Science Advances

AAAS

www.advances.sciencemag.org/cgi/content/full/1/7/e1500391/DC1

Supplementary Materials for

Why do animal eyes have pupils of different shapes?

Martin S. Banks, William W. Sprague, Jürgen Schmoll, Jared A. Q. Parnell, Gordon D. Love

Published 7 August 2015, *Sci. Adv.* **1**, e1500391 (2015)
DOI: 10.1126/sciadv.1500391

The PDF file includes:

Other Supplementary Material for this manuscript includes the following:
(available at www.advances.sciencemag.org/cgi/content/full/1/7/e1500391/DC1)

Supplementary Figures

Figure S1

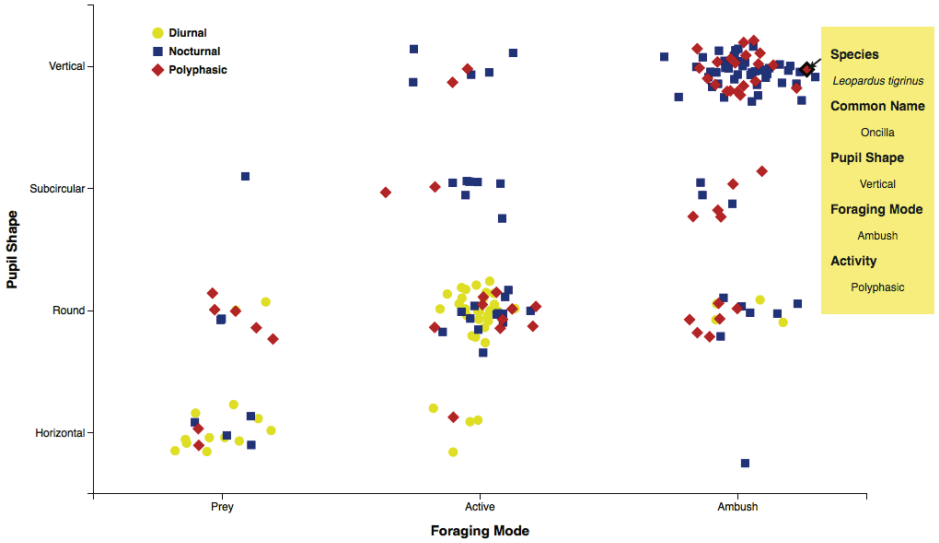


Figure S1. Interactive version of database. The graph above is a screen shot with low resolution. Go to http://pupils.bankslab.org/ to view the interactive version. Pupil shape (vertically elongated, sub-circular, circular, and horizontally elongated) is plotted as a function of foraging mode (herbivorous prey, active predator, and ambush predator). Each dot represents a species; yellow, red, and blue represent diurnal, polyphasic, and nocturnal, respectively. Diurnal, polyphasic, and nocturnal mean respectively primarily active during the day, active during the day and night, and active at night. The dots in each bin have been randomly offset to avoid overlap. Move the cursor over a dot and a panel appears stating the species, common name, pupil shape, foraging mode, and diel activity. Click on the dot and a web resource appears with pictures of the species.

Figure S2

Figure S2. Eye rotation with head pitch. Upper panels: Photographs of a horse with the head pitched down (left) and up (middle). Note that the eye rotates counter-clockwise from the left to the middle photograph thereby maintaining rough alignment with earth horizontal. The right panel is the same as the left but with the photograph rotated so that the head is in roughly the same orientation as in the middle panel. Note that the eye is no longer in the same orientation as in the middle panel again because it has rotated counter-clockwise when the animal pitched its head down to graze.

Movie S1. Video showing sheep changing head pitch. Again the eye undergoes a torsional movement such that the pupil's long axis maintains rough alignment with earth horizontal.

