Foveal vs. peripheral vision

John Greenwood
Department of Experimental Psychology

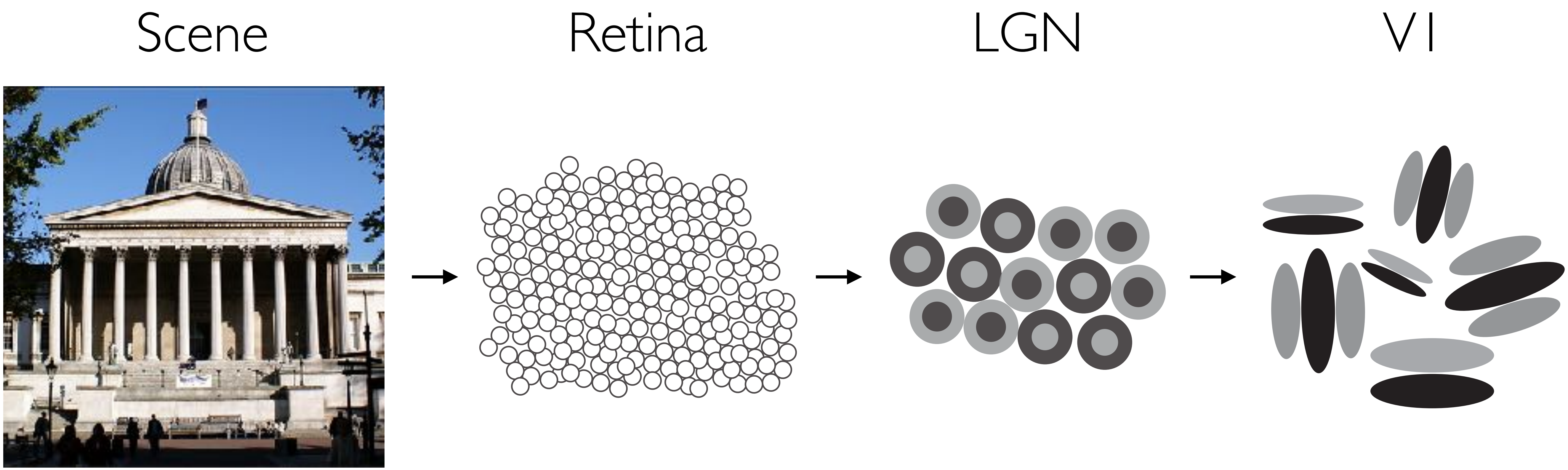
NEUR 0017

Contact: john.greenwood@ucl.ac.uk

Today

- What do we see in our peripheral vision?
  - Physiological limitations
  - Functional consequences for spatial vision
  - Crowding
  - The visual field in other species

Recall: spatial vision

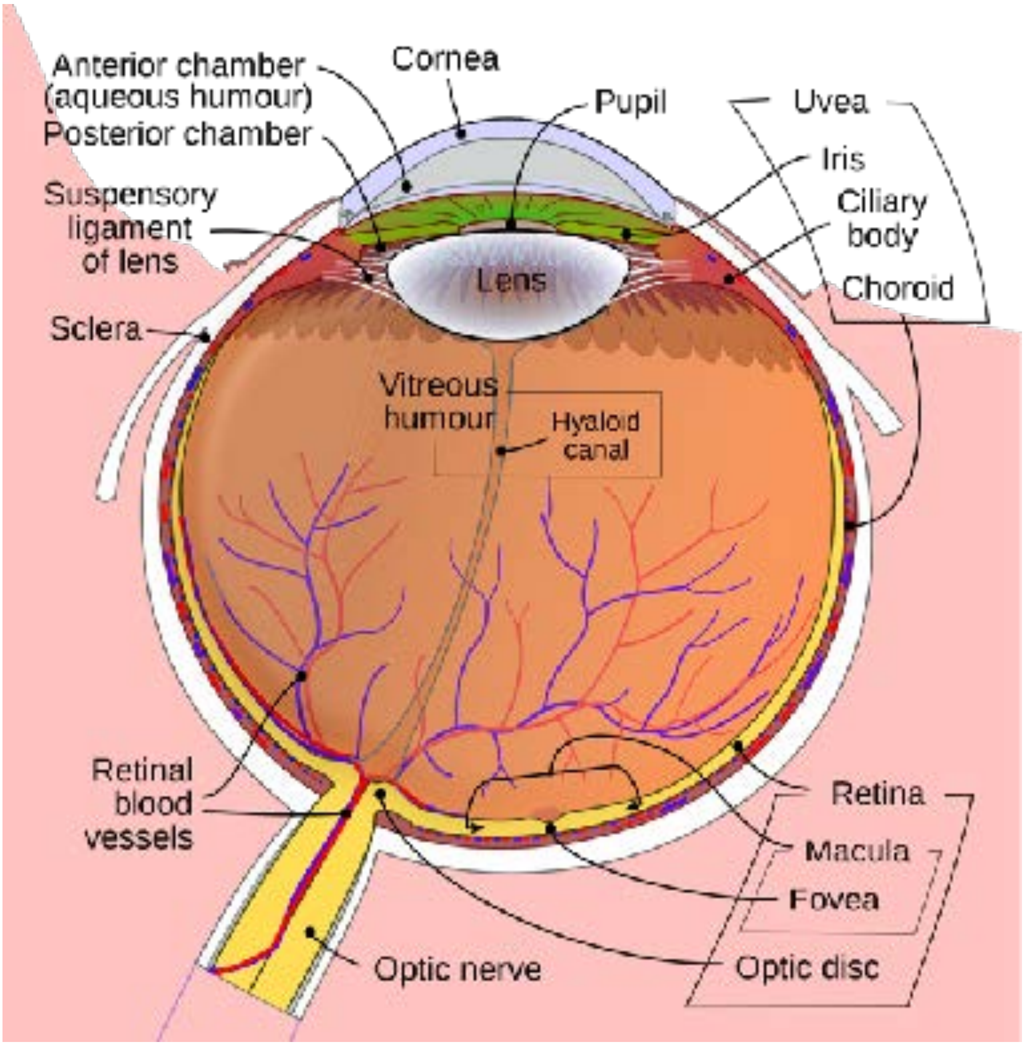


- Perception of the variations in light across the visual field
- Visual system may break down the scene as in Fourier analysis (into orientation, spatial frequency, etc.)
- Common principles in these dimensions: adaptation, contextual effects, population coding

What do we see in our peripheral vision?

