

A prime advantage of monkeys is that they have a visual system that is almost identical to that in humans. They have eyes in the front of their head (not on the side like birds and rodents), a high resolution fovea in the center of the eye (rodents do not), and they move the eyes just as do humans.

Bob Wurtz



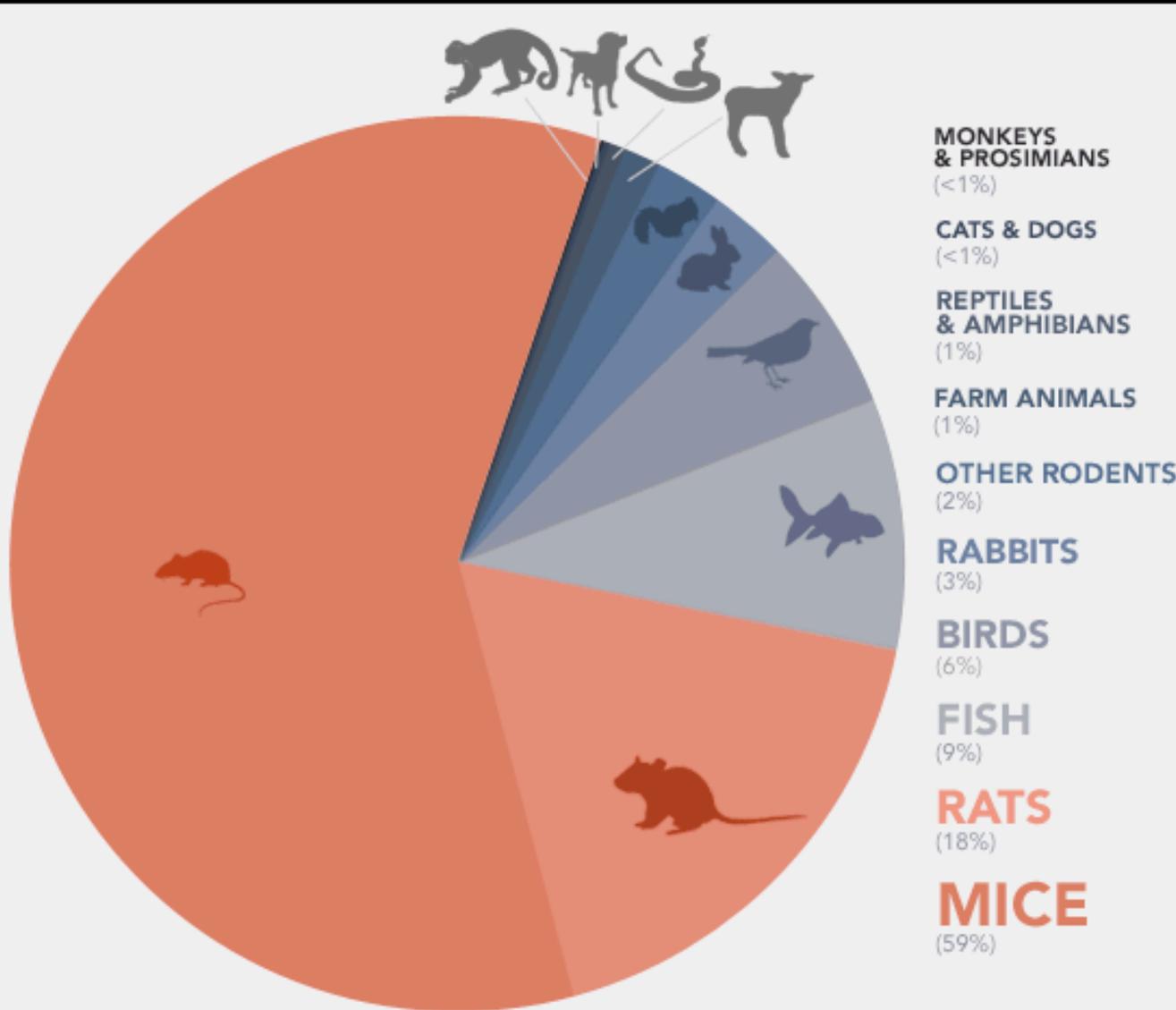
*Which species do we use, and why?*



*"I'm searching for my keys."*

# ANIMALS USED FOR EXPERIEMENTS

EUROPEAN UNION, 2008



DATA FROM: SIXTH REPORT ON THE STATISTICS ON THE NUMBER OF ANIMALS USED FOR EXPERIMENTAL AND OTHER SCIENTIFIC PURPOSES IN THE MEMBER STATES OF THE EUROPEAN UNION (2010)

# ANIMALS CITED IN BIOMEDICAL RESEARCH PAPERS

1950-2010



Mice & Rats



Yeast & Nematodes



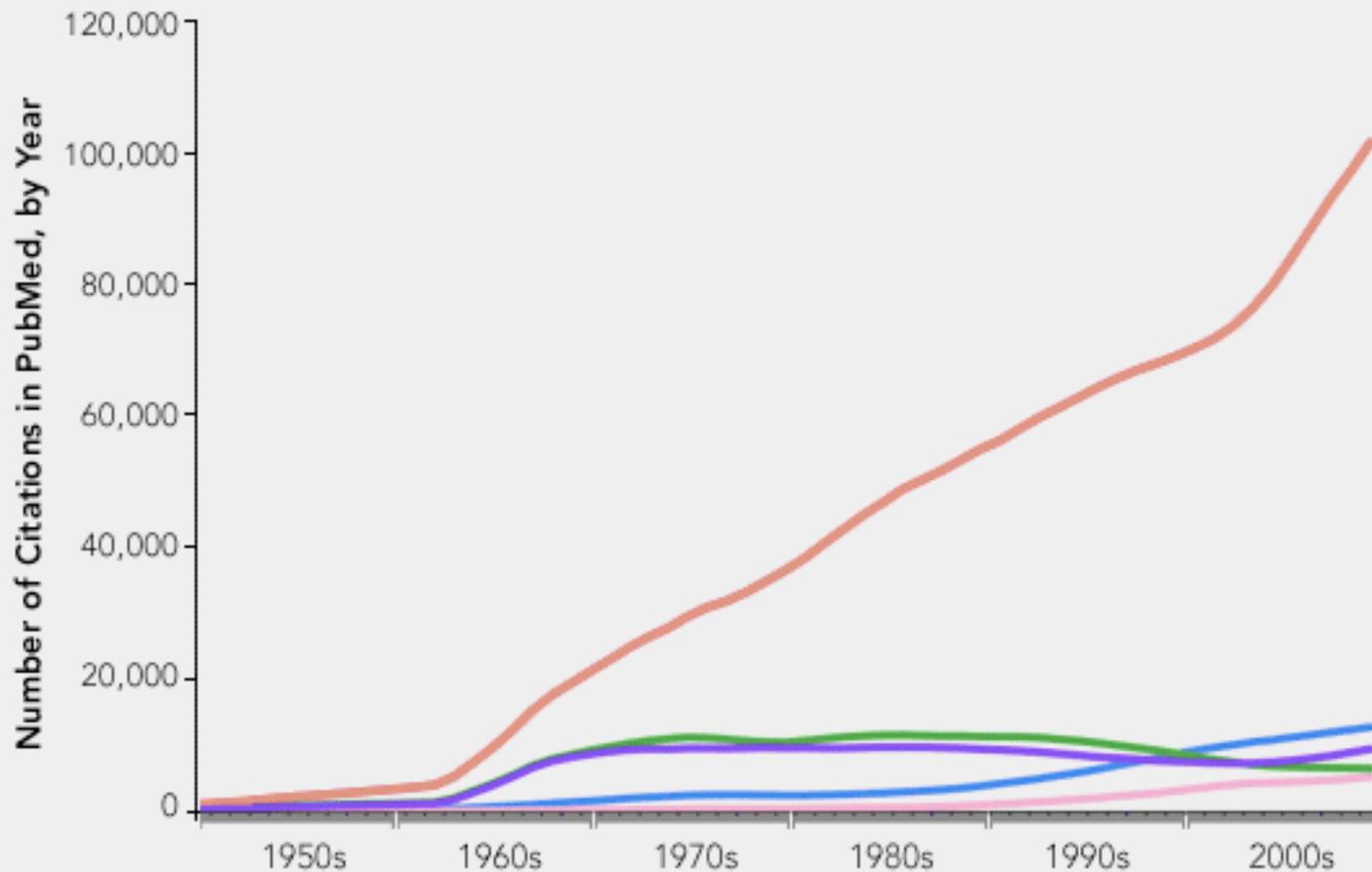
Dogs & Cats



Guinea Pigs & Rabbits

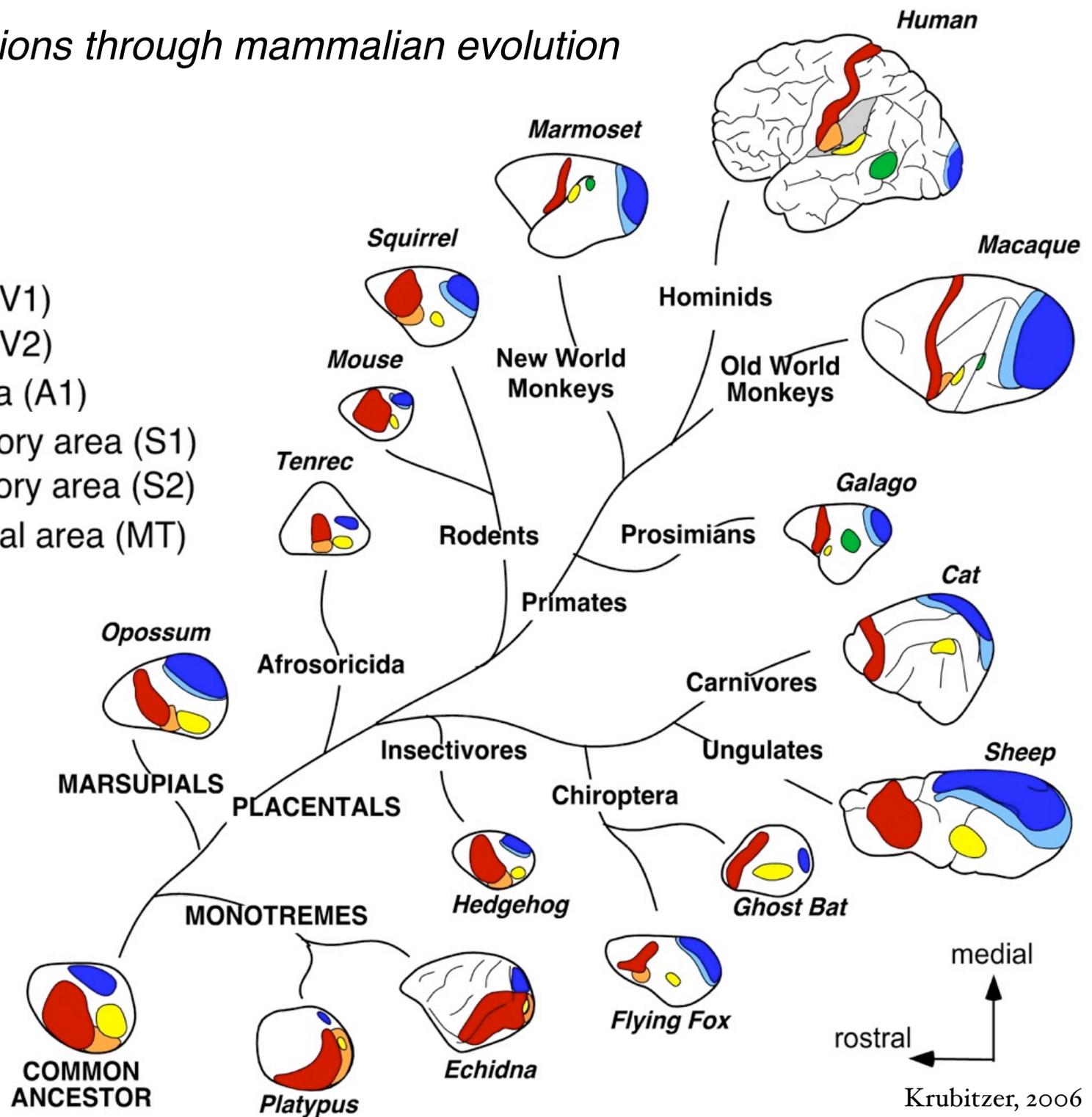


Zebrafish & Fruit Flies



# Sensory representations through mammalian evolution

- Primary visual area (V1)
- Second visual area (V2)
- Primary auditory area (A1)
- Primary somatosensory area (S1)
- Second somatosensory area (S2)
- Middle temporal visual area (MT)



# Retina

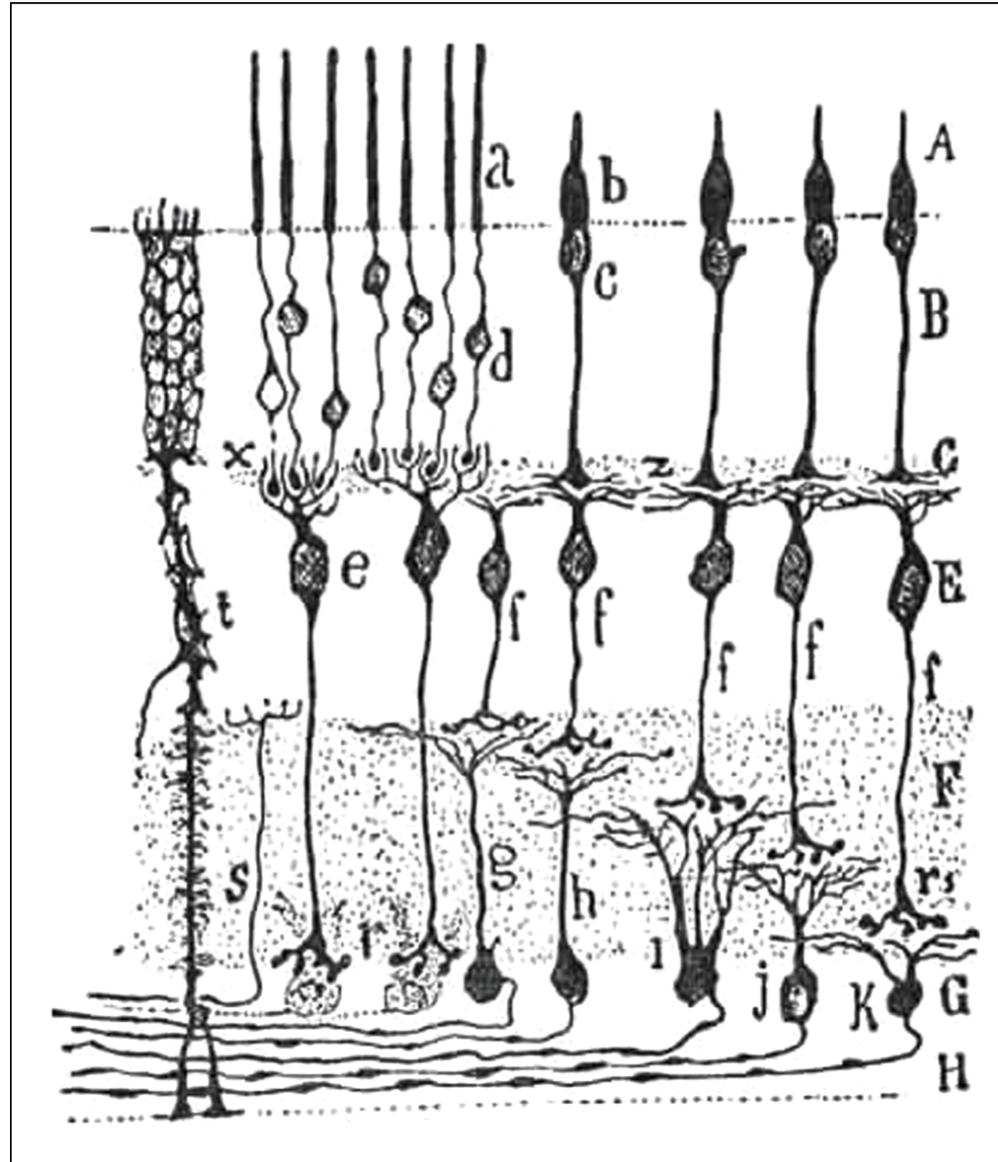
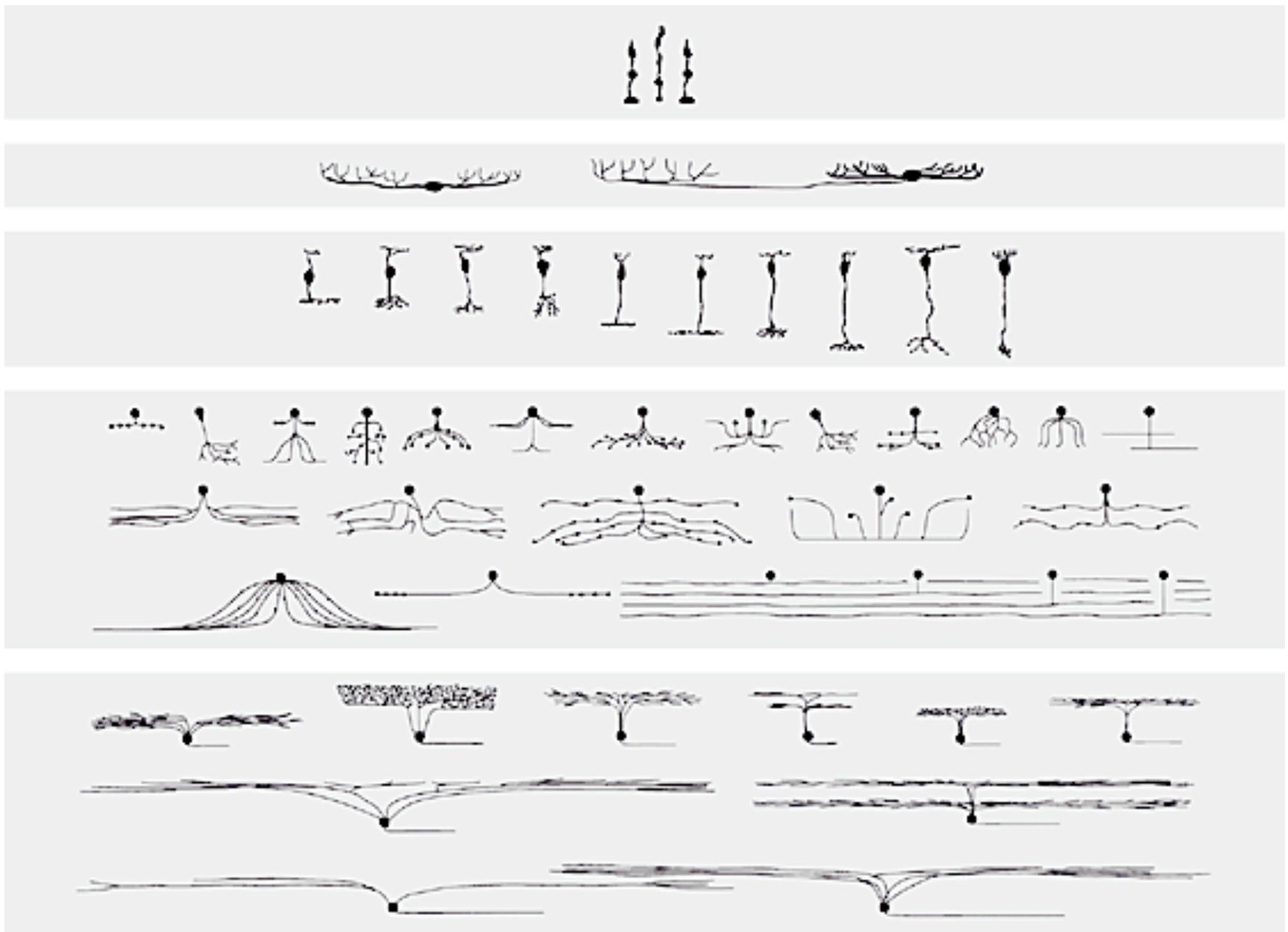
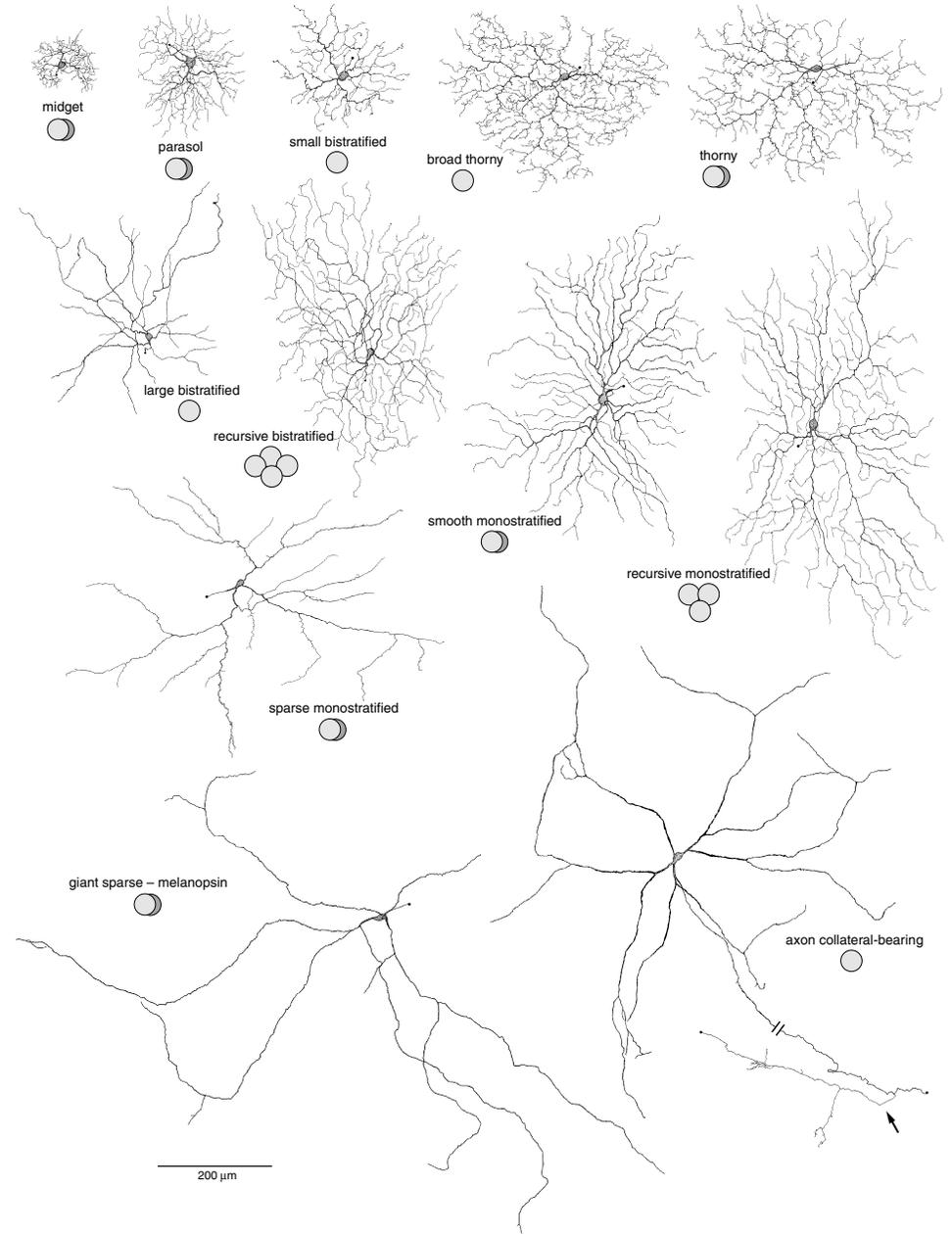
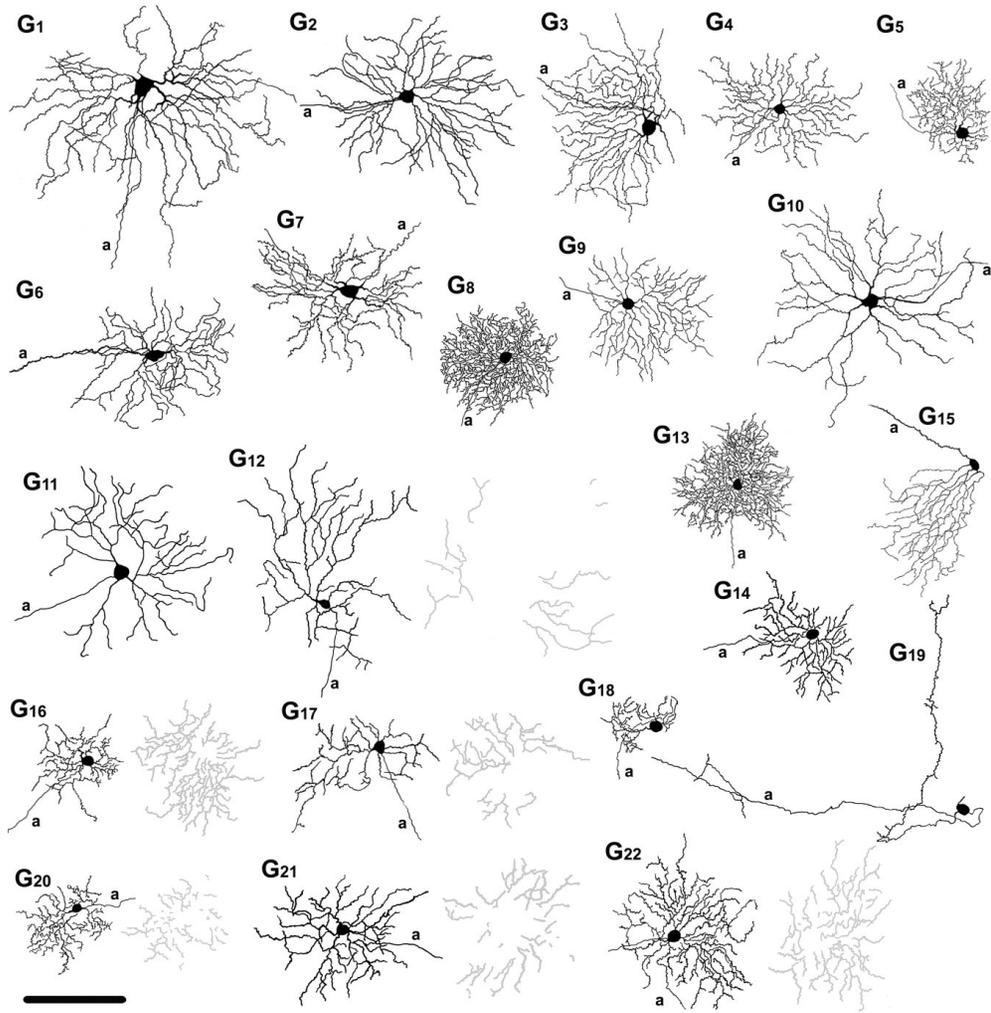


FIG. 45. Scheme of the structure of the retina. A, layer of rods and cones; a, rods; b, cones; E, layer of bipolar cells; G, layer of large ganglion cells; H, layer of nerve fibres; s, centrifugal nerve fibre. (Barker after Ramón y Cajal.)

