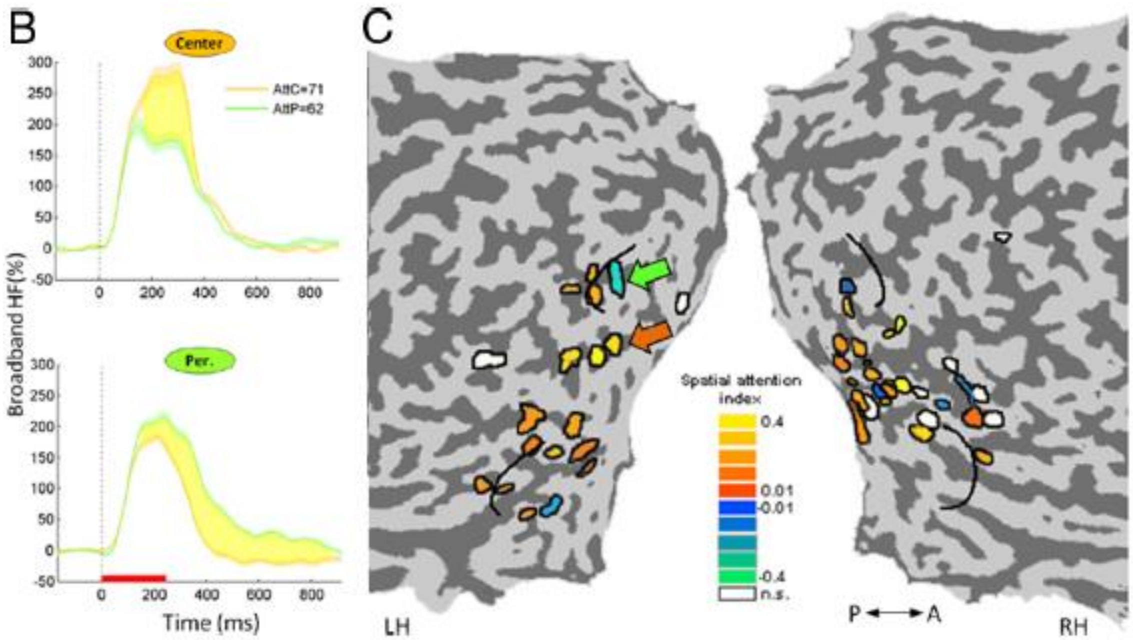


Moran and Desimone

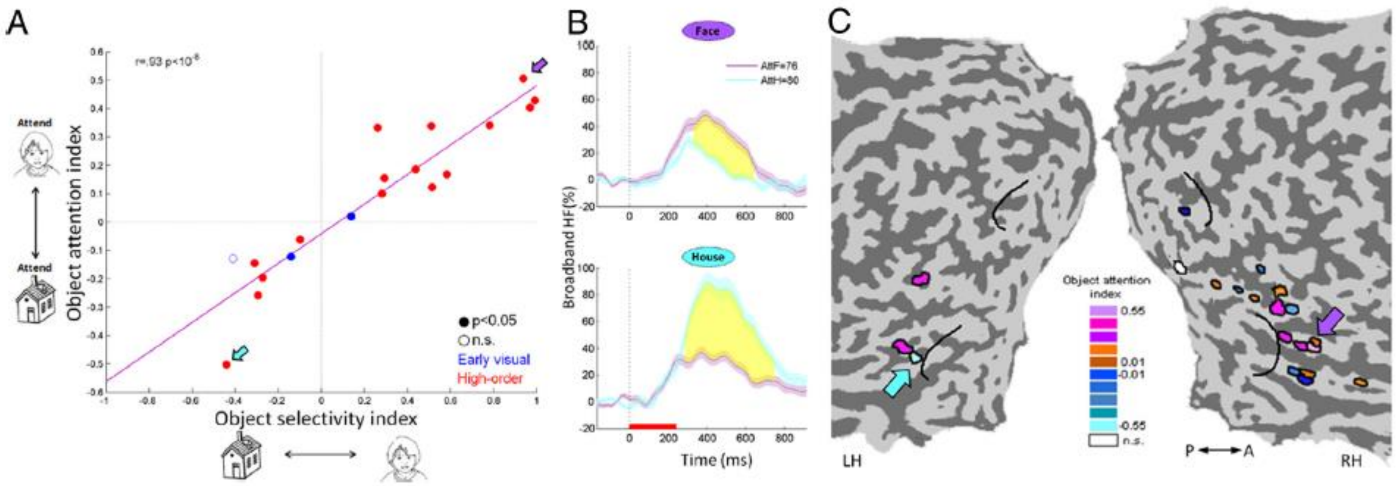
Top down attention in the human visual system