Let's define our terms

- *Fovea:* the central 'pit' of the retina
  - ~1.5mm diameter on the retina, or ~5.2° diameter in the visual field
  - Contains the *foveola* (completely rod-free area ~0.35 mm diameter or ~1° diameter in VF)
  - Contained within the *macula* (~5.5mm diameter)
- *Periphery:* the rest
  - Extends ~60° above, ~80° below, and ~100-110° laterally
  - i.e. ~95-99% of vision is peripheral!



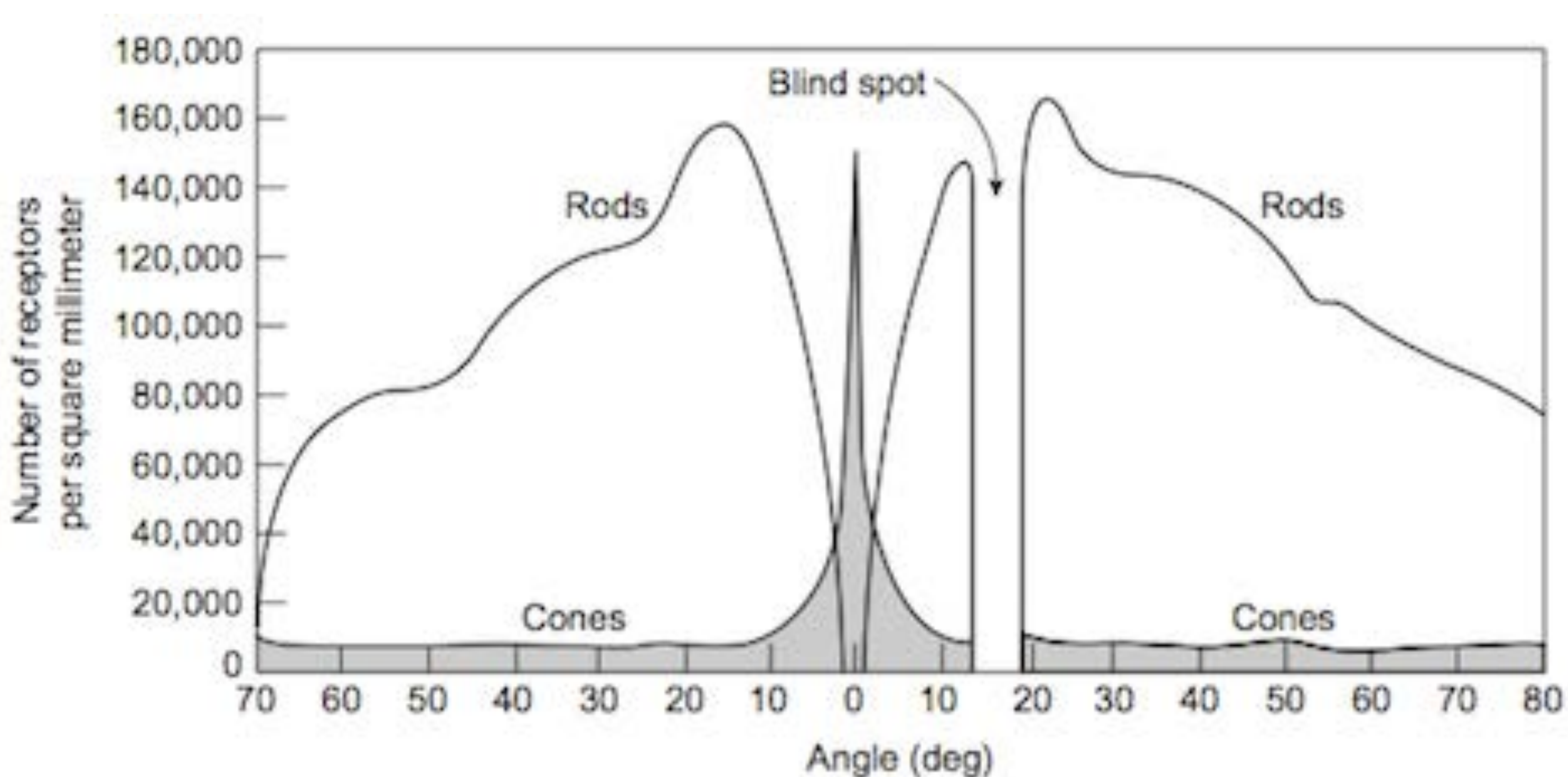
See e.g. Strasburger, Rentschler & Jüttner (2011)

Objects in the periphery are blurry, unclear, indistinct, hard to see.
Why?

