Understanding the retinal basis of vision across species

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Abstract | The vertebrate retina first evolved some 500 million years ago in ancestral marine chordates. Since then, the eyes of different species have been tuned to best support their unique visuoeccological lifestyles. Visual specializations in eye designs, large-scale inhomogeneities across the retinal surface and local circuit motifs mean that all species’ retinas are unique. Computational theories, such as the efficient coding hypothesis, have come a long way towards an explanation of the basic features of retinal organization and function; however, they cannot explain the full extent of retinal diversity within and across species. To build a truly general understanding of vertebrate vision and the retina’s computational purpose, it is therefore important to more quantitatively relate different species’ retinal functions to their specific natural environments and behavioural requirements. Ultimately, the goal of such efforts should be to build up to a more general theory of vision.

Animals use vision to navigate their vastly different environments, whether they are deep-water marine species communicating with bioluminescent displays or birds scanning their environment for prey from high up in the air. The eyes of each animal are exquisitely adapted to allow it to gather the information from its environment that is needed for its survival and procreation. Many adaptations to the visual properties of specific environments are evident in the structure and function of the retinal circuits of particular species (for example, the ratio of rod to cone photoreceptors often depends on the time of day that an animal is most active). However, the comparative studies that are necessary to understand more generally how such adaptations relate to the ecological context of different species and to ultimately arrive at a truly general theory of vision will require detailed knowledge of retinal circuit structure and function across species. Such knowledge may also have a broader impact: it is likely that studies of other neural circuits will profit from a deep understanding of the circuits, computational strategies and coding principles that operate in the retina.

Recent studies have started to reveal the extent to which the retinas of some species are adapted to the statistics of the visual information that they receive, such as the distribution of spatial, temporal and spectral information, as well as to their specific behavioural demands. These studies have demonstrated that retinal circuits may differ even between closely related species. Furthermore, even within a single species, visual input statistics and behavioural demands can be very different across the visual field, and studies have shown that retinal circuits also strongly vary across the retinal surface. These considerations have sparked a new wave of studies probing retinal circuit organization in the context of its function, assessed using natural rather than artificial inputs.

Here, we review the latest developments in this field, with an emphasis on the discovery of species differences and functional distinctions across the retina. We consider what these findings mean for long-held theoretical notions that the retina is adapted to encode the environment of a species efficiently (the so-called efficient coding hypothesis). Finally, we show how current technological developments are starting to provide us with important insights into the ways in which retinal function is constantly retuned to meet ever-changing visual demands.

Retinal organization and diversity

Retinal cell types and their function. The vertebrate retina comprises five classes of neurons that are arranged into three nuclear and two synaptic layers (Fig. 1). In the first synaptic layer, the outer plexiform layer, photoreceptors (comprising rods and cones) release glutamate onto the dendrites of bipolar cells and horizontal cells. Horizontal cells connect laterally to provide feedback and feedforward signals to both photoreceptors and bipolar cells (reviewed in Refs 16,17). Bipolar cells in turn project to the second synaptic layer in the inner retina, the inner plexiform layer. There they contact dendritic processes of amacrine cells and retinal ganglion cells (RGCs) (reviewed in Ref. 18). Like horizontal cells, amacrine cells connect laterally but they also connect across...
Fig. 1  Retinal composition across species. a  The cell types present in the retinas of several contemporary vertebrate species (shown as transverse sections). For comparison, the plexiform (synaptic) layers (the outer plexiform layer (OPL) and inner plexiform layer (IPL)) are demarcated alongside each image. Example morphologies of different retinal neuron classes are highlighted. The schematics were created on the basis of data from the following references: mouse191, human192, chicken193, zebrafish adult194, zebrafish larva195 and salamander196. b  Graph showing the total number of retinal ganglion cells (RGCs) present in the retinas of 105 different species versus their retinal surface area. For comparison, isodensity lines (indicating constant densities) are shown as dashed lines.

The graph was created using data from reFs1,7,15–17,21–23,26,27. Species were selected for inclusion on the basis of the availability of quantitative RGC information for those species in the literature. For each clade for which such information was available, we selected one to four articles for inclusion on the basis of how readily the data could be extracted from a given study. Naturally, this list is therefore non-exhaustive. Detailed information is available in Supplementary Table 1. It can be seen that (in general) larger eyes comprise proportionally more RGCs. However, for any given eye size, RGC numbers across species vary by more than two orders of magnitude. Colours are used to distinguish between major clades of the vertebrate lineage. AC, amacrine cell; BC, bipolar cell; HC, horizontal cell.

Centre–surround receptive fields
An area in visual space or on the retinal surface where presentation of a stimulus in the receptive field centre excites the neuron and presentation of the same stimulus in the receptive field surround (a typically larger and concentric area) instead suppresses the neuron.

