The Distribution and Size of Retinal Ganglion Cells in Cheirogaleus medius and Tarsius syrichta: Implications for the Evolution of Sensory Systems in Primates

Nicole Tetreault, Atiya Hakeem, and John Allman

Sensory specializations, particularly in the visual system, have been crucial factors in the evolution of brain and behavior in primates (Allman, 2000). The entire output of the retina is channeled through the retinal ganglion cells whose axons form the optic nerve connecting the eye and brain. We have mapped the density of retinal ganglion cells in flattened retinal whole mounts in the dwarf lemur, *Cheirogaleus medius*, and the Philippine tarsier, *Tarsius syrichta*. Figure 1 illustrates these maps, which reveal that the ganglion cell density is much lower throughout the retina in dwarf lemur than in the tarsier. In Figure 2, the data for cross sections near the horizontal meridian are depicted for the dwarf lemur and tarsier from our data compared with similar cross sections from the galago (DeBruyn et al., 1980) and mouse lemur (Dkhissi-Benyahya et al, 2001). These data indicate that the retinal ganglion cell densities as a function of eccentricity are similar in tarsier, galago and mouse lemur, and that the ganglion cell densities in dwarf lemur are much lower, particularly near the center of the retina. In Figure 3, we have added comparable cross sectional data for the diurnal rhesus macaque to illustrate the enormous increase in ganglion cell density associated with higher acuity in diurnal anthropoids. This point is further documented in Table 1, which shows peak retinal ganglion cell density and total ganglion cell number for 12 primate species.

We have also measured ganglion cell diameters in the central and peripheral retinae of dwarf and mouse lemurs and tarsiers and combined our data with measurements previously made by Stone and Johnston (1981) (see Figure 4). Stone and Johnston found that retinal ganglion cells tend to be much larger in the periphery than in the center for the cat and the three diurnal anthropoids they examined (squirrel monkeys, rhesus macaques, and humans). There is also a strong tendency for peripheral ganglion cells to be larger than central cells in the nocturnal owl monkey for both the M and P subpopulations (Yamada et al., 2001). The peripheral cells are only slightly larger than the central cells in tarsiers and galagos, are about the same in mouse lemurs, and are slightly smaller in dwarf lemurs. The large size of the peripheral ganglion cells suggests that they may have larger, more rapidly conducting axons than those in the center. The large peripheral cells may thus serve to transmit a rapid signal of changing peripheral images to the brain. These data imply that large peripheral ganglion cells may be a

specialization that evolved separately in cats and in anthropoid primates and that this specialization occurs in both nocturnal and diurnal animals.

The contrast between the dwarf and mouse lemur is particularly striking, since they are members of the same family of primates, the cheirogaleidae. Figure 5 illustrates some other obvious differences between these closely related primates. The mouse lemur has much larger, more complex and mobile pinnae while the dwarf lemur has a larger and more bulbous furless region of exposed rhinarium. The differences between dwarf and mouse lemurs are also revealed by the relative volumes of sensory structures in the brains of these animals (see Figure 6). Using volumetric data (Baron et al., 1987; Frahm et al., 1984; Stephan et al., 1981; Stephan et al., 1984) we found that the olfactory bulb occupies a larger fraction of the total brain volume in dwarf lemurs as compared to mouse lemurs, which is consistent with the obviously larger, furless rhinarium in dwarf lemurs. In mouse lemurs, the brain volume fractions occupied by the lateral geniculate nucleus, which receives the main input from the retina, and the primary visual cortex, are both larger than in dwarf lemurs. The neocortex as a whole also occupies a larger volume fraction in mouse lemurs than in dwarf lemurs. The large, complex, mobile pinnae in mouse lemurs imply that these animals have superior sound localizing abilities and it would be fascinating to compare brain structures involved in sound localization such as the medial superior olive and the inferior colliculus in these animals.