Physiological limitations

Photoreceptor distributions

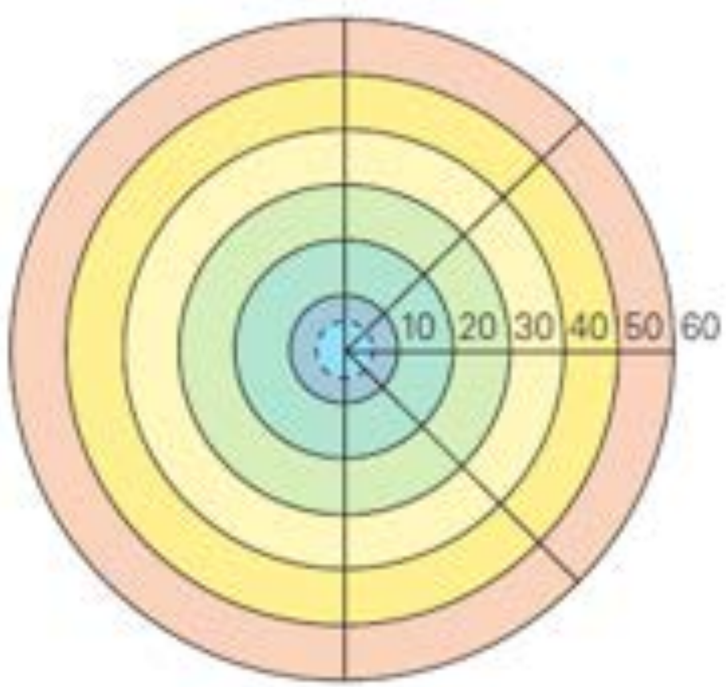
- Retinal cone density decreases markedly with increased distance (eccentricity) from foveal/central vision
  - i.e. peripheral image is sampled by fewer photoreceptors in photopic/high light levels



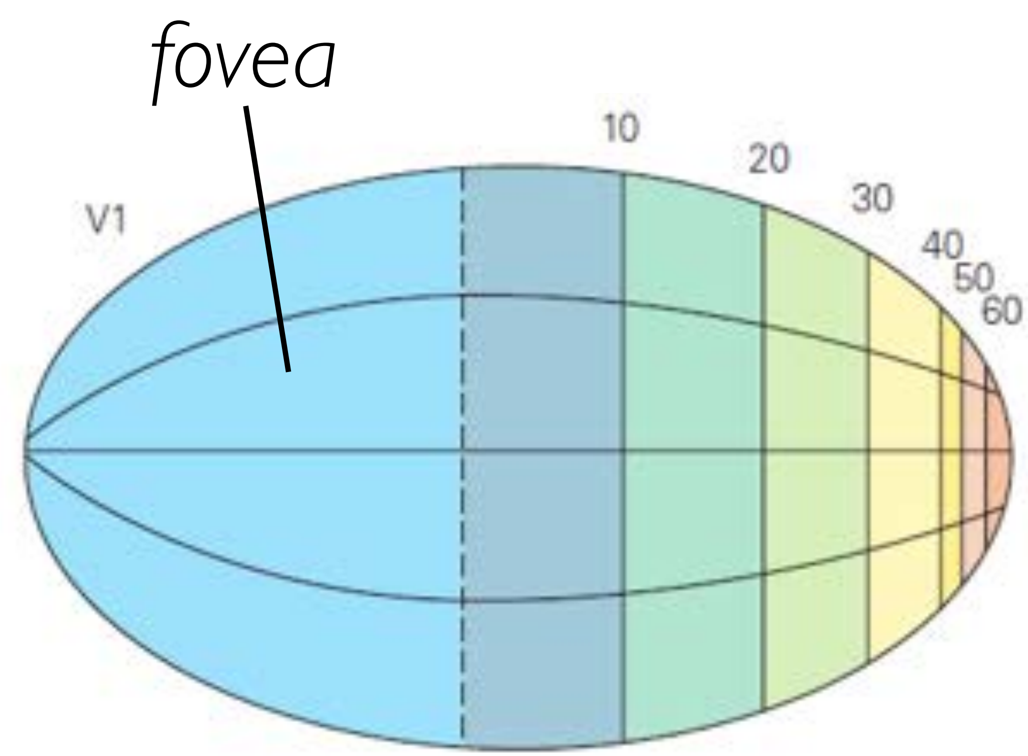
Curcio et al (1990)

Cortical magnification

- Visual areas of the brain show retinotopic mapping (adjacent neurons respond to adjacent regions of the VF)
- Cortical magnification: greater area is devoted to the fovea than to peripheral vision (Daniel & Whitteridge, 1961)