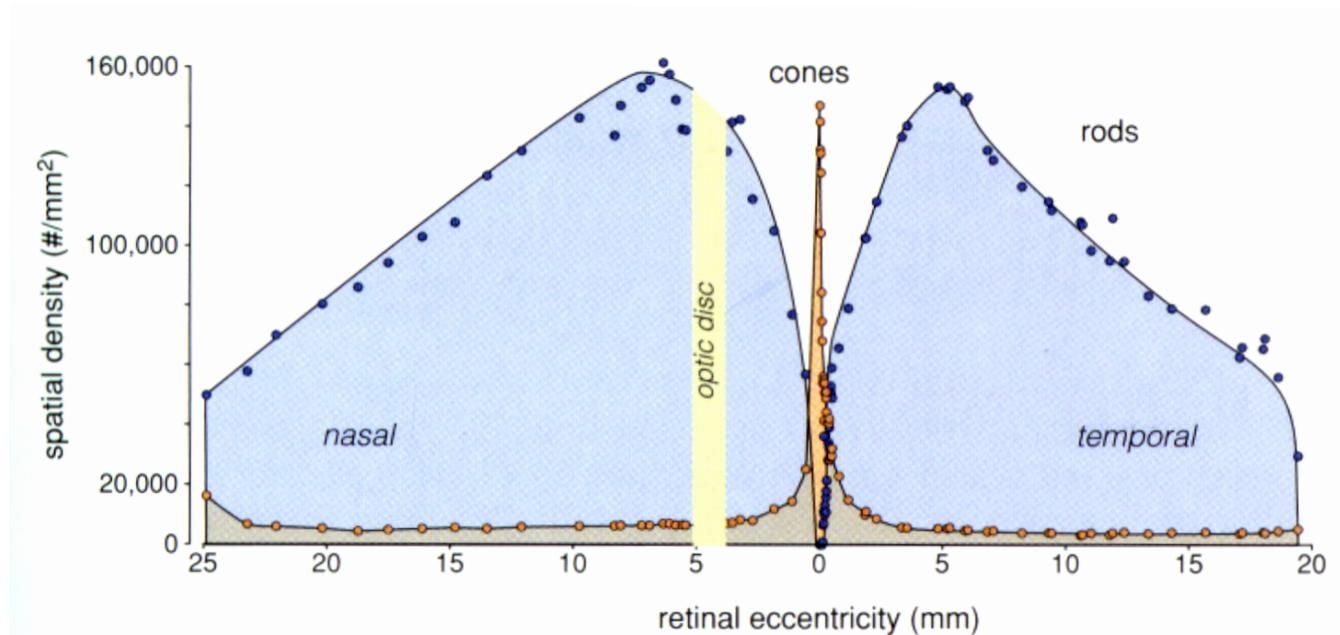
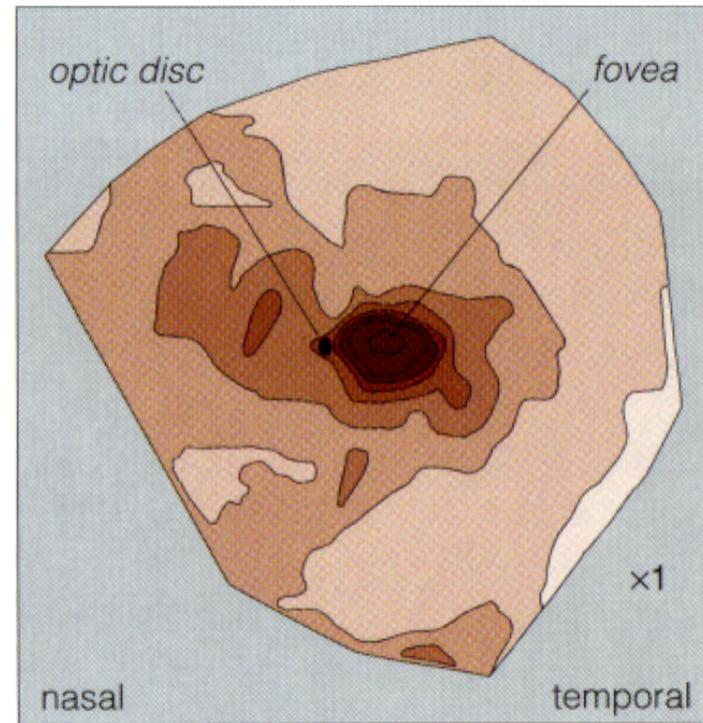
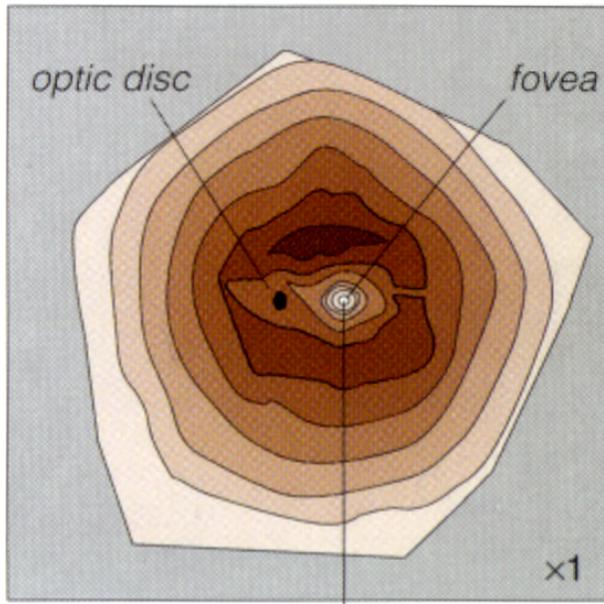
# *Retinal cell type diversity and circuit specificity*



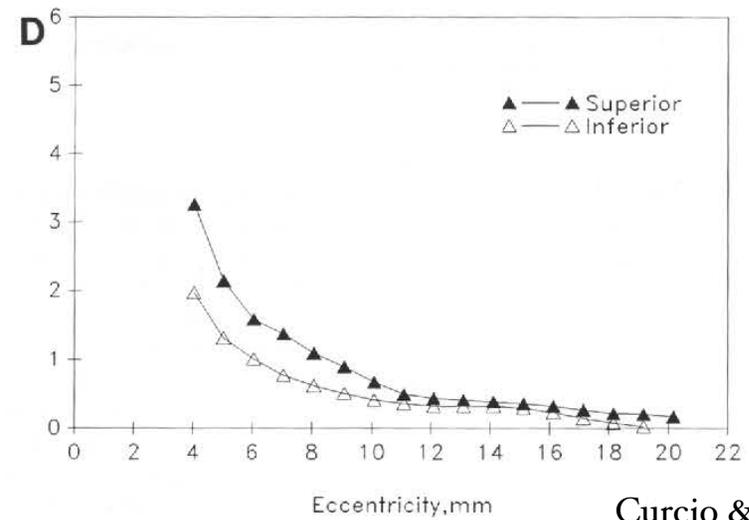
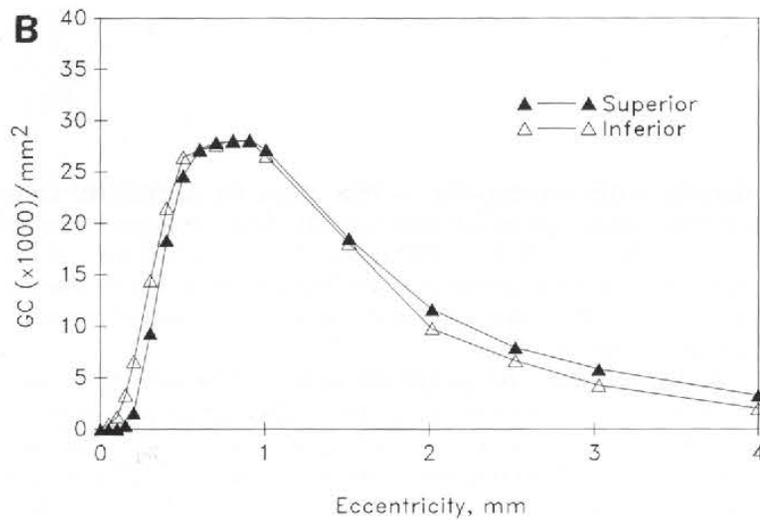
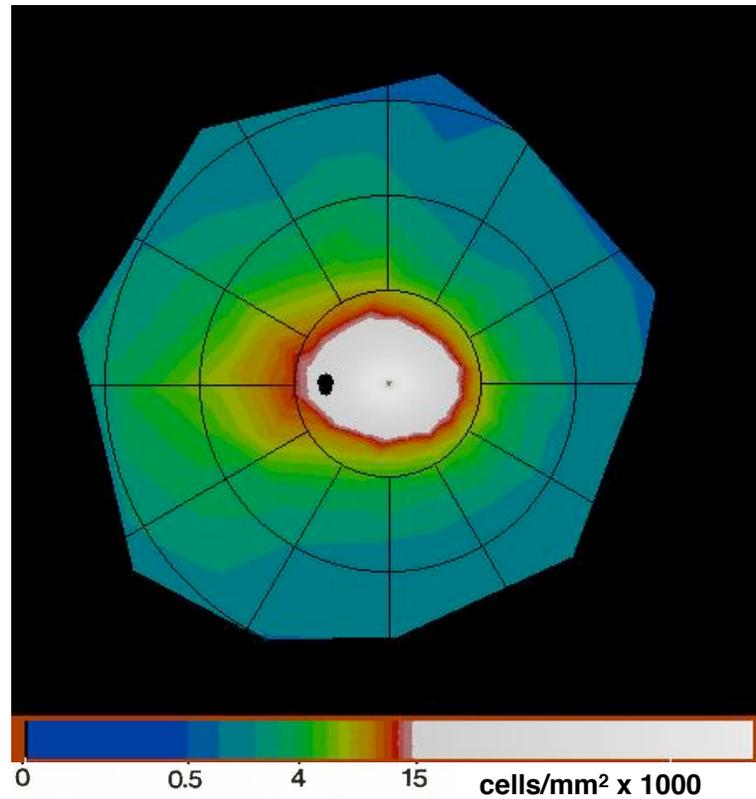
# Diversity of ganglion cell morphology in retina



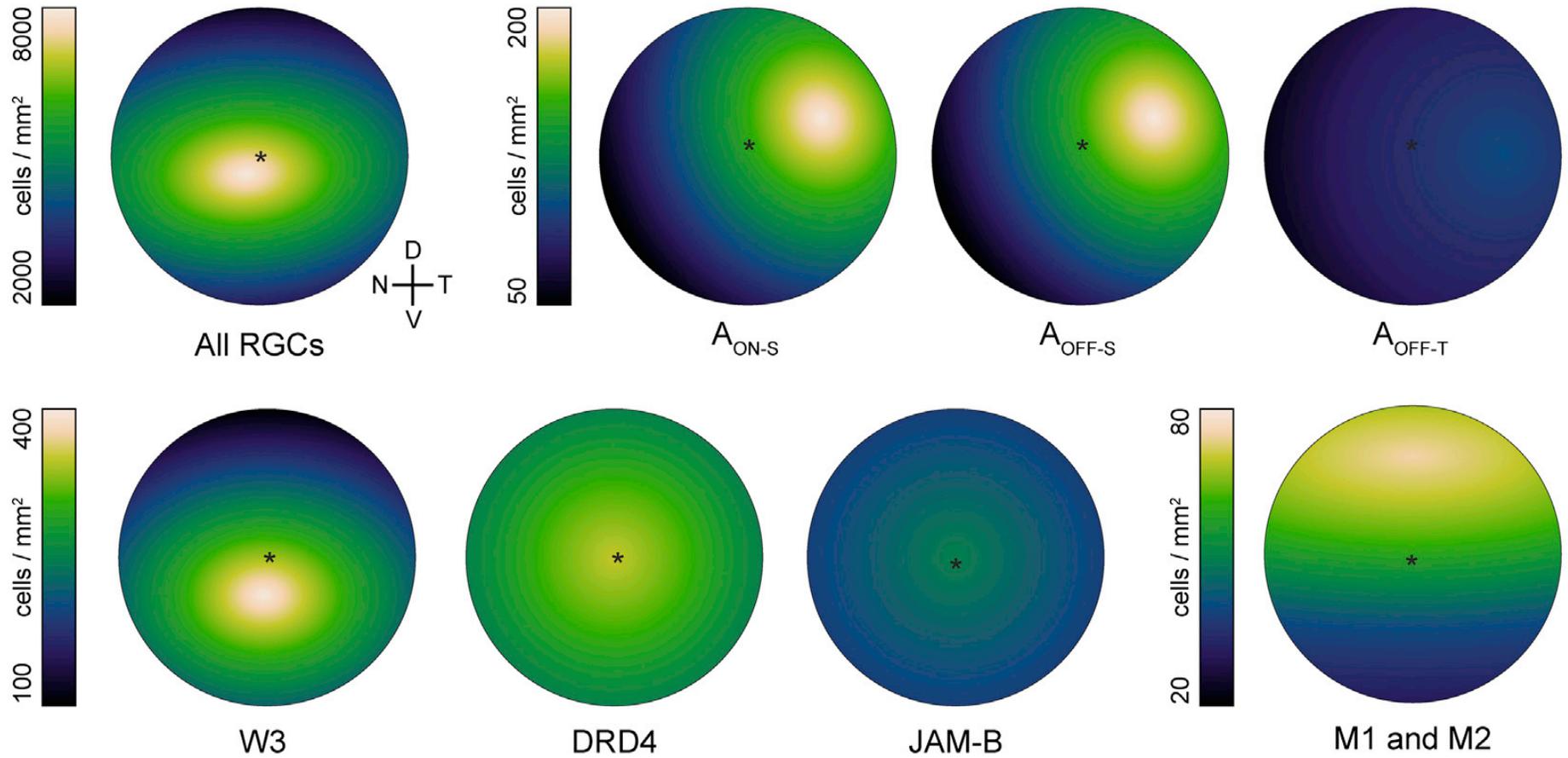
# The distribution of rods and cones in human retina



# Sampling of visual space by human retinal ganglion cells



# Sampling of visual space by different mouse ganglion cell types



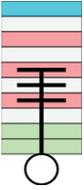
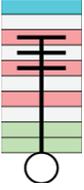
# Diversity of ganglion cell morphology in mammalian retina

Icon	Mouse	Rabbit	Cat	Macaque	Properties
<i>A catalog of retinal ganglion cell types in the mammalian retina<sup>a</sup></i>					
	M1 <sup>1,2</sup>			Outer melanopsin <sup>3</sup>	Large sparse dendrites. ON sluggish synaptic response.
	M2 <sup>1,2</sup>			Inner melanopsin <sup>3</sup>	Large complex dendrites. ON sluggish synaptic response.
	ON DS temporal <sup>4</sup>	ON DS temporal <sup>5</sup>			ON DS. Preferred direction temporal.
	ON DS ventral <sup>4</sup> Spig1 EGFP <sup>6,7</sup>	ON DS ventral <sup>5</sup>			ON DS. Preferred direction ventral.
	ON, DS dorsal <sup>6,7</sup>	ON DS dorsal <sup>5</sup>			ON DS. Preferred direction dorsal.
	ON-OFF DS temporal <sup>8</sup>	ON-OFF DS temporal <sup>8</sup>	Theta <sup>10</sup>	Recursive bistratified <sup>21</sup>	ON-OFF DS. Preferred direction temporal.
	ON-OFF DS dorsal <sup>8</sup>	ON-OFF DS dorsal <sup>8</sup>	Theta <sup>10</sup>	Recursive bistratified <sup>21</sup>	ON-OFF DS. Preferred direction dorsal.
	Drd4-EGFP, <sup>12</sup> W3 <sup>9</sup>	ON-OFF, DS nasal <sup>8</sup>	Theta <sup>10</sup>	Recursive bistratified <sup>21</sup>	ON-OFF DS. Preferred direction nasal.
	BD-CreER, <sup>8</sup> Hb9-EGFP <sup>13</sup>	ON-OFF, DS ventral <sup>8</sup>	Theta <sup>10</sup>	Recursive bistratified <sup>21</sup>	ON-OFF DS. Preferred direction ventral. Asymmetric dendrites in mouse.
	JAM-B <sup>14</sup>	OFF coupled <sup>15</sup> , G3 <sup>16</sup>			OFF DS. Preferred direction ventral. Highly asymmetric dendrites point ventral.
<i>A catalog of retinal ganglion cell types in the mammalian retina<sup>a</sup> (Continued)</i>					
	ON alpha, <sup>17</sup> PV-Cre-1 <sup>18</sup>	ON alpha <sup>19</sup>	ON alpha <sup>20,21</sup>		Large dendritic field. ON response.
	PV-Cre-5 <sup>18</sup>	ON parasol <sup>15</sup>		ON parasol <sup>22</sup>	Medium dendritic field. ON response.
				ON smooth <sup>23</sup>	
		ON beta <sup>15</sup>	ON beta <sup>24</sup>		Small dendritic field. ON response.
				ON midget <sup>22</sup>	Small dendritic field. ON response.
		OFF beta <sup>15</sup>	OFF beta <sup>24</sup>		Small dendritic field. OFF response.
				OFF midget <sup>22</sup>	Small dendritic field. OFF response.
	PV-Cre-4 <sup>18</sup>	OFF parasol <sup>15</sup>	Eta <sup>25</sup>	OFF parasol <sup>22</sup>	Medium dendritic field. OFF response.
	OFF alpha transient <sup>17</sup> , PV-Cre-5 <sup>18</sup>	OFF alpha <sup>19</sup>	OFF alpha <sup>24</sup>	OFF smooth <sup>23</sup>	Large dendritic field. OFF response.
	OFF alpha Sustained, <sup>17</sup> PV-Cre-6 <sup>18</sup>	OFF delta <sup>15</sup>	OFF delta <sup>10</sup>		Large dendritic field. OFF sustained response.
<i>A catalog of retinal ganglion cell types in the mammalian retina<sup>a</sup> (Continued)</i>					
		ON-bistratified <sup>15</sup>			Small-bistratified <sup>11</sup> ON excitation, OFF inhibition, blue-yellow opponent in macaque.
					Large-bistratified <sup>11</sup> Blue-yellow opponent.
	W3 <sup>26</sup>	Local edge Detector <sup>27</sup>	Zeta <sup>28</sup>	Broad thorny <sup>11</sup>	ON-OFF, strong surround, fast ON-OFF inhibition.
			Epsilon <sup>29</sup>	Recursive monostratified <sup>11</sup>	
					ON narrow thorny <sup>11</sup>
					OFF narrow thorny <sup>11</sup>
		Uniformity Detector <sup>29</sup>	Uniformity Detector <sup>21</sup>		Transiently suppressed by visual stimuli. ON-OFF response. Dendrites just outside the ChAT bands.

<sup>a</sup>Each graphic icon illustrates stratification of the dendritic tree in the IPL, divided into 10 laminae (Siebert et al., 2009). For each type we list the defining morphological and physiological features and identify its plausible correspondences in four species, as supported by the cited literature. For further detail on cross-species comparisons, see Berson (2008). Note that many of these ganglion cell types have only sparse and partial entries, emphasizing the need for future work to round out the catalog of retinal output signals.

**References:** <sup>1</sup>Hattar et al. (2006). <sup>2</sup>Schmidt et al. (2011b). <sup>3</sup>Dacey et al. (2005). <sup>4</sup>Sun et al. (2006). <sup>5</sup>Barlow, Hill, & Levick (1964), but see Kanjhan & Snyer (2010) and Hoshi et al. (2011) for finer divisions. <sup>6</sup>Yonehara et al. (2009). <sup>7</sup>Yonehara et al. (2008). <sup>8</sup>Kay et al. (2011). <sup>9</sup>Oyster & Barlow (1967). <sup>10</sup>Isayama, Berson, & Pu (2000). <sup>11</sup>Dacey (2004). <sup>12</sup>Huberman et al. (2009). <sup>13</sup>Irenholm et al. (2011) erroneously identified the preferred direction as temporal. <sup>14</sup>Kim et al. (2008). <sup>15</sup>Roska, Molnar, & Werblin (2006). <sup>16</sup>Hoshi et al. (2011). <sup>17</sup>Pang, Gao, & Wu (2003). <sup>18</sup>Minch et al. (2009). <sup>19</sup>Zhang et al. (2005). <sup>20</sup>Cleland, Levick, & Wässle (1975). <sup>21</sup>Wässle, Peichl, & Boycott (1981). <sup>22</sup>Dacey & Packer (2003). <sup>23</sup>Crook et al. (2008). <sup>24</sup>Wässle, Boycott, & Illing (1981). <sup>25</sup>Berson, Isayama, & Pu (1999). <sup>26</sup>Kim et al. (2010). <sup>27</sup>van Wyk, Taylor, & Vaney (2006). <sup>28</sup>Berson, Pu, & Famiglietti (1998). <sup>29</sup>Pu, Berson, & Pan (1994). <sup>30</sup>Snyer & Vaney (2010). <sup>31</sup>Cleland & Levick (1974).

# *Diversity of ganglion cell morphology in mammalian retina*

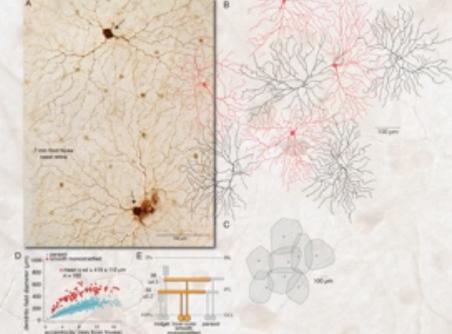
Icon	Mouse	Rabbit	Cat	Macaque	Properties
				ON midget <sup>22</sup>	Small dendritic field. ON response.
				OFF midget <sup>22</sup>	Small dendritic field. OFF response.

