The retina creates 20 neural representations of the “movie” that enters the eye.
Fig. 5. The types of ganglion cells identified thus far in the retina of the cat. Ongoing work in the rabbit and monkey confirms this diversity, and many of the cells observed are probably homologs of those seen in the cat. Courtesy of D. Berson77–80.

Masland, 2001
THE CONTRAST SENSITIVITY OF RETINAL GANGLION CELLS OF THE CAT

BY CHRISTINA ENROTH-CUGELL AND J. G. ROBSON*

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(Received 19 April 1966)
Spatial contrast sensitivity
Ganglion cell receptive field modeled as difference of Gaussians

Rodieck (1965); Enroth-Cugell & Robson (1966)
Cat Retinal Ganglion Cell Additivity Test

(A) Pure center response

(B) Pure surround response

(C) Ganglion cell adds A & B

Stimulus

Computer adds A & B

C & D superimposed

50 spikes sec$^{-1}$

0.5 sec

Enroth-Cugell & Pinto (1970)
Ganglion cell receptive field modeled as difference of Gaussians

Enroth-Cugell & Robson (1966)
Frequency-domain representation of the difference of Gaussians

Enroth-Cugell & Robson (1984)
Linearity of summation in X cells

Enroth-Cugell & Robson (1984)
Linearity of summation in X cells, but not Y cells

Enroth-Cugell & Robson (1966)
Linearity of summation in X cells, but not Y cells

Enroth-Cugell & Robson (1966)
Nonlinear mechanisms of the Y cell receptive field

Enroth-Cugell & Robson (1966); Hochstein & Shapley (1976)
Ganglion cells, and they synapse on each other. Connectivity, they are hard to conceptualize: they feed back to the IPL. Cell image is adapted from Field Amacrine Cells Figure 5. The Structure and Generalized Connectivity of Narrow Field Amacrine Cells

How well has this estimate stood up, and what have we subsequently learned about the functions of amacrine cells? The answer to the first question is that there have been no big surprises and nothing to suggest that the population of amacrine cells in other species is less complex. Those species, to light are actually a release of amacrine mediated inhibition (because amacrine cells release GABA or glycine). It is the finding that some "excitatory" responses of ganglion cells were restricted to branching in narrow strata; the rest communicated "vertically," interconnecting the ON and the OFF layers of the IPL. Cell image is adapted from Menger et al. (1998).

Amacrine cells create contextual effects for the responses of retinal ganglion cells. This includes the classic "center surround" antagonism, but also a variety of other, more subtle, task-specific. An example is amacrine cell A17, a widely distributed amacrine cell in the rabbit retina (Jusuf et al., 2005), but it is to be expected that they will need, at the very least, a fine-tuning. Second, there was uncertainty about the number—perform some variety of vertical integration (the term is meant to contrast with lateral integration, as carried out by horizontal and wide-field amacrine cells). Only a small fraction of the number of wide-field amacrine cell types, which can cover the retina with a very small, absolute number of cells, and thus are adequate experimental sample is virtually impossible. But progress means that some "excitatory" responses of ganglion cells to light are actually a release of amacrine mediated inhibition (because amacrine cells release GABA or glycine). It is the finding that some "excitatory" responses of ganglion cells were restricted to branching in narrow strata; the rest communicated "vertically," interconnecting the ON and the OFF layers of the IPL. Cell image is adapted from Menger et al. (1998).
selectivity that can be predicted simply from the presence of a ganglion cell with a receptive field (discriminate 40 a ganglion cell with a receptive field 500 same for all small regions within the receptive field of the cell; (intelligence and detail, described the key features of the cells the direction of stimulus motion, and, in a report classic for its 
certain ganglion cells of the rabbit retina respond selectively to 
cell. In 1965, Horace Barlow and William Levick reported that 
OFF ganglion cell. and responds to a blue stimulus by slowing its firing—a blue-ON bipolar cell, this amacrine cell performs a sign 
inversion: it inhibits the ganglion cell upon which it synapses, 
by the blue-ON bipolar cell. The amacrine cell, like virtually all amacrine 
It turns out that a specific amacrine is driven directly by the 
retina is the blue-ON bipolar, carrying an excitatory signal? 
nencying to blue-OFF ganglion cell. But electrophysiolog- 
ical recordings have encountered a blue-OFF ganglion cell, in-
A final task-specific case is the role of the starburst amacrine 
cells, is inhibitory to its postsynaptic partners. When excited 
the retina are the blue-ON bipolar, carrying an excitatory signal?

Figure 7

Figure 6. Wide-Field Amacrine Cells Can Span Most of the Surface of the Retina
(A) Whole-mount view of a wide-field amacrine cell termed WA5-1 in the survey of Lin and Masland (2006). This cell’s axonal arbor (green) would affect visual stimuli falling in approximately half of the animal’s field of view. But the cell receives input from only a limited region of their dendritic fields (red), and presumably the population of cells of this type seamlessly affect images throughout the field, without the gaps that appear when a single cell or only a few of them are taken in isolation, as shown in (B). It does not take a large number of these cells to achieve the nearly complete axonal (green) coverage of the retina shown in (C). If we assume that the dendritic fields (ellipses) nearly tile the retina, the network of axonal processes is dense enough to affect the visual input with an adequate spatial resolution. In fact, the illustration shown here does not achieve tiling of the dendritic fields. If we assume a dendritic coverage of at least unity—higher than is shown here—the axonal coverage would blanket the retina at a very high density indeed. This is the arrangement to be predicted from other known types of retinal cells; whether or not it pertains to this cell will await a population stain.