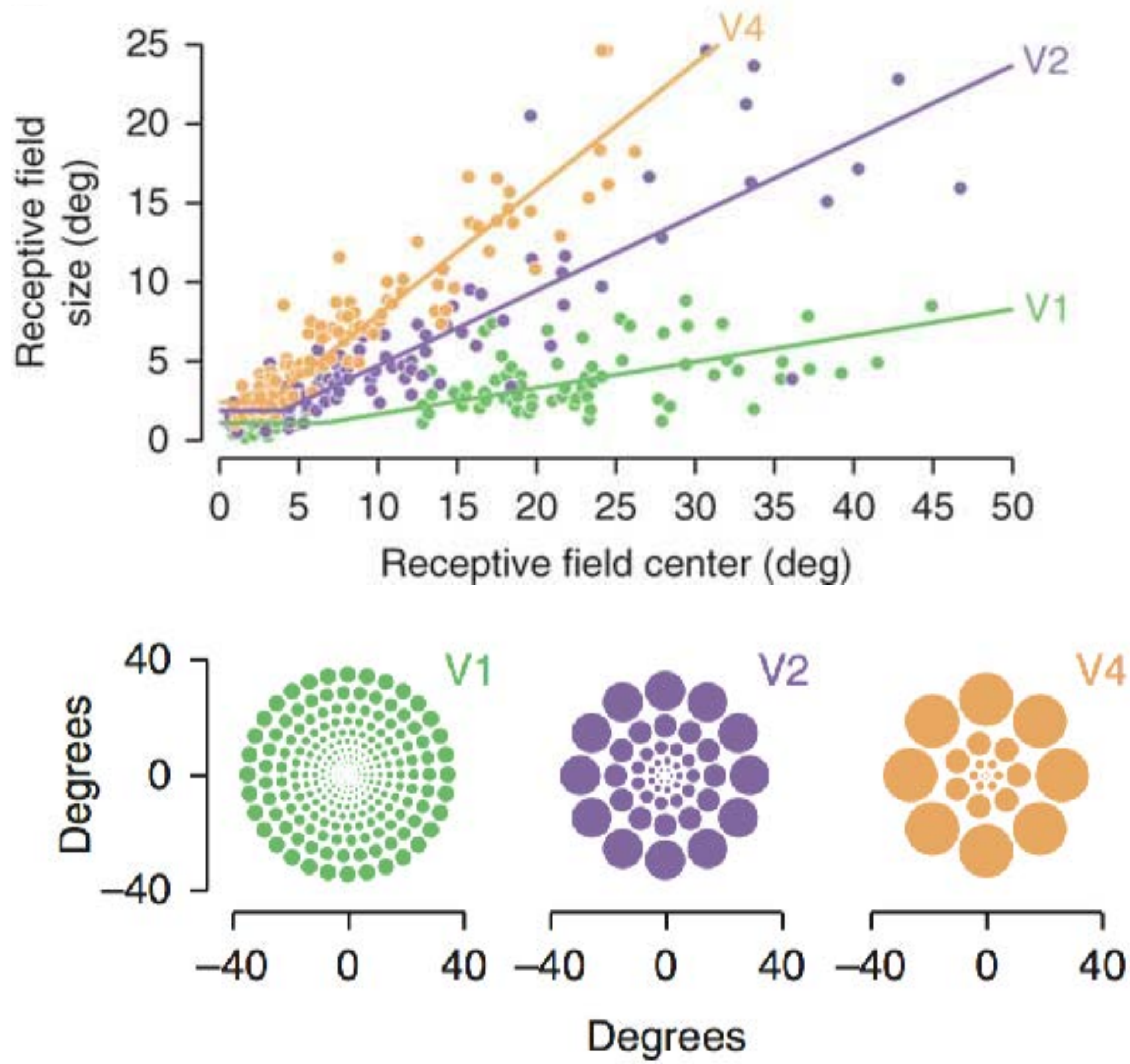
Visual field



Cortical surface (V1)

Peripheral receptive fields

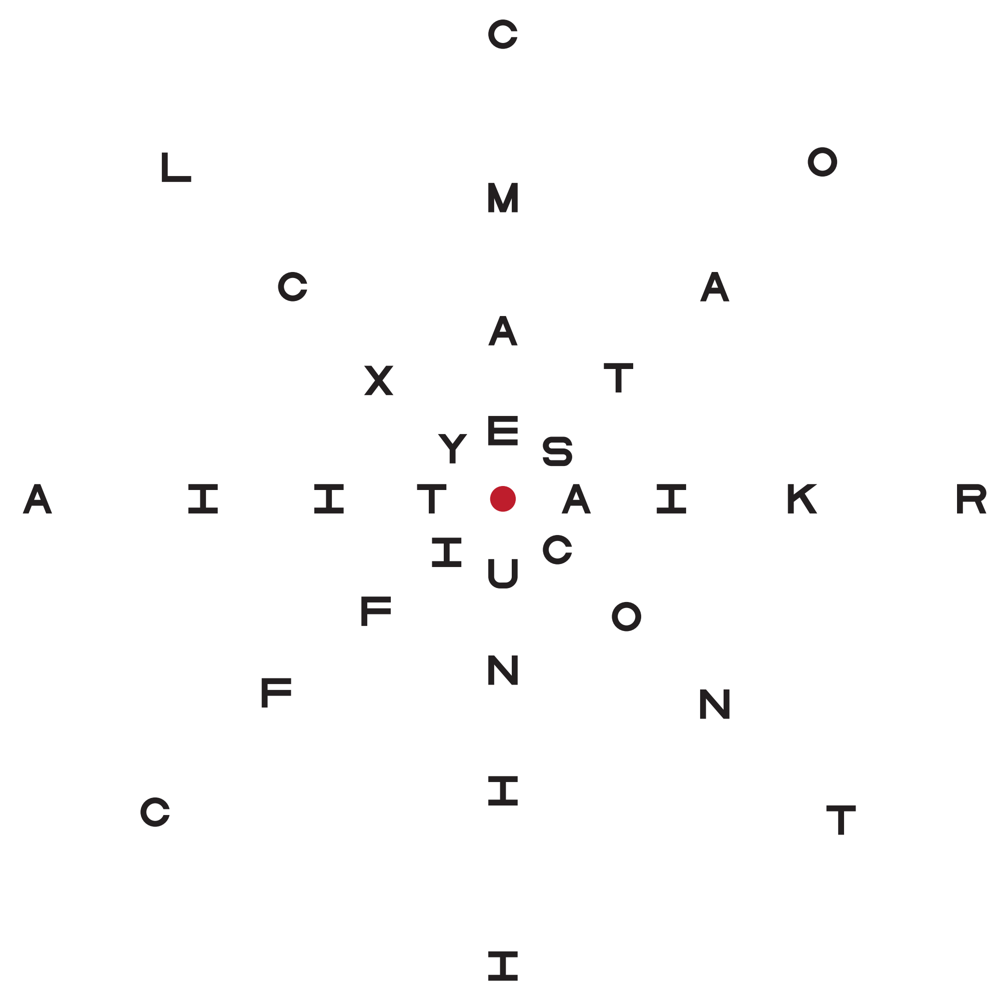
- Receptive fields in visual areas of the brain also grow larger with eccentricity and through the visual hierarchy (Gattass et al., 2005)



Functional consequences

Peripheral acuity

- Peripheral acuity is worse than foveal acuity
  - e.g. a fixed letter size is harder to read in the far periphery vs. near to the fovea



Anstis (1974)