# Diversity of ganglion cell morphology and function in macaque retina

## Morphology, mosaics and targets of diverse ganglion cell populations in macaque retina: approaching a complete account

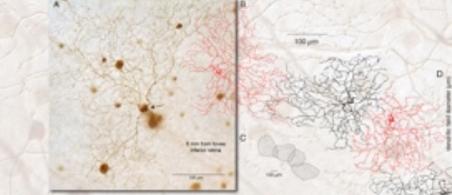
D.M. Dacey, H.R. Joo, B.B. Peterson, T.J. Haun  
Department of Biological Structure, University of Washington, Seattle WA

### Smooth monostratified inner ON-center and outer OFF-center types transient, achromatic, Y-cell receptive fields\*



Smooth monostratified cells comprise ~2.5% of total ganglion cells (coverage: inner cells 1.4; outer cells 1.1) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of two smooth cells intracocularly injected with Neurobiotin and processed for HRP histochemistry. The smooth cells are tracer coupled to a population of small bodied amacrine cells. B. Tracings of 8 inner smooth cells ~7 mm from the fovea, tracer labeled from injections in the superior colliculus and processed for HRP histochemistry. C. Outlines of the overlapping dendritic fields of the 8 cells shown in B. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (inner smooth/parasol cell pairs, n = 4; outer smooth/parasol cell pairs, n = 20). (GCL, ganglion cell layer; IPL, inner plexiform layer; INL, inner nuclear layer).  
\*Cook et al., J Neurosci 2008, 28(14):3264

### Recursive bistratified primate candidate for the ON-OFF direction selective type



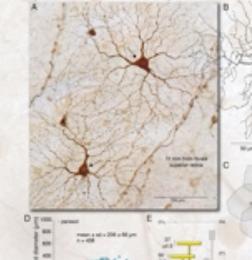
Recursive bistratified cells comprise ~1.5% of total ganglion cells (coverage ~1.3) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a recursive bistratified cell intracocularly injected with Neurobiotin and processed for HRP histochemistry. The cell shows tracer coupling to large and small bodied amacrine cell populations. B. Tracings of 7 cells of one from the fovea, tracer labeled from injections in the superior colliculus and processed for HRP histochemistry. C. Outlines of the overlapping dendritic fields of the 7 cells shown in B. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (recursive bistratified/parasol cell pairs, n = 3).

### Recursive monostratified primate candidate for the ON direction selective type



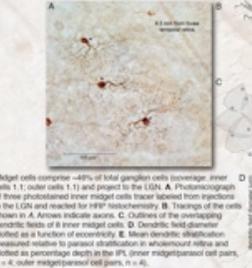
Recursive monostratified cells comprise ~4.5% (3 populations; single population ~1.5%) of total ganglion cells (coverage: single population 1.2; 3 populations 3.3) and project to the LGN and pretectum. A. Photomicrograph of photostained cells tracer labeled from injections in the pretectum and processed for HRP histochemistry. Dendrites of the four labeled cells and other nearby cells (not bodied not shown) form a dense plexus of collocated processes. Inset: Magnified view of boxed area in A. Arrows indicate 5 examples of collocation. Numbers correspond to the dendrites' cells of origin as shown in A. B. Tracing of a recursive monostratified cell 8.8 mm from the fovea (dendritic field diameter ~300 μm). Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 3 neighboring recursive monostratified cells ~8.8 mm from the fovea. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (recursive monostratified/inner parasol cell pairs, n = 3).

### Parasol inner ON-center and outer OFF-center types primate correlate of the alpha Y-cell\*



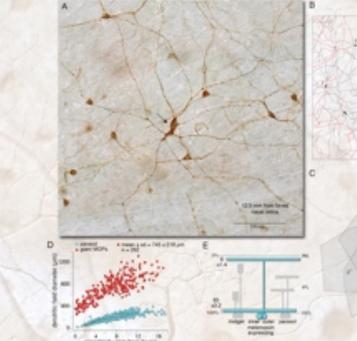
Parasol cells comprise ~14% of total ganglion cells (coverage: inner cells 1.3; outer cells 1.6) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of two photostained cells tracer labeled from injections in the superior colliculus and processed for HRP histochemistry. B. Tracing of an inner parasol cell 7.7 mm from the fovea (dendritic field diameter ~270 μm). Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 8 neighboring outer parasol cells ~7.7 mm from the fovea. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured in whorlmount retina and plotted as percentage depth in the IPL. (inner cells, n = 20; outer cells, n = 20).  
\*Cook et al., J Neurosci 2008, 28(4):1127

### Midget inner ON-center and outer OFF-center types



Midget cells comprise ~40% of total ganglion cells (coverage: inner cells 1.1; outer cells 1.1) and project to the LGN. A. Photomicrograph of three photostained inner midget cells tracer labeled from injections in the LGN and processed for HRP histochemistry. B. Tracings of the cells shown in A. Arrows indicate axons. C. Outlines of the overlapping dendritic fields of 8 inner midget cells. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (inner midget/parasol cell pairs, n = 4; outer midget/parasol cell pairs, n = 4).

### Melanopsin-expressing inner and outer types, inherently photosensitive; S-OFF opponency



Giant melanopsin cells comprise ~7% of total ganglion cells (coverage: inner cells 1.5; outer cells 2.0) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a giant melanopsin cell intracocularly injected with Neurobiotin and processed for HRP histochemistry. The cell shows tracer coupling to several populations of amacrine cells. B. Tracings of 7 inner (black) and 1 outer (red) giant cells ~13 mm from the fovea, melanopsin immunolabeled and processed for HRP histochemistry. C. Outlines of the overlapping dendritic fields of 5 inner ganglion cells. Numbers correspond to cells shown in B. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (inner giant melanopsin/parasol cell pairs, n = 3; outer giant melanopsin/parasol cell pairs, n = 1).

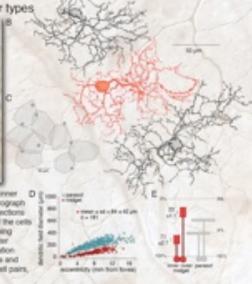
### Purpose

Our goal is a complete description of primate visual pathway origins, providing an anatomical basis for targeted physiological analysis, dissection of underlying circuitry and for making trans-species comparisons, most notably with the mouse, for which transgenic technology offers increasing access to retinal pathways.

### Methods

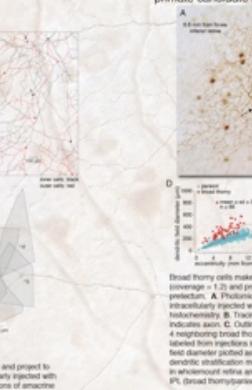
To observe the morphology of macaque ganglion cells we used the 'fireworks' photostaining technique (Dacey et al., Neuron 2003, 37:15) from central tracer injections made into the lateral geniculate nucleus (LGN) or the superior colliculus-pretectum. Fireworks staining completely reveals the dendritic trees of large numbers of retrogradely labeled ganglion cells. In this way we can measure type-specific stratification depth in the inner plexiform layer and relative density from the mosaics formed by overlapping dendritic trees of the same type. (Right: photostained cells retrogradely tracer labeled from injections in the superior colliculus.)

### Small bistratified 'blue-ON' cell: S vs LM cone opponency



Small bistratified cells make up ~4% of total ganglion cells (coverage = 1.6) and project to the LGN. A. Photomicrograph of a small bistratified cell intracocularly injected with Neurobiotin and processed for HRP histochemistry, with the focus on the inner (upper) and outer (lower) dendritic arbors. B. Tracings of the inner arbors of 3 neighboring small bistratified cells ~8.8 mm from the fovea, tracer labeled from injections in the LGN and processed for HRP histochemistry. Overlapping dendrites show collocation. Arrows indicate axons. C. Outlines of the overlapping dendritic fields of the 3 cells shown in B. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (small bistratified/parasol cell pairs, n = 11).

### Broad thorny ON-OFF receptive field primate candidate for the local edge detector



Broad thorny cells make up ~1.5% of total ganglion cells (coverage = 1.2) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a broad thorny cell intracocularly injected with Neurobiotin and processed for HRP histochemistry. B. Tracing of the axon cell shown in A. Arrow indicates axon. C. Outlines of the overlapping dendritic fields of a neighboring broad thorny cell ~5 mm from the fovea, tracer labeled from injections in the superior colliculus. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (broad thorny/parasol cell pairs, n = 8).

### Large bistratified second type of S-opponent blue-ON cell



Large bistratified cells make up ~3% of total ganglion cells (coverage ~2) and project to the LGN. A. Photomicrograph of a large bistratified cell intracocularly injected with Neurobiotin and processed for HRP histochemistry. Focus is on the inner (upper) and outer (lower) dendritic arbors. B. Tracing of the same cell shown in A. Outer dendritic arbor is shown in red. Arrow indicates axon. C. Outlines of the dendritic fields of two neighboring large bistratified cells with overlapping dendritic fields. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (large bistratified cell pairs, n = 5).

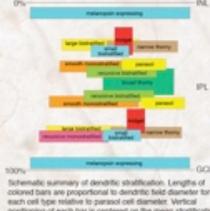
### Narrow thorny inner and outer types, transient, achromatic



Narrow thorny cells comprise ~3% of total ganglion cells (coverage: inner cells 1.0; outer cells 1.0) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a narrow thorny cell intracocularly injected with Neurobiotin and processed for HRP histochemistry. B. Tracing of the same cell shown in A. Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 3 neighboring narrow thorny cells tracer labeled from injections in the superior colliculus. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whorlmount retina and plotted as percentage depth in the IPL. (inner narrow thorny/parasol cell pairs, n = 4; outer narrow thorny/parasol cell pairs, n = 4).

### Conclusions

- The 17 cell populations shown here represent ~85% of the total number of ganglion cells.\*
- At least 3 other cell types have been identified: axon collateral-bearing ganglion cells (Peterson & Dacey, Vis Neurosci 1998, 15:377) large, sparsely branched monostratified cells (inner and outer types).
- Taken together, and assuming ~2% density for the remaining 3 cell types, the 20 types account for ~90% of the ganglion cells. If multiple ON-OFF direction selective mosaics exist in primate (as found in other mammals) even ~5% would be accounted for.

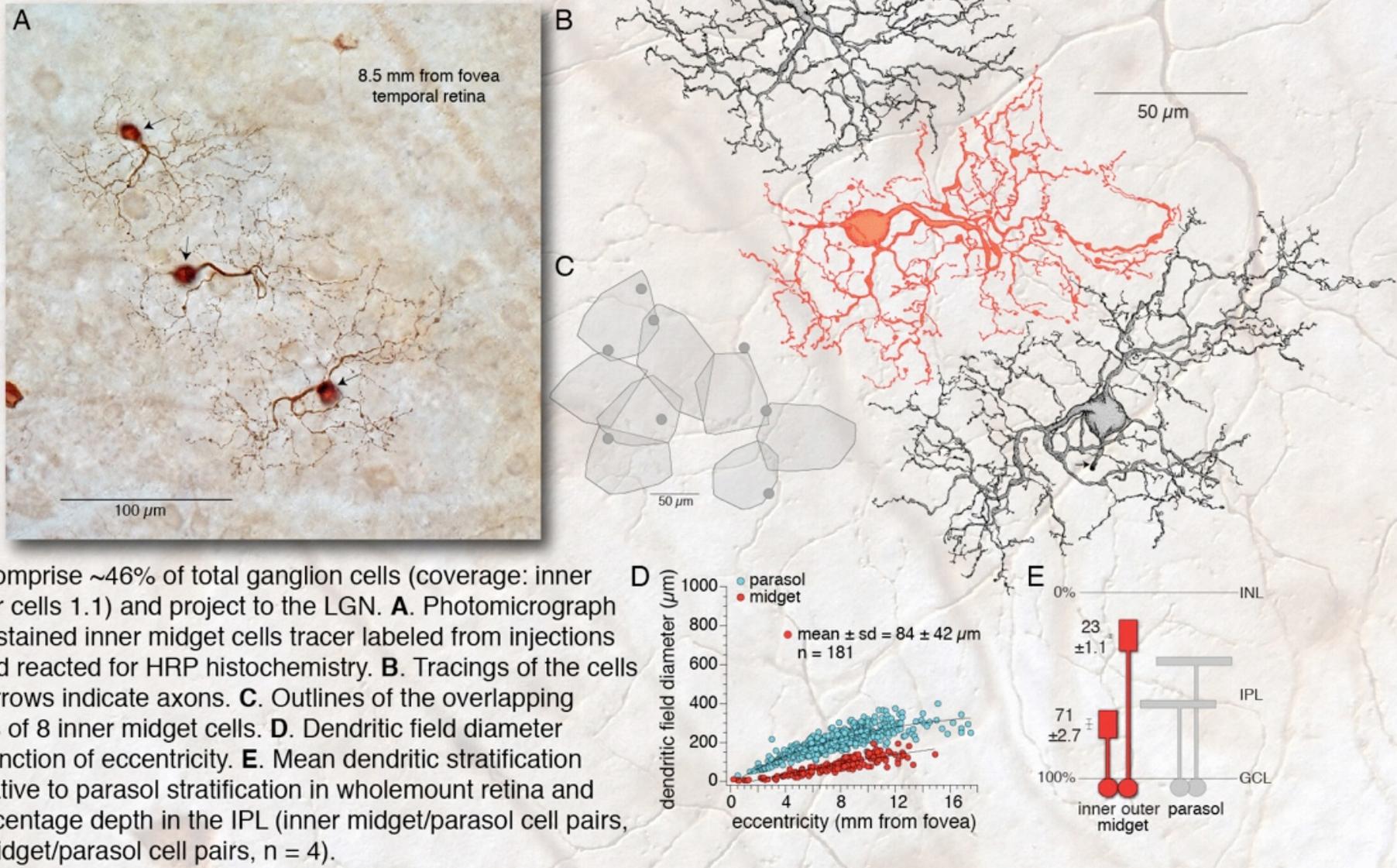


\*Total ganglion cell density is from Wässle et al., Nature 1980, 341:543. Density estimates for individual cell types were derived from the mosaics.

# Midget cells are about half of all primate ganglion cells

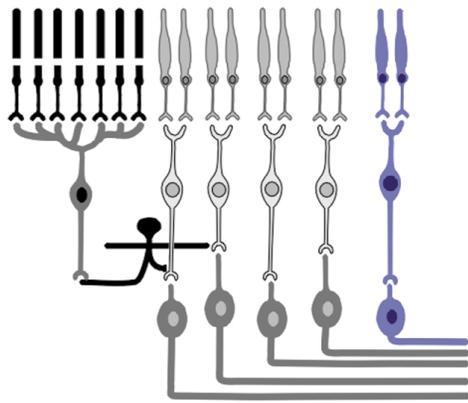
## Midget

inner ON-center and outer OFF-center types



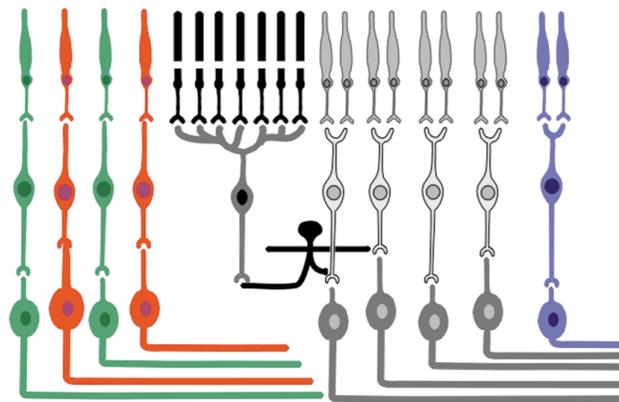
Midget cells comprise ~46% of total ganglion cells (coverage: inner cells 1.1; outer cells 1.1) and project to the LGN. **A.** Photomicrograph of three photostained inner midget cells tracer labeled from injections in the LGN and reacted for HRP histochemistry. **B.** Tracings of the cells shown in **A.** Arrows indicate axons. **C.** Outlines of the overlapping dendritic fields of 8 inner midget cells. **D.** Dendritic field diameter plotted as a function of eccentricity. **E.** Mean dendritic stratification measured relative to parasol stratification in wholemound retina and plotted as percentage depth in the IPL (inner midget/parasol cell pairs, n = 4; outer midget/parasol cell pairs, n = 4).

# Color-opponent midget cells: a primate specialization

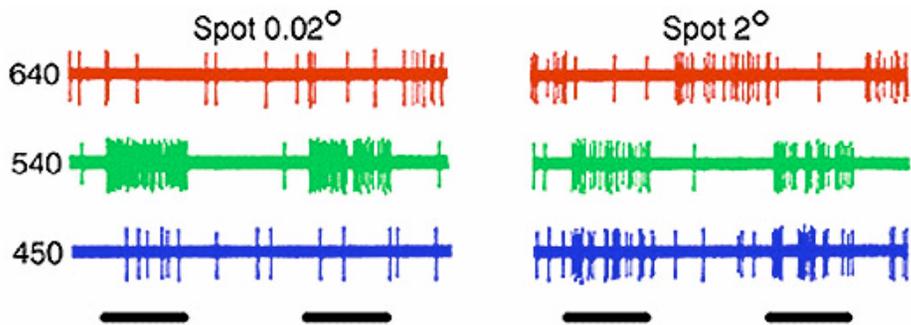


Generic mammalian retina

Primates  
→

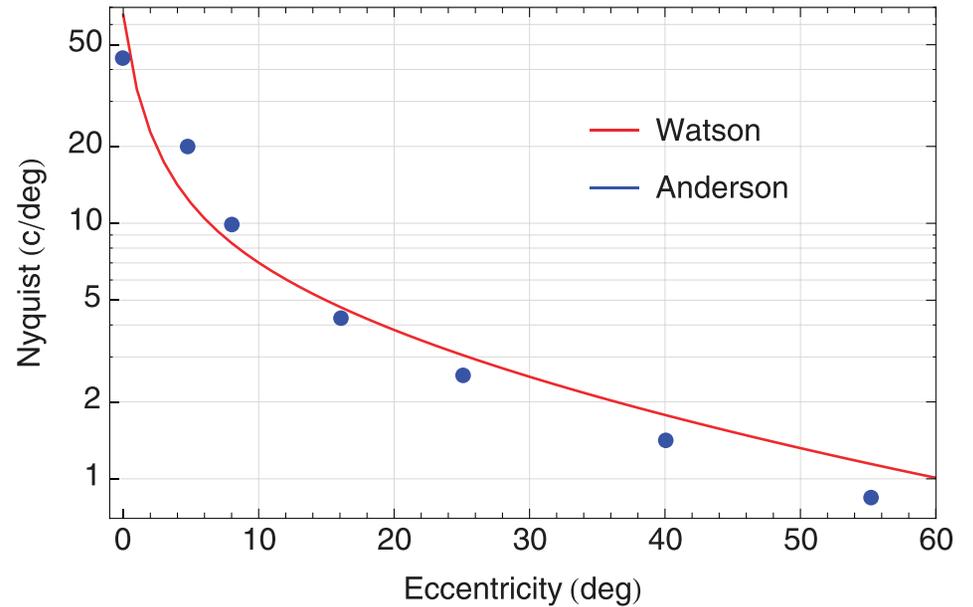
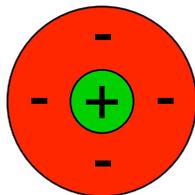


Primate Color Opponent Ganglion Cells



DeMonasterio & Gouras (1975)

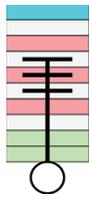
Inferred Receptive Field Description



Masland, 2001;  
DeMonasterios & Gouras, 1975;  
Watson, 2014

# Diversity of ganglion cell morphology in mammalian retina

Icon	Mouse	Rabbit	Cat	Macaque	Properties
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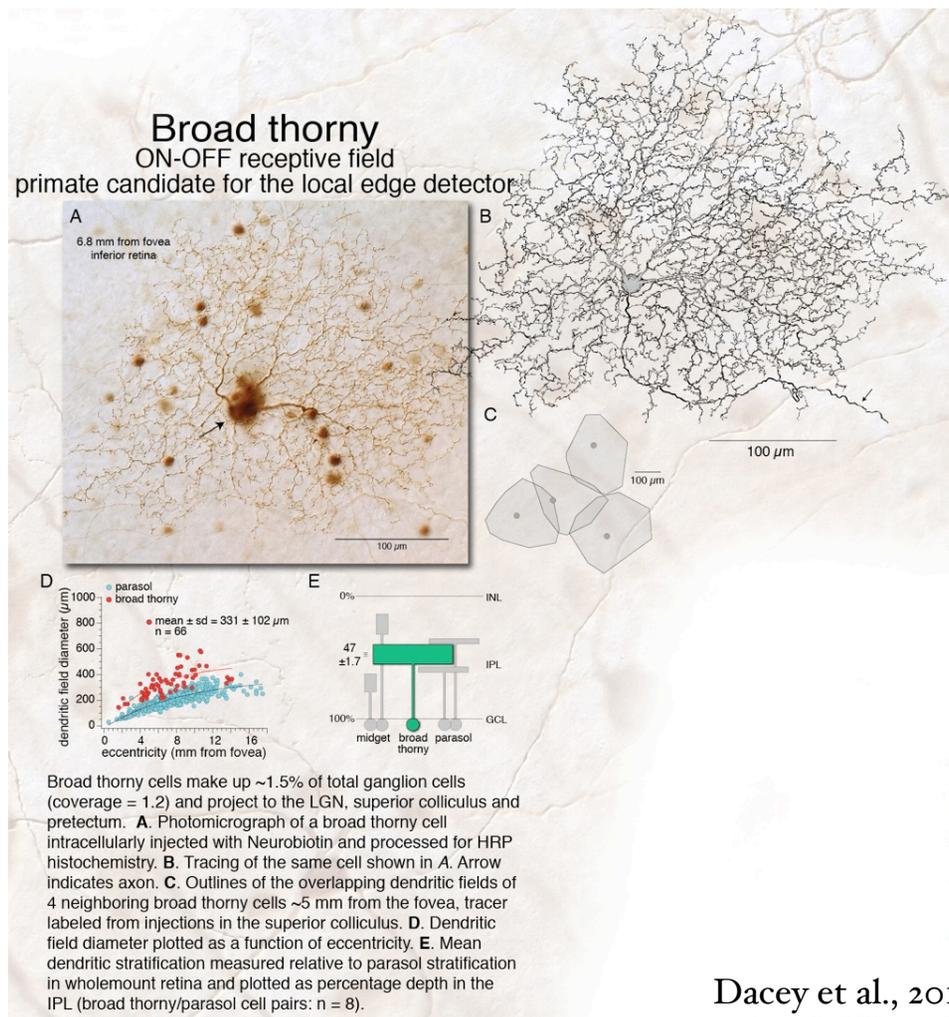
W3<sup>26</sup>

Local edge  
Detector<sup>5,27</sup>

Zeta<sup>28</sup>

Broad thorny<sup>11</sup>

ON-OFF, strong surround, fast  
ON-OFF inhibition.