The mouse retina as a benchmark. The fundamental retina blueprint outlined in the previous section is highly conserved across species, as are several aspects of its general functional organization. For example, neurons present at different circuit levels within vertebrate retinas consistently use centre–surround receptive fields28 and rely heavily — though not exclusively23–35 — on analogue processing of visual information, before its arrival at the dendrites of RGCs (reviewed in REFS36). Nonetheless, there are only a few species for which we have a detailed understanding of the anatomical and functional properties of individual retinal circuits, the most notable of
which is the mouse (reviewed in REF.\textsuperscript{37}). In addition to detailed studies on specific circuits, such as the pathway that feeds rod photoreceptor signals into cone photoreceptor circuits\textsuperscript{8} or the circuits that compute the direction of motion\textsuperscript{1}, a near-complete parts list (that is, an account of all of the neuron types that make up a given class of neuron) is available for most retinal cell classes in the mouse\textsuperscript{7,40–47}. From these studies we know that, in the mouse retina, the signals of three photoreceptor types and one horizontal cell type are distributed to a set of 14 bipolar cell types, modulated by some 40 amacrine cell types and relayed to the brain via 40–50 types of RGCs. This rich knowledge of the mouse retina’s neuronal building blocks has allowed targeted studies into circuit mechanisms that offer a key to understanding the underlying computational principles of the retina and — perhaps — insights into the functional purpose of the retina. For example, we now know that in the mouse retina there are at least eight types of direction-selective RGC\textsuperscript{48,49}, at least four types of orientation-selective RGC\textsuperscript{50–53}, two pairs of ‘alpha’ RGCs (characterized by their large receptive fields)\textsuperscript{54,55}, four ‘ultra-small-field’ RGCs\textsuperscript{49,55–56}, a wealth of RGCs that encode visual features such as image blur\textsuperscript{57}, looming\textsuperscript{58} and uniformity\textsuperscript{59} (often referred to as being suppressed by contrast)\textsuperscript{60} and several intrinsically photosensitive RGCs\textsuperscript{61}. Similarly detailed functional characterizations of key amacrine cells are available: these include the AII and A17 amacrine cells, which shape rod pathway signalling\textsuperscript{32,59}, and the more recently described VGLUT3-expressing amacrine cells, which act as a central hub for motion-sensitive RGC circuits\textsuperscript{62–65}. While our knowledge of most amacrine cell types is still incomplete\textsuperscript{50,51}, the aforementioned examples reveal circuit motifs that underpin a wide range of retinal functions. Thus, the findings of anatomical, functional, computational and genetic studies in mice are beginning to converge into the first coherent picture of a mammalian retina.

What does this accumulated knowledge tell us about the fundamental principles that govern animal vision? After all, the mouse is but one species, with its own set of species-specific needs, behavioural repertoires and evolutionary history. If we ever were to truly understand this specific retina (and despite the rosy picture painted above, we are still a long way from such an understanding), what might this teach us about vision in other species, including our own? To gain insight into the general principles of retinal function\textsuperscript{6}, it will be critical to build a better understanding of which aspects of the mouse retina reflect general circuit principles and which are particular to mice, mammals or species with a similar visuoecological niche. For this, we need to study the retinas of at least a handful of other species at similar depth.

Structural and functional retinal diversity. The retinas of all sighted vertebrates on Earth today stem from an ancient circuit blueprint that first evolved in early marine vertebrates more than 500 million years ago (BOX 1). Since then, the retinas of different species have therefore had up to 500 million years to adjust their structure and function to species’ needs. Indeed, starting with the work of Ramon y Cajal\textsuperscript{39} and contemporaries, a more than 120-year history of comparative anatomy reveals a sizable diversity of retinal layouts across contemporary vertebrate eyes (FIG. 1a). Some retinas — such as those of salamanders — appear structurally simple, with small numbers of large cell bodies flanking relatively thin synaptic layers\textsuperscript{7}. Other retinas appear to be rather complex, such as those of birds, with thick synaptic plexi and stacks of cell bodies in every nuclear layer\textsuperscript{7–10}. This diversity prompts us to ask what each animal’s eyes tell its brain\textsuperscript{74}: do all retinas transmit the same amount and kind of information to the brain or does the apparent ‘complexity’ of a species’ retina reflect the type and complexity of the information that it transmits? Here, retinal complexity is defined by features that include the density and interconnectedness of its neural processes, while ‘computational complexity’ refers to the extent to which visual information is preprocessed before it leaves the retina, as well as its functional diversity.

The amount of information that can be passed from the retina to the brain per unit of retinal surface area might be assumed to approximately scale with RGC density, which has been measured for hundreds of vertebrates\textsuperscript{8} (Supplementary Table 1). A preliminary overview of the information on RGC density that is currently available in the literature (FIG. 1b) raises the notion that animals belonging to different clades tend to exhibit different approximate RGC densities. For example in our limited sample, most birds and reptiles appear to feature higher RGC densities than most mammals or sharks\textsuperscript{8}. It is also clear that animals with vastly different eye sizes can have similar overall numbers of RGCs. For example, in our limited sample, most birds and reptiles appear to feature higher RGC densities than most mammals or sharks\textsuperscript{8}. On the other hand, the sizes of mouse and hummingbird eyes are similar, yet mice have almost an order of magnitude fewer RGCs\textsuperscript{57}.

Does the increased RGC density of the retinas of certain species (such as the hummingbird) make them more computationally complex than the retinas of other species (such as mice and humans) and thus able to transmit more information to the brain? The answer is that we do not yet know: a high RGC density could indeed be a consequence of higher computational complexity as it could allow more parallel feature processing channels; however, it may simply relate to a higher spatial acuity as a result of a higher RGC density per processing channel. These two factors are fundamentally entwined in any given retina, meaning that examining RGC densities alone is unlikely to yield a satisfactory answer. Instead, it will be vital to develop a deeper understanding of the functional, structural and genetic diversity of different animals’ retinal outputs.