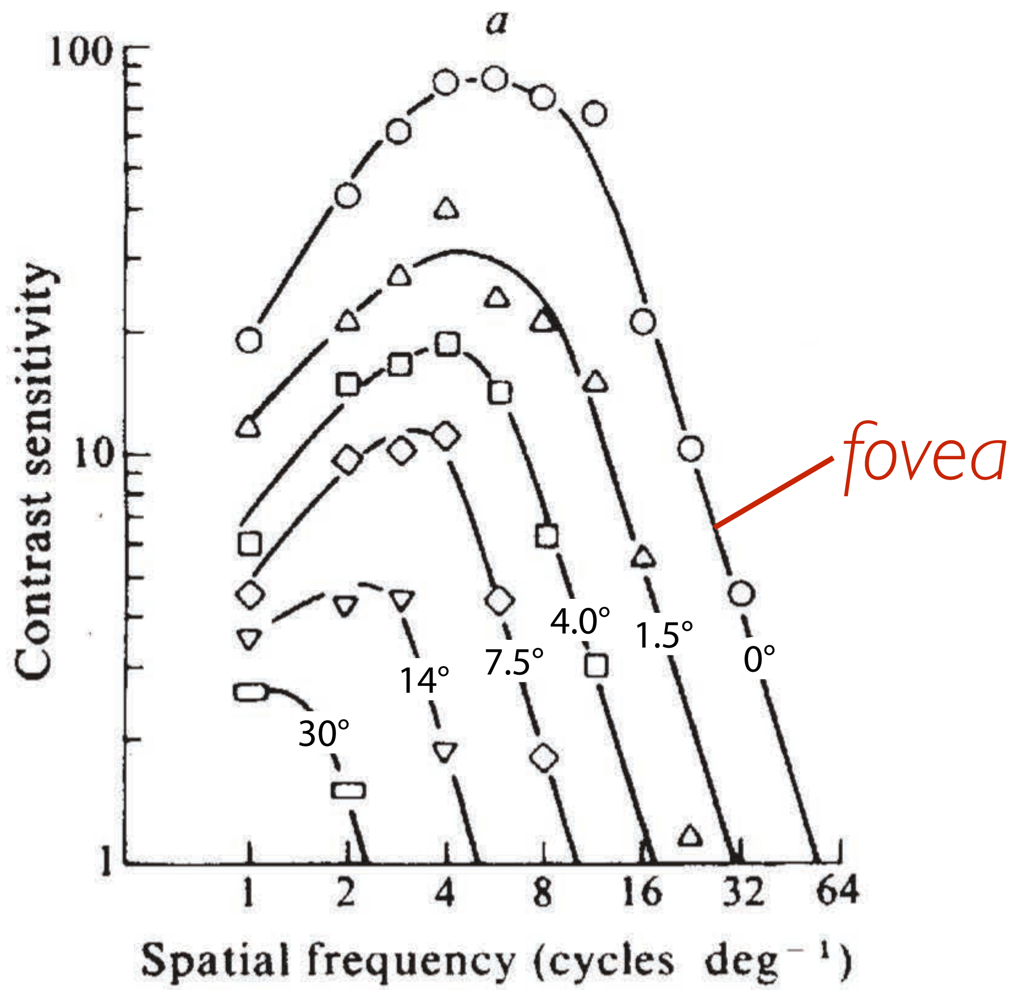
Peripheral acuity

- Peripheral acuity is worse than foveal acuity
  - e.g. a fixed letter size is harder to read in the far periphery vs. near to the fovea
- We can overcome this by increasing letter size (scaling)
- NB this scaling is exaggerated (Rosenholtz, 2016)

Anstis (1974)