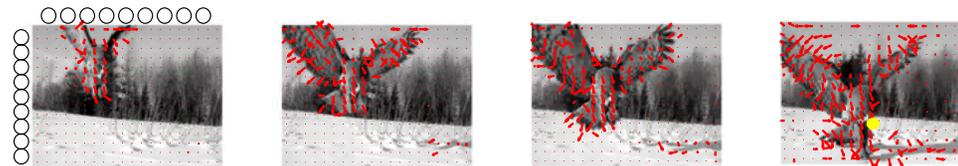
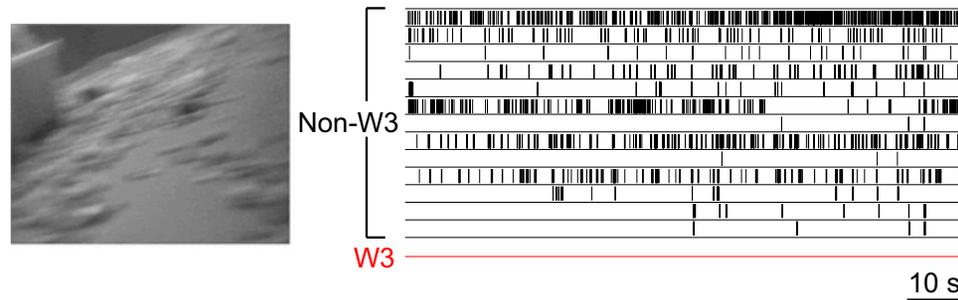
Dacey et al., 2010

Roska and Meister, 2014

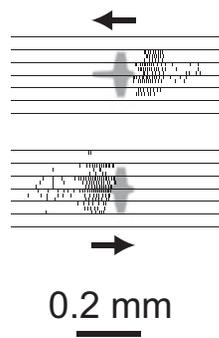
# The most numerous ganglion cell type of the mouse retina is a selective feature detector

Yifeng Zhang<sup>1</sup>, In-Jung Kim<sup>2</sup>, Joshua R. Sanes<sup>3</sup>, and Markus Meister<sup>3,4</sup>

Department of Molecular and Cellular Biology, Center for Brain Science, Harvard University, Cambridge, MA 02138

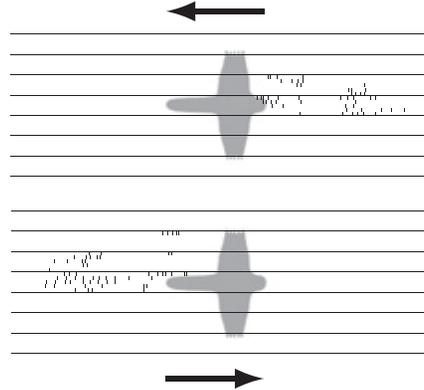


owl at 14 m distance  
~2 s time to impact

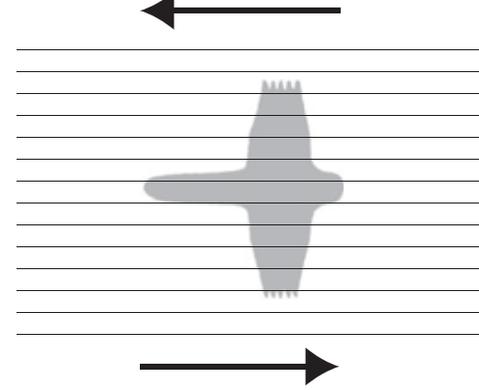


W3 RF ○

7 m, ~1 s

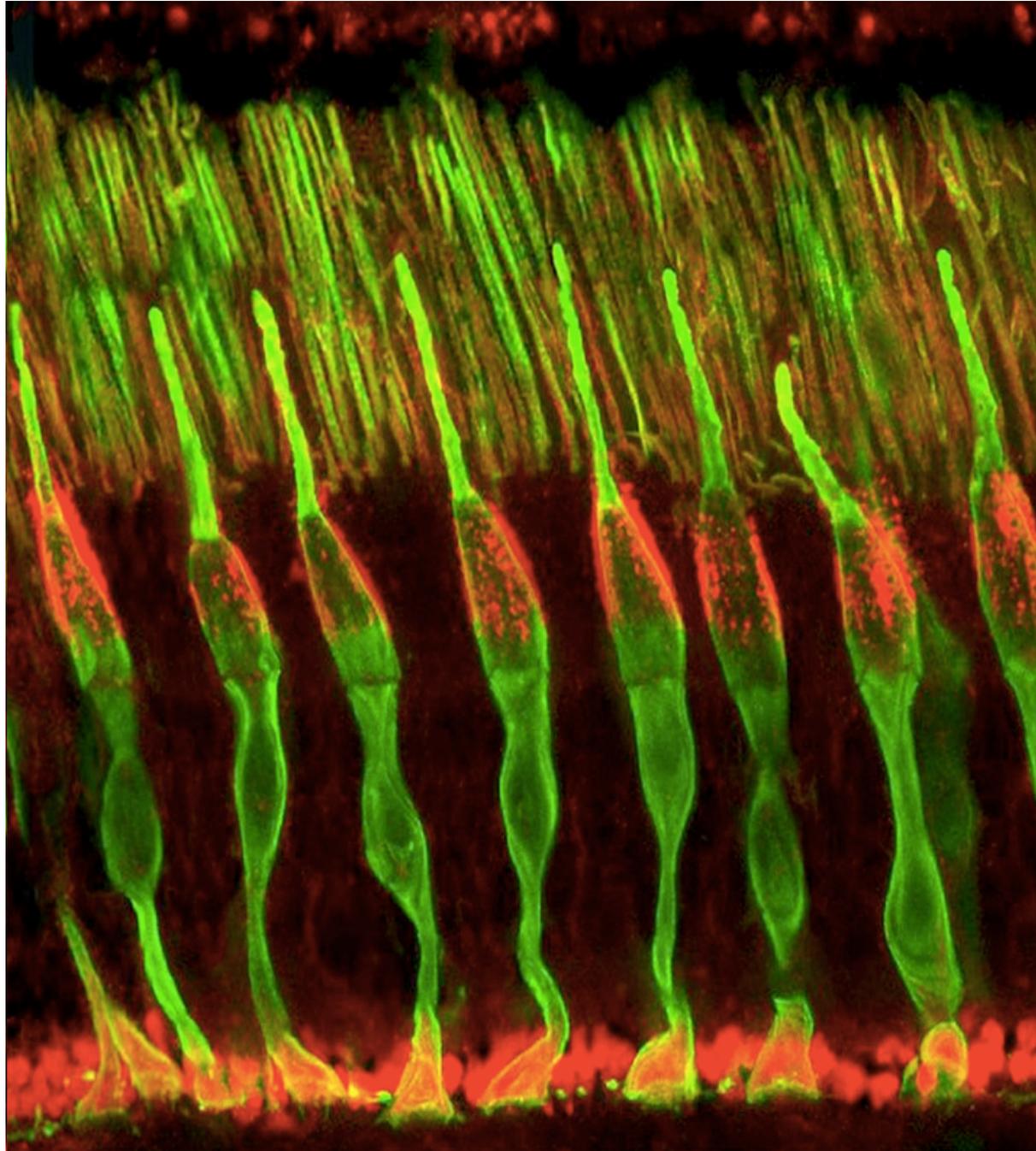


3 m, ~0.4 s

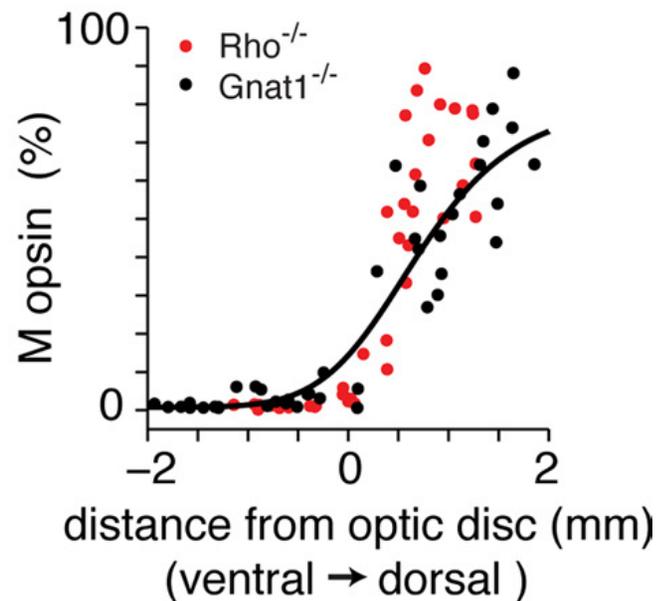
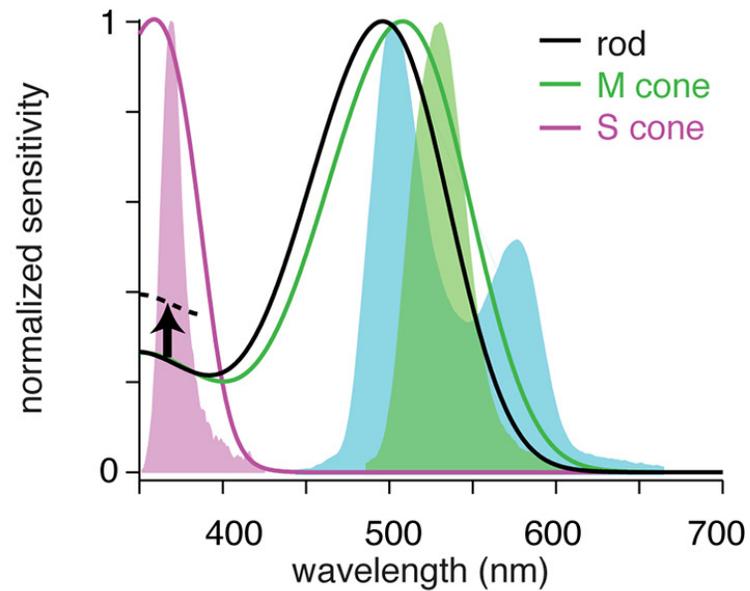
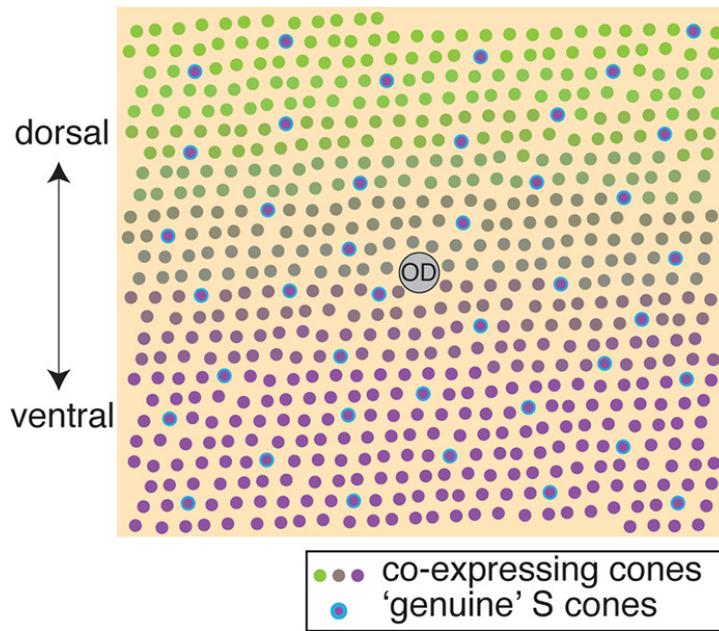


Zhang et al., 2012

# *Cones*



# Most mouse cones express two opsins in a regionally varying pattern



*All retinas are not the same*

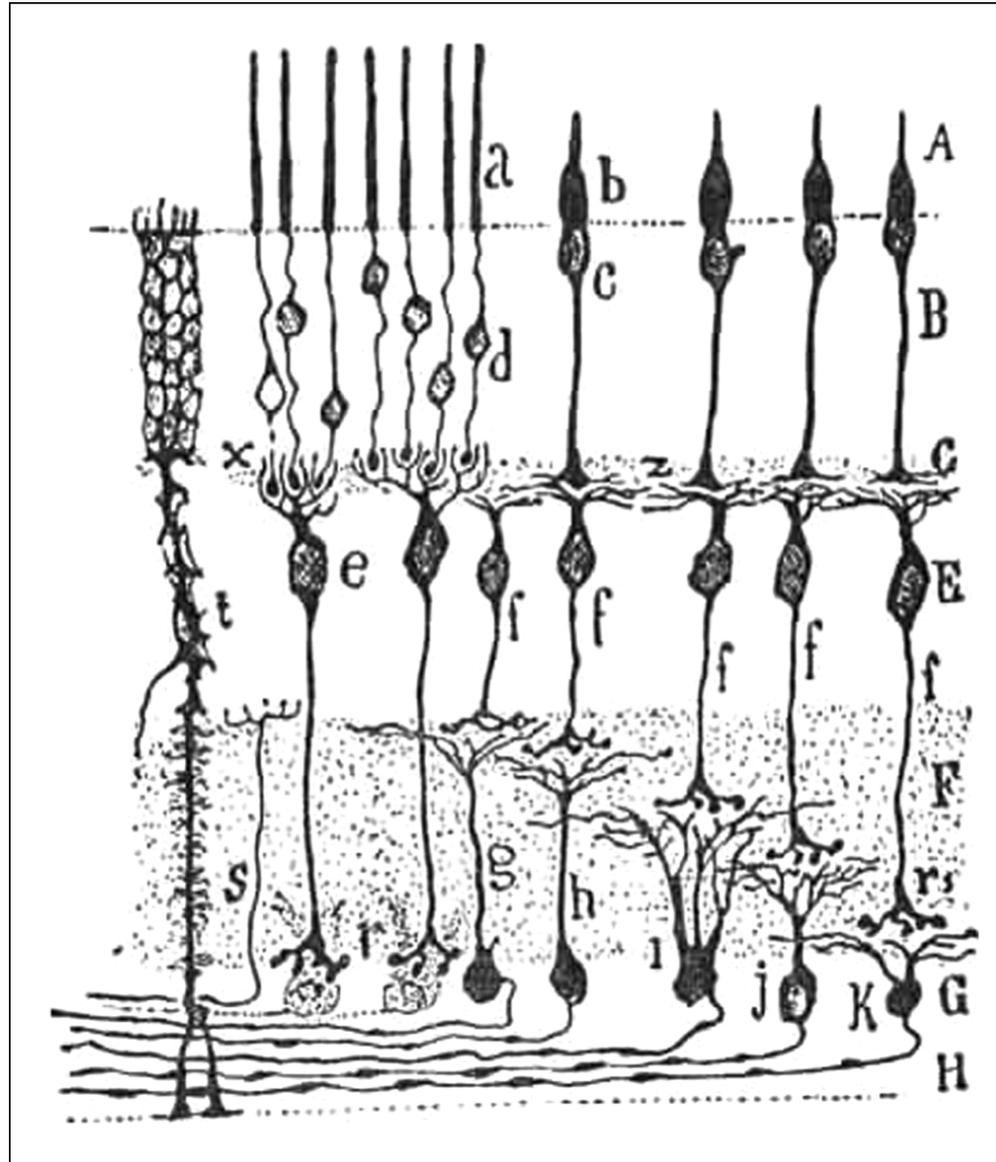
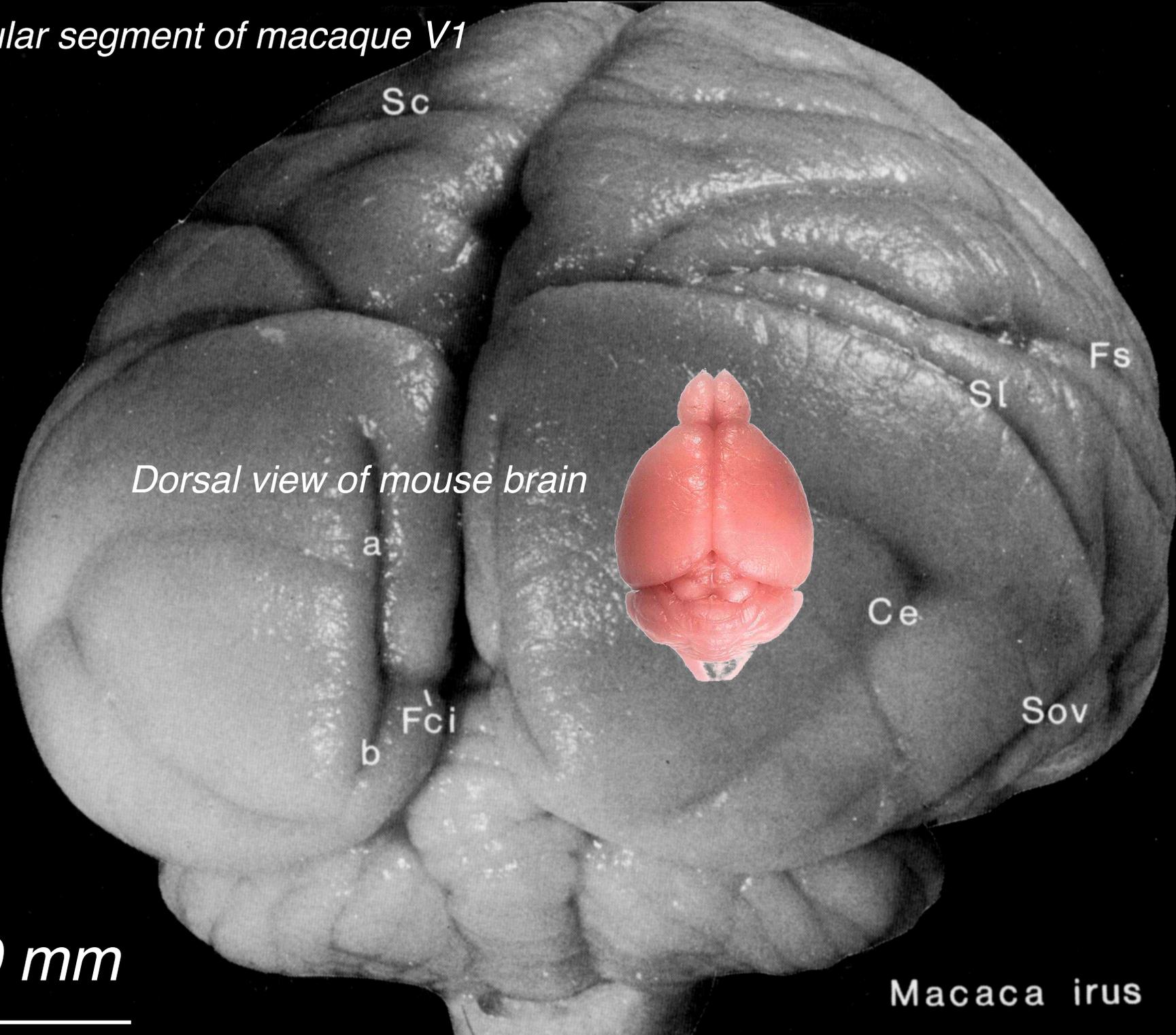


FIG. 45. Scheme of the structure of the retina. A, layer of rods and cones; a, rods; b, cones; E, layer of bipolar cells; G, layer of large ganglion cells; H, layer of nerve fibres; s, centrifugal nerve fibre. (Barker after Ramón y Cajal.)

*Opercular segment of macaque V1*



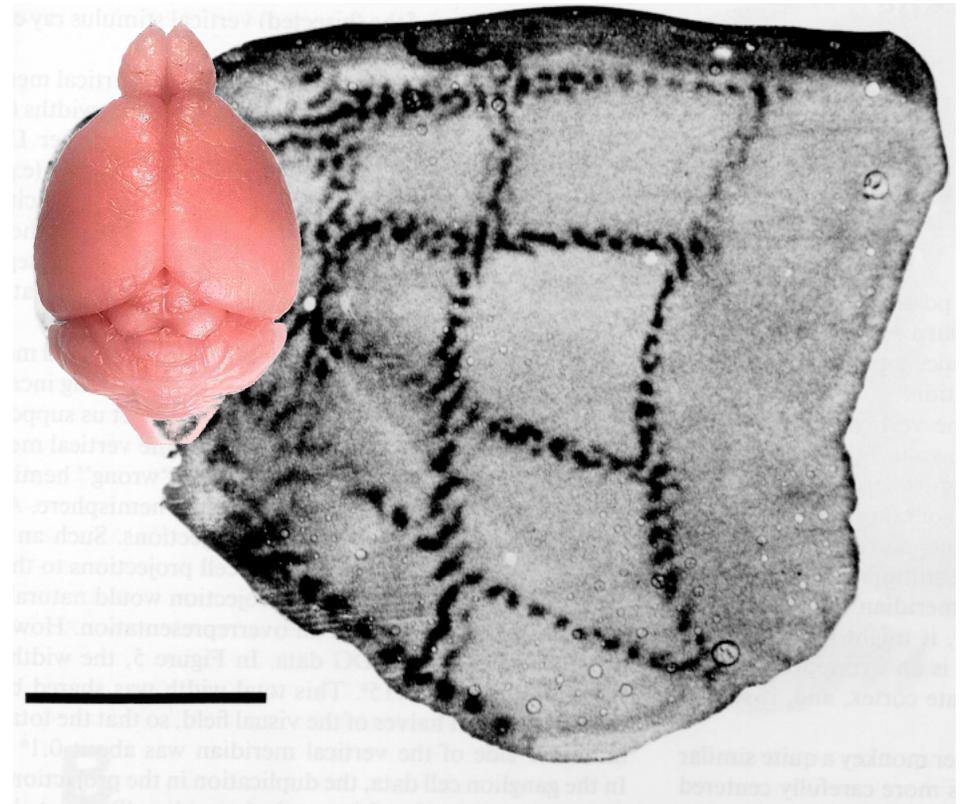
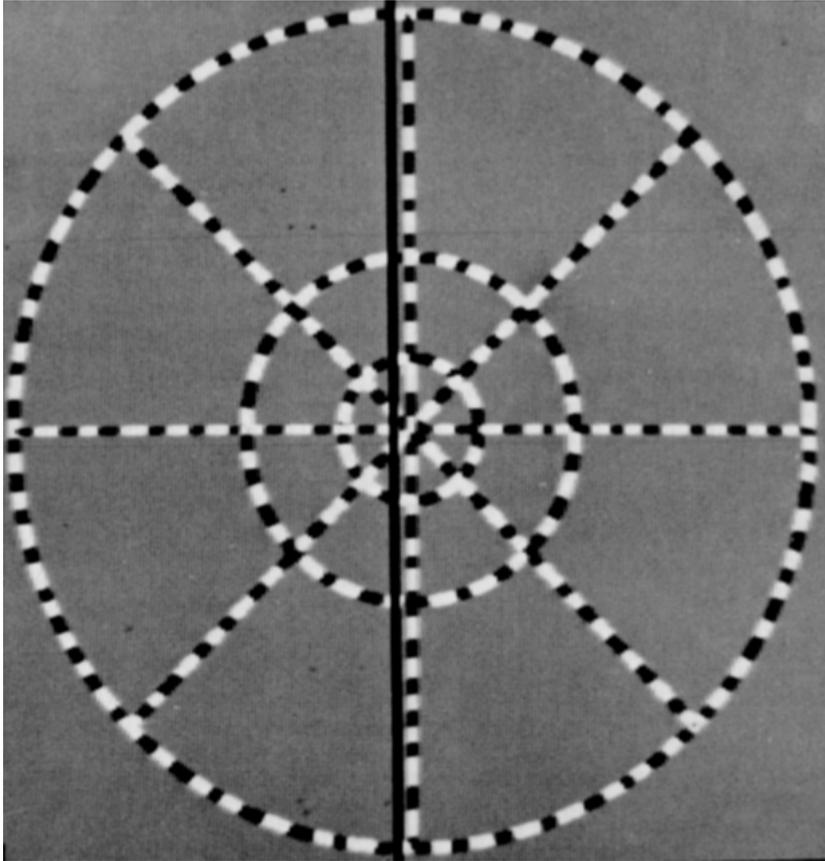
*Dorsal view of mouse brain*

10 mm

Macaca irus

## *Visuotopic organization of macaque V1*

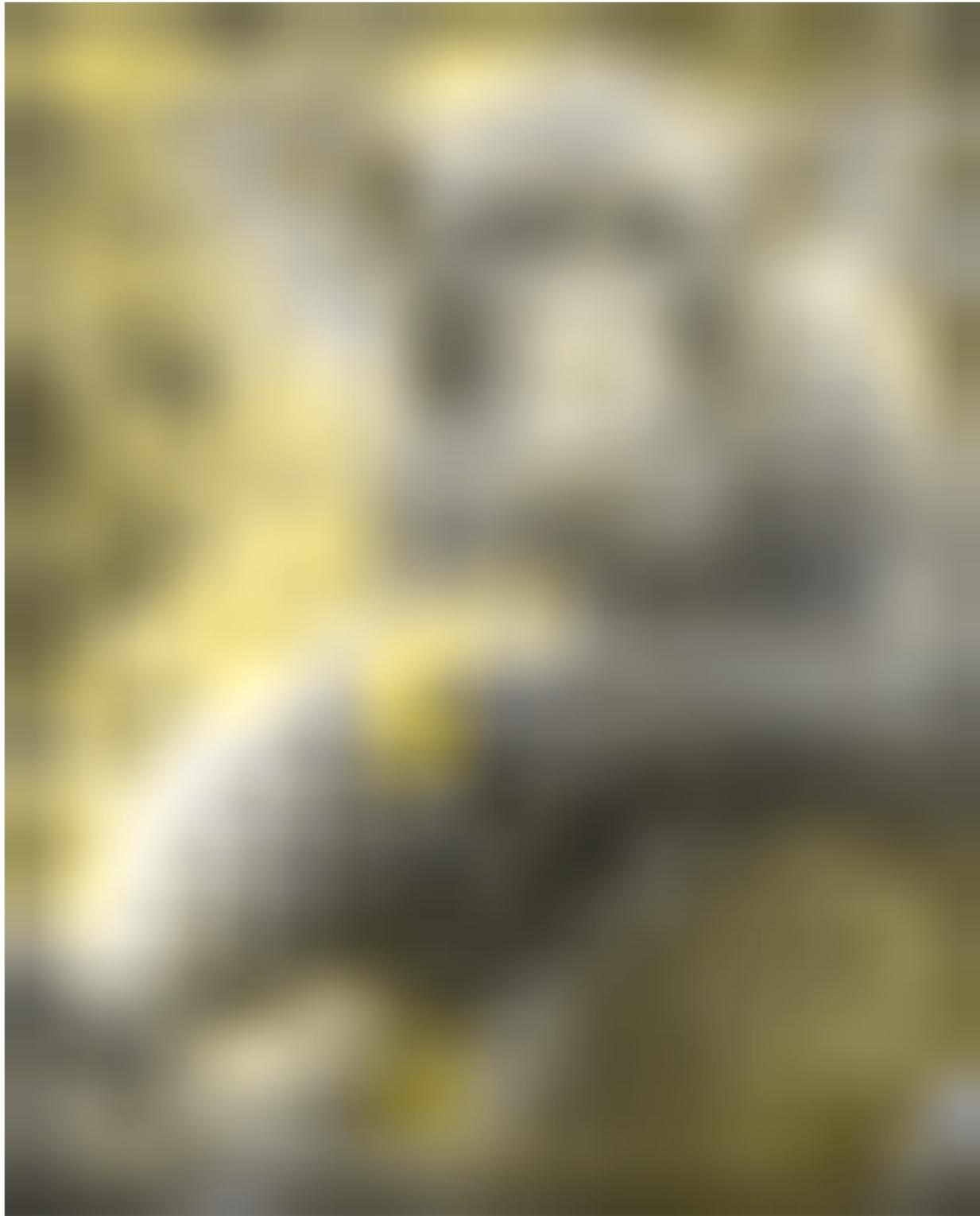
*The entire mouse brain is the same size as the representation of the central 2 deg of visual field in macaque V1*