What drives retinal diversity? It has been posited that the dumber the animal, the smarter the retina\textsuperscript{19,29}. In support of this idea, primate vision heavily relies on the midget pathway, perhaps one of the simplest of all retinal circuits. In this pathway, which is numerically dominant across the primate retina\textsuperscript{20}, signals generated by photoreceptors are more or less directly relayed via bipolar cells to RGCs and there are few inner retinal inhibitory connections (a hallmark
Box 1 | The evolution of the vertebrate retina

At the end of the Cambrian explosion, the three-layered duplex retina common to all classes of jawed vertebrates—which include cartilaginous and bony fish, amphibians, reptiles, birds and mammals—evolved over a period of less than 100 million years (see the figure showing the approximate timeline of vertebrate retinal evolution, based on data reviewed in Ref. 179). What initially was likely to have been a mere collection of non-image-forming, ciliated photoreceptors evolved into a simple, two-layer proto-retina about 550 million years ago (mya), as can still be seen today in a ‘living fossil’, the hagfish170,171. These earliest jawless vertebrates (of the class Myxinida) diverged from the jawed vertebrate lineage 530 mya and their lensless eyes, which are buried beneath a transparent layer of skin, mostly serve circadian functions and for basic light detection172. Around the same time, fossil records show that two other groups of early stem-vertebrates, those of the genera Metaspriggina174 and Haikouichthys175,176, emerged: like hagfish, these soft-bodied fish had camera-type eyes (that is, eyes that use a single lens, presumably to focus light onto a retina lining the back of the eyeball) but, at least macroscopically, their eyes were already remarkably reminiscent of those of small contemporary teleosts such as zebrafish177.

Did these animals feature the earliest image-forming retinas in vertebrates? Here, another group of living fossils, the lampreys (Cephalaspidomorphi), provide important insights. Lampreys diverged from our lineage ~30 million years after hagfish and were equipped with both camera-type eyes with a lens and, importantly, interneurons (bipolar cells)171 that connected a diverse set of ciliated photoreceptors to the retina’s output neurons, the retinal ganglion cells (RGCs)172,173. This suggests that the three-layered retina evolved between 530 and 500 mya and may thus have been present in stem vertebrates such as members of the genera Metaspriggina and Haikouichthys. This early retina still may have lacked rod photoreceptors and their postsynaptic circuits171,177, however, it is likely that such rod pathways emerged shortly after173.

In parallel, the contractile iris and muscles attached to the lens to allow for accommodation evolved, as seen in modern-day sharks, rays and skates (of the class Chondrichthyes), which diverged from our lineage at least ~420 mya (REFS 178,179). Taken together, these findings show that the major features of a blueprint for the vertebrate retina are truly ancient.

Deep neural networks

Machine learning algorithms consisting of many processing layers that combine linear operations such as convolutions with non-linear stages such as rectification. Such networks have been shown to achieve human-like performance in many visual tasks.

of more complex retinal circuits180. Rodents, on the other hand, lack an obvious midget pathway and instead feature a more balanced mix of different types of retinal circuits180. Finally, zebrafish feature a retina with an RGC density that rivals that of birds181,182, and in which bipolar cells exhibit a number of complex functional properties that have traditionally been associated with RGCs in mammalian retinas (discussed later). Because half of all the central neurons of larval zebrafish are located in their eyes’, their visual processing is heavily ‘front-loaded’ and it can be hypothesized that this necessitates a more sophisticated output from the eye in this species than in other species. Indeed, a similar concept was famously put forward in Lettin’s‘bug detector’ neurons of the frog retina183. In further support of this idea, a recent computational study that used deep neural networks with a bottleneck architecture to model visual pathways showed that, in order to maintain coding accuracy, a more ‘complex’ retina is required to compensate for a ‘simpler’ brain (that is, one with fewer non-linear processing layers)184.

However, the proposed inverse relationship between retinal circuit complexity and brain processing capacity breaks down when vertebrates are considered more broadly. For example, the RGC densities of birds185,186 and some frogs187 appear to be similar, as do those of mammals and sharks188—despite the presumably more ‘complex’ brains of birds and mammals compared with those of frogs and sharks. Clearly, the computational power of an animal’s central brain (alone) does not predict retinal complexity. Instead, we might expect other factors to dominate. These include eye size, photoreceptor complement and, perhaps most importantly, species-specific visual needs.

Eye and animal size. As eyes become larger, physical constraints on vision change. Both spatial resolution and the absolute number of photons available for vision increase due to improved optics. Larger eyes project a larger image at the level of photoreceptor outer segments, but retinal neurons do not necessarily become

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Visual angle
The angle that encompasses a certain feature in the visual world, from the point of view of an animal’s eye.

Colour-opponent RGCs
Retinal ganglion cells (RGCs) that are excited by the presentation of light at one range of wavelengths and suppressed by presentation of light at another range of wavelengths.

Binocular region
The region in the visual space that is simultaneously surveyed by both eyes.

Goal-directed saccades
Rapid eye movements that bring specific objects into a retinal region’s field of view.

As eye size increases, absolute distances on the retinal surface per degree of visual angle increase. Therefore, any computations that require the retina to integrate information over large receptive fields must adapt. For example, mice and rabbits have very different eye sizes, meaning that the image of an object moving the same distance in the outside world traverses very different absolute distances on each of their retinas’ surfaces. As a result, the two species cannot use the exact same neural implementation for motion computation: indeed, recent work has shown that the need to match motion velocity to eye size has driven distinct dendritic wiring motifs in the motion detection circuits of these two animals9. Thus, factors such as eye size can constrain how a specific computation can be implemented and this, in turn, might lead to the need to organize circuits differently in different species.