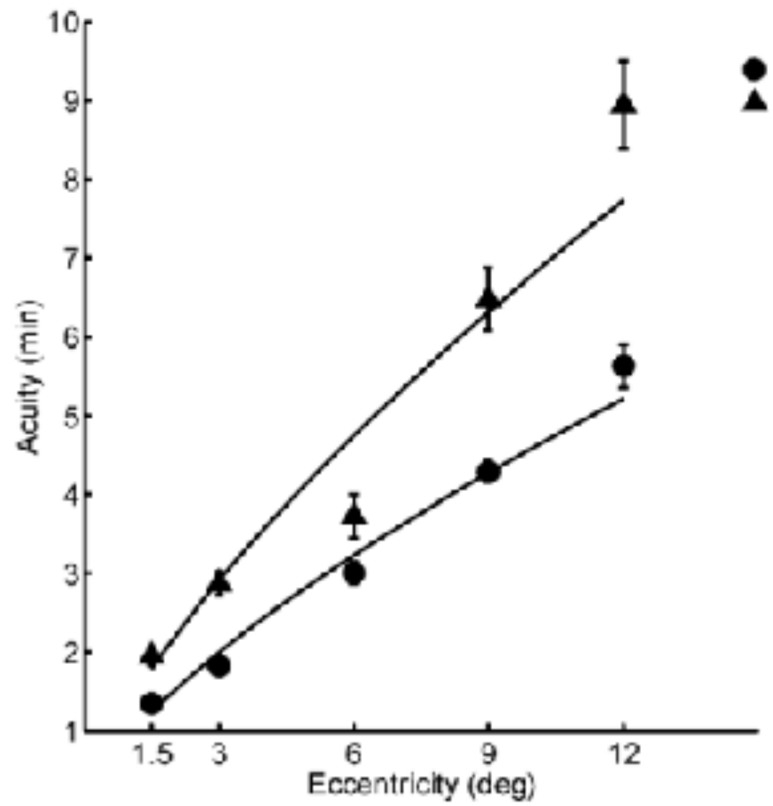
CSF: eccentricity

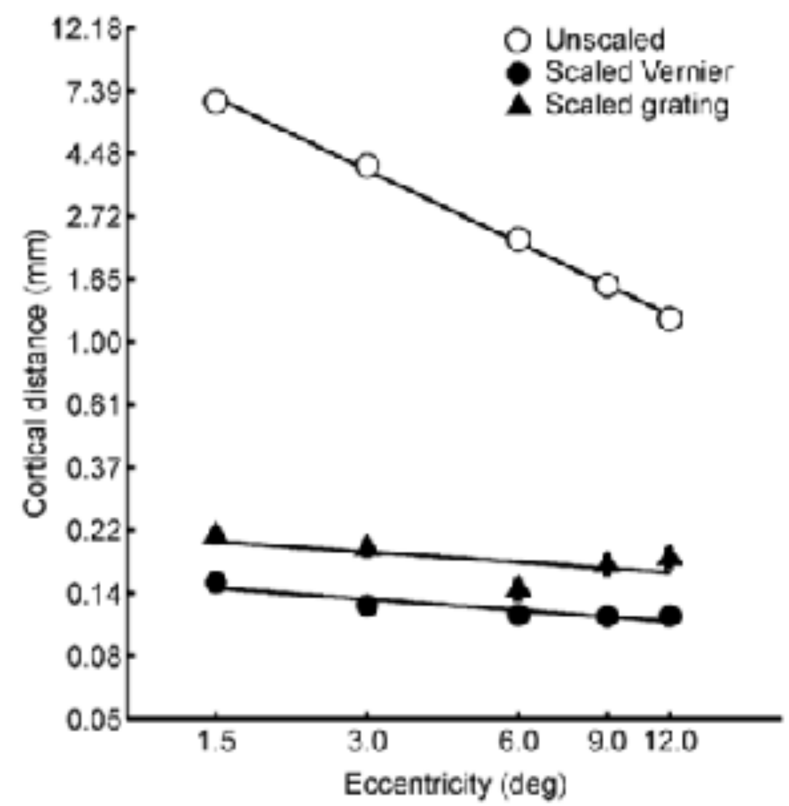
- What about the contrast sensitivity function?
- With increasing eccentricity, the CSF shifts to lower SFs (Rovamo et al, 1978)
  - High SF cutoff decreases (as seen with acuity)
  - Peak sensitivity shifts to lower frequencies



Acuity & cortical magnification

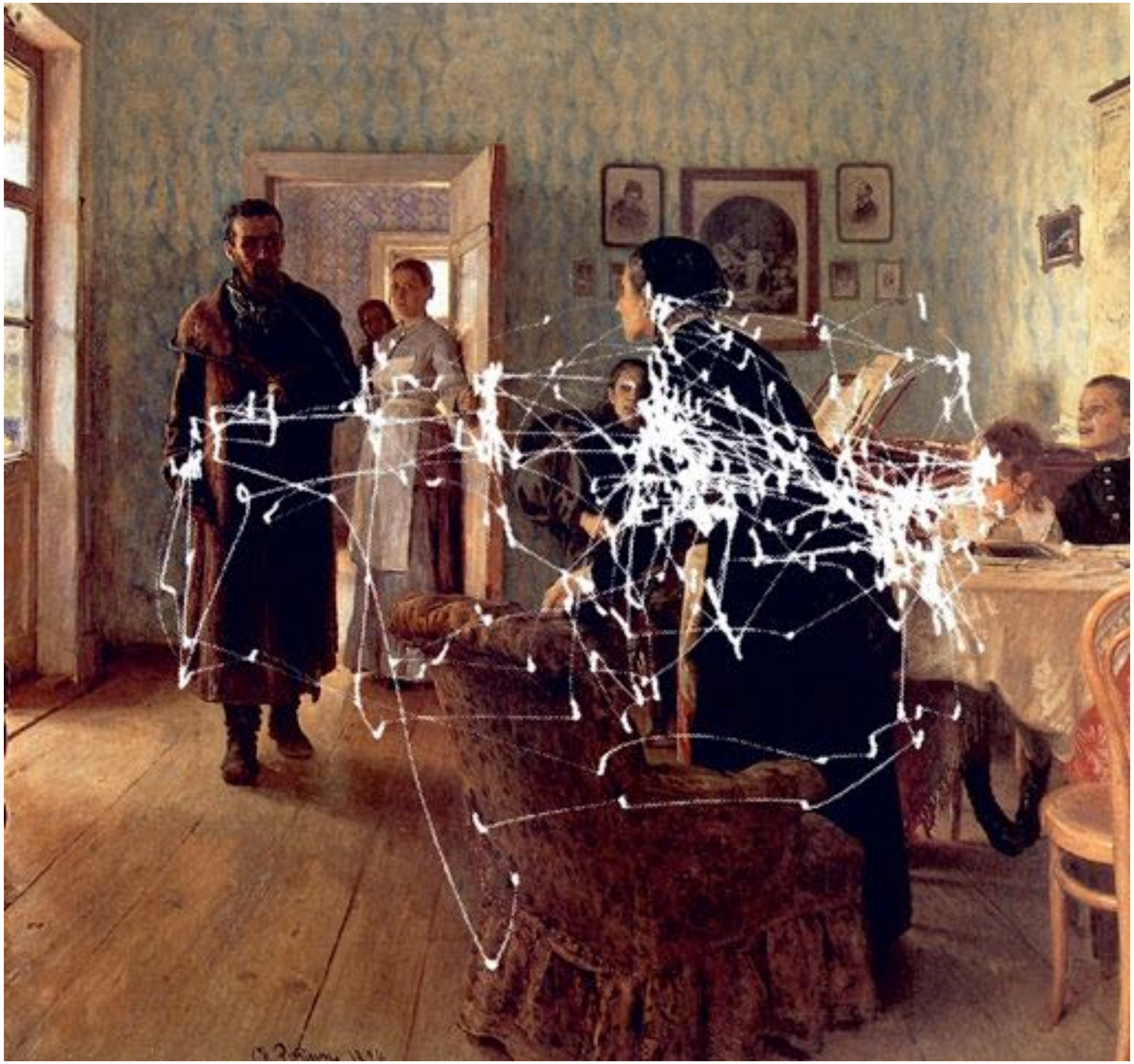
- Duncan & Boynton (2003):
  - Both Vernier and grating acuity decline with eccentricity
  - Projection of these thresholds onto the cortical surface reveals a constant cortical distance regardless of eccentricity (vs. an unscaled fixed separation that shows the effect of cortical magnification)





Scanning behaviours

- A behavioural consequence of these functional limitations can be seen with eye movements
- When shown an image, we scan the scene (Yarbus, 1967)



Can these factors alone explain peripheral vision?