*Monkey vision*



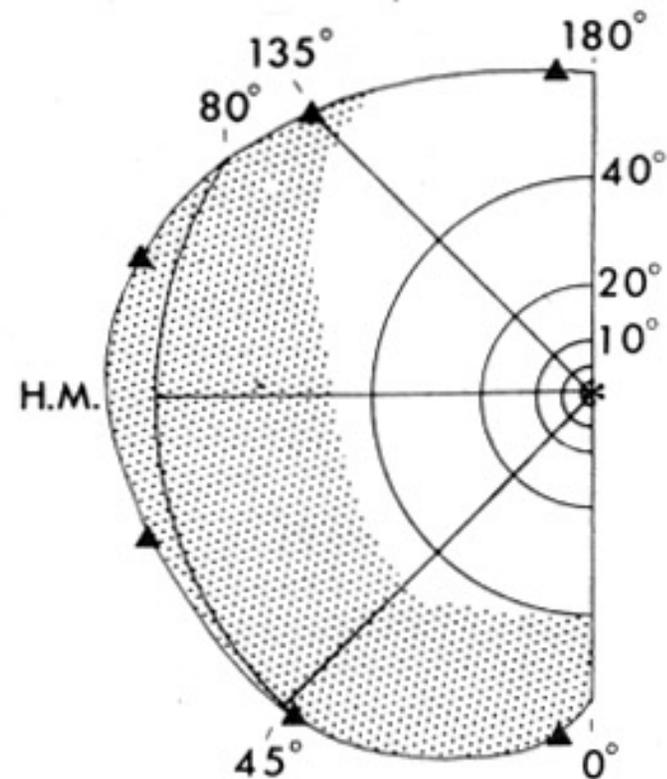
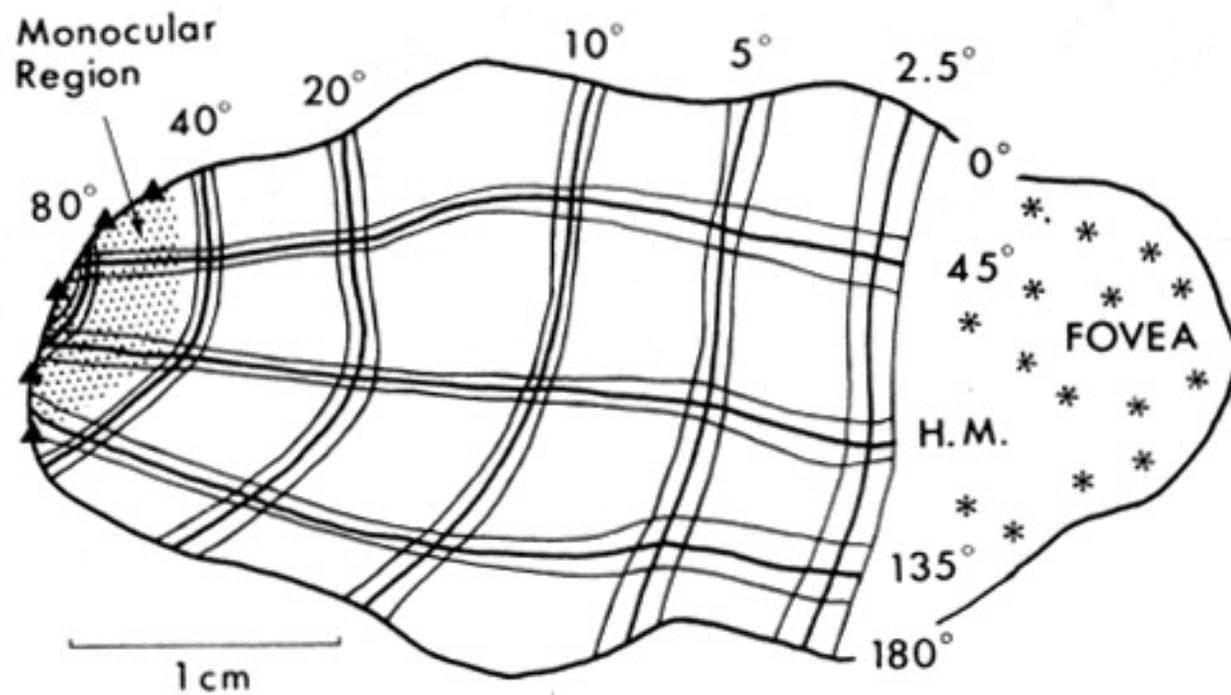
*Mouse vision*



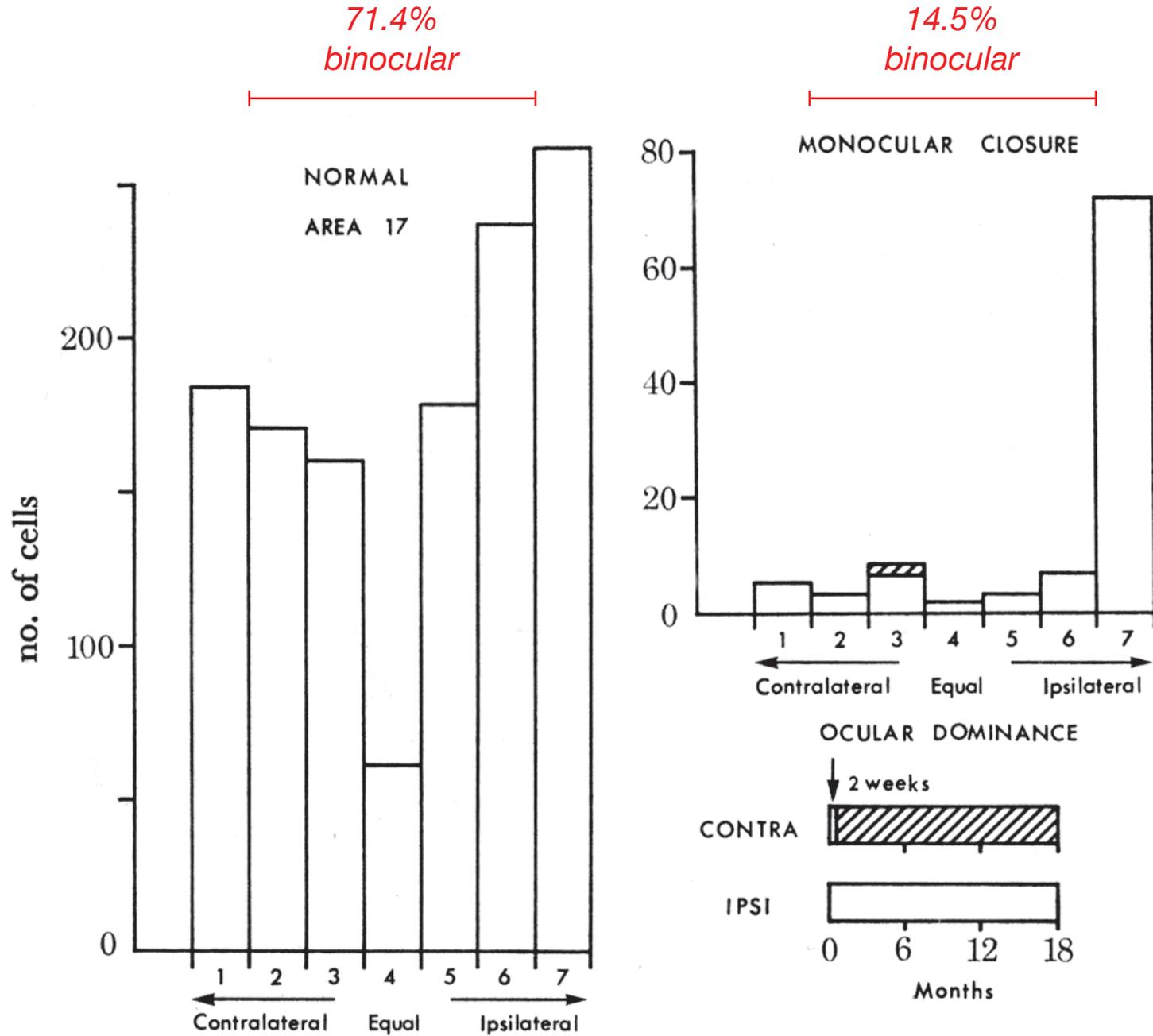


# Magnification factor and binocularity

## Macaque

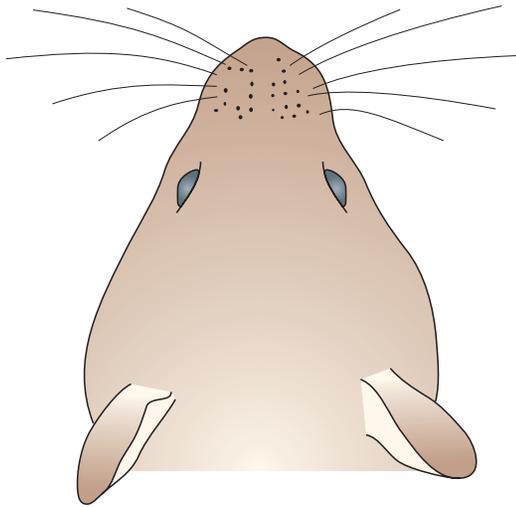


# Monocular deprivation – monkey

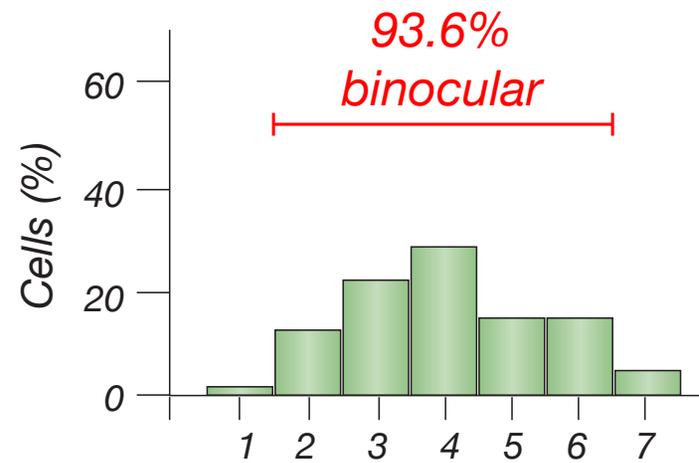
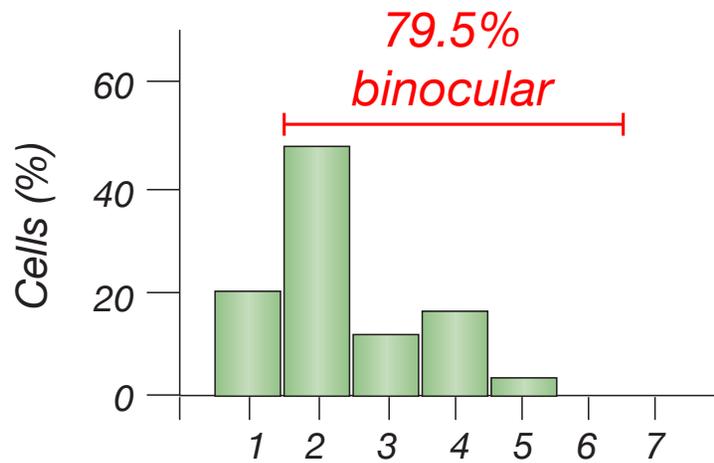
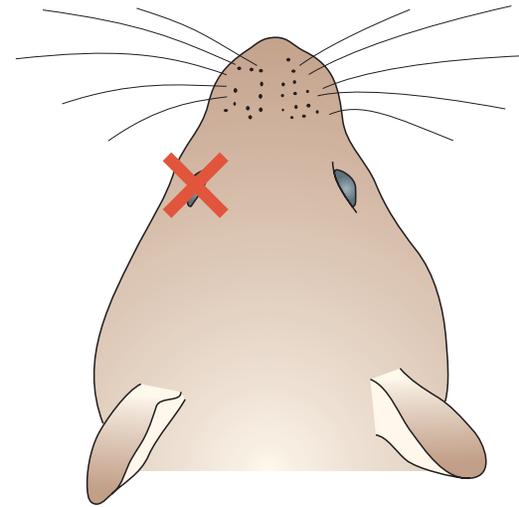


# Monocular deprivation – mouse

## Normal mouse



## Contralateral eye occluded



Ocular dominance

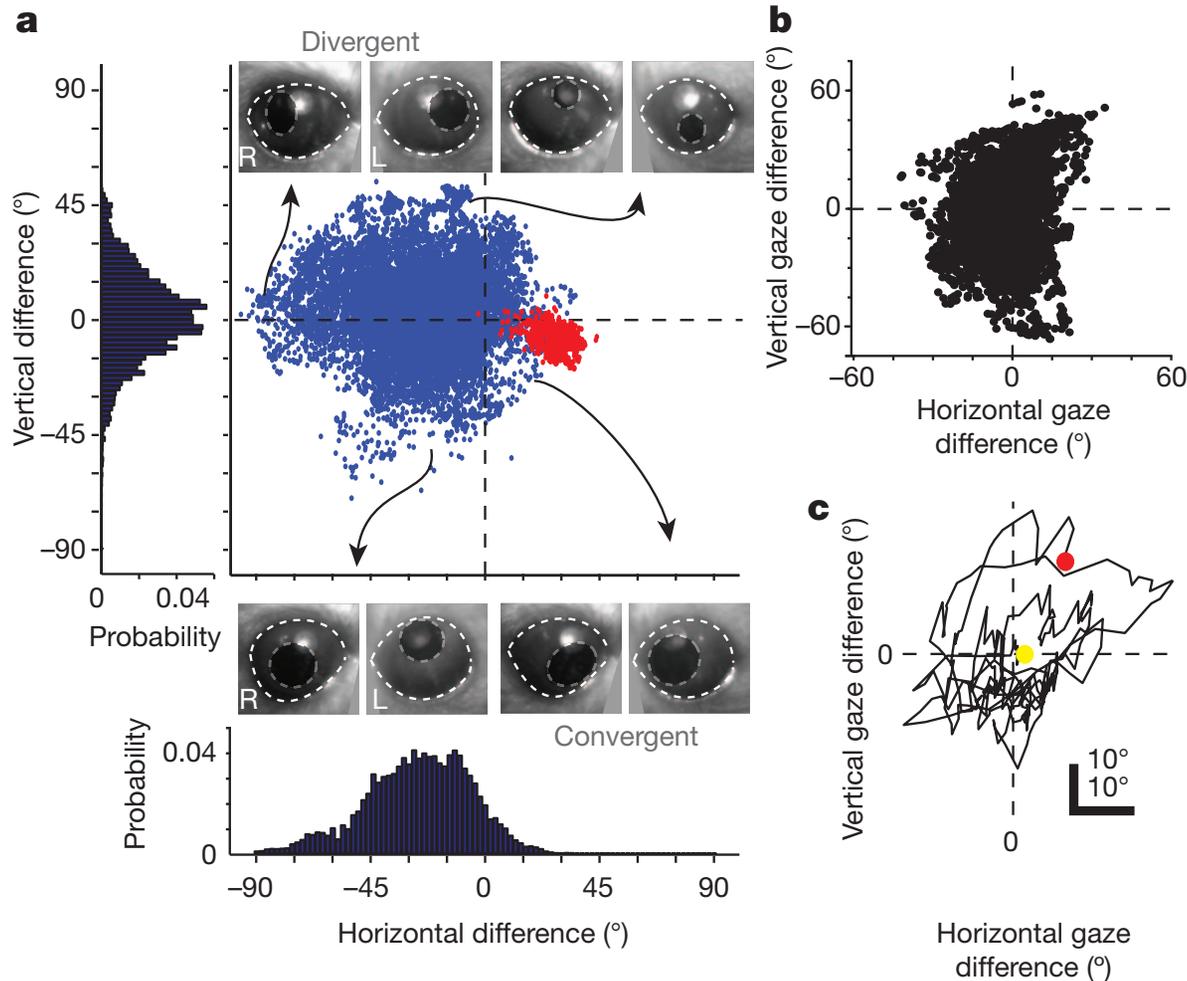


# Rats maintain an overhead binocular field at the expense of constant fusion

Damian J. Wallace<sup>1\*</sup>, David S. Greenberg<sup>1\*</sup>, Juergen Sawinski<sup>1\*</sup>, Stefanie Rulla<sup>1</sup>, Giuseppe Notaro<sup>1,2</sup> & Jason N. D. Kerr<sup>1,2</sup>

Fusing left and right eye images into a single view is dependent on precise ocular alignment, which relies on coordinated eye movements. During movements of the head this alignment is maintained by numerous reflexes. Although rodents share with other mammals the key components of eye movement control, the coordination of eye movements in freely moving rodents is unknown. Here we show that movements of the two eyes in freely moving rats differ fundamentally from the precisely controlled eye movements used by other mammals to maintain continuous binocular fusion. The observed eye movements serve to keep the visual fields of the two eyes continuously overlapping above the animal during free movement, but not continuously aligned. Overhead visual stimuli presented to rats freely exploring an open arena evoke an immediate shelter-seeking behaviour, but are ineffective when presented beside the arena. We suggest that continuously overlapping visual fields overhead would be of evolutionary benefit for predator detection by minimizing blind spots.

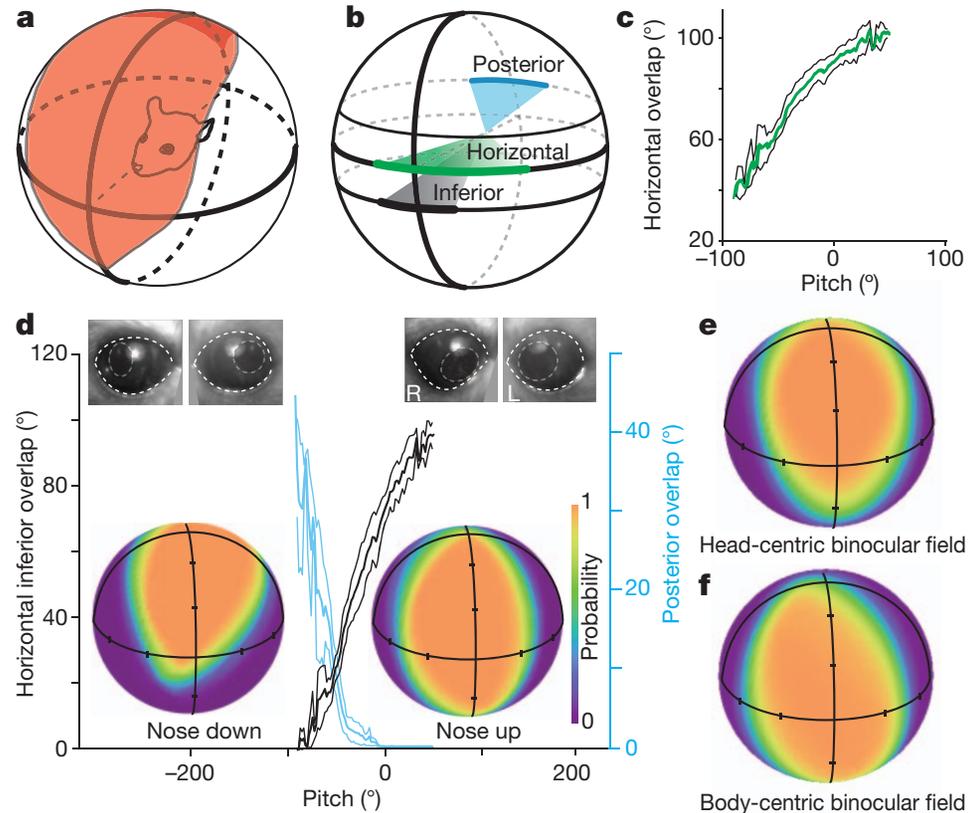
## Binocular eye movements



**Figure 3 | Asymmetrical eye movements in freely moving rats.**

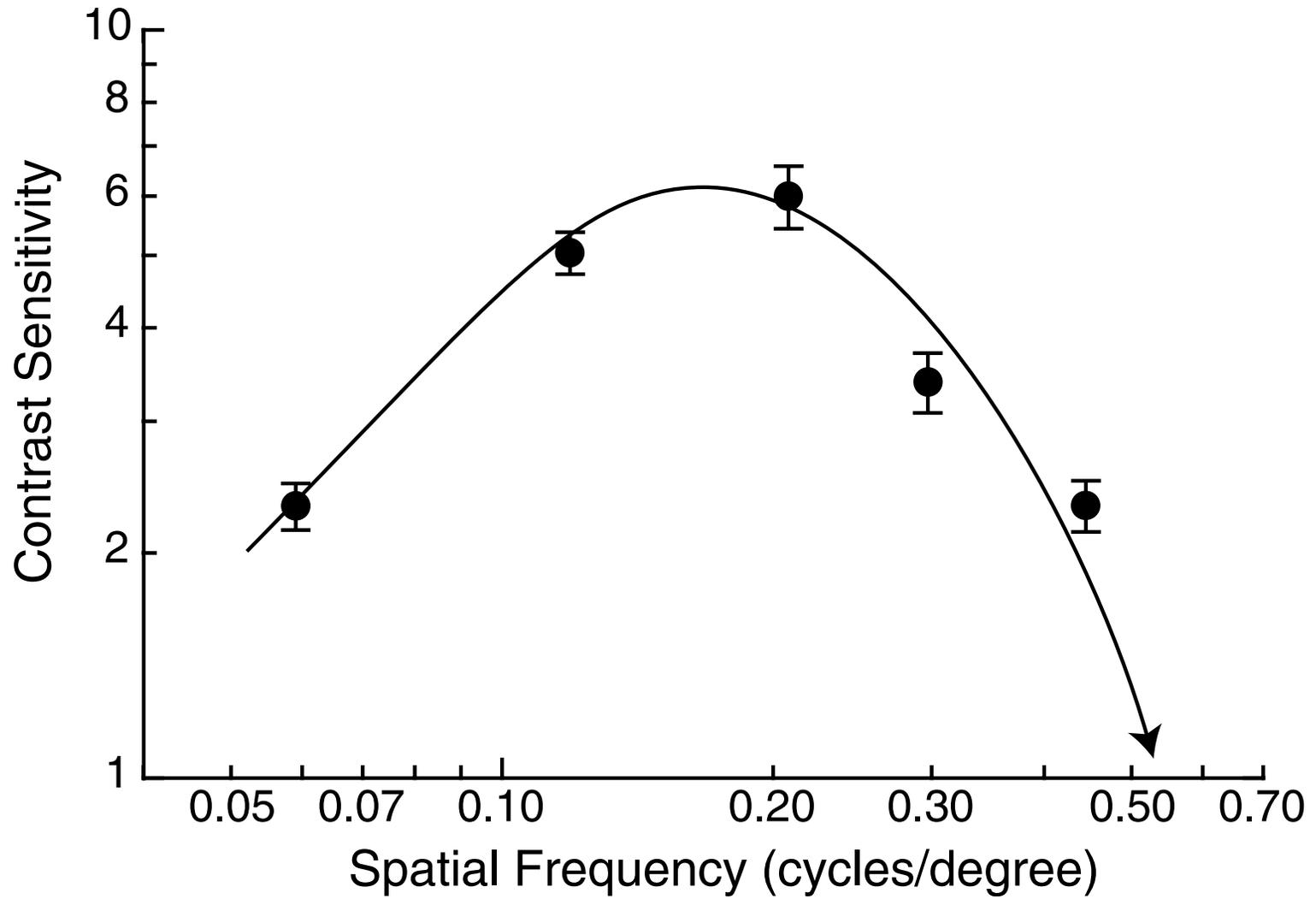
**a**, Distributions of the difference between left and right eye positions for a freely moving (blue) and head-restrained (red) rat. Each point represents the right eye position minus the left eye position for a single frame. Histograms are shown for  $x$  and  $y$  axes. Example image pairs (inset) from positions in the distribution (arrows). Conventions for eye images as in Fig. 1a. **b**, Scatter plot of the difference in left and right eye gaze vectors during free movement. **c**, Plot of the difference in left and right eye gaze vectors during free movement for a single continuous 1.7 s data segment including a gap cross.