(D and E) These cells appear to mediate a variety of contextual effects, in which visual events surrounding a particular stimulus condition the response of a ganglion cell to that stimulus. An example is “object motion detection,” in which objects that move relative to the general visual field are preferentially reported to the brain (Ólveczky et al., 2003). The effect of this computation is artificially simulated in the

lower panels. A native image is shown in (D). The image transmitted to the brain after object motion enhancement is shown in (E): the retinal ganglion cells respond most strongly to objects that are moving relative to the stationary surroundings. (D) and (E) reprinted from (Masland, 2003).

Masland, 2012
Fig. 1. Shift-effect in retinal neurons of rhesus monkey. (a) Shift responses of an on-center retinal ganglion cell and stimulus configuration. The grating is shifted to and fro in about 20° distance from the receptive field center. Blank area diameter 40 degrees; grating bar width and shift amplitude 2 degrees (arrows); stationary spot diameter 1.8 degrees; total pattern covering 100×100 deg. of the visual field. (b) Shift response of an off-center retinal ganglion cell after the introduction of a dark stationary center spot. Top: during the first 10 seconds, bottom: during the 50th—60th sec. (c) Shift response of the same neuron as in b. Top: A grating covered the total 100 deg. field including the receptive field (Bar width and shift amplitude 0.6 deg.). A slow drift of about 0.1 deg./sec was superposed on the grating shifts in order to exclude a stimulus configuration fortuitously symmetrical to the receptive field center. The dot display shows the similarity of all single responses. Bottom: Same grating restricted to the receptive field center. Other stimulus parameters unchanged. The ordinate in the post-stimulus time histograms is spike frequency, the numbers at right are peak frequencies in the two halves of the histogram (in spikes/second). A grating shift occurs each 500 ms (step trace below all frames). Ten to 60 stimulus presentations were averaged depending on the clarity of the response.
On- and off-cells are each other's inverses

Enroth-Cugell & Robson (1984)
On-off asymmetry

Dacey & Peterson, 1992; Chichilnisky & Kalmar, 2002
The retina creates 20 neural representations of the “movie” that enters the eye.

Roska and Meister, 2014
Figure 13. Ganglion cells of one type cover the retina with a regular mosaic. (A) Cell bodies and dendrites of ON alpha ganglion cells in a wholemount view of the cat retina. Note that the dendrites cover space uniformly, and the cell bodies are placed at regular distances (Wässle, 2004). (B) Cell body locations of ON alpha (open circles) and OFF alpha (closed circles) ganglion cells in a patch of cat retina (Wässle, Peichl, & Boycott, 1981). (C) Each of the two cell types forms a regular mosaic independent of the other. Spatial autocorrelation of the ON (solid blue line) and OFF (red) cell locations, showing the probability per unit area of finding a cell at a given distance from another cell of the same type. Note the prominent hole for distances <0.2 mm. Cross-correlation (green) shows the probability of finding an OFF cell at a given distance from an ON cell. Dotted lines are the average densities of ON (blue) and OFF (red) cells in this patch. Masland, 2012.
Primate Retinal Ganglion Cell Receptive Field Mosaics

Field & Chichilnisky (2007)
Midget Retinal Ganglion Cell Dendritic Field Mosaic

Dacey (1993)
Coordinated Fine Structure of Receptive Fields
The Retina Dissects the Visual Scene into Distinct Features

Several antibody markers label the same strata across these species, and a number of cell types are conserved. For example, both the mouse (Puller & Haverkamp, 2011) and the macaque (Dacey & Packer, 2003) have a bipolar cell specialized for signals from blue cones. In Table 13.1 we compile a catalog of retinal ganglion cell types across the major species in which the topic has been studied. This illustrates a number of "canonical" cell types found in many species (Berson, 2008). For other cell types the correspondence is more difficult to identify, although this may improve as we learn more about their visual responses.

There are also distinct differences among mammals. For example, in the mouse retina the spacing of cells in a given mosaic is almost uniform across the retina; at the other extreme, in the primate retina the cell density rises sharply toward a small patch of retina in the center called the fovea. The fovea, therefore, has high spatial resolution and is used for encoding details in the visual scene. Different mammals have different degrees of nonuniformity in the spatial density of ganglion cell mosaics, resulting in specialized retinal regions such as the area centralis in cats or the visual streak in rabbits.

A second difference is in the circuits processing color. Most mammals have two cone types, one expressing a short-wavelength pigment and the other medium wavelength. Some primates also have cones with a long-wavelength pigment. The circuitry connected to short-wavelength cones has common circuit motifs across mammals, such as the specialized blue cone cell, but the differential handling of color information for medium and long wavelengths is unique to a group of primates. Some mammals such as mice and rats express more than one pigment in many of their cones, and the ratio of these pigments varies in a dorsoventral gradient. Because of this gradient the part of the eye that looks at the blue sky is more sensitive at short wavelengths, and the part that looks at the ground is more sensitive at longer wavelengths.

The anatomical evidence that the retina contains 20 ganglion cell mosaics along with their associated circuits has emerged gradually over the last 50 years.

Figure 13.5 Comparing the retinas of humans and mice. Vertical sections of human (left) and mouse (right) retinas. Staining with three antibodies against tyrosine hydroxylase (TH), choline acetyl transferase (ChAT), and protein kinase C alpha (PKCa) identifies strata with similar positions in the two species.