Table S1: List of species

Species	Common Name	Diel Activity	Foraging Mode	Pupil Shape
Acanthophis antarcticus	Common death adder	Polyphasic	Ambush	Vertical
Acanthophis hawkei	Not found	Polyphasic	Ambush	Vertical
Acanthophis praelongus	Not found	Nocturnal	Ambush	Vertical
Acanthophis pyrrhus	Desert death adder	Nocturnal	Ambush	Vertical
Acanthophis rugosus	Not found	Polyphasic	Ambush	Vertical
Acanthophis wellsi	Not found	Polyphasic	Ambush	Vertical
Acrochordus arafurae	Not found	Nocturnal	Active	Circular
Antaresia childreni	Children's python	Nocturnal	Ambush	Vertical
Antaresia maculosa	Not found	Nocturnal	Ambush	Vertical
Antaresia perthensis	Not found	Nocturnal	Ambush	Vertical
Antaresia stimsoni	Not found	Nocturnal	Ambush	Vertical
Aspidites melanocephalus	Not found	Nocturnal	Ambush	Vertical
Aspidites ramsayi	Not found	Nocturnal	Ambush	Vertical
Austrelaps ramsayi	Not found	Diurnal	Active	Circular
Austrelaps superbus	Lowland copperhead	Diurnal	Active	Circular
Cacophis harriettae	Not found	Nocturnal	Active	Subcircular
Demansia angusticeps	Not found	Diurnal	Active	Circular
Demansia calodera	Not found	Diurnal	Active	Circular
Demansia olivacea	Not found	Diurnal	Active	Circular
Demansia papuensis	Not found	Diurnal	Active	Circular
Demansia psammophis	Not found	Diurnal	Active	Circular
Demansia quaesitor	Not found	Diurnal	Active	Circular
Demansia rimicola	Not found	Diurnal	Active	Circular
Demansia rufescens	Not found	Diurnal	Active	Circular
Demansia simplex	Not found	Diurnal	Active	Circular
Demansia torquata	Not found	Diurnal	Active	Circular
Demansia vestigiata	Not found	Diurnal	Active	Circular
Dendrelaphis punctulata	Not found	Diurnal	Active	Circular
Denisonia devisi	Mud adder	Nocturnal	Ambush	Subcircular
Denisonia maculata	Ornamental snake	Nocturnal	Ambush	Subcircular
Drysdalia coronoides	White-lipped snake	Polyphasic	Active	Circular
Drysdalia mastersii	Not found	Nocturnal	Active	Circular
Drysdalia rhodogaster	Not found	Nocturnal	Active	Circular
Echiopsis curta	Not found	Nocturnal	Ambush	Subcircular
Elapognathus coronata	Not found	Polyphasic	Active	Circular
Elapognathus minor	Short-nosed snake	Nocturnal	Active	Circular
Furina barnardi	Not found	Nocturnal	Active	Subcircular
Furina diadema	Not found	Nocturnal	Active	Subcircular
Furina ornata	Not found	Nocturnal	Active	Subcircular
Furina tristis	Not found	Nocturnal	Active	Subcircular
Hemiaspis damelii	Not found	Nocturnal	Active	Circular
Hemiaspis signata	Not found	Polyphasic	Active	Circular
Hoplocephalus bitorquatus	Not found	Nocturnal	Ambush	Circular
Hoplocephalus bungaroides	Broad-headed snake	Nocturnal	Ambush	Circular
Hoplocephalus stephensii	Not found	Nocturnal	Ambush	Circular
Liasis fuscus	Not found	Nocturnal	Ambush	Vertical
Liasis olivaceus	Not found	Nocturnal	Ambush	Vertical