Taking the eye size-related constraints on implementation to the extreme, in the 300-μm-diameter eye of larval zebrafish, RGC dendrites span some 10° of visual space in a mere 30 μm (Ref.7). Therefore, the retina of this animal can compute across large parts of visual space using small and presumably electrotonically compact neurons. At least some intraretinal strategies for feature computation in these small fish’s eyes differ from those in mammals. For example, mouse and rabbit retinal circuits feature several types of orientation-selective RGCs, which become orientation selective due to the interaction of non-orientation-selective bipolar cell input with input from amacrine cells at the RGC level10,11. In contrast, recent work suggests that larval zebrafish already exhibit orientation selectivity at the level of their bipolar cells12,13. To what extent this organizational principle persists in the larger adults remains to be tested. Different computational strategies in animals such as larval zebrafish may also be necessitated by their tiny RGC axon diameters (often less than 100 nm (Ref.7)), compared with 300–2,500 nm in humans14, which it can be hypothesized could make them unreliable in propagating action potentials15,16, and hence may require larval zebrafish RGCs to use a different ‘code’ to talk to the brain. However, these ideas still require experimental exploration.

Photoreceptor complement.
Retinal circuit differences may also be linked to an animal’s photoreceptor complement. The vertebrate standard — which applies to many fish, amphibians, reptiles and birds — uses up to five spectral cone photoreceptor types and one or two rod photoreceptor types17,18. In contrast, most mammals possess only two types of cone and one type of rod, while most marine mammals and sharks have even fewer photoreceptor types19,20. The reduced photoreceptor complement might be hypothesized to drive reduced retinal complexity in these species because fewer circuits for comparing chromatic channels are required21,22,23. In support of this idea, the retina of freshwater turtles, which is known to perform rich colour computations, contains more than ten distinct varieties of colour-opponent RGCs102, compared with the typical mammalian two or three103. However, there are numerous exceptions to this rule: for example, salamanders and frogs have similar photoreceptor complements19,20, but the retina of frogs tends to be much more complex than that of salamanders104. Notably, it has been shown that strong correlations in the spectral structure of natural light mean that the theoretical information benefit of increasing photoreceptor diversity and the number of different colour-opponent circuits rapidly declines as their number increases105,106. Accordingly, adding ever-more-spectral photoreceptor types and associated colour-opponent retinal circuits is unlikely to substantially increase the amount of spectral information that can be harnessed from most natural scenes. On the other hand, some groups of animals (such as many birds) produce complex reflectance patterns on their body surfaces, which may be linked to the existence of diverse spectral photoreceptor types, and it may therefore be the case that these species stand to disproportionately gain from the use of multiple spectral detectors for social signalling.

Viewing strategy and visual requirements.
Depending on an animal’s visuoecological needs — for example, avoiding predators as prey or being a predator itself — its eyes can be positioned either to the sides of the head, yielding horizontal viewing angles of up to 170° per eye (in rabbits)108, or in the front of the head, allowing a large binocular region and improved depth estimation (as in case of cats)107. Eye position also affects viewing strategy. For example, while rodents do make goal-directed saccades108, an important role of their eye movements is to stabilize the retinal image in the presence of head and body motion, while simultaneously using their extended visual field to survey their environment for the presence of potential threats109,110. In contrast, many primates, including humans, reconstruct their visual world by scanning their environment. This viewing strategy is likely a consequence of having a fovea — a small central retinal region in which cone density is maximal and the neural circuits are tailored for high-acuity vision (such that some complex computations are shifted downstream, as discussed earlier) and even laterally displaced on the retinal surface to improve optical properties. Hence, in primates, the combination of a foveated, spatially limited field of view with highly motile eyes ensures good spatial acuity while gathering substantial
In addition to the eye motility discussed above, a feature of vertebrate vision is the presence of small and fast angular displacements of the eye's optical axis (fixational eye movements). In general, the average size of these fixational eye movements can be related to the average receptive field diameters in a species' retina and the size of its visual field, suggesting that these eye movements contribute to providing the visual system with uncorrelated inputs in natural scenes.

How these considerations link to variations in the functional properties of the retinal circuits of these species remains to be established. However, a comparison of a well-studied circuit, the retinal direction-selective circuit, across species may provide some insight. Mice, rabbits, salamanders and turtles all feature a rather conserved set of direction-selective RGCs; however, primates seem to lack a similarly rich complement of direction-selective cells (reviewed in Ref. 48; but see Ref. 116) and instead seem to compute the direction of motion in the cortex (reviewed in Ref. 49). It can be hypothesized that the dominance of active exploratory eye movements in primates, in combination with the need to send signals from single cone photoreceptors to the brain to maximize spatial acuity at the foveal centre, means that the computation of motion direction in the eye is secondary to other requirements. However, how differences in vertebrates' viewing strategies, eye movements and lifestyles can be linked to functional differences at the level of their retinal circuits remains scarcely explored outside primates. To answer this question, it will therefore be important to systematically gather large-scale physiological datasets from a range of species under different experimental conditions, and to link these with their respective natural statistics and behavioural demands.

Finally, other major factors that drive retinal design include energy limitations, body temperature, lifestyle, the statistics of the scenes that are viewed (such as a habitat's visual clutter) and an animal's behavioural and visual interaction range (Box 2). Together, these factors mean that the likelihood of encountering specific visual features in different animals' natural visual worlds, their usefulness for guiding important behavioural decisions and the ability of the nervous system to detect and process these features all are highly species specific. We should therefore expect the organization of retinal circuits and their computations to reflect this species specificity.

Regional retinal specializations

The visual world is highly diverse. This is the case not only when we are comparing the natural environments inhabited by different species, but also when we compare the different parts of the visual field of a single species. Most prominently, many sighted animals live in a visual world that is segregated along the vertical axis. For land-living animals, the horizon often bisects the world into the ground, where food and mates are likely to be found, and an upper visual field covering the sky, a region where aerial predators might appear (Ref. 117) (Fig. 2a,b). High up in the sky, birds experience a similarly bisected world (Fig. 2c), and in addition may encounter different navigational information in the sky and on
the ground. For animals that live beneath the water surface, the vertical axis can carry multiple instances of stepwise variations in brightness, spectrum and visual clutter[FIG. 2d]. For example, in the shallow freshwaters inhabited by zebrafish, the ground is near and offers the greatest spatial detail. The horizon looks along the water column and tends to be featureless, except for objects in the foreground. Immediately above the horizon is a scattered reflection of the ground, and, finally, Snell’s window118 (the region directly above the animal) contains a typically featureless view of mostly sky above the water. Presumably as a direct consequence of the fact that properties of the visual input change across scenes, the neural circuits processing different parts of the visual field within the same species have often evolved to perform different sets of computations.