Roska & Meister, 2014
Diversity of ganglion cell morphology in macaque retina

Dacey, 2004
psychology seems important (see below).

pect that the geniculostriate system receives non-midget, non-
ganglion cell population of an entire cat or rabbit retina within
1,050,000 midget ganglion cells could comfortably 'contain' the
small fraction of the total cells. A monkey retina that has
total number of ganglion cells increases, and they end up as a
There is no particular need for this number to increase as the
level of illumination, which controls the pupillary aperture.

Visual function: new certainties and new questions

Now providing an increasingly clear anatomical view of the other
cat suprachiasmatic nucleus, presumably to entrain circadian
rhythms. Remarkably, this cell seems to be directly photosen-
se to control pupillary size. A similarly rare neuron projects to the

The primate fovea, with its huge number of midget cells,
For this purely statistical reason, non-midget, non-parasol
sections that were little changed during the primate's evo-
morphologies of non-midget, non-parasol cells that project
optic system and drives optokinetic responses

A reward of structural studies is the level of certainty that their
A different kind of contribution comes from the quan-
ters are struggling; the cortical coding of color has been a tan-
•  volume 4  no 9  •  september 2001

Fig. 5. The types of ganglion cells identified thus far in the retina of
the cat. Ongoing work in the rabbit and monkey confirms this
diversity, and many of the cells observed are probably homologs

Masland, 2001
We found that 14 ganglion cell populations showed heterologous coupling to amacrine cells, whose arbors were often visible, allowing for examination of their soma/dendritic morphologies. Interestingly, all coupled amacrine cells observed in this study were either polyaxonal or wide-field amacrine cells, whereas we found no evidence of coupling between ganglion cells and narrow-field amacrine cells. However, labels of many coupled amacrine cells were restricted to their soma and yet to be morphologically characterized.

Role of ganglion cell coupling

Overall, our results indicate that nearly three-quarters of the ganglion cells in the mouse retina are coupled to ganglion cell and/or amacrine cell neighbors. This extensive coupling in the retina is widespread and extends to the peripheral areas, as illustrated in the diagram. The high degree of connectivity suggests a complex network of information processing within the retina.

Figure 13.

Summary diagram showing camera lucida drawings of representative ganglion cells. G1–G22 labels on the top represent the name of each ganglion cell subtype. Proximally and distally stratifying dendrites of bistratified ganglion cells are shown in black and gray, respectively. a, axon. Scale bar 100 µm.

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B. Völgyi ET AL.

Diversity of ganglion cell morphology in mouse retina

Völgyi, Chheda & Bloomfield, 2009
The distribution of rods and cones in human retina
Sampling of visual space by human retinal ganglion cells

Curcio & Allen, 1990
Sampling of visual space by different mouse ganglion cell types


Figure 4. Sampling of Frontal Visual Space Is Enhanced in A ON-S RGC Distributions, which Contrast with the Distributions of Known RGC Types (A) Azimuthal equilateral projections of retina space for A ON-S RGC distributions from right (red) and left (blue) eyes shown in Figures 1 and S1, reconstructed and plotted using the Retistruct package. Isodensity lines demarcate 5%, 25%, 50%, 75%, and 95% contours of the peak density located at the asterisk (180 cells/mm²). Cyan lines delineate computed sutures of the original relief cuts made for flat-mount preparation. (B) Sinusoidal projection of mouse visual space for A ON-S RGC distributions from retinas in (A) (see the Supplemental Experimental Procedures). Red outline represents the edge of the right retina; blue outline represents the edge of the left retina. N, nasal; D, dorsal; V, ventral; T, temporal, indicate the projection of the corresponding pole of the retina. Gray circle represents the position of the optic nerve head. Note the peak densities for right and left retinas (red and blue asterisks) and increased density (75% and 50% isodensity lines) are biased toward the vertical midline (0) corresponding to rostral frontal visual fields of mice. (C) The density of the total RGC population peaks at a location just nasal and ventral of the optic nerve head (black asterisk) (schematized from; see also) (D) In contrast, we show here that A ON-S and likely A OFF-S RGCs have peak densities in the temporal-dorsal retina, whereas A OFF-T RGCs are relatively more uniformly distributed across the retina. (E) Furthermore, the distributions of previously characterized RGCs show varied or flat distributions. The density color maps in (C) and (E) are schematics based on previously reported RGC densities and changes in dendritic arbor sizes (see the Supplemental Experimental Procedures). Density color maps in (D) are schematics based on the distributions of A ON-S and A OFF-T RGCs shown in Figure S1 and predicted from A OFF-S dendritic arbor sizes illustrated in Figure S2. See also Figure S2.
## Diversity of ganglion cell morphology in mammalian retina

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</table>

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

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

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

Methods
To observe the morphology of macaque ganglion cells we used the "fireworks" photostaining technique (Dacey et al., Neuron 49B, 37-53) from single tracer infusions made into the lateral geniculate nucleus (LGN) of the superior colliculus (SC). Fireworks' scaling completely reveals the dendritic zones of large numbers of retrogradely labeled ganglion cells. In this way we can measure type-specific stratification depth in the inner plexiform layer relative density from the nucleus through crossing dendrites to the same type. Right, photostained cells retrogradely labeled from injections in the superior colliculus.

Conclusions
- The 17 cell populations shown here represent ~85% of the total number of ganglion cells.
- No other cell types have been identified: an axonal photostaining ganglion cells (Peterson & Dacey, Vis Neurosci 10B, 15-37)
- Large, sparsely branched monosynaptic cells (inner and outer types)
- Taken together, and assuming ~2%, density for the remaining 3 cell types, the 30 types account for ~99% of the ganglion cells. If multiple ON-OFF interaction selective neuronal models (in primate and/or in a mouse) are also included we would be able to account for ~100%.