Morelia amethistina	Not found	Nocturnal	Ambush	Vertical
Morelia bredli	Not found	Nocturnal	Ambush	Vertical
Morelia carinata	Not found	Nocturnal	Ambush	Vertical
Morelia oenpelliensis	Not found	Nocturnal	Ambush	Vertical
Morelia spilota	Not found	Nocturnal	Ambush	Vertical
Morelia viridis	Not found	Nocturnal	Ambush	Vertical
Notechis scutatus	Tiger snake	Diurnal	Active	Circular
Oxyuranus microlepidotus	Inland taipan	Diurnal	Active	Circular
Oxyuranus scutellatus	Coastal taipan	Diurnal	Active	Circular
Pseudechis australis	Not found	Polyphasic	Active	Circular
Pseudechis butleri	Not found	Nocturnal	Active	Circular
Pseudechis colletti	Collett's snake	Nocturnal	Active	Circular
Pseudechis guttatus	Not found	Diurnal	Active	Circular
Pseudechis porphyriacus	Red-bellied black snake	Diurnal	Active	Circular
Pseudonaja nuchalis	Not found	Polyphasic	Active	Circular
Pseudonaja textilis	Eastern brown snake	Diurnal	Active	Circular
Simoselaps approximans	Not found	Nocturnal	Active	Circular
Simoselaps australis	Not found	Nocturnal	Active	Circular
Simoselaps bertholdi	Not found	Polyphasic	Active	Subcircular
Simoselaps fasciolatus	Not found	Nocturnal	Active	Subcircular
Simoselaps littoralis	Not found	Polyphasic	Active	Subcircular
Suta suta	Not found	Nocturnal	Active	Subcircular
Tropidechis carinatus	Not found	Polyphasic	Active	Circular
Tropidonophis mairii	Not found	Nocturnal	Active	Circular
Felis catus	Domestic cat	Polyphasic	Ambush	Vertical
Felis silvestris	Wildcat	Polyphasic	Ambush	Vertical
Felis libyca	African wildcat	Polyphasic	Ambush	Vertical
Felis bieti	Chinese mountain cat	Nocturnal	Ambush	Vertical
Felis margarita	Sand cat	Nocturnal	Ambush	Vertical
Felis nigripes	Blackfooted cat	Nocturnal	Ambush	Vertical
Felis chaus	Jungle cat	Polyphasic	Ambush	Vertical
Otocolobus manul	Pallas' cat	Polyphasic	Ambush	Circular
Prionailurus rubiginosus	Rusty-spotted cat	Nocturnal	Ambush	Vertical
Prionailurus bengalensis	Leopard cat	Polyphasic	Ambush	Vertical
Prionailurus viverrinus	Fishing cat	Nocturnal	Ambush	Vertical
Prionailurus planiceps	Flat-headed cat	Polyphasic	Ambush	Vertical
Puma concolor	Cougar	Nocturnal	Ambush	Circular
Puma yagouaroundi	Jaguarundi	Diurnal	Ambush	Circular
Acinonyx jubatus	Cheetah	Diurnal	Active	Circular
Lynx pardinus	Iberian lynx	Polyphasic	Ambush	Subcircular
Lynx lynx	Lynx	Polyphasic	Ambush	Subcircular
Lynx canadensis	Canada lynx	Polyphasic	Ambush	Subcircular
Lynx rufus	Bobcat	Polyphasic	Ambush	Subcircular
Leopardus pardalis	Ocelot	Nocturnal	Ambush	Vertical
Leopardus wiedii	Margay	Nocturnal	Ambush	Vertical
Leopardus braccatus	Pantanal cat	Polyphasic	Ambush	Vertical
Leopardus colocolo	Colocolo	Polyphasic	Ambush	Vertical
Leopardus geoffroyi	Geoffroy's cat	Nocturnal	Ambush	Vertical
Leopardus guigna	Kodkod	Polyphasic	Ambush	Vertical
Leopardus tigrinus	Oncilla	Polyphasic	Ambush	Vertical