## Binocular eye movements

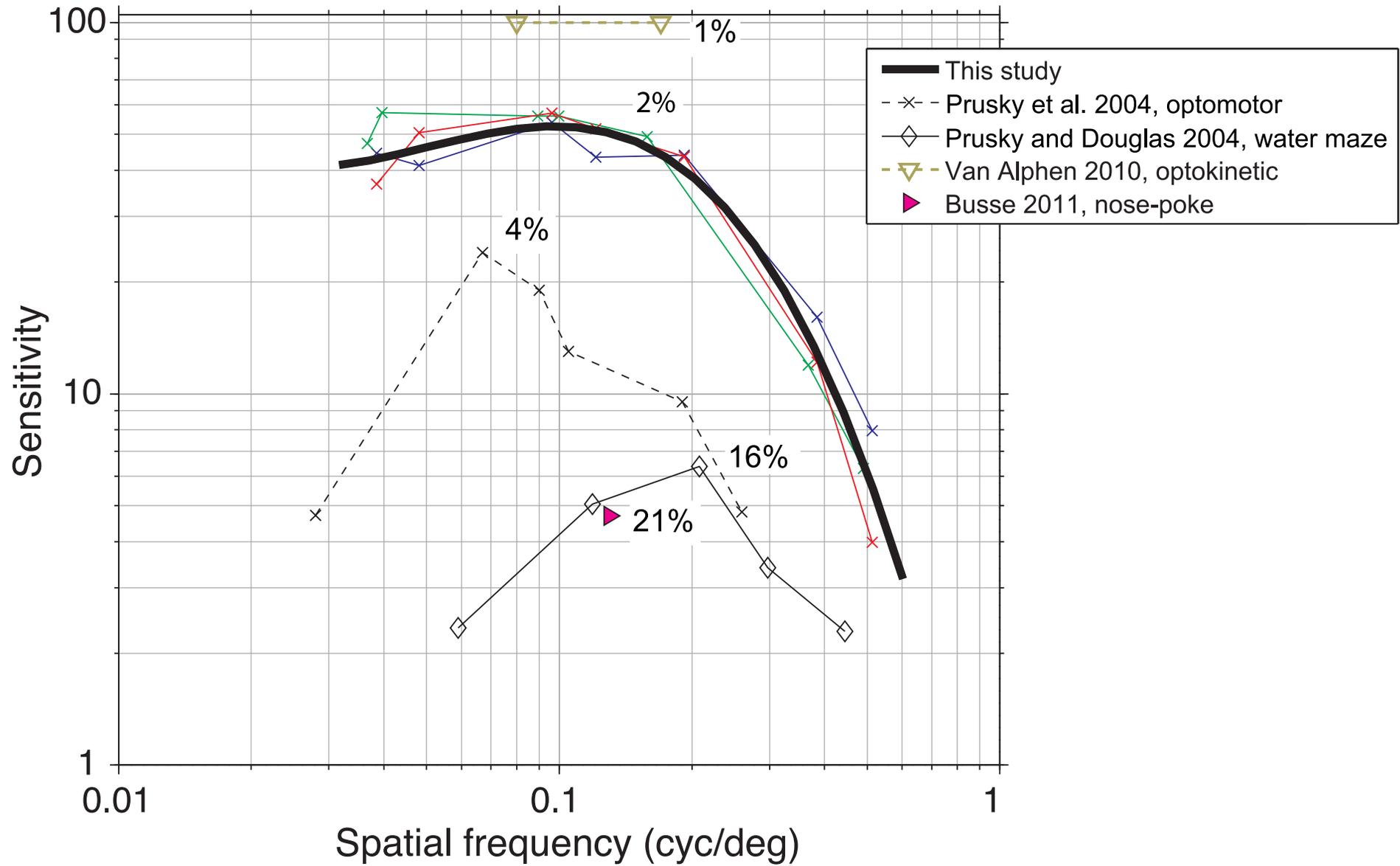


**Figure 5 | Overhead binocular overlap.** **a**, Schematic outlining binocular overlap (red, modified from ref. 1). **b**, Schematic for data in **c** and **d**. **c**, Average (green) dependence of horizontal overlap on head pitch (s.e.m., thin black lines,  $n = 4$  animals). **d**, Dependence of horizontal inferior (black) and posterior (blue) overlap on head pitch (s.e.m., thin black lines,  $n = 4$  animals). Head-centric density plots (insets) showing probability of visual field overlap (pseudo-colour) when animal is pitched down ( $\leq 10$ th centile of head pitch angles, insert left) or pitched up ( $\geq 90$ th centile, insert right,  $30^\circ$  ticks on vertical and horizontal axes). Note that average head roll was  $18 \pm 1^\circ$  during nose-down pitch. Images (upper insets) show example eye positions for negative and positive head pitch (same as in Fig. 3a). **e**, Head-centric density plot of average overlap of monocular visual fields during free movement for all head positions (conventions as in **d**,  $n = 4$  animals). **f**, Body-centric density plot of the overlapping fields that includes head and eye movements (conventions as in **d**, **e**,  $n = 4$  animals). See Supplementary Fig. 11 for body-centric definition.

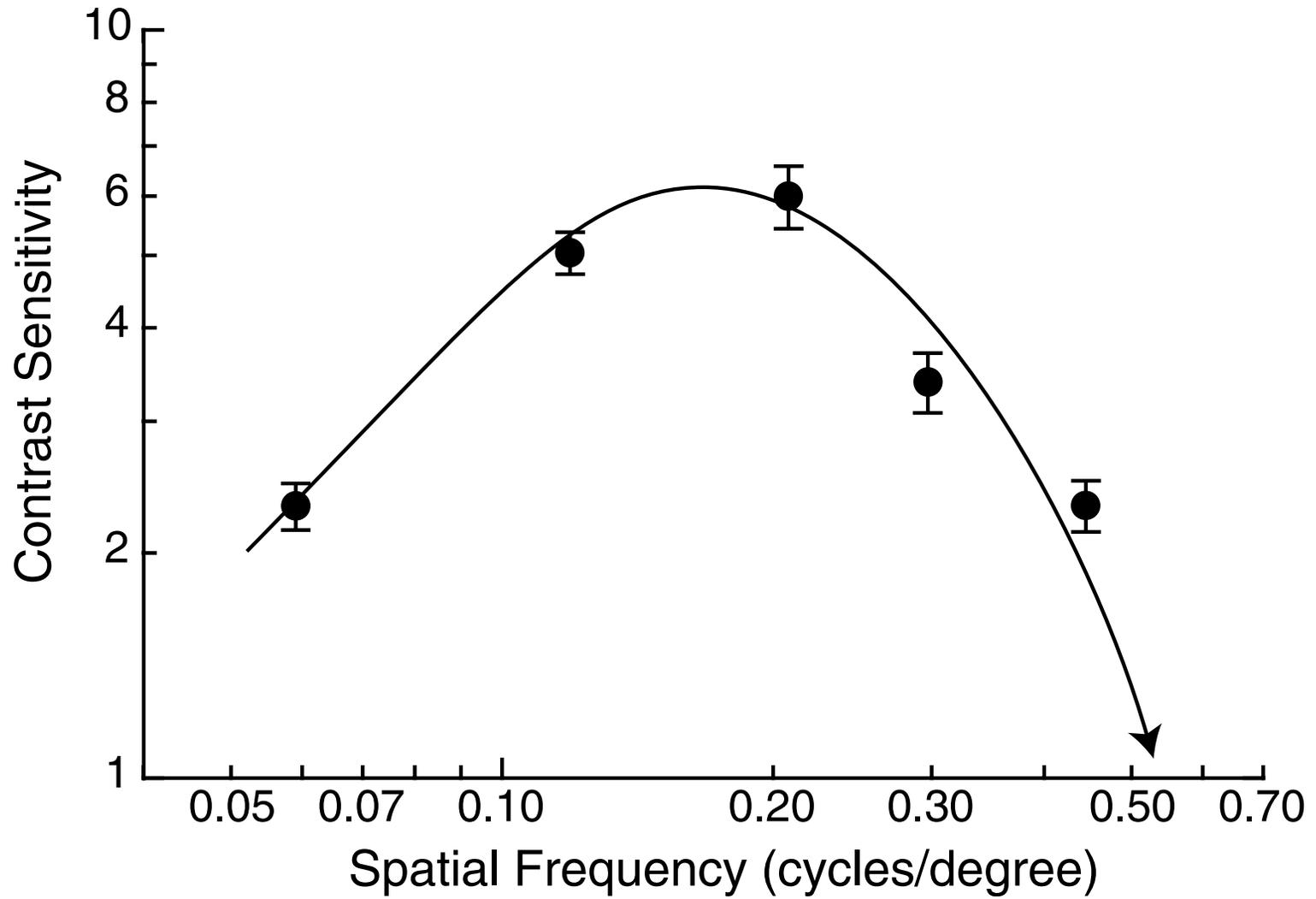
# *Spatial contrast sensitivity of the mouse*



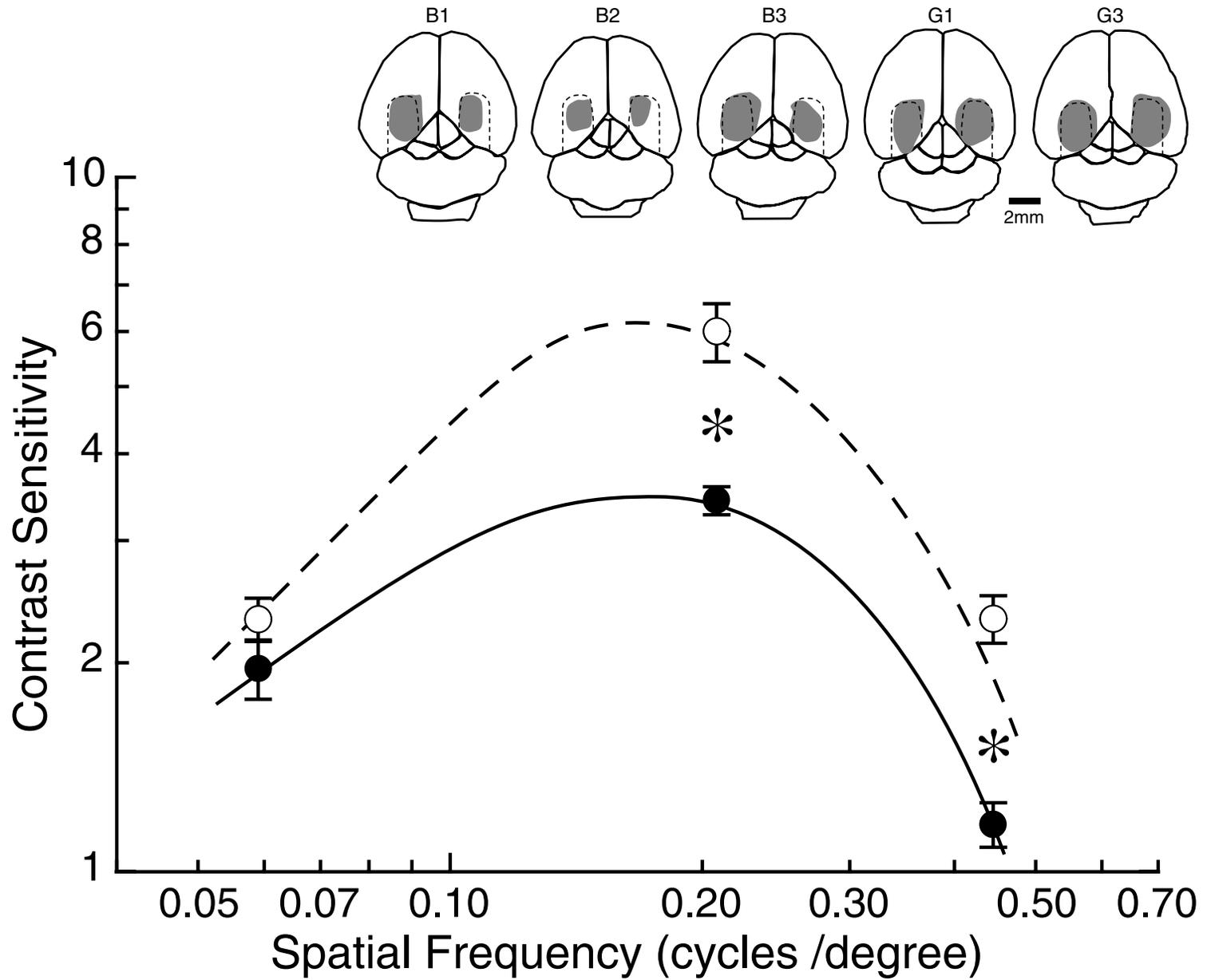
# Spatial contrast sensitivity of the mouse



# *Spatial contrast sensitivity of the mouse*

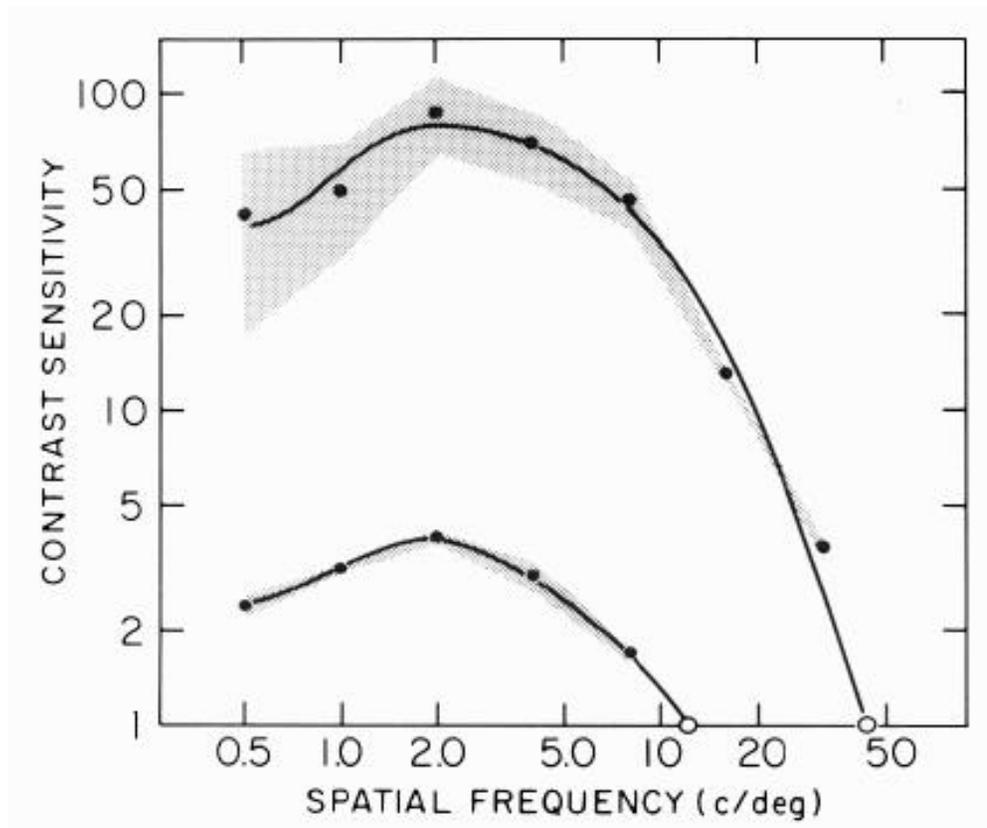


# Effects of striate cortex removal in mouse

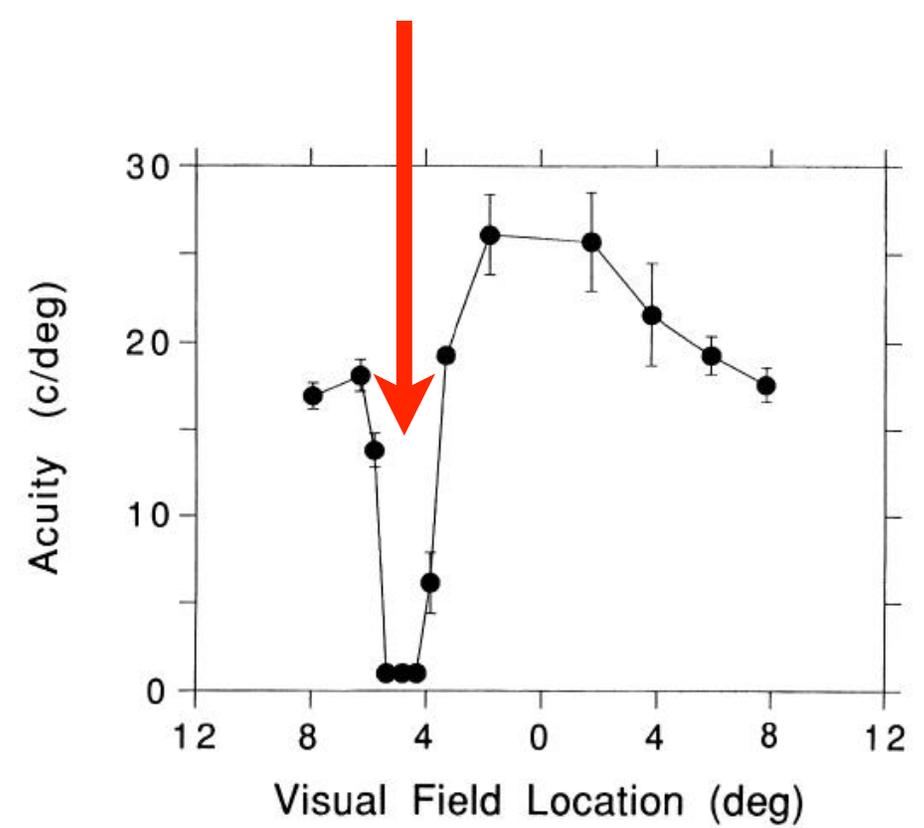


# Effects of striate cortex removal in monkey

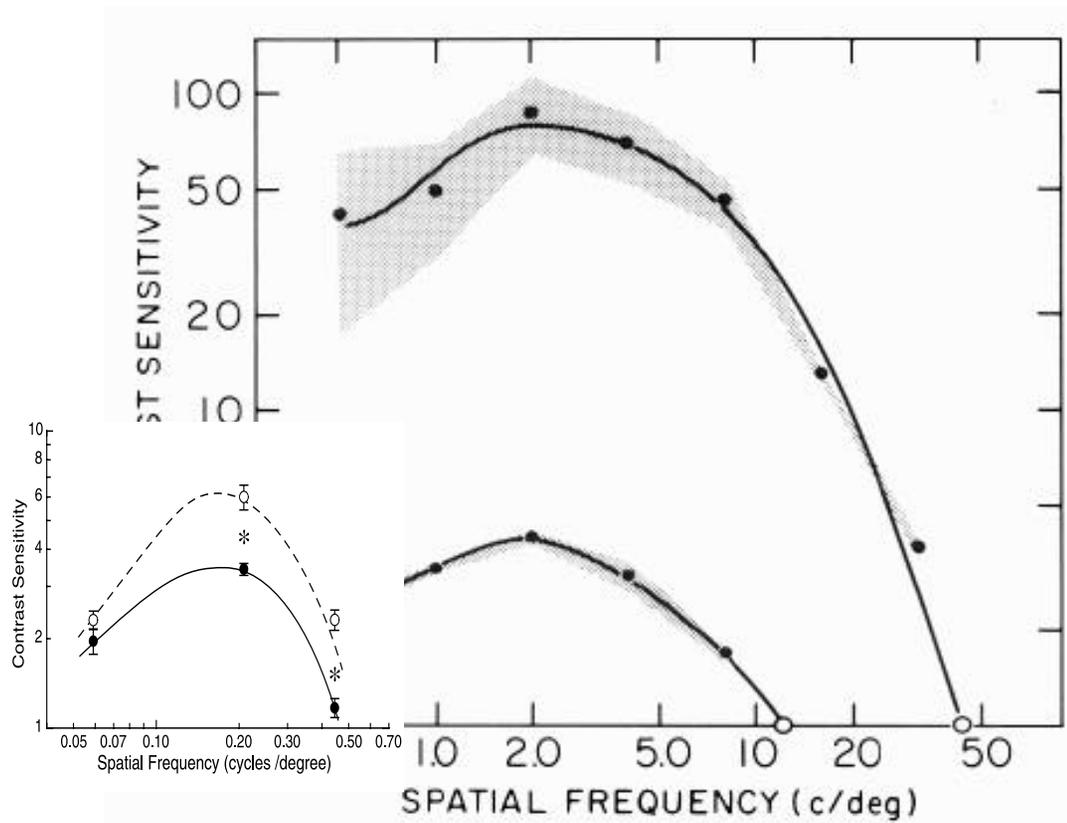
## Complete V1 lesion



## Focal V1 lesion



# Effects of striate cortex removal in monkey and mouse



*Other rodents may be different  
(Lashley, Schneider, ... Reinagel, and many others)*