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

Parasol cells comprise ~14% of total ganglion cells (coverage: inner cells 1.9; outer cells 1.6) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of two photostained cells tracer labeled from injections in the superior colliculus and reacted for HRP histochemistry. B. Tracing of an inner parasol cell 8.7 mm from the fovea (dendritic field diameter = 213 μm). Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 5 neighboring outer parasol cells ~6 mm from the fovea. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured in wholemount retina and plotted as percentage depth in the IPL (inner cells, n = 36; outer cells, n = 20).

*Crook et al., J Neurosci 2008, 28(44):11277
Smooth monostratified inner ON-center and outer OFF-center types transient, achromatic, Y-cell receptive field*

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

*Crook et al., J Neurosci 2008, 28(48):12654
Recursive monostratified cells comprise ~4.5% (3 populations; single population: ~1.5%) of total ganglion cells (coverage: single population 1.2; 3 populations 3.5) and project to the LGN and pretectum. **A.** Photomicrograph of photostained cells tracer labeled from injections in the pretectum and reacted for HRP histochemistry. Dendrites of the four labeled cells and other nearby cells (cell bodies not shown) form a dense plexis of cofasciculated processes. Inset: Magnified view of boxed area in A. Arrows indicate 5 examples of cofasciculation. Numbers correspond to the dendrites’ cells of origin as shown in A. **B.** Tracing of a recursive monostratified cell 8.9 mm from the fovea (dendritic field diameter = 399 μm). Arrow indicates axon. **C.** Outlines of the overlapping dendritic fields of 3 neighboring recursive monostratified cells ~6.8 mm from the fovea. **D.** Dendritic field diameter plotted as a function of eccentricity. **E.** Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (recursive monostratified/inner parasol cell pairs, n = 3).
Recursive bistratified
candidate for the ON-OFF direction selective type

Recursive bistratified cells comprise ~1.5% of total ganglion cells (coverage = 1.3) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a recursive bistratified cell intracellularly injected with Neurobiotin and processed for HRP histochemistry. The cell shows tracer coupling to large and small bodied amacrine cell populations. B. Tracings of 7 cells ~7 mm from the fovea, tracer labeled from injections in the superior colliculus and processed for HRP histochemistry. C. Outlines of the overlapping dendritic fields of the 7 cells shown in B. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in whole mount retina and plotted as percentage depth in the IPL (recursive bistratified/parasol cell pairs, n = 3).
Small bistratified cells make up ~6% of total ganglion cells (coverage = 1.6) and project to the LGN. A. Photomicrographs of a small bistratified cell intracellularly injected with Neurobiotin and processed for HRP histochemistry, with the focus on the inner (upper) and outer (lower) dendritic arbors. B. Tracings of the inner arbors of 3 neighboring small bistratified cells ~9.8 mm from the fovea, tracer labeled from injections in the LGN and processed for HRP histochemistry. Overlapping dendrites show cofasciculation. Arrows indicate axons. C. Outlines of the overlapping dendritic fields of the 3 cells shown in B, D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (parasol/small bistratified pairs: n = 11).
Large bistratified cells make up ~3% of total ganglion cells (coverage: ~2) and project to the LGN. **A.** Photomicrographs of a large bistratified cell intracellularly injected with Neurobiotin and processed for HRP histochemistry. Focus is on the inner (upper) and outer (lower) dendritic arbors. **B.** Tracing of the same cell shown in A. Outer dendritic arbor is shown in red. Arrow indicates axon. **C.** Outlines of the dendritic fields of two neighboring large bistratified cells with overlapping dendritic fields. **D.** Dendritic field diameter plotted as a function of eccentricity. **E.** Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (parasol/large bistratified cell pairs: n = 5).
Narrow thorny cells comprise ~3% of total ganglion cells (coverage: inner cells 1.0; outer cells 1.0) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of an outer narrow thorny cell intracellularly injected with Neurobiotin and processed for HRP histochemistry. B. Tracing of the same cell shown in A. Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 3 neighboring outer narrow thorny cells tracer labeled from injections in the superior colliculus. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (inner narrow thorny/parasol cell pairs, n = 4; outer narrow thorny/parasol cell pairs, n = 4).
Broad thorny cells make up ~1.5% of total ganglion cells (coverage = 1.2) and project to the LGN, superior colliculus and pretectum. A. Photomicrograph of a broad thorny cell intracellularly injected with Neurobiotin and processed for HRP histochemistry. B. Tracing of the same cell shown in A. Arrow indicates axon. C. Outlines of the overlapping dendritic fields of 4 neighboring broad thorny cells ~5 mm from the fovea, tracer labeled from injections in the superior colliculus. D. Dendritic field diameter plotted as a function of eccentricity. E. Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (broad thorny/parasol cell pairs: n = 8).
Giant melanopsin cells comprise ~1% of total ganglion cells (coverage: inner cells 1.5; outer cells 2.0) and project to the LGN, superior colliculus and pretectum. **A.** Photomicrograph of a giant melanopsin cell intracellularly injected with Neurobiotin and processed for HRP histochemistry. The cell shows tracer coupling to several populations of amacrine cells. **B.** Tracings of 7 inner (black) and 8 outer (red) giant cells ~10 mm from the fovea, melanopsin immunolabeled and processed for HRP histochemistry. **C.** Outlines of the overlapping dendritic fields of 5 inner giant cells. Numbers correspond to cells shown in B. **D.** Dendritic field diameter plotted as a function of eccentricity. **E.** Mean dendritic stratification measured relative to parasol stratification in wholemount retina and plotted as percentage depth in the IPL (inner giant melanopsin/parasol cell pairs, n = 3; outer giant melanopsin/parasol cell pairs, n = 5).
midget cells - 46% - coverage inner 1.1, outer 1.1
parasol cells - 14% - coverage inner 1.9 outer 1.6
smooth monostratified cells- 2.5% - coverage inner 1.4 outer 1.4
recursive monostratified - 4.5% (3 populations each 1.5%, coverage 1.2)(on ds?)
recursive bistratified - 1.5% - coverage 1.3 (on-off ds?)
small bistratified - 6% - coverage 1.6 - blue on yellow off
large bistratified - 3% - coverage 2 - blue on yellow off
narrow thorny - 3% - coverage inner 1.0, outer 1.0 - transient achromatic
broad thorny - 1.5% - coverage 1.2 - on-off "local edge detector"
melanopsin - 1% - coverage inner 1.5, outer 2.0 - S off