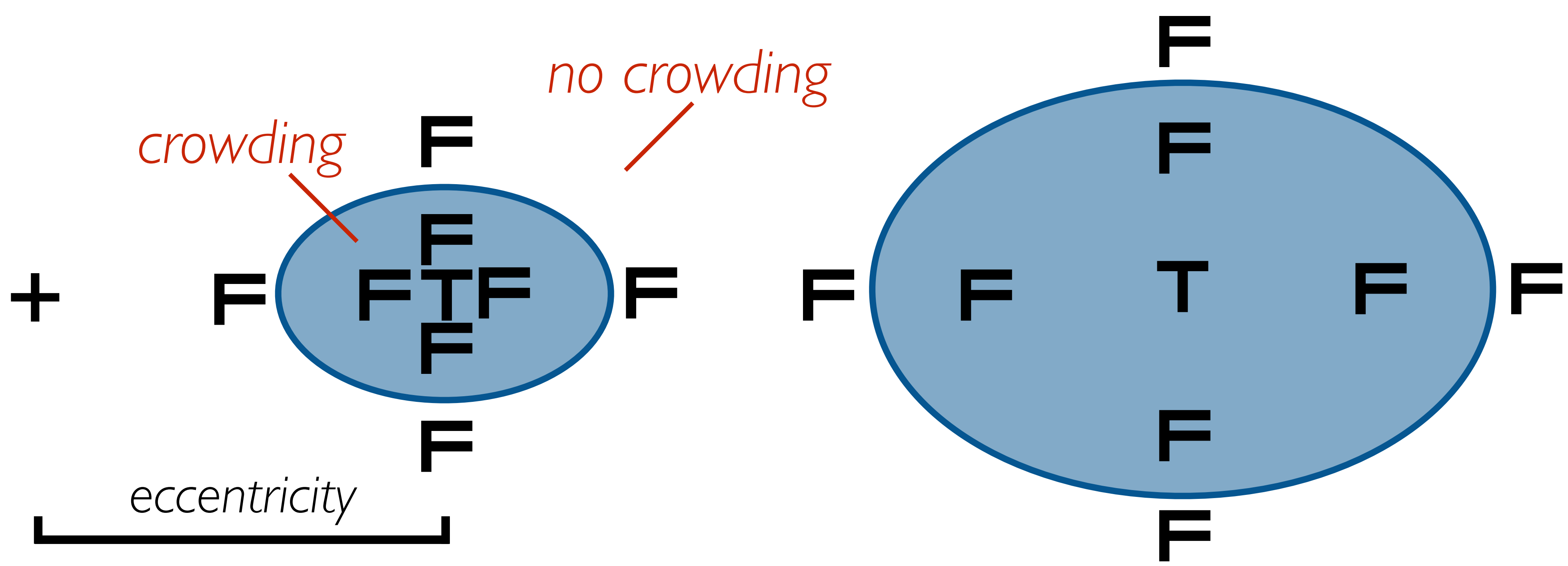
Identification in clutter

Crowding

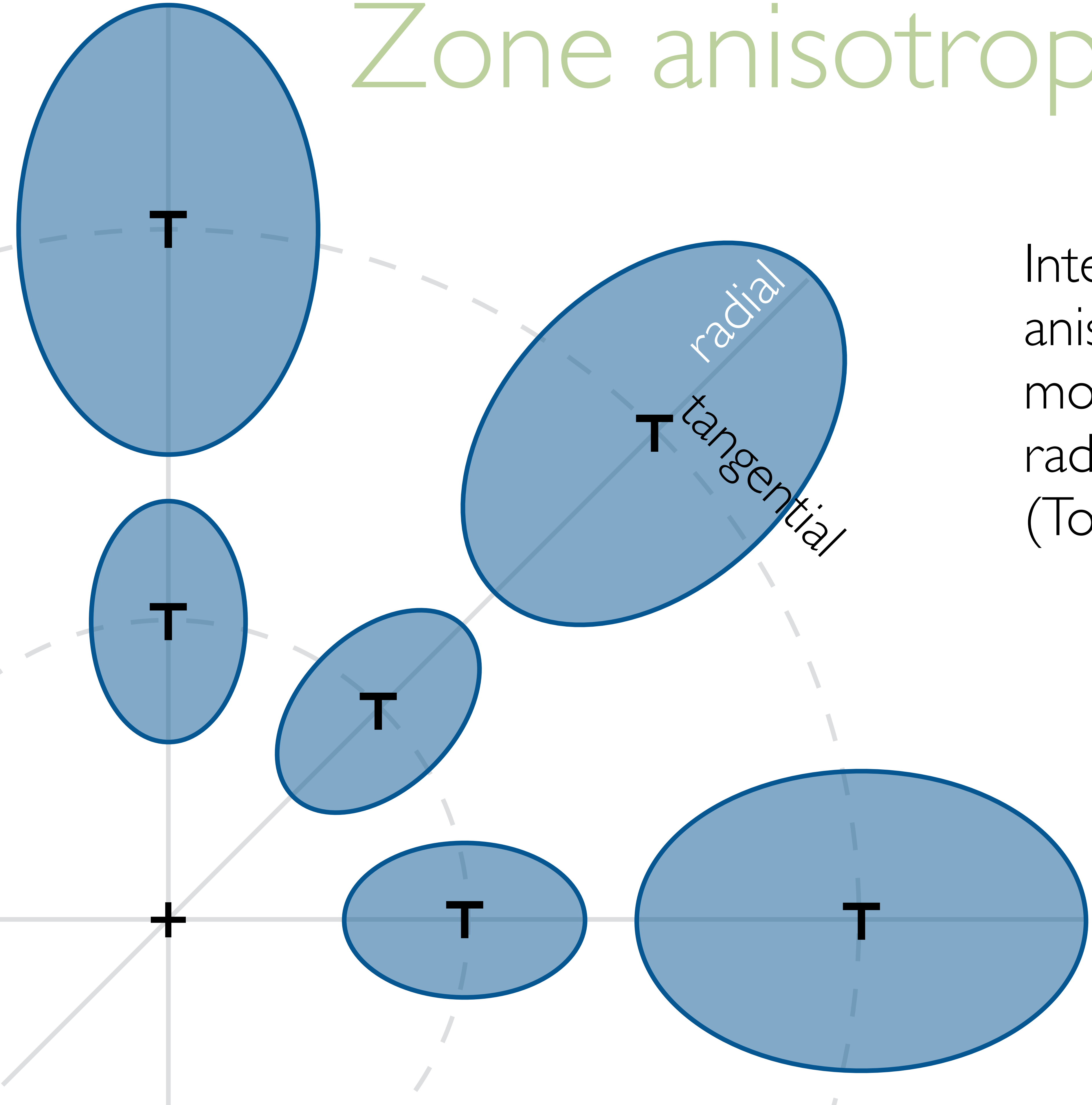
- Impaired recognition of objects in clutter
- Not a limitation in acuity: affects objects that are otherwise visible in isolation (Bouma, 1970)
- Strong in peripheral vision; weak/absent in foveal vision
  - i.e. the periphery is not just a blurry version of the fovea (Rosenholtz, 2016)