Caracal caracal	Caracal	Polyphasic	Ambush	Subcircular
Caracal aurata	African golden cat	Polyphasic	Ambush	Vertical
Caracal serval	Serval	Nocturnal	Ambush	Vertical
Pardofelis temminckii	Asian golden cat	Diurnal	Ambush	Circular
Pardofelis marmorata	Marbled cat	Nocturnal	Ambush	Vertical
Panthera leo	Lion	Nocturnal	Ambush	Circular
Panthera onca	Jaguar	Polyphasic	Ambush	Circular
Panthera pardus	Leopard	Polyphasic	Ambush	Circular
Panthera tigris	Tiger	Nocturnal	Ambush	Circular
Panthera uncia	Snow leopard	Polyphasic	Ambush	Circular
Neofelis nebulosa	Clouded leopard	Nocturnal	Ambush	Vertical
Crocuta crocuta	Spotted hyena	Nocturnal	Active	Vertical
Genetta genetta	Common genet	Nocturnal	Ambush	Vertical
Canis lupus	Gray wolf	Nocturnal	Active	Circular
Canis latrans	Coyote	Diurnal	Active	Circular
Canis simensis	Ethiopian wolf	Polyphasic	Active	Circular
Canis aureus	Golden jackal	Polyphasic	Active	Circular
Canis adustus	Side-striped jackal	Nocturnal	Active	Circular
Canis mesomelas	Black-backed jackal	Nocturnal	Active	Circular
Cuon alpinus	Dhole	Diurnal	Active	Circular
Lycaon pictus	African wild dog	Polyphasic	Active	Circular
Cerdocyon thous	Crab-eating fox	Nocturnal	Ambush	Vertical
Lycalopex culpaeus	Culpeo	Polyphasic	Ambush	Vertical
Lycalopex fulvipes	Darwin's fox	Polyphasic	Active	Vertical
Lycalopex griseus	South american gray fox	Nocturnal	Ambush	Vertical
Lycalopex gymnocercus	Pampas fox	Nocturnal	Ambush	Vertical
Lycalopex sechurae	Sechuran fox	Nocturnal	Ambush	Vertical
Lycalopex vetulus	Hoary fox	Nocturnal	Active	Vertical
Chrysocyon brachyurus	Maned wolf	Polyphasic	Ambush	Circular
Speothos venaticus	Bush dog	Diurnal	Active	Circular
Vulpes lagopus	Arctic fox	Polyphasic	Ambush	Vertical
Vulpes vulpes	Red fox	Polyphasic	Ambush	Vertical
Vulpes velox	Swift fox	Nocturnal	Ambush	Vertical
Vulpes macrotis	Kit fox	Nocturnal	Ambush	Vertical
Vulpes corsac	Corsac fox	Nocturnal	Ambush	Vertical
Vulpes chama	Chama fox	Nocturnal	Ambush	Vertical
Vulpes pallida	Pale fox	Nocturnal	Ambush	Vertical
Vulpes bengalensis	Bengal fox	Polyphasic	Ambush	Vertical
Vulpes cana	Blanfords fox	Nocturnal	Ambush	Vertical
Vulpes rueppelli	Rueppell's fox	Nocturnal	Ambush	Vertical
Vulpes zerda	Fennec fox	Nocturnal	Active	Vertical
Urocyon cinereoargenteus	Gray fox	Nocturnal	Ambush	Vertical
Urocyon littoralis	Island fox	Polyphasic	Active	Vertical
Otocyon megalotis	Bat-eared fox	Nocturnal	Active	Vertical
Nyctereutes procyonoides	Raccoon dog	Nocturnal	Ambush	Vertical
Bassaricyon gabbi	Northern olingo	Nocturnal	Herbivorous	Horizontal
Cryptoprocta ferox	Fossa	Polyphasic	Ambush	Vertical
Fossa fossana	Malagasy civet	Nocturnal	Active	Vertical
Galidia elegans	Ring-tailed mongoose	Diurnal	Active	Horizontal
Suricata suricatta	Meerkat	Diurnal	Active	Horizontal