All these data imply that there must be a major behavioral difference between dwarf and mouse lemurs. Dwarf lemurs eat fruit and crawling insects and appear to lack the dexterity to catch flying insects (Patricia Wright, personal communication). Their foraging for fruit may be enhanced by a superior sense of smell. Mouse lemurs also eat fruit but prey on flying insects which they detect through superior visual acuity and sound localizing ability and capture though superior manual dexterity.

Taken together these data suggest that there have been three or possibly four stages in the evolution of sensory systems in primates that can be discerned from comparative studies of living animals. The behavioral specializations of the early primates are controversial. Cartmill (1972) hypothetized that the early primates were visual predators. Martin (1990) hypothesized that the early primates were specialized for foraging in the fine terminal branches of trees, the "fine branch niche". Both theories purport to explain the large frontally directed eyes and grasping fingers characteristic of the early primates and their descendants. Implicit in both theories is the assumption that superior acuity was linked to the proposed behavioral specialization (Allman,2000). Tarsiers, galagos, mouse and dwarf lemurs all have grasping fingers and move about in the fine terminal branches quite well, but the primarily frugivorous dwarf lemurs lack the visual acuity found in the more predatory tarsiers, galagos, and mouse lemurs. This implies that the relatively high visual acuity characteristic of nearly all primates may have begun as a

prey detecting mechanism in the early primates.   There are two ways to view the dwarf lemur.   The first, and we believe more likely concept, is that the reduced ganglion cell density and enlarged olfactory system are derived specializations in the dwarf lemur. This interpretation is based on the fact that relatively high visual acuity, mobile pinnae and visual predation of flying insects are widely distributed in prosimian primates and thus may represent the primitive condition for primates.   The second way of viewing the dwarf lemur is that it is the survivor of an even more primitive population of ancient primates and that mouse lemur, galago and tarsier have independently evolved into more predatory niches.

The larger size of the peripheral versus central retinal ganglion cells in anthropoid primates suggests that this emerged as a specialization related to the fast communication of information from the retinal periphery to the brain in early anthropoids.   The dramatic enhancement of the central ganglion cell density in diurnal anthropoids implies that very high acuity vision emerged at some point in a diurnal anthropoid ancestor and is possibly related to diurnal foraging and the discrimination of individual identity and affect within social groups (see Bush et al., this volume).

Methods

The eyes of a Philippine tarsier, *Tarsius syrichta*, and a dwarf lemur, *Cheirogaleus medius*, that died of natural causes at the Duke Primate Center were kindly provided to us by Patricia Wright and Elwyn Simons. The retinas were dissected from the eyes and mounted on gelatin coated slides. Each retina was traced and outlined at 14X, noting the shape and major blood vessels. A grid dividing the retina into 0.5 mm x 0.5 mm squares was superimposed on the drawing, and every other square in a checkerboard array was marked, so that counts were taken at approximately 1 mm intervals in both the vertical and horizontal dimensions. In each of these alternating 0.5 mm x 0.5 mm squares, the ganglion cells within three randomly selected 0.1 mm x 0.1 mm square fields were counted using a Reichert-Jung Polyvar microscope. Cells intersecting only 2 sides of the 0.1mm x 0.1 mm counting box were included in the count to avoid oversampling. The ganglion cells were traced at 40X using Normarski optics and a camera lucida attachment. These methods were similar to those used by De Bruyn et al. (1980).

The ganglion cells were distinguished from amacrine and glial cells by soma size and morphology based on the criteria of Johnston and Stone (1981). We measured the average diameters of 100 cells from the center and 100 cells from the periphery using the same procedures as Johnston and Stone (1981).

The photographs of the Microcebus and Cheirogaleus were taken with a Minolta Dimage 7 digital camera.