17 populations, 85% of cells
## Summary of ganglion cell types in macaque retina

<table>
<thead>
<tr>
<th>Morphological type</th>
<th>% of ganglion cell population</th>
<th>Central projections</th>
<th>Some physiological properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Midget Inner</td>
<td>26%</td>
<td>LGN parvo 5, 6</td>
<td>ON-center; OFF-surround Achromatic/chromatic L vs M cone opponent</td>
</tr>
<tr>
<td>2 Midget Outer</td>
<td>26%</td>
<td>LGN parvo 3, 4</td>
<td>OFF center; ON surround Achromatic/chromatic L vs M cone opponent S cone OFF opponent group?</td>
</tr>
<tr>
<td>3 Parasol Inner</td>
<td>8.0%</td>
<td>LGN magno 1, 2</td>
<td>ON-center; OFF-surround Achromatic L+M cone input S cone input controversial</td>
</tr>
<tr>
<td>4 Parasol Outer</td>
<td>8.0%</td>
<td>LGN magno 1, 2</td>
<td>OFF-center; ON-surround Achromatic L+M cone input S cone input controversial</td>
</tr>
<tr>
<td>5 Small bistratified</td>
<td>6.2%</td>
<td>LGN konio 3</td>
<td>S ON; L+M OFF opponent</td>
</tr>
<tr>
<td>6 Large bistratified</td>
<td>2.7%</td>
<td>LGN</td>
<td>S ON opponent details unknown</td>
</tr>
<tr>
<td>7 Thorny monostratified Inner</td>
<td>1.2%</td>
<td>LGN Superior colliculus</td>
<td>Unknown</td>
</tr>
<tr>
<td>8 Thorny monostratified Outer</td>
<td>1.2%</td>
<td>LGN Superior colliculus</td>
<td>Unknown</td>
</tr>
<tr>
<td>9 Broad thorny monostratified Inner</td>
<td>1.2%</td>
<td>LGN Superior colliculus</td>
<td>Unknown</td>
</tr>
<tr>
<td>10 Recursive bistratified</td>
<td>4.2%</td>
<td>Superior colliculus</td>
<td>Possible correlate of ON-OFF direction selective</td>
</tr>
<tr>
<td>11 Recursive monostratified</td>
<td>1.9%</td>
<td>Superior colliculus LGN? Pretectal area (NOT?)</td>
<td>Possible correlate of ON direction selective</td>
</tr>
<tr>
<td>12 Moderate monostratified Inner</td>
<td>1.3%</td>
<td>Superior colliculus</td>
<td>Unknown</td>
</tr>
<tr>
<td>13 Moderate monostratified Outer</td>
<td>1.3%</td>
<td>Superior colliculus</td>
<td>Unknown</td>
</tr>
<tr>
<td>14 Sparse monostratified Inner</td>
<td>2.0%</td>
<td>LGN</td>
<td>L+M ON; S OFF opponent</td>
</tr>
<tr>
<td>15 Sparse monostratified Outer</td>
<td>1.2%</td>
<td>LGN</td>
<td>Unknown</td>
</tr>
<tr>
<td>16 Giant monostratified Melanopsin-containing Inner/outer Weakly bistratified</td>
<td>1.0%</td>
<td>LGN Pretectal area, PON SCN?</td>
<td>Sustained ON response S OFF; L+M ON opponent Strong rod input Intrinsically photosensitive via novel photopigment</td>
</tr>
<tr>
<td>17 Giant monostratified intrinsic axon-collaterals</td>
<td>1.0%</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

*Total ganglion cell density is from Wässle et al., 1989, for temporal retina ~ 8 mm from the fovea. Individual cell type densities were determined from cell density at ~8 mm (parasol cells, Perry & Cowey, 1985) or from dendritic field area at ~ 8 mm and coverage factor where known (thorny and giant monostratified cells, Dacey, unpublished; midget cells Dacey, 1993). All other cell type densities were determined from measured dendritic field area at ~8 mm and estimated coverage. For abbreviations, see Figure 1.*
Schematic summary of dendritic stratification. Lengths of colored bars are proportional to dendritic field diameter for each cell type relative to parasol cell diameter. Vertical positioning of each bar is centered on the mean stratification depth for that cell type (values not shown). Widths of the bars are arbitrary for all cell types except midget and broad thorny cells, where it represents the mean innermost and outermost dendrites for these broadly stratifying cell types.
Conclusions

• The 17 cell populations shown here represent ~ 85% of the total number of ganglion cells.*

• At least 3 other cell types have been identified: axon collateral-bearing ganglion cells (Peterson & Dacey, Vis Neurosci 1998, 15;377) large, sparsely branched monostratified cells (inner and outer types).