Herpestes auropunctatus	Small asian mongoose	Diurnal	Active	Horizontal
Helogale parvula	Common dwarf mongoose	Diurnal	Active	Horizontal
Cynictis penicillata	Yellow mongoose	Polyphasic	Active	Horizontal
Paracynictis selousi	Selous' mongoose	Nocturnal	Ambush	Horizontal
Ailurus fulgens	Red panda	Polyphasic	Herbivorous	Subcircular
Camelus bactrianus	Bactrian camel	Diurnal	Herbivorous	Horizontal
Camelus dromedarius	Dromedary	Diurnal	Herbivorous	Horizontal
Lama glama	Llama	Diurnal	Herbivorous	Horizontal
Lama guanicoe	Guanaco	Diurnal	Herbivorous	Horizontal
Vicugna pacos	Alpaca	Diurnal	Herbivorous	Horizontal
Vicugna vicugna	Vicuna	Diurnal	Herbivorous	Horizontal
Hippopotamus amphibius	Hippopotamus	Nocturnal	Herbivorous	Horizontal
Hexaprotodon liberiensis	Pygmy hippopotamus	Nocturnal	Herbivorous	Horizontal
Equus ferus	Horse	Diurnal	Herbivorous	Horizontal
Equus africanus	Donkey	Diurnal	Herbivorous	Horizontal
Equus quaga	Plains zebra	Diurnal	Herbivorous	Horizontal
Okapia johnstoni	Okapi	Diurnal	Herbivorous	Horizontal
Giraffa camelopardalis	Giraffe	Polyphasic	Herbivorous	Horizontal
Odocoileus virginianus	White-tailed deer	Polyphasic	Herbivorous	Horizontal
Gazella dorcas	Dorcas gazelle	Nocturnal	Herbivorous	Horizontal
Tapirus terrestris	Brazilian tapir	Polyphasic	Herbivorous	Circular
Tapirus indicus	Malayan tapir	Nocturnal	Herbivorous	Circular
Tapirus bairdii	Baird's tapir	Nocturnal	Herbivorous	Circular
Tapirus pinchaque	Mountain tapir	Polyphasic	Herbivorous	Circular
Ceratotherium simum	White rhinoceros	Polyphasic	Herbivorous	Circular
Diceros bicornis	Black rhinoceros	Polyphasic	Herbivorous	Circular
Rhinoceros unicornis	Indian rhinoceros	Polyphasic	Herbivorous	Circular
Loxodonta africana	African elephant	Diurnal	Herbivorous	Circular
Elephas maximus	Asian elephant	Diurnal	Herbivorous	Circular
Connochaetes taurinus	Common wildebeest	Diurnal	Herbivorous	Horizontal
Bison Bison	American bison	Diurnal	Herbivorous	Horizontal
Bison Bonasus	European bison	Diurnal	Herbivorous	Horizontal
Litocranius walleri	Gerenuk	Diurnal	Herbivorous	Horizontal
Ourebia ourebi	Oribi	Polyphasic	Herbivorous	Horizontal
Raphicerus campestris	Steenbok	Diurnal	Herbivorous	Horizontal
Procapra gutturosa	Mongolian gazelle	Polyphasic	Herbivorous	Horizontal
Oreotragus oreotragus	Klipspringer	Polyphasic	Herbivorous	Horizontal
Redunca redunca	Bohor reedbuck	Nocturnal	Herbivorous	Horizontal
Pelea capreolus	Grey rhebok	Diurnal	Herbivorous	Horizontal
Cervus elaphus	Red deer	Polyphasic	Herbivorous	Horizontal
Pudu mephistophiles	Pudu	Polyphasic	Herbivorous	Horizontal
Mazama gouazoubira	Gray brocket	Polyphasic	Herbivorous	Horizontal
Tragulus napu	Greater mouse-deer	Nocturnal	Herbivorous	Horizontal
Hyemoschus aquaticus	Water chevrotain	Nocturnal	Herbivorous	Horizontal
Tragulus javanicus	Java mouse-deer	Nocturnal	Herbivorous	Horizontal
Procavia capensis	Rock hyrax	Polyphasic	Herbivorous	Horizontal
Heterohyrax brucei	Yellow-spotted rock hyrax	Diurnal	Herbivorous	Horizontal
Equus zebra	Mountain zebra	Diurnal	Herbivorous	Horizontal
Equus hemionus	Onager	Polyphasic	Herbivorous	Horizontal
Cynomys ludovicianus	Black-tailed prairie dog	Diurnal	Herbivorous	Circular

Tamias striatus	Eastern chipmunk	Diurnal	Herbivorous	Circular
Sus scrofa	Wild boar	Polyphasic	Herbivorous	Circular
Sus barbatus	Bornean bearded pig	Diurnal	Herbivorous	Circular
Chrysemys picta	Painted turtle	Diurnal	Active	Circular
Pseudemys alabamensis	Alabama red-bellied cooter	Diurnal	Active	Circular
Alligator mississippiensis	American alligator	Nocturnal	Ambush	Vertical
Crocodylus porosus	Saltwater crocodile	Nocturnal	Ambush	Vertical
Sphenodon punctatus	Northern tuatara	Nocturnal	Ambush	Vertical
Gekko gecko	Tokay gecko	Nocturnal	Ambush	Vertical
Iguana Iguana	Green iguana	Nocturnal	Herbivorous	Subcircular
Xenosaurus Grandis	Knob-scaled lizard	Diurnal	Ambush	Circular
Agkistrodon piscivorus	Cottonmouth	Polyphasic	Ambush	Vertical
Coluber constrictor	Yellow-bellied racer	Diurnal	Ambush	Circular
Boa constrictor	Boa constrictor	Nocturnal	Ambush	Vertical
Pituophis catenifer	Western gopher snake	Diurnal	Active	Circular
Sistrurus catenatus	Massasauga rattlesnake	Polyphasic	Ambush	Vertical
Thamnophis sirtalis	Common garter snake	Polyphasic	Ambush	Circular

Table S2: Number of species in each category

	Pupil Shape	*horizontal*	*circular*	*sub-circular*	*vertical*	*all*
Activity	**Foraging Mode**					
diurnal	*herbivorous*	18	5	0	0	23
	active	4	27	0	0	31
	ambush	0	4	0	0	4
polyphasic	*herbivorous*	10	6	1	0	17
	active	1	9	2	2	14
	ambush	0	6	5	22	33
nocturnal	*herbivorous*	8	2	1	0	11
	active	0	13	7	5	25
	ambush	1	6	3	46	56
all		42	78	19	75	214

Table S2. The number of species in each category, where the categories are diel activity, foraging mode, and pupil shape.