Acknowledgements

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Table

	retinal area mm^2	total ganglion cells per retina	max cells per mm^2	activity cycle	tapetum	body mass in g
STREPSIRHINES						
Microcebus murinus	114	565,000	28,000	N	yes	109
Cheirogaleus medius	172	192,000	3,700	N	yes	180
Galago senegalensis	332	519,000	12,200	N	yes	202
Otolemur crassicaudatus	344	755,000	11,300	N	yes	1,350
HAPLORHINES						
Tarsius syrichta	341	797,000	13,300	N	no	125
Aotus trivirgatus	660	465,000	12,900	N	no	935
Cebus apella	611	1,370,000	49,300	D	no	3,050
Macaca mulatta	670	1,600,000	33,000	D	no	7,650
Macaca fascicularis	527	1,583,000	48,000	D	no	5,400
Papio anubis	793	1,580,000	58,000	D	no	21,000
Cercopithecus aethiops	707	1,229,000	43,000	D	no	3,950
Homo sapiens	944	1,275,000	>50,000	D	no	65,000

Table Caption

Table 1. Data for peak retinal ganglion cell density, retinal area, total number of retinal ganglion cells and other parameters for a variety of primate species. N = nocturnal; D = diurnal. Data for *M. murinus,* Dkhissi-Benyahya et al. 2001; *G. senegalensis* and *O. crassicaudatus*, DeBruyn et al. 1980; *A. trivirgatus*, Webb and Kass 1976, Silveira et al. 1993, Jones 1965, Jacobs 1977; *C. apella*, Silveira et al. 1989, Perry and Cowey 1985; *M. mulatta*, Perry and Cowey 1985; *M. fascicularis*, Wassle et al. 1990, Reese and Ho 1988; *P. anubis*, Fischer and Kirby 1991; *C. aethiops*, Herbin et al. 1997; *H. sapiens*, Van Buren 1963; Jonas et al. 1992; Curcio et al. 1990. The human total ganglion cell count of 1,275,000 is the median for a population of young adults. The human totals counts range from 800,000 to 1,700,000.   The table is based on Herbin et al. (1997) except for *Microcebu*s, *Cheirogaleus*, *Tarsiu*s, and *Homo*.

Figure Captions

Figure 1. Retinal ganglion cell density maps from the Philippine Tarsier, *Tarsius syrichta* (top) and the dwarf lemur, *Cheirogaleus medius* (bottom). The area enclosed by each isodensity contour contains counts equal to or higher than the contour level indicated by the color scale at right. Note that the upper and lower plots have different contour spacing, but are shown on the same x-y spatial scale to indicate the relative sizes of the two retinae.

Figure 2. A plot of retinal ganglion cell density as a function of eccentricity. Each trace corresponds to a cross section near the horizontal meridian from the retina of the indicated species. In some cases the strip does not intersect the optic disk. Galago data from De Bruyn et al. (1980).