• Taken together, and assuming ~ 2% density for the remaining 3 cell types, the 20 types account for ~ 90% of the ganglion cells. If multiple ON-OFF direction selective mosaics exist in primate (as found in other mammals) another ~5% would be accounted for.

*Total ganglion cell density is from Wässle et al., Nature 1989, 341;643. Density estimates for individual cell types were derived from the mosaics.
In the first step, we used an automatic unsupervised clustering procedure to identify response prototypes of GCL cells (Methods), making our analysis as objective and quantitative as possible. For all cells, we measured Ca signals from the light-driven Ca response and accounted for all known RGC types in the mouse retina. This framework yielded a total of 46 groups (Methods). Specifically, we used sparse principal component analysis (sPCA) to extract features from the light-driven Ca signals. In the second step, we post-processed the clustered data and used a Mixture of Gaussian model on this feature set for clustering different kinetics or selectivity to different temporal frequencies. We then temporal response features such as ON and OFF responses with different temporal kernels. Rightmost column, direction- and orientation-selectivity: directions, full-field alternating green/blue and binary noise for space-selective responses. This provided the unprecedented opportunity for an unbiased characterization of the retinal output. Since the data set (11,210 cells, 20 cells. Regions of interest (ROIs) (right), were placed semi-automatically. Bottom, montage of nine consecutively recorded fields.

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types, each preferring a different motion direction. For example, the coverage factor of 7.7, consistent with four ON–OFF direction-selective groups may indicate groups consisting of multiple types. For example, Table 1 and Supplementary Discussion). Coverage factors higher than coverage factors for mouse RGCs (roughly 2–3; see Supplementary Data). A coverage factor of A single RGC type would yield a coverage factor of 1 may indicate that a type has been artificially split. Extended Data Fig. 3e and the fraction of extended Data Fig. 4; Methods). The allocation of cells to individual clusters (left) and distribution of coverage factors across groups (right). Scale bar in d, 50μm.
Figure 4 | Direction and orientation selectivity. a, Pairs of retinocentric polar plots showing distributions of preferred motion directions of selected direction-selective (DS) RGC groups (V, ventral; N, nasal). Top plot of each pair: preferred directions, with length representing direction-selective index and grey level $p_{DS}$ (Methods). Bottom plot of each pair: circular area-normalized histogram. b, As for a, but for selected orientation-selective (OS) RGCs. Further direction-selective/orientation-selective groups detailed in Extended Data Fig. 7. c, Motion directions in the visual space of the mouse.
Physiologically and morphologically characterized ganglion cell types that project to the macaque LGN

Figure 5. Parasol cells have Y-cell physiology

A

B

4 Hz →

400 pA

C

D

Figure 6. Parasol cells of all eccentricities exhibit Y-like second harmonic responses to counterphase gratings.
Figure 10. Summary and hypothesis for the origin of the F2 receptive field component in parasol cells

Figure 4. Morphology of inner and outer smooth cells and parasol cells

Figure 6. Smooth cell dendritic diameter increases with increasing eccentricity and is twice the size of parasol cells.
Figure 7. Smooth and parasol dendritic trees co-stratify within the IPL.
Figure 9. Smooth cells have large receptive fields with center and surround organization.

A

B

center diameter = 346 μm

surround diameter = 1344 μm

2 Hz

norm. amplitude (mV)

spatial frequency (cpd)

10.5 Hz

C

D

smooth cells

parasol cells

Figure 11. Smooth cells, like parasol cells, have transient responses and encode high temporal frequencies.
Figure 13. Smooth cells have Y-cell like physiology
Figure 15. Summary of the central projections, dendritic morphology and receptive field spatial structure for smooth and parasol ganglion cell classes of the macaque retina found in this and a companion study (Crook et al., 2008)
Figure 16. Physiologically and morphologically characterized ganglion cell types that project to the macaque LGN
**Table 13.1** A catalog of retinal ganglion cell types in the mammalian retina

<table>
<thead>
<tr>
<th>Icon</th>
<th>Mouse</th>
<th>Rabbit</th>
<th>Cat</th>
<th>Macaque</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="ON midget" /></td>
<td></td>
<td></td>
<td></td>
<td>ON midget&lt;sup&gt;22&lt;/sup&gt;</td>
<td>Small dendritic field. ON response.</td>
</tr>
<tr>
<td><img src="image" alt="OFF midget" /></td>
<td></td>
<td></td>
<td></td>
<td>OFF midget&lt;sup&gt;22&lt;/sup&gt;</td>
<td>Small dendritic field. OFF response.</td>
</tr>
</tbody>
</table>

Roska and Meister, 2014
Color-opponent midget cells: a primate specialization

Primate Color Opponent Ganglion Cells

Inferred Receptive Field Description

DeMonasterio & Gouras (1975)

Masland, 2001;
DeMonasterios & Gouras, 1975;
Watson, 2014
Midget ganglion cells show red-green
L vs M cone opponency

Jo Crook & Dennis Dacey
**random-wiring**

**achromatic-chromatic**

L cone

L cone & M cone

e.g. Paulus & Kroger-Paulus, 1983
Lennie et al., 1991

cone-selective

**pure color**

L cone

M cone

Shapley & Perry, 1986
Lee, 1999
Reid & Shapley, 2002
Shapley, 2006
Buzas et al., 2006