## Effects of striate cortex removal in human

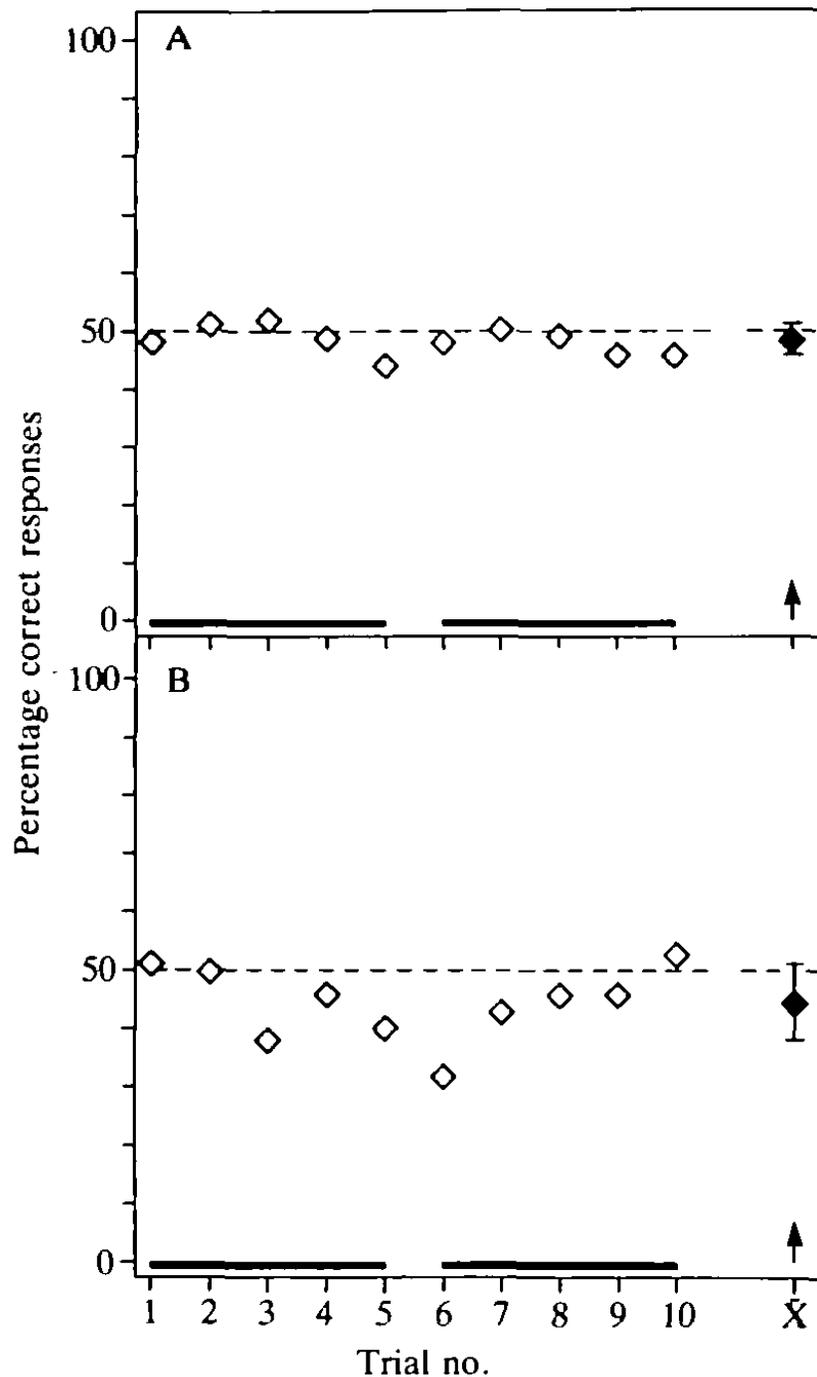
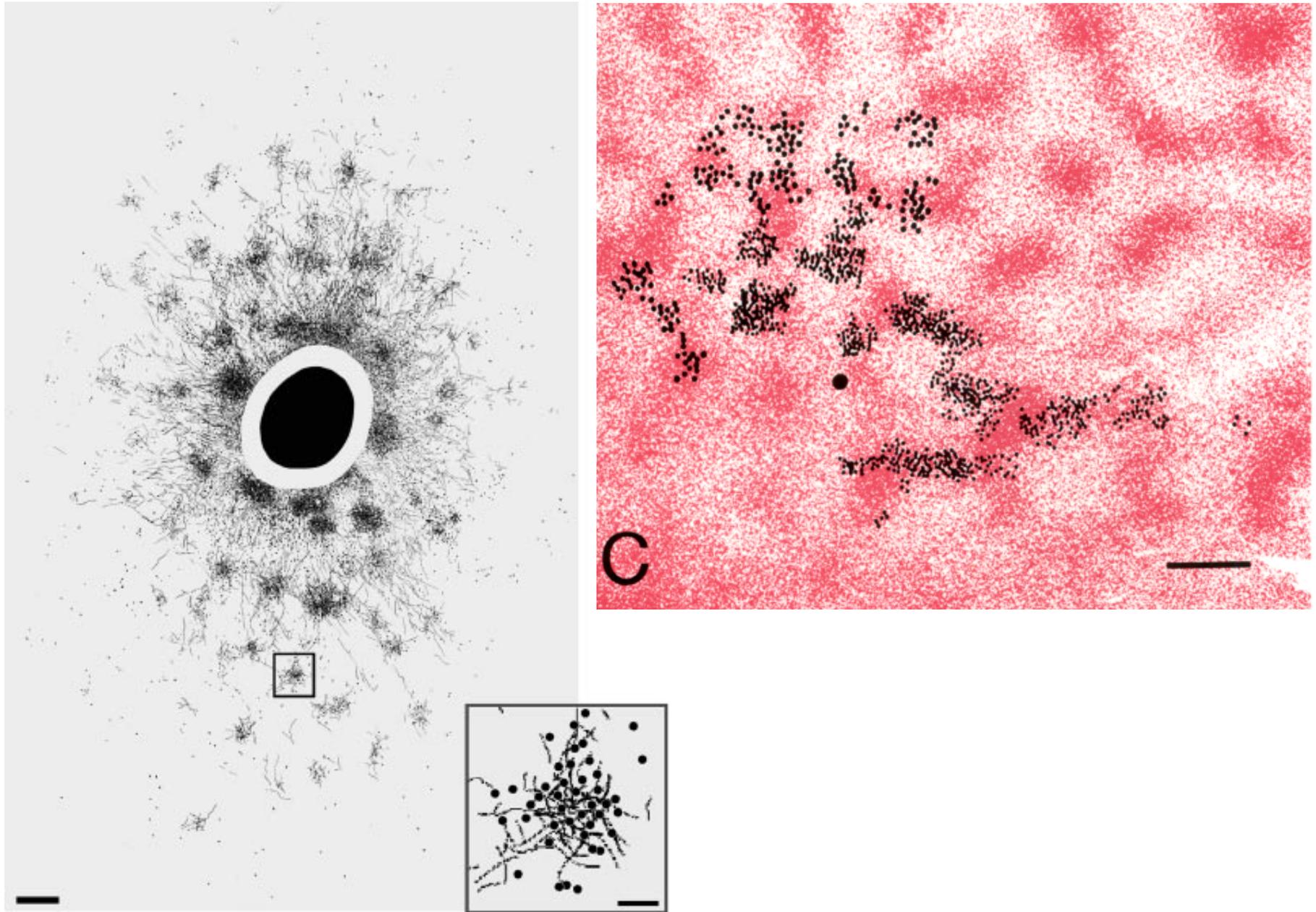
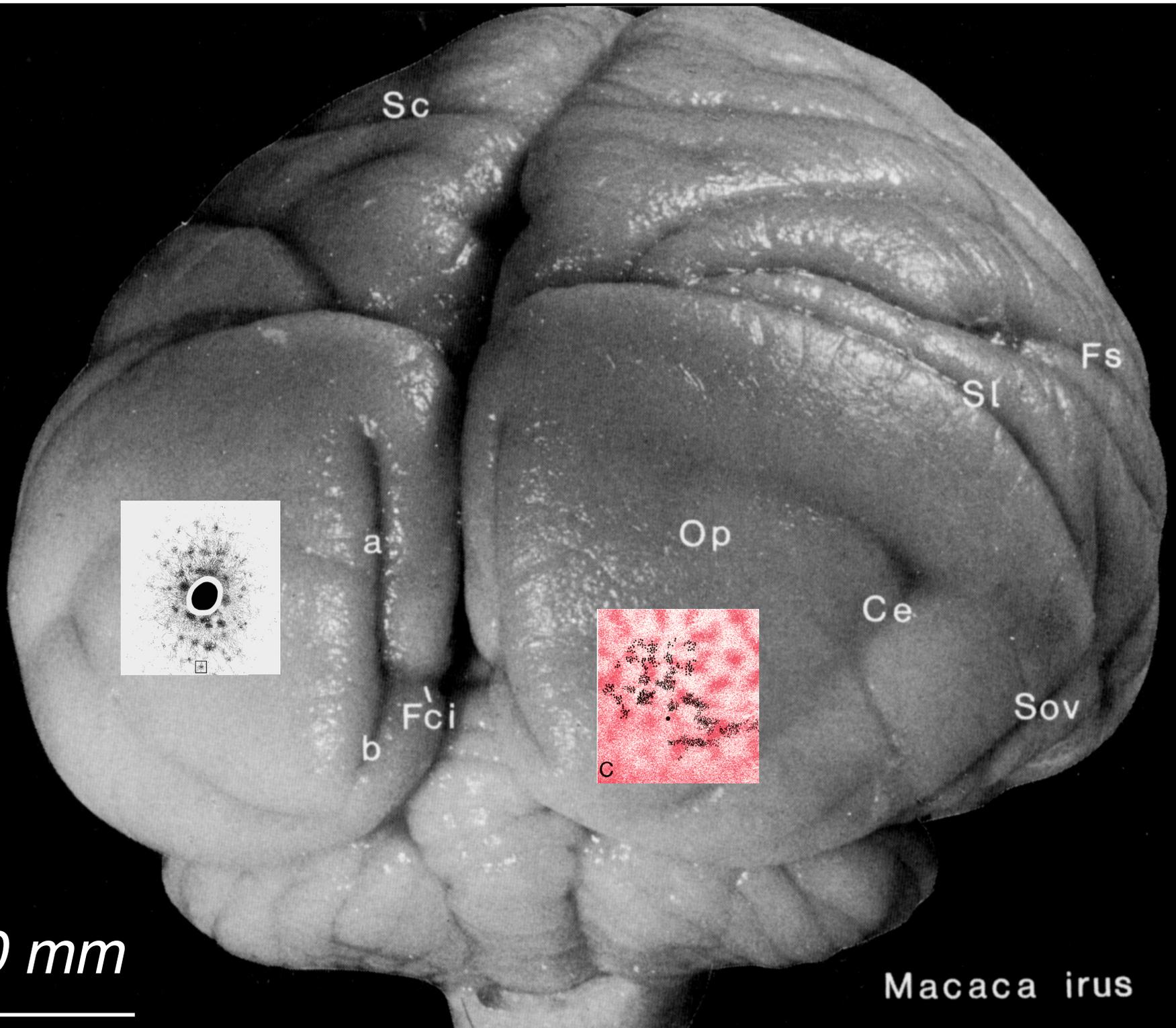


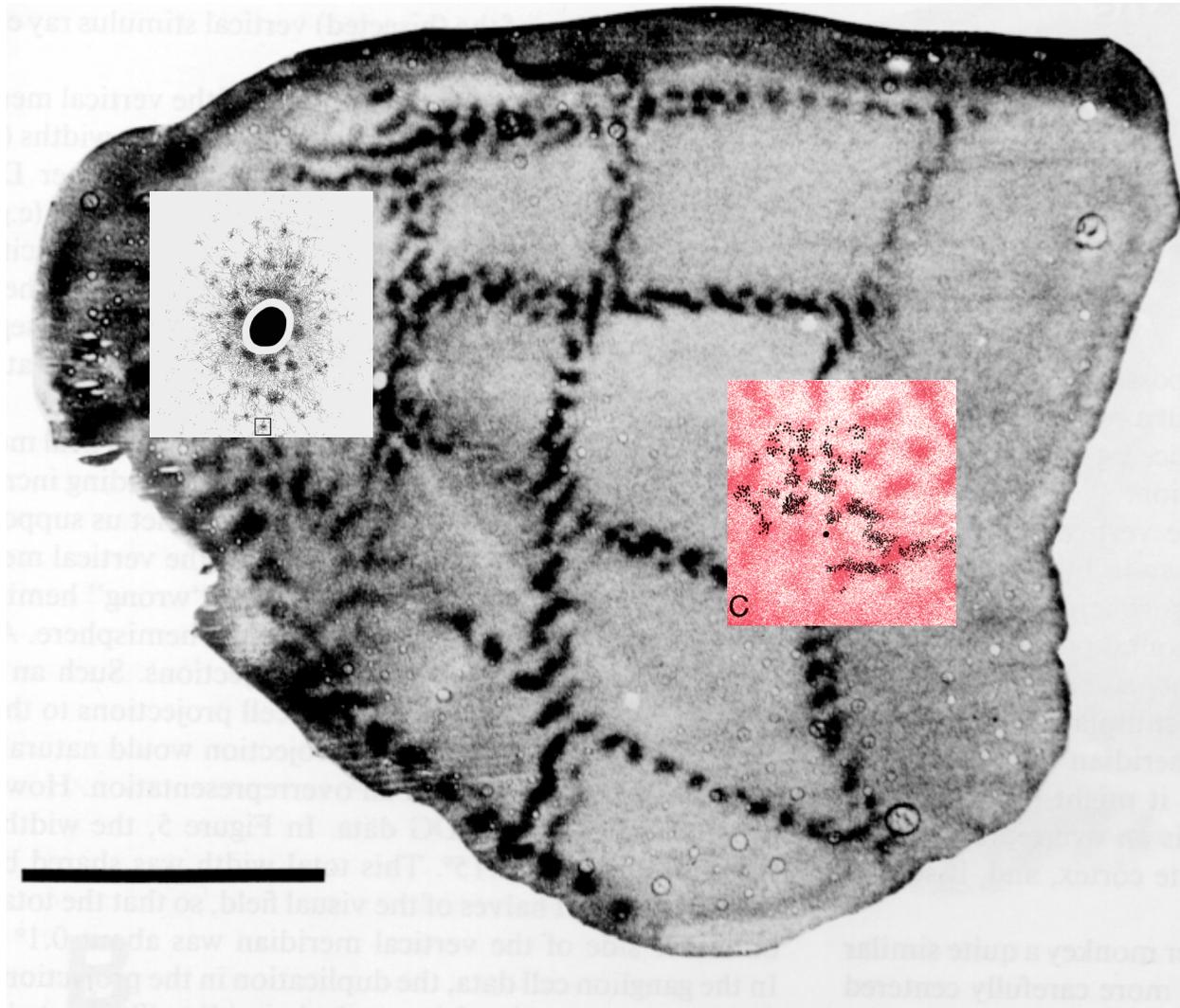
FIG. 20. Result of repeated experimental trials in the perimetrically-blind hemifield of *Case 1*. The data were generated in two series of  $5 \times 100$  frequency of seeing trials at each of two contrast levels. A, results of trials at 90% contrast; B, of trials at 30% contrast. The test location for all trials was  $20^\circ$  eccentric in the perimetrically-blind hemifield. Temporal modulation frequency was 5 Hz, corresponding to this subject's peak modulation response at the same eccentricity in the sighted hemifield (see fig. 11A). The isolated datum point indicated by a vertical arrow to the right of the abscissa in both A and B is the mean ( $\pm 1$  SD) of the total of  $10 \times 100$  trials.

# *Intrinsic cortical connections in macaque*

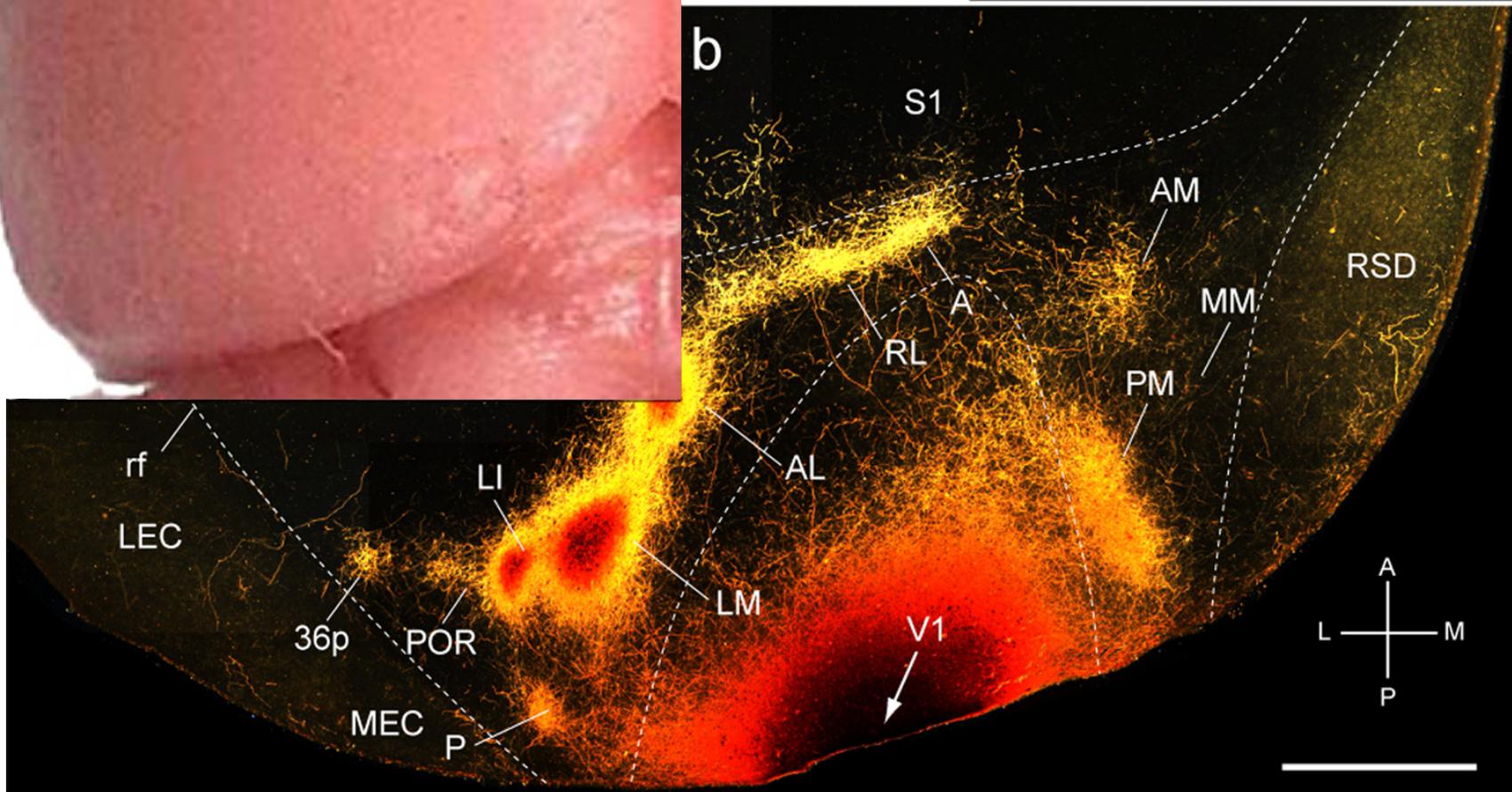
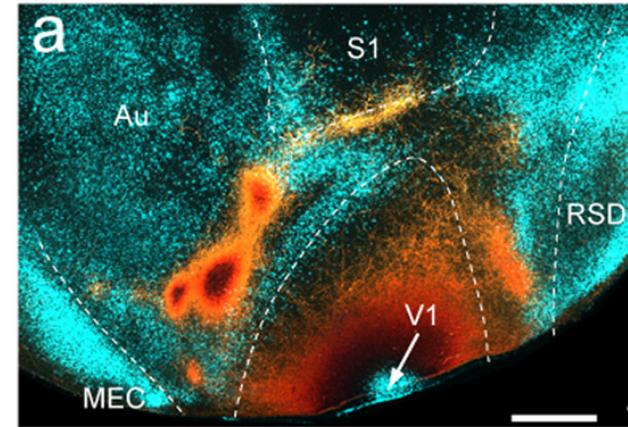




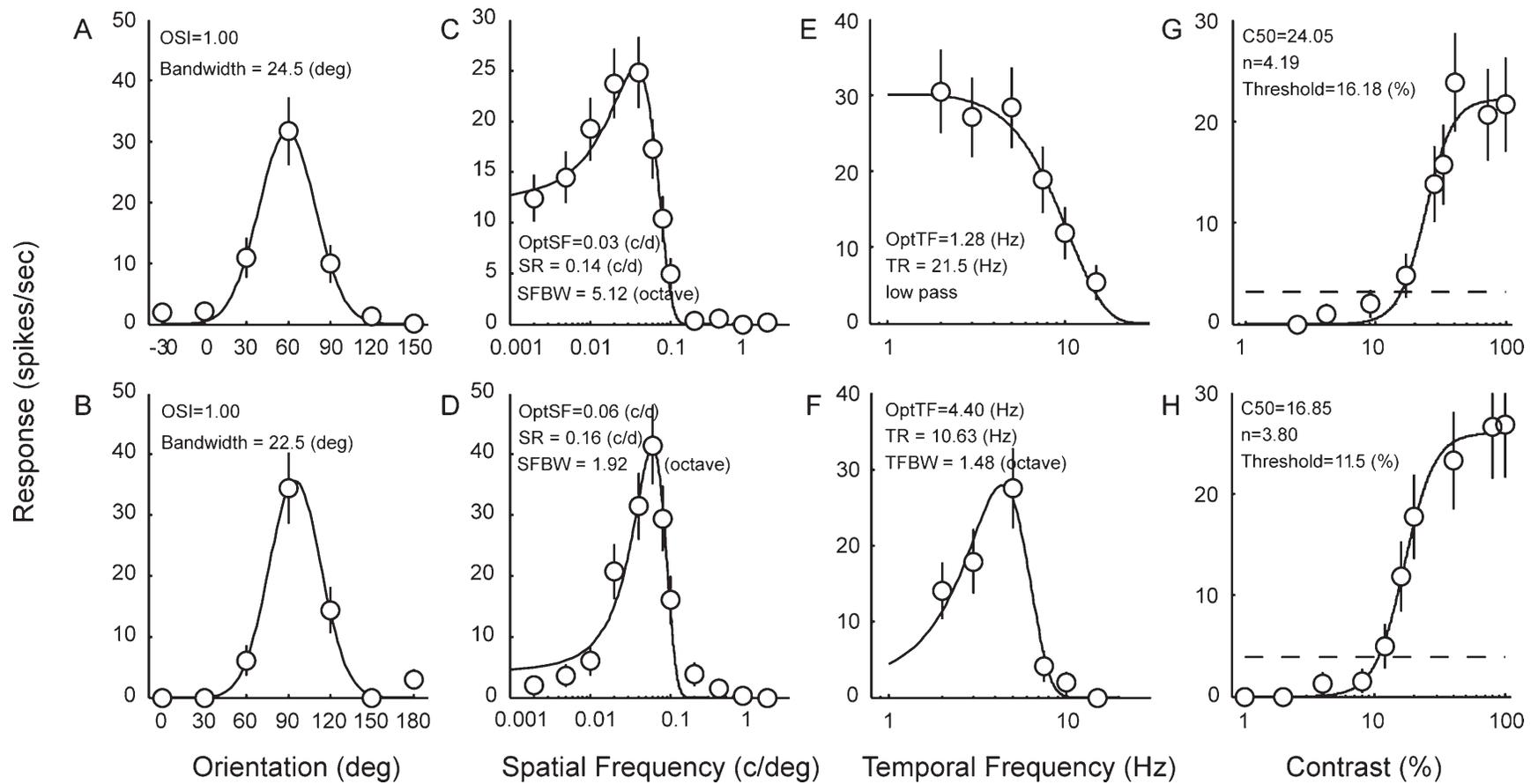
## *Local connectivity of macaque V1*



# Cortical connections in mouse

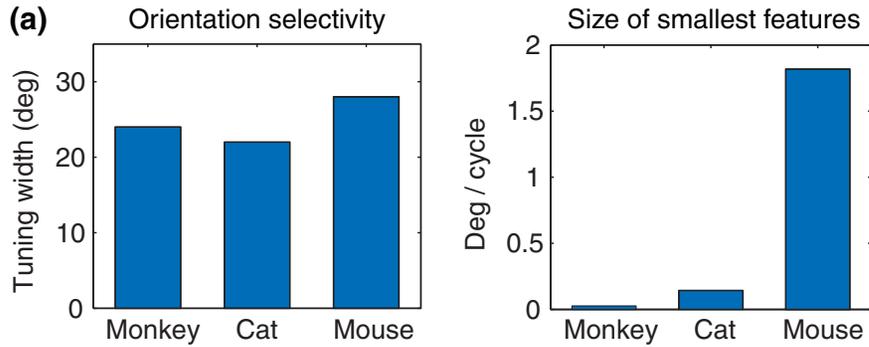


# Response properties in mouse cortex

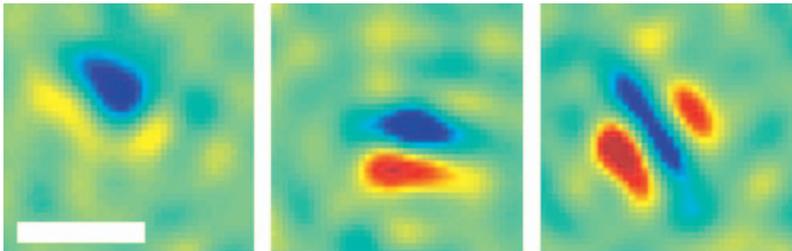


**Figure 3.** Representative tuning curves for stimulus orientation (A,B), spatial frequency (C,D), temporal frequency (E,F), and contrast (G,H) in mice.