Table S3. Relative-risk ratios with horizontal pupil as reference

		Pupil Shape	*circular*	*sub-circular*	*vertical*
Constant	**Subset**	**Comparison**			
Activity	*diurnal*	*herbivorous to active*	24.3	4.50	4.50
		active to ambush	5926	40001	40001
	polyphasic	*herbivorous to active*	15	20	2.00E+05
		active to ambush	6667	25002	1.10E+05
	nocturnal	*herbivorous to active*	5.20E+05	5.60E+05	4.00E+09
		active to ambush	0	0	0
Foraging Mode	*herbivorous*	*diurnal to polyphasic*	2.16	18002	1.80
		polyphasic to nocturnal	0.417	1.25	1.25
	active	*diurnal to polyphasic*	1.33	79998	79998
		polyphasic to nocturnal	14446	35002	25002
	ambush	*diurnal to polyphasic*	1.50	50001	2.20E+05
		polyphasic to nocturnal	0	0	0

Table S3. Relative-risk ratios with horizontal pupil as the reference. Relative risk (*RR*) is a measure of how likely a particular pupil shape is relative to horizontally elongated:

$$RR(PupilShape, a_i, f_j) = \frac{p(PupilShape \mid a_i, f_j)}{p(HorizPupil \mid a_i, f_j)}$$

where a_i is the *i*-th diel activity (*i* = 1 is diurnal, 2 polyphasic, 3 noctural) and f_j is the *j*-th foraging mode (1 is prey, 2 active predator, 3 ambush predator). The denominator was sometimes zero. To avoid divide by zero, we added an increment of 10^{-4} to the numerator and denominator. Relative-risk ratio (*RRR*) is a measure of how the probability of having a particular pupil shape changes as activity or foraging mode is incremented from one value to the next. When incrementing foraging mode, the ratio is:

$$RRR(PupilShape, a_i, f_{j+1}) = \frac{RR(PupilShape, a_i, f_{j+1})}{RR(PupilShape, a_i, f_j)}$$

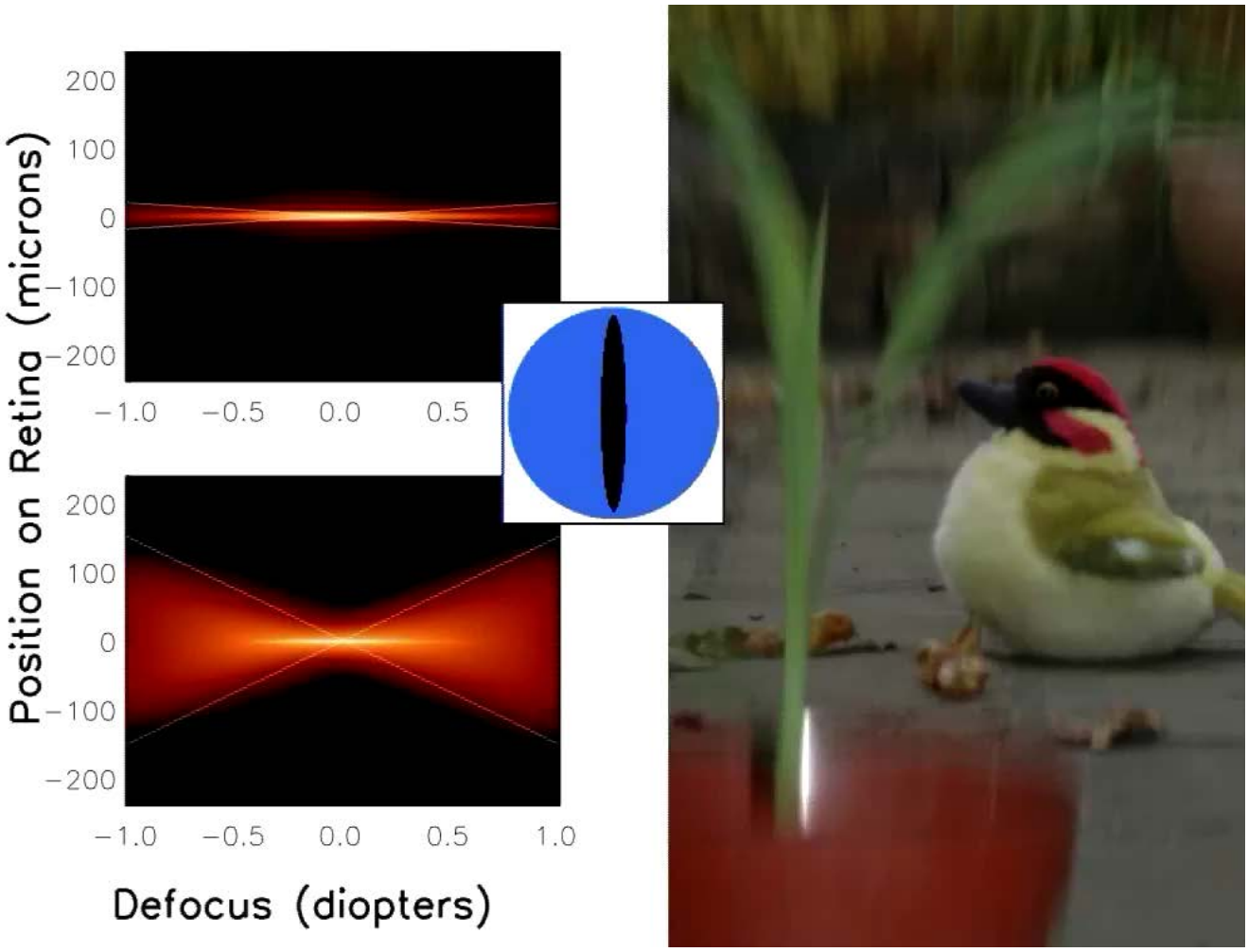
The values in the table are RRR. The pink boxes indicate values that were significantly affected by the increment of 10^{-4}. They are all cases where the relative-risk ratio is much greater than 1.