Figure 3. A plot of retinal ganglion cell density as a function of eccentricity, as in Figure 2, with the addition of data for the rhesus macaque (Wassle et al., 1990).
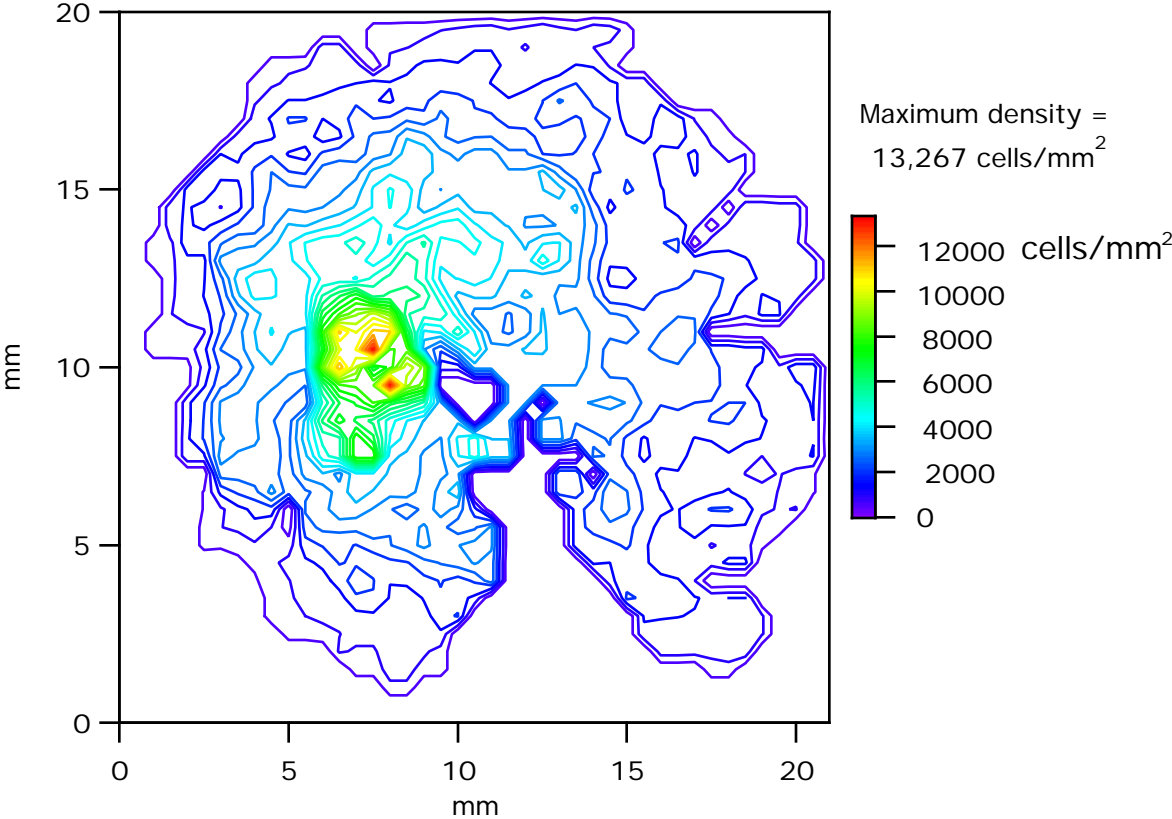
Figure 4. A comparison of ganglion cell size distributions in the central and peripheral retina of the cat and various primate species. Each distribution was made by measuring mean soma diameter for 100 cells. Mean soma diameter for each distribution is indicated by a number with an arrow pointing to the appropriate histogram. The peripheral distributions are distinguished by the use of bold lines. Data for cat, galago, squirrel monkey, macaque, and human from Stone and Johnston, (1981).

Figure 5. Photographs of the mouse lemur, *Microcebus murinus* (top) and the dwarf lemur, *Cheirogaleus medius* (bottom), showing the large differences between the external auditory and olfactory structures in these two species.