Jo Crook & Dennis Dacey
Record from midget cells with multiple cone inputs to the receptive field center
Record from midget cells with multiple cone inputs to the receptive field center

Martin et al., 2001
Solomon et al., 2005
Buzas et al., 2006

Jo Crook & Dennis Dacey
Mixed L and M cone input weights to midget center and surround supports random wiring

### Mixed L and M cone input weights

**Pure Center Chromatic**
- Amplitude (spks sec⁻¹):
  - L-ON: (data points)
  - M-OFF: (data points)
  - M-ON: (data points)
  - L-OFF: (data points)
- Phase (deg):
  - L-ON: (data points)
  - M-OFF: (data points)
  - M-ON: (data points)
  - L-OFF: (data points)

**Mixed Center Chromatic**
- Amplitude (spks sec⁻¹):
  - L-ON: (data points)
  - M-OFF: (data points)
  - M-ON: (data points)
  - L-OFF: (data points)
- Phase (deg):
  - L-ON: (data points)
  - M-OFF: (data points)
  - M-ON: (data points)
  - L-OFF: (data points)

**Mixed Center Achromatic**
- Amplitude (spks sec⁻¹):
  - M & L-OFF: (data points)
- Phase (deg):
  - M & L-OFF: (data points)

---

**Chromatic midgets** (n = 109)

**Achromatic midgets** (n = 74)

---

Jo Crook & Dennis Dacey
Mosaic of Red, Green and Blue Cones of the Living Human Retina

Hofer et al. (2005)
Mixed L and M cone input weights to midget center & surround supports random wiring

Chromatic midgets
(n = 109)

L% to center

25

# cells

L% to surround = 49%

Achromatic midgets
(n = 74)

L% to center = 50%

L% to surround = 48%

L% input L/(L+M)

Jo Crook & Dennis Dacey
Cone inputs to the receptive field suggest random wiring

- inputs to the midget center are variable
- all midgets show mixed cone input to the surround
- all midgets are achromatic to narrow stimuli
- many midgets are purely achromatic
As predicted by random-wiring the surround arises by indiscriminate horizontal cell feedback to cones

Dacey et al., 1996

H1 horizontal cell
Cell-type classification and receptive fields at single-cone resolution.

OFF midget

OFF parasol

Small bistratified

ON midget

ON parasol

a, Receptive fields of 323 RGCs recorded simultaneously from isolated macaque retina were measured using reverse correlation with white noise stimuli. Centre panel shows receptive-field radius versus first principal component of response time course; clusters reveal distinct cell types. a.u., arbitrary units. Hexagons surrounding centre panel show outline of electrode array and ellipses show Gaussian fits to receptive fields of cells from each cluster. The outer panels show fine-grained spatial receptive-field profiles for highlighted cells. Scale bars, 50 μm
Cone-type identification and inputs to RGCs.

**a**, The spectral sensitivity of cones providing input to two cells is represented by the relative magnitude of the red, green and blue spike-triggered average values (a.u.) at their locations.

**b**, For every cone in one recording, these values are shown as points on a sphere. Coloured lines indicate spectral sensitivity of macaque cones. Point colour indicates classification as L (red), M (green), or S (blue).

**c**, L- and M-cone discriminability quantified by projection along the line joining L- and M-cone loci. Bar colour indicates classification. S cones excluded.

**d**, Assembled cone mosaic from all RGCs over a region. Cones from **a** are circled.

**e**, Full mosaic of 2,373 cones from one recording.
Full functional sampling of cone lattice by four RGC types

Each panel shows cones identified in a single recording (red, green and blue dots) sampled by receptive-field centres of RGCs of a single type. Cones are identical in all panels. Cones providing input to at least one RGC are highlighted with an annulus. Scale bar, 50 µm.
Rabbit Direction-Selective Retinal Ganglion Cells

Barlow et al (1964)


Oyster (1968)
Rabbit Starburst Amacrine Cells

Vaney (1990)
Receptive field properties of on-off directionally selective ganglion cells

Barlow & Levick, 1965
The two main schemes for the directionality of receptive fields have been illustrated, and these are based on the anatomy of the retina. The left-hand drawing shows the excitatory mechanism, while the right-hand drawing shows the inhibitory mechanism. The preferred direction is indicated by an arrow, and the null direction is indicated by a reversed arrow.

The excitatory mechanism involves the interaction of horizontal cells with bipolar cells, resulting in an excitatory response in the ganglion cells. The inhibitory mechanism involves the interaction of horizontal cells with amacrine cells, resulting in an inhibitory response in the ganglion cells. The preferred direction is determined by the relative timing of the input signals from the bipolar cells, while the null direction is determined by the relative timing of the input signals from the amacrine cells.