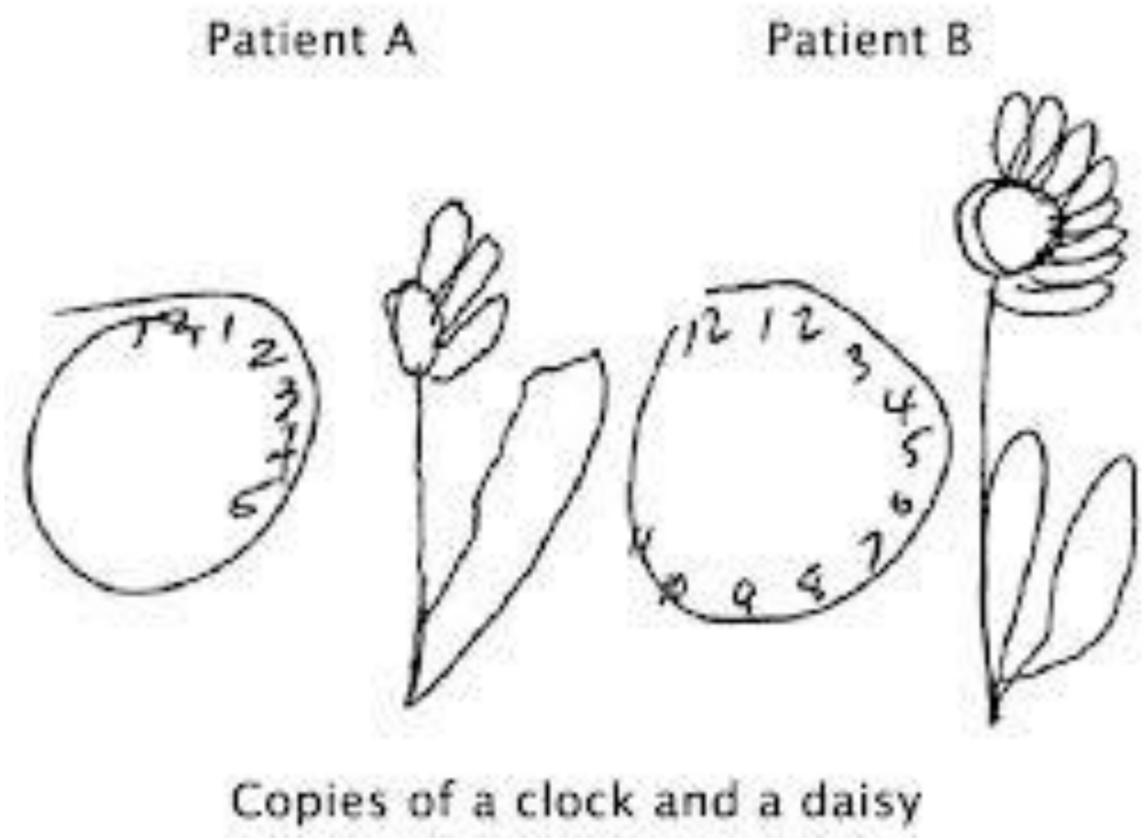
Spatial ("spot-light")attention in early visual system



Template –selective attention in high order, ventral stream



Spatial attention is mediated via the right dorsal stream



Visual Neglect following right parietal lobe lesion

Summary

Parallel to the feed-forward hierarchical flow there is a massive top-down information flow

The top-down flow implements attentional selection:
Spatial attention:

Enhances activity in attended retinotopic locations

Feature- based/form attention

Enhances activity in attended feature/form representations

Damage to the top-down mechanism results in visual neglect