Figure 6. A comparison between dwarf lemur and mouse lemur of the ratio between the volumes of olfactory bulb, lateral geniculate nucleus, area 17 gray matter and neocortex with whole brain. Values are plotted on a logarithmic scale to accommodate the wide range of values. Unfilled bars are for the dwarf lemur; filled bars are for the mouse lemur. Brain and structure volume data from Baron et al. (1987), Stephan et al. (1984, 1981), and Frahm et al. (1984).
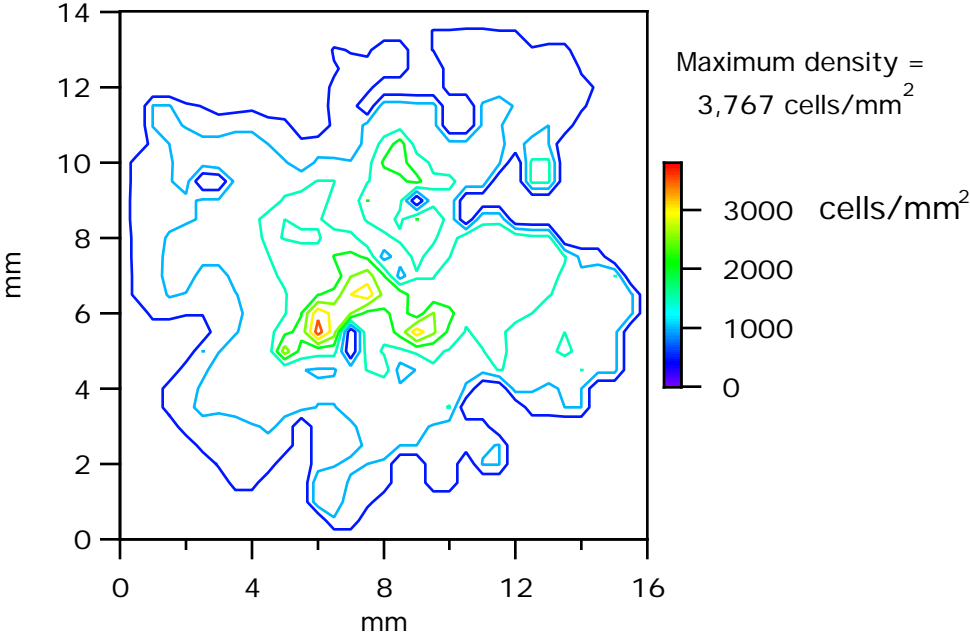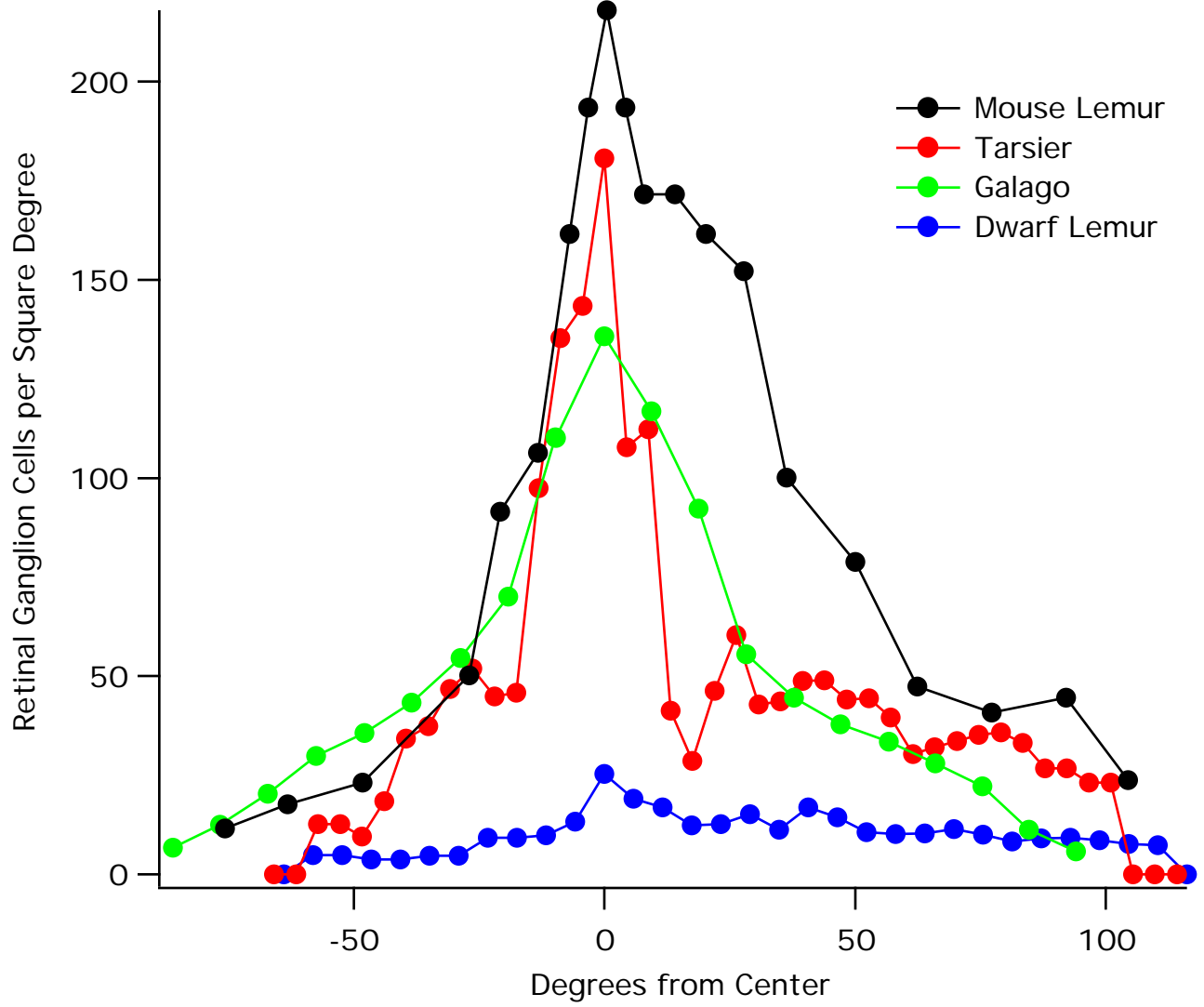
Figure 1