**Regional variability in RCG density.** These adaptations start in the retina, as is immediately apparent when one is looking at the much-studied density distributions of

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**Fig. 2 | Differential retinal ganglion cell topographies support vision in different visual environments.** a–d | Snapshots of the typical visual habitats of different animals. e | Representative retinal ganglion cell (RCG) density distributions across the whole retinas of different species. The schematics were created by our tracing published cell-count maps and subsequently using approximate graphical stitching to fit the images to a circular projection (human234, adult zebrafish198, hawk85, red kangaroo120, tree kangaroo120, wolf122 and dog122). The schematic of the mouse retina was sketched by hand on the basis of data in reFs6,7,235. For each of the published maps, we identified a number of density ‘contours’, for each of which we estimated the total area and RGC density. We used this information to calculate the mean RGC density across the bulk of the retina. In each schematic, areas shaded in the lightest grey are those in which RGC density corresponded to this mean density, and regions with darker shading show approximate relative elevations above this mean. The densities shown in each region are approximate, having been estimated from RGC density schematics of flat-mounted retinas depicted in the original publications. The white circles indicate the position of the optic nerve head in each retina. The optics of the eye invert the incoming image, meaning that the dorsal retina (D) surveys the ground, while the ventral retina (V) surveys the sky. N, nasal, T, temporal. Part a is adapted, with permission, from the database as described in REF. 167, Tkacik, G. et al., Natural images from the birthplace of the human eye. PLoS ONE 6, e20409 (2011).
RGCs across species [Fig. 2e]. Acute zones are regions of the retina in which RGC density is higher than in the rest of the retina and a key feature of many vertebrate retinas: even mice may have one acute zone in the temporal retina [but see Ref. 5], allowing them to somewhat oversample the visual space just in front of their nose. Importantly, even animals belonging to the same family can, when they live in different habitats, differ in the shape, location and extent of their acute zones. For example, animals living in open plains, such as the red kangaroo (Macropus rufus) or the Arctic fox (Alopex lagopus), tend to feature a lengthy, horizontal streak of high RGC density that allows them to relatively oversample what is presumably the most important part of their visual world — the distant horizon [19,120]. In contrast, species that dwell in cluttered environments, such as forests that lack an obvious horizon — including the tree kangaroo (Dendrolagus dorianus) and the red fox (Vulpes vulpes) — instead usually have a spot-like RGC density distribution, dubbed ‘area centralis’ [19,120]. These types of traits can evolve rapidly: wolves, for example, feature a pronounced horizontal streak leading into a dense area temporals; however, dogs — following only some 15,000 years of domestication [21] — exhibit much less pronounced versions of this pattern [104,105,122] [Fig. 2a]. Some species have more than one acute zone. For example, hippopotamuses, rhinoceroses and elephants have two to three acute zones, which have presumably evolved to compensate for their difficulty in rapidly turning their body and head [108,109,121,122].

An acute zone is generally considered to be a fovea if there is additional structural rearrangement in the retinal circuits to more directly expose photoreceptors to incoming photons, thus limiting scatter and maximizing spatial acuity. Among mammals, only some primates (including humans) are foveated; however, foveas are also found in many birds and reptiles, as well as in some fish [112,125,126]. Some species, including many birds of prey, even have two foveas: a shallow fovea that is not unlike the human fovea and that is used when looking forward into potentially binocular space, and an even-higher-resolution deep fovea that is used when looking sideways (for example, to aid monocular object detection at a distance) [127] [Fig. 2e].

A consequence of the presence of visual acute zones is that the function of one part of the retina is not representative of the function of the entire eye. Here, a well-studied example is the primate fovea, in which the peripheral retina’s mix of rod and cone photoreceptor pathways is replaced by simplified circuits (the midget pathway) [128] in which there is a 1:1:1 connectivity between cones, bipolar cells and RGCs (reviewed in Ref. 5). The midget pathway also lacks substantial lateral interactions with inner retinal inhibitory circuits and is driven by cones that exhibit slower responses to light than their counterparts outside the fovea [14] (the latter is suggested to be an adaptation to cope with the high noise levels that invariably accompany its low-convergence connectivity [108,124,125]). In primates, this regional specialization is complemented by additional processing hardware beyond the retina: The rod-free centre of the fovea occupies only ~0.04% of the retinal surface (~2° visual angle) but a large percentage of the primary visual cortex (V1) is dedicated to processing its output (giving a foveal magnification factor of ~8 mm/° at 1° eccentricity) [130].

Regional variability in retinal functional cell types. Mice feature a wide range of retinal specializations associated with the vertical axis. Most famously, and in common with many other vertebrates (reviewed in Ref. 134), mice have a pronounced dorsoventral gradient in opsin expression across their cone photoreceptors [131,132]: cones expressing only the UV-sensitive S opsin (S cones) are sparse (~5%) and homogeneously distributed across the whole retina [133]; however, the ratio of S cones to the population of cones expressing the green-sensitive M opsin (M cones) changes along the dorsoventral axis of the retina, being M cone dominated in the dorsal retina and S cone dominated in the ventral retina [Fig. 3a]. This renders the upper visual field strongly UV sensitive [134]. Furthermore, this retinal asymmetry is accompanied by a dorsal–ventral shift in the contrast sensitivity of the M cones from those responding in an approximately equal and opposite manner to light and dark stimuli to those preferring a dark stimulus, potentially supporting aerial predator detection (see below; Ref. 137). Despite the S-cone dominance of the ventral retina, behavioural experiments indicate that mice can still discriminate colours with this part of the retina [135], likely through a mechanism involving rod photoreceptor (green sensitive) versus S-cone opponency mediated by horizontal cells [136,137].