Table S4: Niche and pupil shape for Felids and Canids

		Felids		**Canids**	
Sub-circular with	Polyphasic with	Activity	Foraging	Activity	Foraging
circular	diurnal	p<0.07	p=0.722	p<0.04	p<0.0001
circular	nocturnal	p<0.03	p=0.722	p<0.005	p<0.0001
vertical slit	diurnal	p=0.239	p<0.14	p<0.04	p<0.0001
vertical slit	nocturnal	p<0.001	p<0.14	p<0.006	p<0.0001

Table S4. Statistical significance of relationships between ecological niche and pupil shape for Felids and Canids with pylogenetic relatedness taken into account. The data from the Felid and Canid families for which ancestral trees were known were subjected to Pagel's correlation analysis (*52-54*). There were three pupil values (circular, sub-circular, and vertical), three diel activities (diurnal, polyphasic, and nocturnal), and two foraging modes (active predator and ambush predator). The categories with three values were binarized for the analysis. We therefore created two pairs for the two traits with three values: for pupils, sub-circular with circular and sub-circular with vertical slit; for activity, polyphasic with diurnal and polyphasic with nocturnal. Those yielded four combinations of pairings that yielded in turn four significance values as shown above.

Movie S2



Movie S2. Video showing changes in image properties for different amounts of defocus and pupil orientations. Left: Cross-sections of PSFs as a function of focal distance for an eye with an elongated pupil (major axis of 12mm, minor axis of 1.5mm). The orientation of the pupil rotates from vertical to horizontal and back again. The object was white. The PSFs incorporate diffraction and chromatic aberration. Log amplitude is represented by brightness, brighter corresponding to high amplitude. Amplitudes lower than 10^{-3} of the peak amplitude have been clipped. The upper panel shows horizontal cross-sections (relevant for imaging vertical contours) and the lower panel shows vertical sections (for imaging horizontals). The faint dashed white lines are from Eqns 3 and 4 and show that the equations are a good approximation to the PSF cross-sections. Right: Photograph of a depth-varying scene taken with a camera with a slit aperture that rotates from vertical to horizontal and back. The camera was focused on the toy bird. Objects nearer and farther than the bird are blurred, but the direction of greatest blur depends strongly on the orientation of the aperture. For example, when the aperture is vertical, near and far vertical contours are sharper than horizontal contours. When the aperture is horizontal, the opposite holds.