Tarsier

Maximum density =
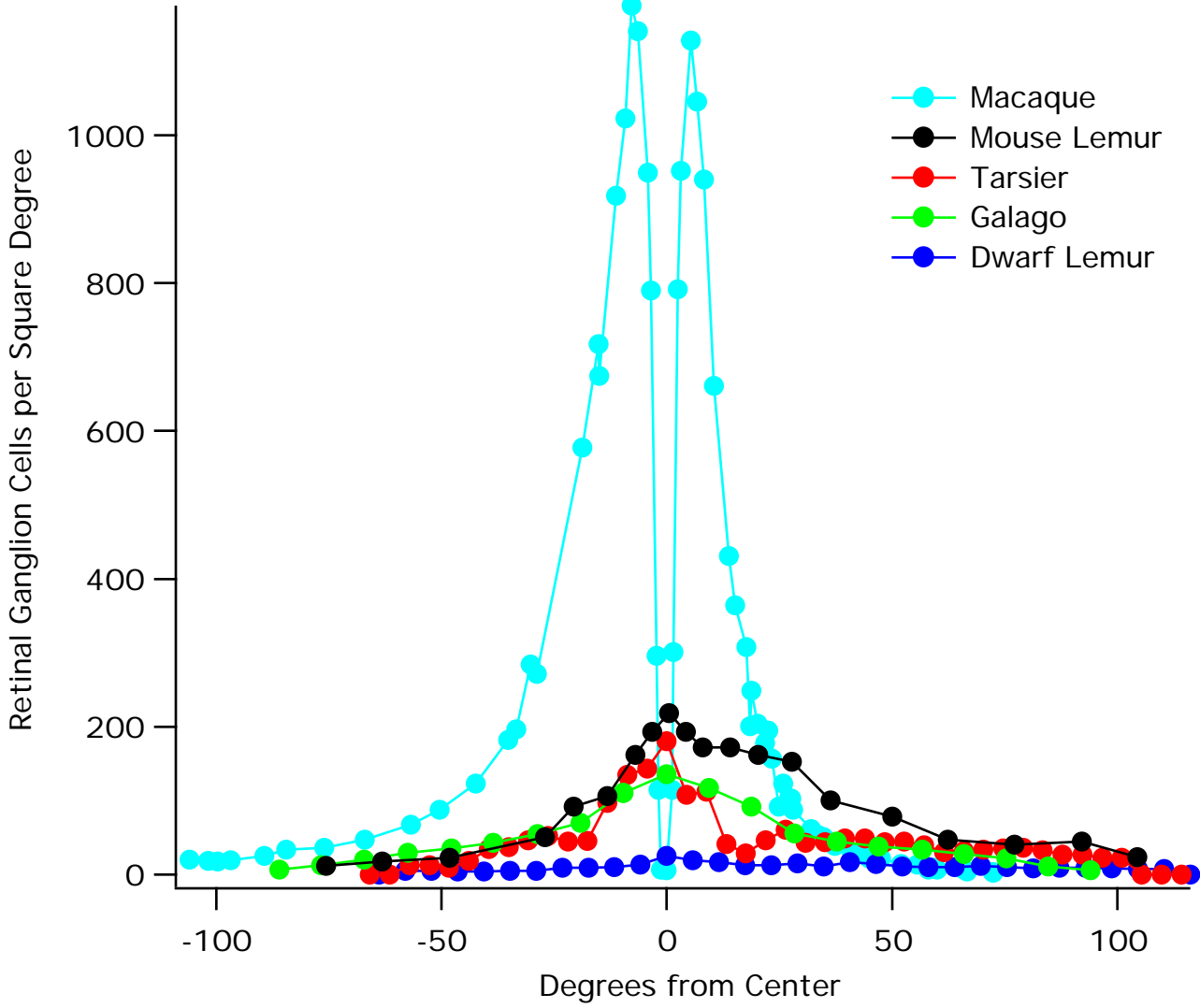13,267 cells/mm^2

12000 cells/mm^2
10000
8000
6000