Through genetic targeting, a large number of regional variations at the level of specific RGC types from the mouse retina’s established parts list have recently been reported [138,139–140] [Fig. 3b], suggesting that there may be regional adaptations of their upstream circuits. For example, the so-called alpha RGCs have been identified in many mammals and are some of the largest RGC types — in terms of both soma and dendritic arbor [139]. Different types of alpha RGCs seem to follow different regional patterns: those that display sustained responses to the onset or offset of light (‘sustained on’ and ‘sustained off’ alpha RGCs, respectively) have smaller dendritic fields and are denser in the dorsotemporal region of the retina than in other parts of the retina (a difference that is predicted to affect spatial integration). By contrast, alpha RGCs that display a transient response to the light offset (‘transient off’ RGCs) are rather homogeneous in dendritic field size and distribution; however, a change in their temporal response profile along the dorsoventral axis of the retina has been reported [139]. Another example is the JAM-B RGC, named after the transgenic marker line in which it was first described [138]. This RGC type has been reported to feature a strongly asymmetrical dendritic field morphology across most of the retina; however, in the ventral (and potentially the dorsal) periphery of the retina these RGCs become symmetrical [138]. JAM-B RGCs are orientation selective [50] as well as, under low-light conditions, direction selective [136,138] across most of the retina; however, they become additionally colour opponent in the ventral retina [138]. Finally, complex patterns of regional specialization occur for classical direction-selective RGCs [138]: it has been reported that there is a systematic tilt in the preferred motion direction of these cells that depends on their retinal
location, which allows them to align and respond better to self-motion flow fields associated with self-motion and eye motion\(^9\). This is reminiscent of the local motion sensitivities of tangential neurons in flying insects, which exhibit complex receptive fields that directly reflect the distribution of local motion signals on the animal’s eye during self-motion\(^14^1\). It is likely that more regionalization patterns exist in mice; however, it is at times difficult to disentangle true regional specializations from artefacts resulting from regionally restricted transgene expression patterns. For instance, so-called W3 RGCs, which detect small dark moving objects\(^5^6\), have been reported to be much denser in the medioventral retina than in the rest of the retina. However, these W3 RGCs are only one of several RGC subpopulations that are labelled in this transgenic mouse line, and it is therefore still unclear to what extent the high medioventral density of labelled RGCs can be attributed to a concentration of this cell type versus differential transgene expression\(^5^5\).

While we have some knowledge of functional asymmetries at the level of the retina’s input (photoreceptors) and its output (RGCs), we are only just beginning to build an understanding of regional variations in the cell types that mediate the steps in between\(^4^2\). Here, work in larval zebrafish shows that functional inhomogeneities across the retinal surface can be rather pronounced. In this tiny animal, both the anatomy and the function of bipolar cells vary substantially across the retina\(^3\). Because there is little chromatic information available directly above the animal, it appears that larval zebrafish invest in achromatic silhouette detection circuits over colour-opponent ones in the ventral retina. In contrast, the natural horizon is colour-rich and, in response, the retinal horizon features multiple colour-opponent bipolar cell circuits alongside a near doubling of the inner retina’s thickness. In addition, the region of the retina receiving input from the visual space just above the horizon and in front of the animal is heavily dominated by specialized UV-sensitive cone photoreceptors and inner retinal UV-on circuits, which is likely to support visually guided prey capture of UV-bright plankton\(^3\,1^0\).

From the findings taken together, it is clear that retinal circuits and neuron types vary in anatomy and function across the retinal surface. This is in contrast to the traditional view that a neuron type that tiles the retina regularly also exhibits one stereotyped (though
potentially size-scaled) morphology and one function\textsuperscript{143,144}. In the end, irrespective of whether it is shown that these properties all systematically vary across the retinal surface, it seems likely that our growing understanding of the structure and function of the retina’s neuronal building blocks will continue to be central to the ongoing debate on neuron typing across the brain\textsuperscript{144}.

**Linking retinal diversity to behaviour**

How can differences between species in the complement of retinal cell types or in regional retinal specializations be related to the natural visual environment inhabited by different animals and their strategies to view the world? On an intuitive level, one may argue that the anisotropy in cone opsin distribution in the mouse retina may reflect an adaptation to the distinct contrast distributions in the sky and on the ground, improving the mouse’s ability to detect aerial predators (usually dark moving objects against the sky)\textsuperscript{15}. Likewise, the potentially higher density of W3 RGCs in the upward-looking ventral retina\textsuperscript{13}, coupled with this RGC type’s preference for small dark objects moving on a bright background\textsuperscript{13}, makes it tempting to speculate that there is an early warning system located in the ventral retina and roughly tuned to the silhouettes of predatory birds\textsuperscript{15} (but see earlier).

Still, it is often difficult to convincingly link functional local adaptations to properties of the natural environment, even when the link to the natural habitat and behaviour seems obvious, because there is always danger of oversimplification. For instance, the aforementioned W3 RGCs would presumably also respond to a wide range of harmless stimuli such as wind-driven movements in overhanging branches. Alternatively, we can attempt to go beyond such ‘word models’ and instead try to quantitatively link the properties of retinal neurons in different animals to the statistics of their respective natural environments and a mathematically precise formulation of their ecological necessities.