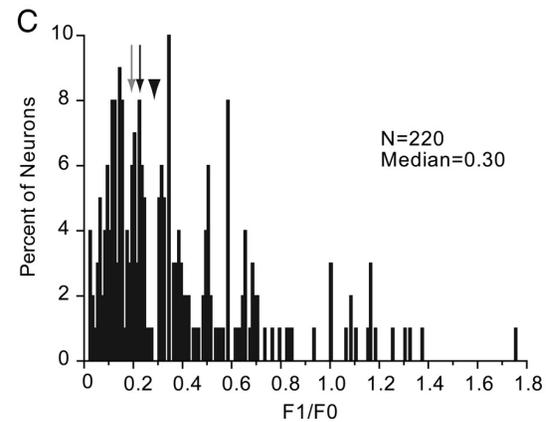
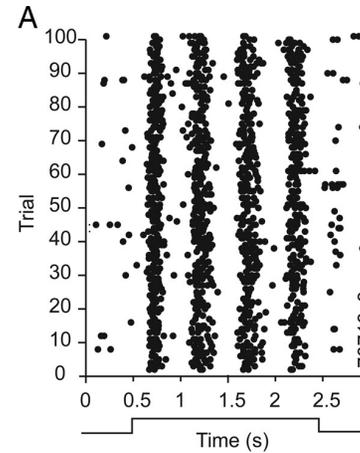
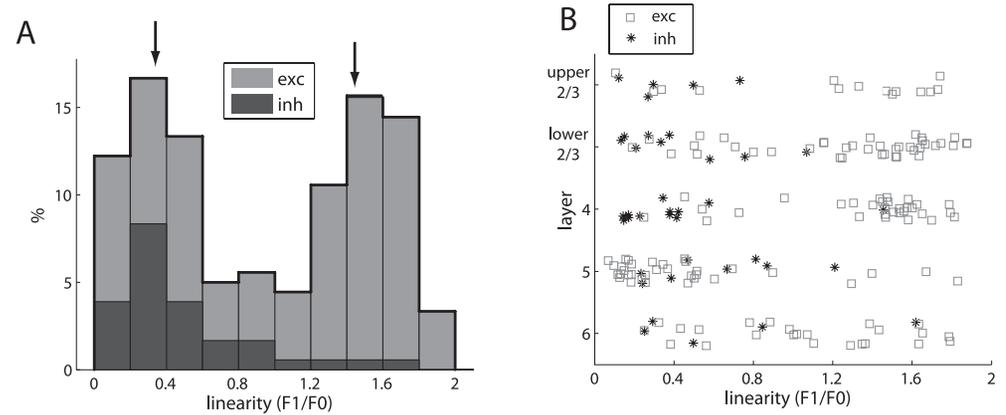
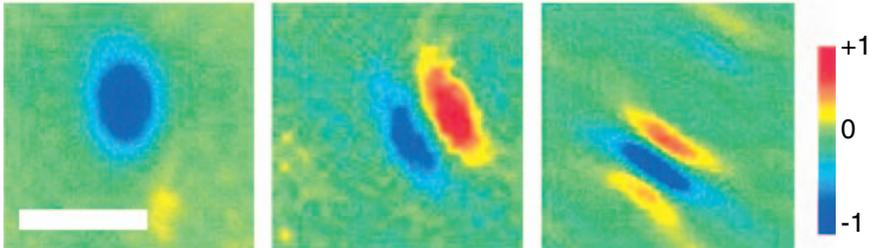
# Response properties in mouse cortex



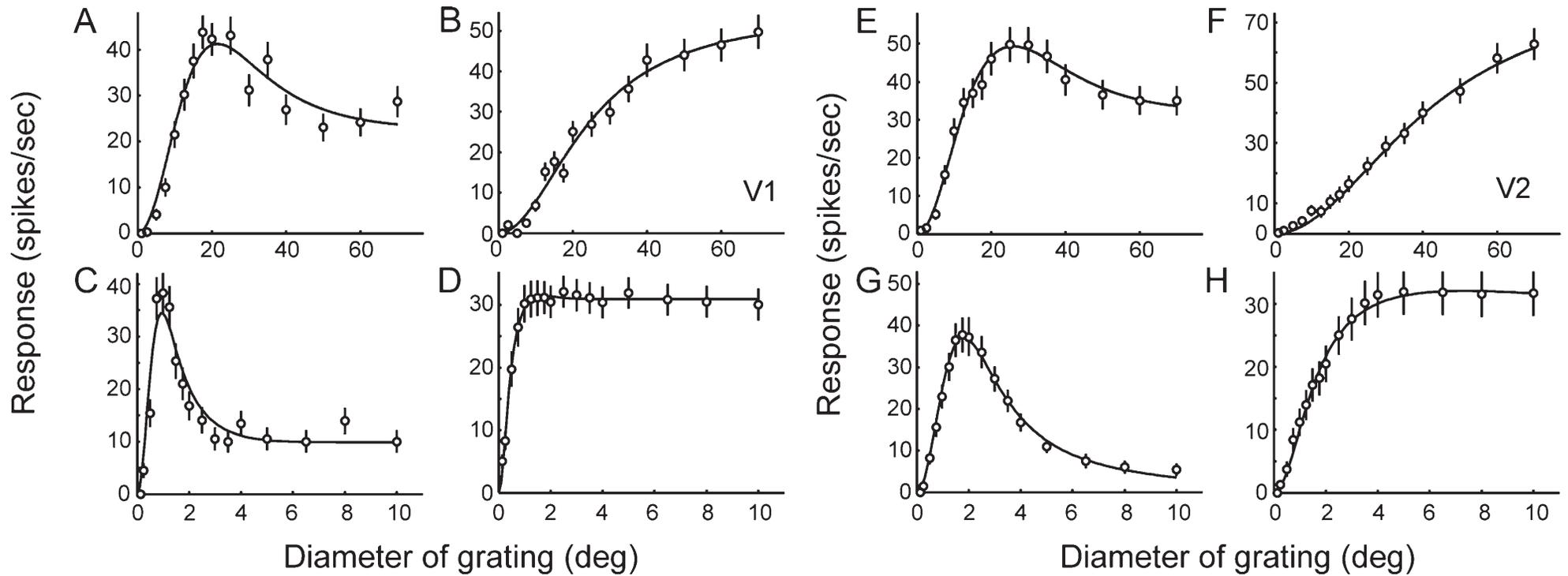
**(b)** Mouse V1 receptive fields



Monkey V1 receptive fields



## Response properties in mouse cortex



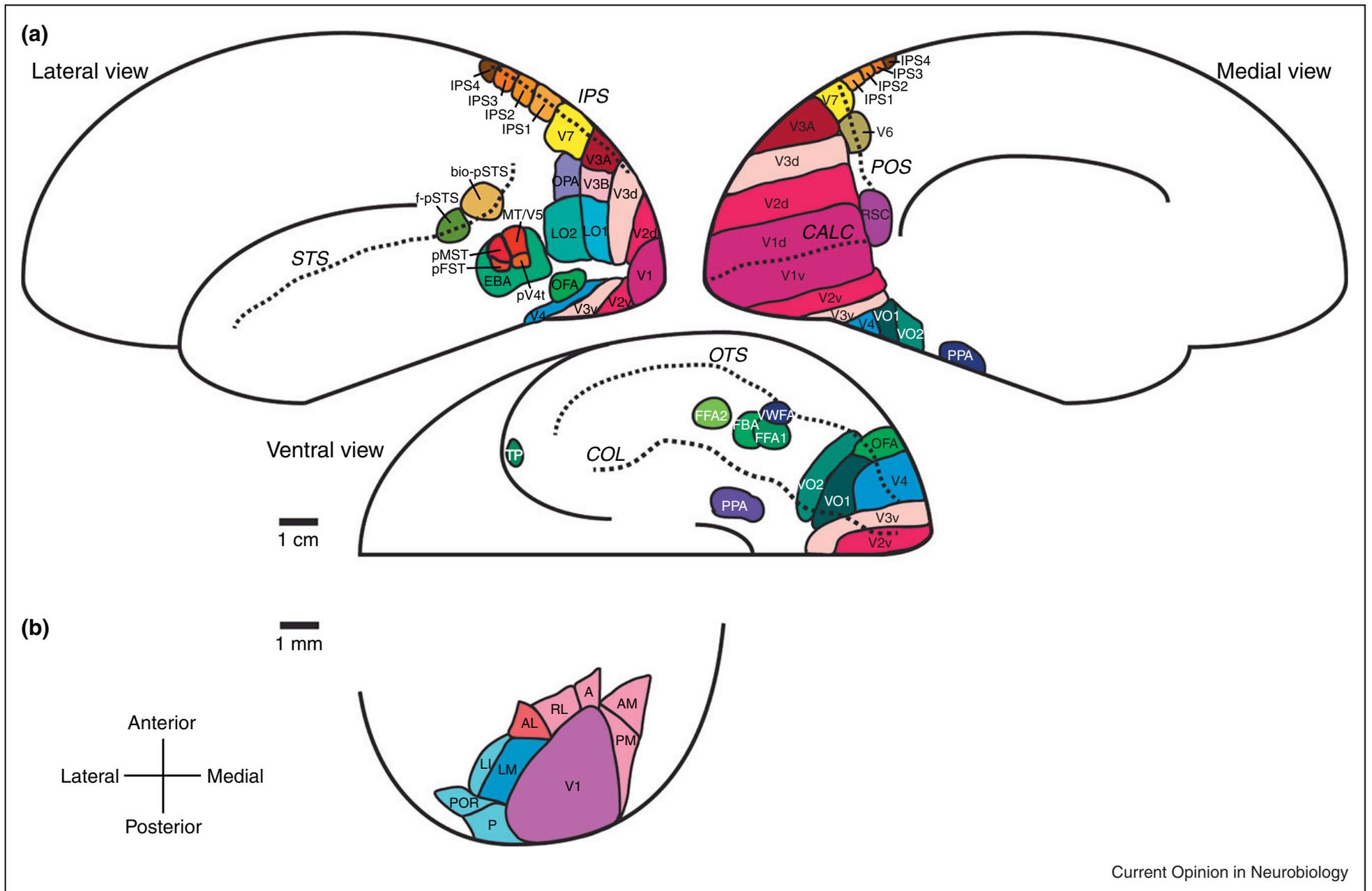
**Figure 9.** Representative size tuning functions of V1 (A–D) and V2 neurons (E–H) in mice (top: A,B,E,F) and macaque monkeys (bottom: C,D,G,H). Data points were fitted with the ratios of Gaussians (Cavanaugh et al., 2002). For each species, units with and without surround suppression are illustrated.

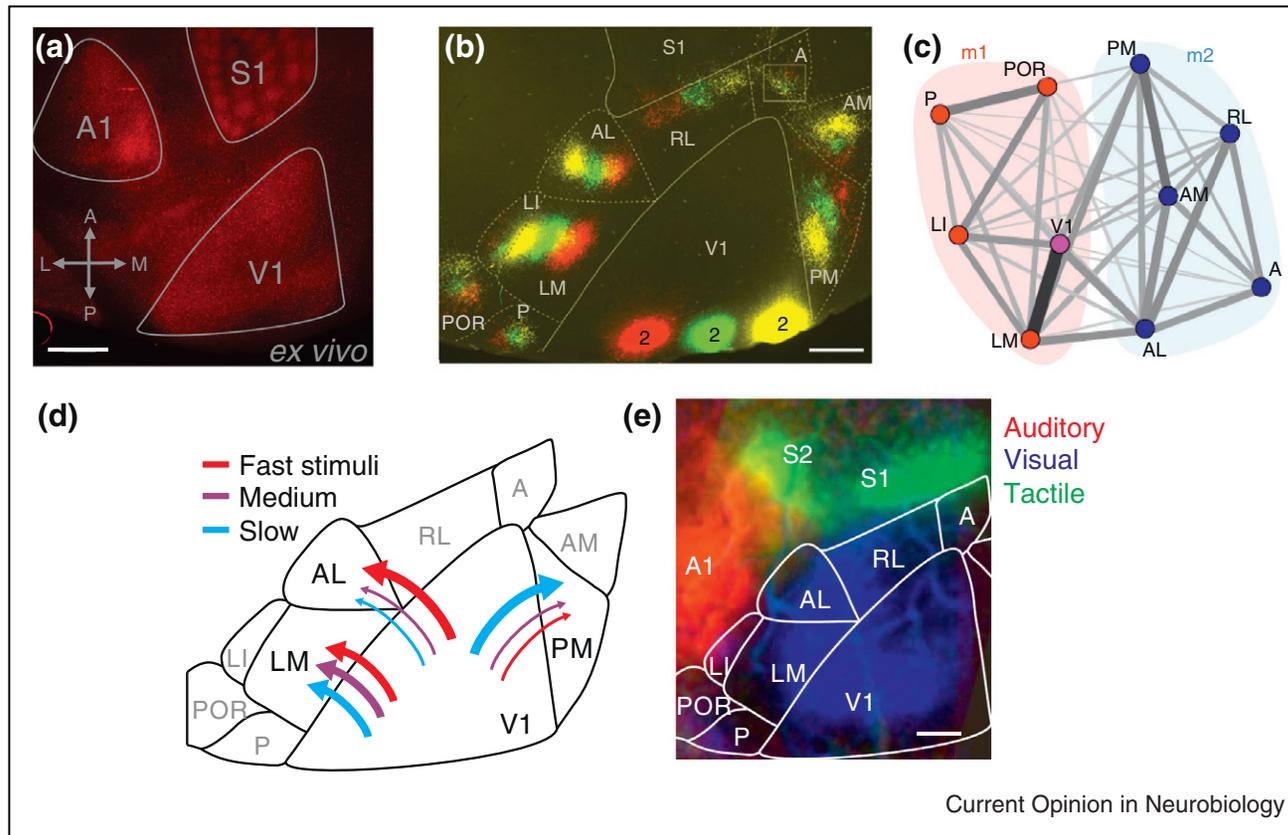


Understanding of the functional organization of visual cortex started when people recognized that neurons in inferotemporal cortex were doing things that neurons in V<sub>I</sub> weren't doing. That observation fell into place largely because V<sub>I</sub> and IT are very far apart on many dimensions. Looking for understanding of functional organization in a brain the size of a mouse's, which has to cram all of its limited capacities into a tiny volume, is like working with one hand tied behind our backs.

John Maunsell

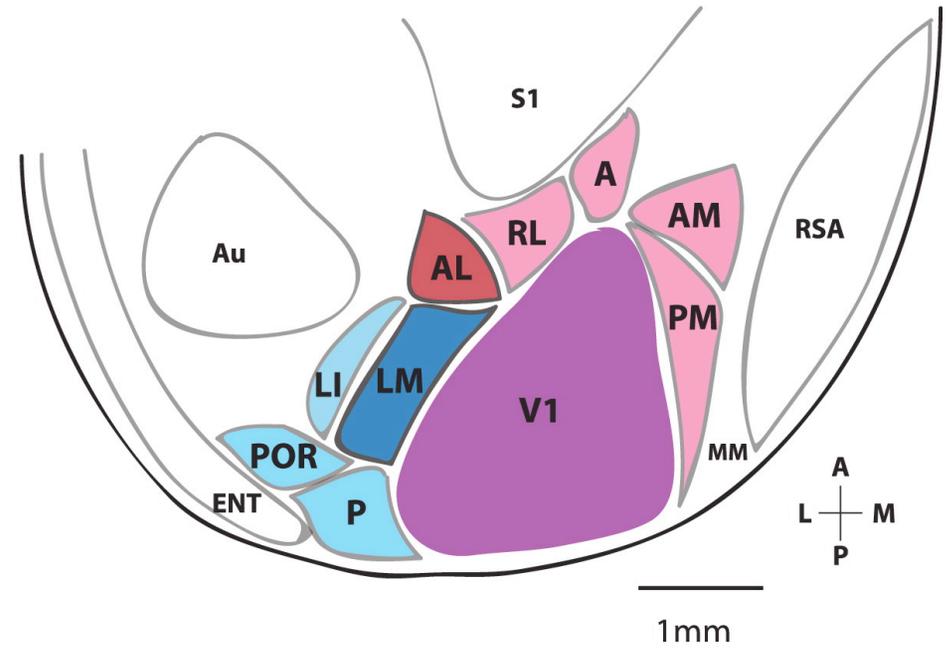
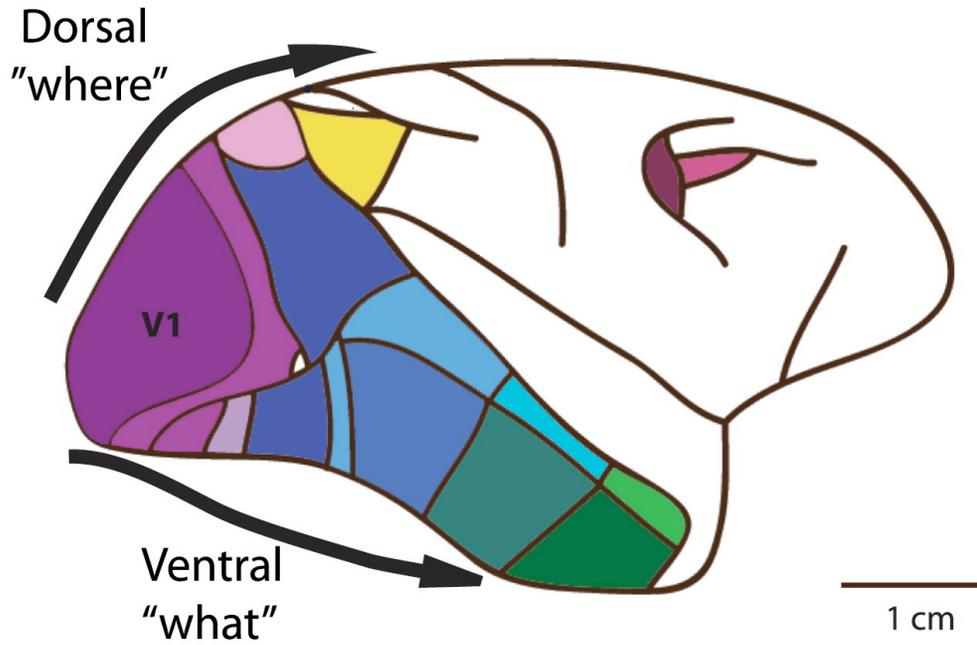




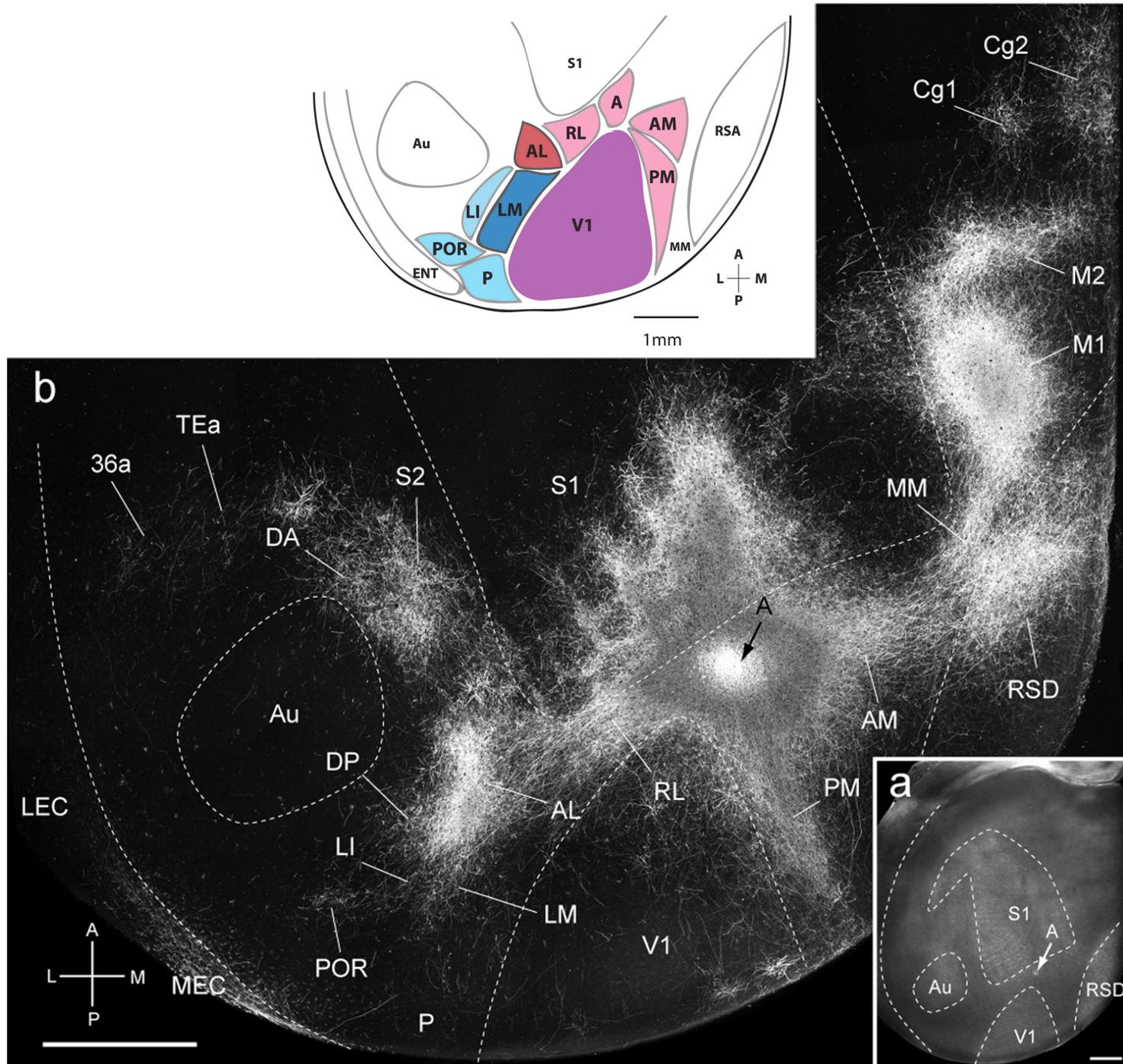


Anatomical and functional organization of mouse visual cortex. **(a)** Fluorescent images from a mouse expressing td-Tomato in parvalbumin positive interneurons (*PV-cre:Ai9* mice) from a flatmount *ex vivo* section. Td-Tomato expression highlights primary sensory areas (V1 — primary visual cortex; S1 — primary somatosensory cortex; A1 — primary auditory cortex). Data courtesy of D. Roumis. **(b)** Anterograde labeling of V1 projection neurons via fluorescently conjugated dextran injections reveal retinotopically organized arborizations within the higher visual areas. Adapted with permission from Wang and Burkhalter, 2007. **(c)** Connectivity matrix between V1 and nine higher visual areas. Thickness of lines represents the average reciprocal connectivity between areas as measured by the density of axonal projections. Areas are divided into two functional modules: ventral (m1, red) and dorsal (m2, blue). Adapted with permission from Wang, Sporns and Burkhalter, 2012. **(d)** Projections from the same region within V1 to the higher visual areas carry distinct visual information; namely, projections to AL prefer stimuli moving at fast (red) speeds while those to PM prefer slow (blue) speeds. LM receives comparatively diverse input from V1; this could explain the increased anatomical density of this projection. **(e)** Pseudocolor map of cortical regions sensitive to auditory (red), visual (blue) and tactile (green) stimulation. Note that lateral area LI responds to both visual and auditory stimuli. Area labels were determined by tonotopy, somatotopy and retinotopy. Data courtesy of N. Jikomes. All scales: 500  $\mu$ m.

# Extrastriate visual areas in macaque and mouse

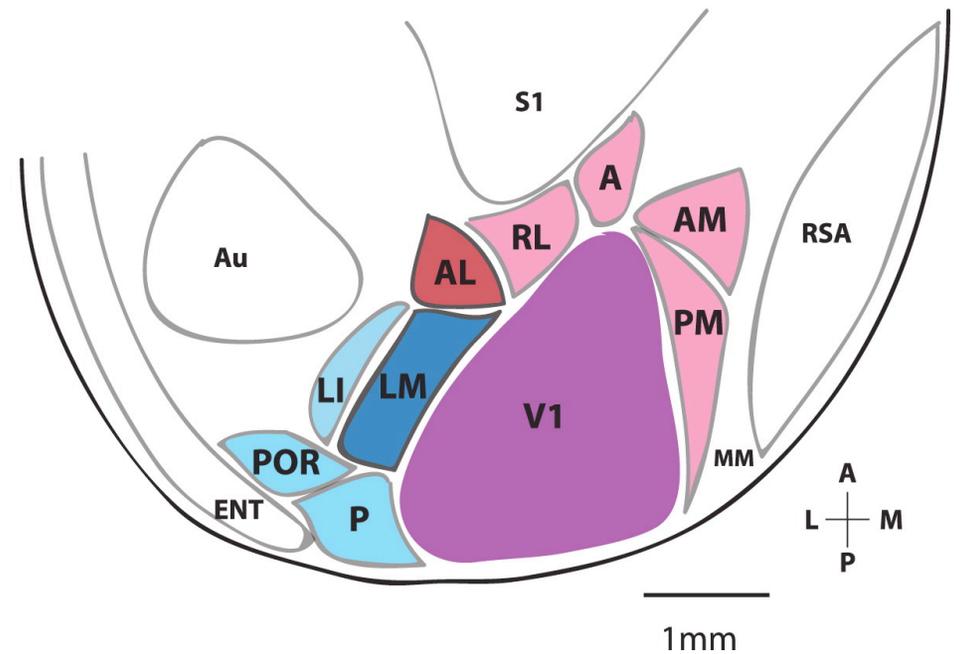


# Extrastriate visual areas in mouse



## Extrastriate visual areas in mouse

	Mean OSI	Mean DSI	Pref. SF (cpd)	Pref. TF (Hz)
V1	0.5	0.26	0.045	0.69
LM	0.55	0.27	0.028	1.8
LI	0.56	0.28	0.04	1.5
AL	0.72	0.35	0.022	1.2
RL	0.69	0.35	0.025	1.3
AM	0.81	0.38	0.033	1.6
PM	0.67	0.29	0.046	0.87



# Mouse cortex is hyperconnected