4000
2000
0

Dwarf Lemur

Maximum density =
3,767 cells/mm^2

3000 cells/mm^2
2000
1000
0
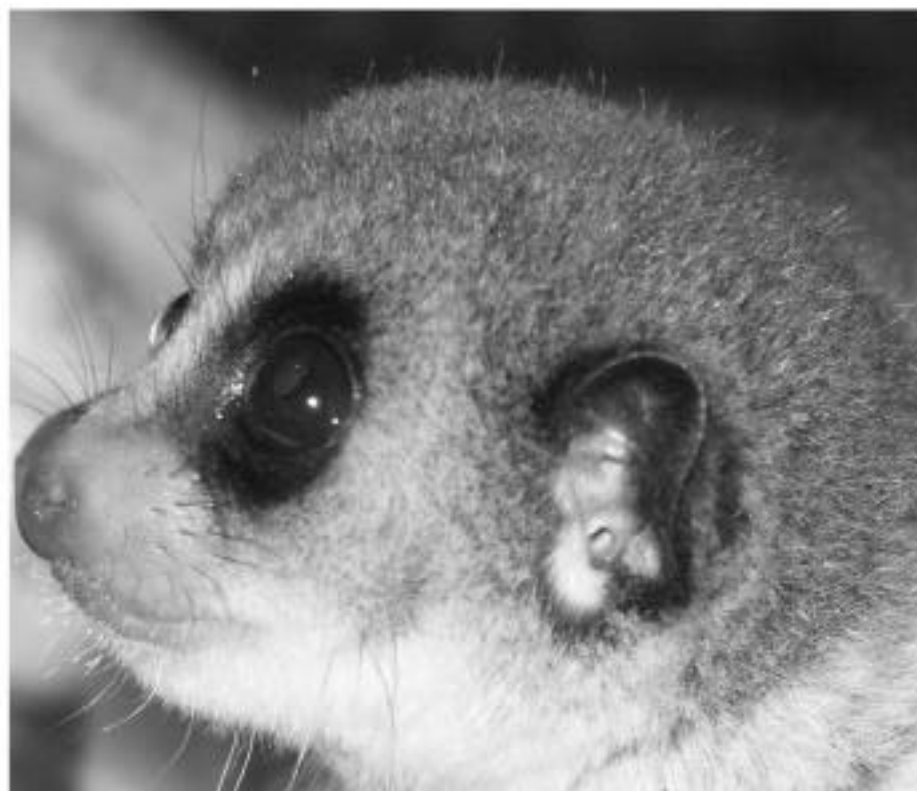