The quest for a quantitative theory of the retina’s purpose has fascinated researchers for many years. Several theories have been proposed that try to explain the physiology of retinal neurons from statistical properties of the natural environment of the animal\textsuperscript{13,14,145,146}. In the natural environment, there are strong correlations between the spatial and temporal features of typical visual scenes, as well as in their spectral composition. These correlations in photographs of natural scenes can be seen in the typical 1/f power spectrum, where low spatial frequencies have more power than high spatial frequencies\textsuperscript{147,148}.

The classical efficient coding theory suggests that one purpose of the retina is to find the least redundant representation of the visual input by ‘whitening’ the power spectrum, which is equivalent to removing the spatial correlations. This ensures that the relevant visual information can be effectively transferred over the bottleneck that the optic nerve represents\textsuperscript{14,145,147,149}.

This theory offers a solid theoretical account of various properties of retinal circuits: For example, one can show mathematically that whitening of the power spectrum can be achieved by elliptical centre–surround receptive fields, suggesting that this feature of many retinal neurons may have evolved to provide an efficient representation of visual scenes\textsuperscript{149}. It even predicts the red–green and blue–yellow antagonism found in colour-opponent RGCs in primates, showing that these cells are ideally suited to decorrelate the colour space of natural visual scenes\textsuperscript{150}. Beyond the general organization of receptive field structure, the efficient coding hypothesis has also provided accurate accounts of the fine mosaic structure of RGC receptive fields in the primate retina\textsuperscript{150}.

Finally, retinal non-linearities such as those that allow adaptation to natural scene statistics have been linked to efficient coding\textsuperscript{151,152}.

Nonetheless, from a theoretical viewpoint the retina remains far from solved. Perhaps the most obvious mismatch between experimental observations and theory is a numerical one: primates have on the order of 20 distinct RGC types\textsuperscript{146,153} and mice have at least 40 (REF\textsuperscript{44,45,154}). These cells have been shown to have a wide range of computational properties\textsuperscript{149}, yet efficient coding theory typically accounts for only a small number of simple centre–surround types of RGCs. To what extent can the emergence of this multitude of different RGC types be accounted for by theory? The first steps towards this goal have been taken. For example, it has been shown that splitting the visual signal into on and off channels aids signal coding\textsuperscript{149}. In addition, the emergence of a few specific RGC types with different spatio-temporal characteristics has been explained in terms of efficient coding\textsuperscript{146,156,157}. Extending the simple linear model of efficient coding to a neural network model including non-linearities reveals an optimal encoding scheme in which there are four cell types, matched in two on and off pairs with different spatial characteristics, resembling primate midget and parasol RGCs\textsuperscript{157} (FIG. 4).

To what extent the diversity of retinal cell types will ever be explained by a unifying theory is an open question. It is probably naive to believe that simply plugging videos capturing the natural environment of a species into a model or theory alone will ever yield a precise account of all the receptive field properties of the species’ RGC types, as the latter will also require a careful account of the species’ behavioural demands and necessities for survival. However, ideas about the specific feature channels that might encode survival-critical information have been much harder to make quantitatively precise\textsuperscript{147,148}.

Use of deep neural networks as task-driven models of the visual system may offer an interesting way to formalize these notions (reviewed in REF\textsuperscript{159}). For example, in the case of the ventrotemporal retina’s UV dominance in larval zebrafish\textsuperscript{13,14}, simply considering the statistical frequency of UV light in the visual field will not account for the neural response properties — for this, we need to know about the behavioural interest of the larvae in UV-scattering prey (that is, the task). If the UV scatter were just a nuisance, the retina might do well to discard it early on to avoid wasting costly resources in representing it. Thus, part of any theory would need to account for ecological demands of a species. Possibly, this could be encoded in the cost function that we might assume the retina to solve optimally. Thus, extending classical notions by formally encoding behavioural necessities may provide a viable path forward to reconcile the finding of many RGC types with theory.
Predictions of efficient coding have often been formulated on the descriptive level of cellular properties such as receptive field structure but have provided few constraints on the implementation level. For example, many RGCs do not simply implement their receptive field by pooling inputs, but instead show non-linear centre-surround interactions through circuits that, in turn, consist of non-linearly integrated subunits. Indeed, a recent study and preliminary findings have shown that taking this subunit structure into account can markedly improve the predictions of statistical RGC models in response to artificial and natural stimuli. Also, three-layer deep neural network models inspired by retinal circuits currently yield the best predictions of neural activity at the RGC level and provide non-trivial predictions for other properties of retinal processing. Circles and lines indicate nodes (photoreceptors (PRs), bipolar cells (BCs) and RGCs) and the connections between them (synapses), respectively. Arrows indicate the direction of connectivity via within-layer inhibitory networks (horizontal cells (HCs) between PRs and amacrine cells (ACs) between BCs). Two-layer networks typically seek to explain RGC responses on the basis of functional connections to PRs alone. In contrast, three-layer networks include BCs to form internal subunits. Both at the PR stage and the BC stage, lateral interactions via HCs and ACs, respectively, can be included to increase model accuracy. Three-layer networks can often outperform two-layer networks when aiming to model responses to complex or natural stimuli.