Barlow & Levick, 1965
Receptive field properties of on-off directionally selective ganglion cells

On–Off DSGCs

Preferred direction

Bar of light moving left then right

Preferred direction

Null direction

On 1ȭ
–66 mV
0.5 s
On 1ȭ

b
a
c
d
e

\[ \Delta t \]

A
A′

B

A

\[ \div \Delta t \]

B

B′

50 µm

Figure 7. The Cardinal Features of the ON-OFF Direction-Selective Cell, and the Mechanism by Which Direction Selectivity Is Created

(A) The cell can discriminate the direction of motion of small stimuli falling within its receptive field (large circle), and it does not matter where within the field the small stimulus falls—there is a local subunit that is direction selective. (B and C) The fundamental mechanism of direction selectivity. (B) Shows the dendritic arbor of a starburst amacrine cell. A sector of the arbor (outlined in red) is (1) an independent functional unit, electrically separate from the rest of the cell, and (2) directionally polarized, such that it releases GABA when the stimulus moves in one direction—left to right in this example—and not in others. (C) Starburst sectors pointing in a single direction (red) selectively synapse upon dendrites of an ON-OFF DS ganglion cell (outlined by the black circle). In this example, they would provide inhibition when the stimulus moves from left to right. This cell would thus have a preferred direction for movement right-to-left and a null direction for movement left-to-right. The sectors are smaller than the dendritic field, thus accounting for the ganglion cell’s ability to discriminate small movements within the field. Other sectors of the starburst cell, pointing in other directions, would contact other direction selective ganglion cells; those cells would prefer different directions of stimulus movement.

Masland, 2012
Functional and structural identification of DSGCs

Blood vessel visible in both ganglion cell layer (superimposed onto a two-photon image from the recorded region of the Fig. 1). We denoted those groups, which are known to correspond toffered directions clustering in 4 groups (Fig. 1a and Supplementary cell layer (Fig. 1b). Among those were 25 On–Off DSGCs with pre-neuronal somata in a 300

Figure 1

Figure 1

a

Off =
On =

b

c

Figure 2 | Skeleton reconstructions of DSGCs and SACs. a, b, DSGCs, colour-coded by preferred direction (inset), projected parallel to (a) and norma to (b) the plane of the retina. Note bi-stratification in the inner plexiform layer c, Parallel projections of 24 SACs (11 On SACs, 13 Off SACs, black). Scale bar are 50 μm.

Briggman et al, 2011
We measured the angle (dendrite vector oriented from its presynaptic SAC soma to the synapse location of individual DSGCs. For each SAC–DSGC synapse, we constructed between On and Off sublayers (data not shown).

We observed no obvious difference in the selectivity that occur, in particular for dendrites oriented in between the cardinal directions. We also noted that the specificity was found across all reconstructed SACs (Fig. 4b). A given SAC synapsed onto the southward preferring (orange) DSGC. Despite a large overlap of these northward branches with the dendritic trees of a branch does not exclusively synapse onto only one type of DSGC; was found across all reconstructed SACs (Fig. 4b). A given SAC synapsing onto them. The specificity is even more apparent in the westward (red) and eastward (purple) DSGC (Fig. 4a), they avoided the SAC dendrite (and hence aligned with the null direction). For synapses preferred DSGCs with a preferred direction antiparallel to Off SAC; black dots in Fig. 4a and Supplementary Fig. 3). Output varicosities on the dendrites of these two SACs (413 On SAC; 452 red, W; orange, S). In addition, we identified all of the remaining six DSGCs and colour-coded their output synapses by the preferred SAC (Fig. 4a and Supplementary Fig. 3) that each overlapped with the perspective of individual SACs. We chose one Off and one On example, the northward oriented branches of the SACs mostly

Figure 4 | Specificity of SAC outputs. a, An Off SAC (black skeleton), with varicosities indicated by black dots. DSGC dendritic trees are indicated by colour-coded dashed ellipses. Synapses are colour-coded by the preferred direction of the postsynaptic DSGC. b, Output synapse locations ($n = 831$ synapses) relative to SAC somata from all 24 SACs. Scale bars are 50 μm.
it should (Fig. 6a, lower panel). Our analysis (Fig. 6b) shows that for panel); however, if, instead, the dendrite angle is the determinant then closely with the null direction than the soma–soma axis (Fig. 6a, upper SAC-soma–DSGC-soma axis (Fig. 6a). In this case the connectivity should not depend on whether a dendrite is aligned more or less is solely determined by the relative locations of the corresponding probability of forming a synapse between a SAC and a DSGC dendrite.

Discussion

Although we found a strong correlation between SAC dendrite the DSGCs' inputs (Fig. 5). Dendritic branches of SACs are individu- and associated SAC input synapses (smaller cyan and blue circles) from 18 connected On and Off SAC somata (large cyan and blue circles, respectively) indicates null direction; and associated SAC input synapses (smaller cyan and blue circles) from 18 SACs. b. The distribution of all SAC dendrite angles ($\theta_{dendr}$) for each of the six DSGCs; $\theta_{dendr}$ is defined by the vectors (cyan and blue lines in a) oriented from SAC somata to synapse location. Triangle markers indicate the preferred direction for each DSGC. c, Polar histograms of $\theta_{dendr}$ (black, plotted as the square root of $\theta_{dendr}$ frequencies) together with the DSGC tuning curves (as in Fig. 1). Asterisk denotes the DSGC shown in a.

Figure 5 | Specificity of DSGC inputs. a, DSGC (grey skeleton) and the connected On and Off SAC somata (large cyan and blue circles, respectively) and associated SAC input synapses (smaller cyan and blue circles) from 18 SACs. b, The distribution of all SAC dendrite angles ($\theta_{dendr}$) for each of the six DSGCs; $\theta_{dendr}$ is defined by the vectors (cyan and blue lines in a) oriented from SAC somata to synapse location. Triangle markers indicate the preferred direction for each DSGC. c, Polar histograms of $\theta_{dendr}$ (black, plotted as the square root of $\theta_{dendr}$ frequencies) together with the DSGC tuning curves (as in Fig. 1). Asterisk denotes the DSGC shown in a.