Figure 2

Figure 3

Figure 4
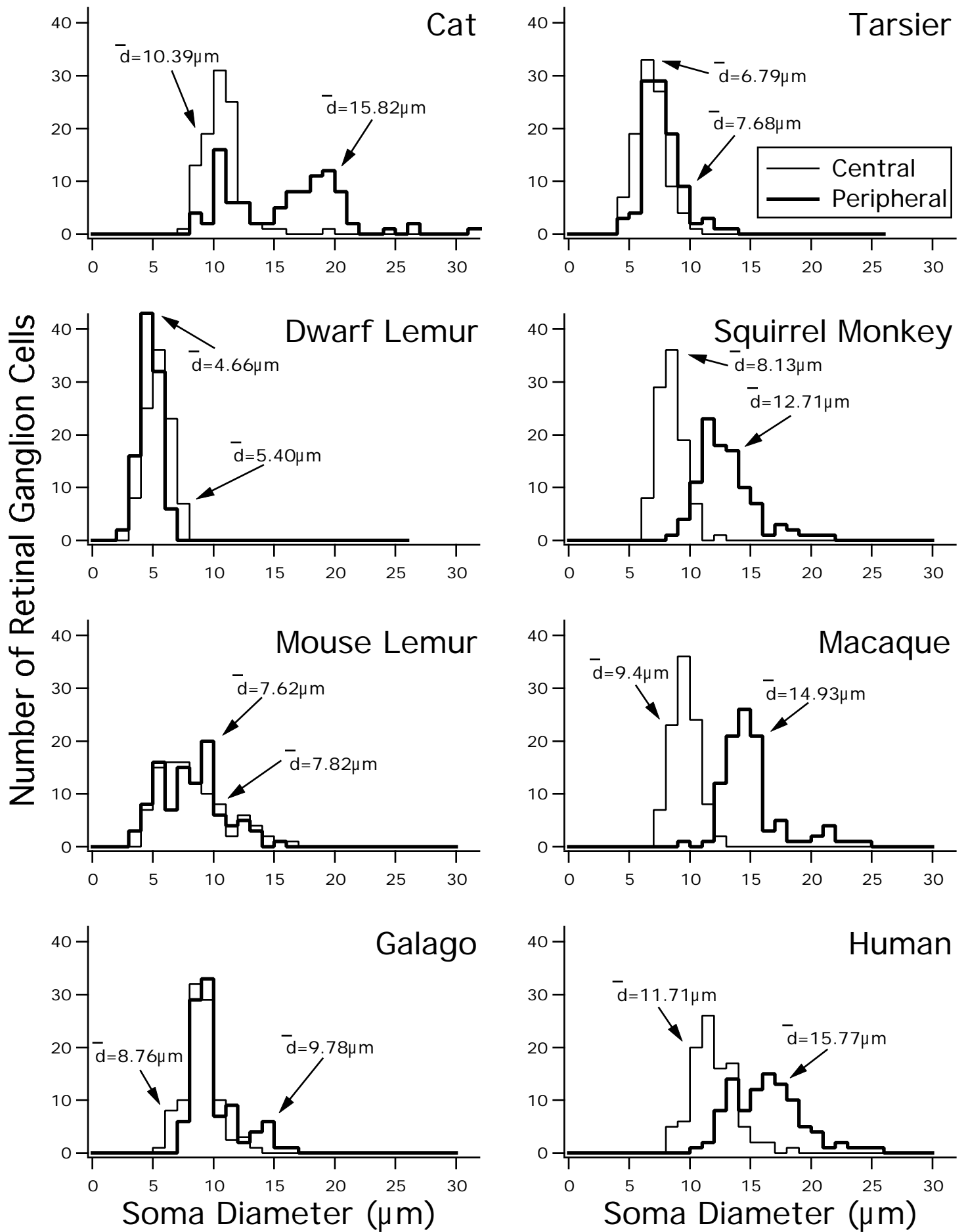
Figure 5

Mouse Lemur

Dwarf Lemur

Figure 6