**Fig. 4** | Theoretical accounts of retinal designs. a | A deep neural network (DNN) model with fixed firing rate budget reveals an optimal encoding scheme with four cell types with properties reminiscent of primate midget and parasol retinal ganglion cell (RGC) types. The top panel shows spatial and temporal receptive fields of off (left) and on (right) parasol (large) and midget (small) RGCs computed from spiking data measured in primate retina. The bottom panel shows spatial and temporal receptive fields of the four cell types found in the DNN model. b | When presented with natural scene data, RGC centre–surround interactions can be highly non-linear. The top panel shows a natural scene with a macaque’s eye movement trajectory indicated in white. The boxes to the right show examples of single-frame centre (green), surround (purple) and centre–surround (black) stimuli extracted from the same part of this scene, as seen by a model RGC. Upper traces show responses measured from an example RGC in the macaque retina when presented with the centre-only (green) and surround-only (purple) stimuli. The lower trace shows that the sum of the independently measured centre and surround responses (grey) overestimates the measured response when centre and surround stimuli are presented simultaneously (black). c | Examples of two-layer and three-layer models of retinal processing. d, e | Two- and three-layer models were used to fit measured tiger salamander RGC responses to a complex stimulus (part d). The three-layer model consistently outperformed the two-layer model, as quantified in the correlation coefficient of each model prediction to the measured data (part e). Part a was modified with permission from REF. 157, Neural Information Processing System. Part b was modified with permission from REF. 156, CC-BY-4.0, https://creativecommons.org/licenses/by/4.0/. Parts d and e were modified with permission from REF. 149, CC-BY-4.0, https://creativecommons.org/licenses/by/4.0/.

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Box 3 | A non-exhaustive list of open questions

• To what extent is the strongly elevated density of retinal neurons in some species, such as many birds, related to higher spatial acuity as opposed to the presence of additional circuits for potentially novel computations? If the latter, what are those computations?
• Do foveated non-primate vertebrates have a primate-like 1:1:1 midget pathway?
• Do direction-selective circuits across species draw on the same cellular and synaptic hardware in all species? Do ancient vertebrates such as lampreys or sharks have mammalian like direction-selective circuits?
• Is the presence of orientation selectivity in cells upstream of retinal ganglion cells in larval zebrafish a general phenomenon? What other computations typically thought of as being unique to retinal ganglion cells can be performed earlier in the network? Is computational ‘front-loading’ related to phylogeny and/or eye size?
• Do all retinal neurons vary in some way across the retinal surface?
• To what extent can the computational complement of output channels of any one species be explained by its visuoecological niche and behavioural demands? Alternatively, can a description of a given visuoecological niche quantitatively predict how a given retina is functionally organized?
• What is the full extent of neuromodulatory influences on retinal function in vivo, and how are key neuromodulatory circuits controlled?

Circuits165,166. Thus, developing theoretical accounts of retinal function which allow constraints to be placed on the necessary building blocks on the mechanistic level is an additional avenue for future research.

Finally, to return to our original question, the theory of efficient coding has rarely been used to derive experimentally testable predictions about retinal specializations in different species or parts of the retina (as discussed in REFS 5,8,56). The recent publication of several datasets consisting of images and movies that mimic the natural statistics of the environment of different species will likely facilitate such work165,166. For example, these datasets could be used to ask whether a theory can predict quantitatively the differences in the response properties of cells located across the retina of a given species. Alternatively, they could be used to ask whether a theory can predict differences and similarities in the complement of RGC types found in different species, on the basis of differences in their natural environment. It is likely that, in addition to efficient coding constraints, such a future theory of early visual processing would need to consider the ecological demands of a species in order to make realistic predictions. The plethora of experimental data that are becoming available would provide strong tests of any such theory.

Outlook

We have seen that the structure and function of retinal circuits profoundly vary both between species and between different regions across the retina of a single species. Indeed, further variations exist within retinal regions across the time of day or even seasons (Supplementary Box 1). Accordingly, to understand our own sense of vision and to study biological solutions to vision in a more general sense, it will be critical to (re-) expand our currently narrow focus on but a handful of models and often non-naturalistic experimental conditions. Only a representative cross section across all these levels can guide our understanding of which (if any) circuit motifs and computational solutions are broadly conserved, which are unique solutions that apply to only a narrow set of circumstances and how retinal circuits can switch between them on physiological and evolutionary timescales (Box 3).

In particular, we suggest that expanding work on birds, which in many ways are the pinnacle of vertebrate retinal complexity, might aid our understanding of what retinal circuits — and thus neuronal networks — can achieve if pushed to the limit. Similarly, pursuing some of the long-standing questions raised in the classical literature on amphibians might greatly enrich our understanding of retinal organization in a more general sense. For example, how directly can the activity of single or small groups of RGCs alone trigger complex behaviour, as implied for the ‘bug detectors’ that Lettvin described in the frog retina167?

In parallel, it will be important to build additional depth in our understanding of species that are already well studied, to further delineate how their circuits vary in retinal space and circadian/seasonal time. A possible focus might be the inner retina165, the regional specializations of which remain scarcely explored even in mice. In aid of in-depth circuit comparisons, it will be important to simultaneously boost work on at least one or two additional species to eventually attain a level of understanding similar to that currently held for mice. Promising candidates include non-human primates (because their eyes are similar to those of humans) and zebrafish (for their ease of experimental access, the large body of existing literature and their distant phylogenetic relation to mammals). Any such efforts are set to immensely benefit from current high-throughput tools for mapping neuronal structure, function and gene expression.

Ultimately, retinal circuits evolved to operate in the live, behaving animal as it responds to changes in its visual environment and internal state on timescales from milliseconds to seasons168. Understanding how these factors play into the flexibility and design of retinal circuits in vivo will require direct, and ideally unperturbed, measurements of retinal structure and function over long timescales alongside reversible experimental manipulations at the circuit level.

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Author contributions

The authors contributed equally to all aspects of the article.