When does crowding occur?

- The presence of flankers (F) affect recognition within an *interference zone* around the target (T)
- The 'Bouma law': interference zones increase in size with eccentricity (Bouma, 1970)
  - Scaled to ~0.5x the target eccentricity (Pelli & Tillman, 2008)

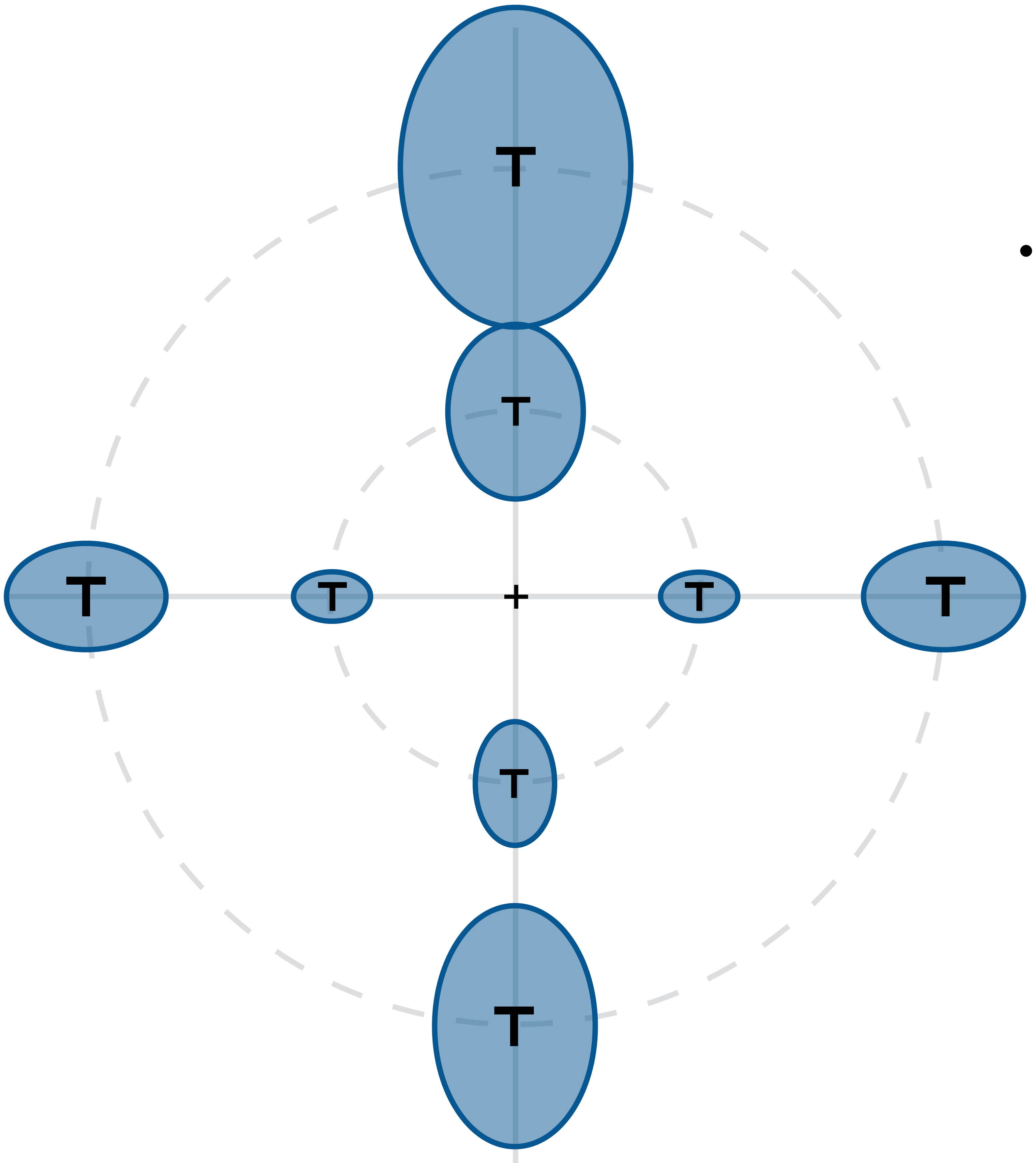


Zone anisotropies



Interference zones are anisotropic:
more crowding along radial vs. tangential axis (Toet & Levi, 1992)

Visual field anisotropies



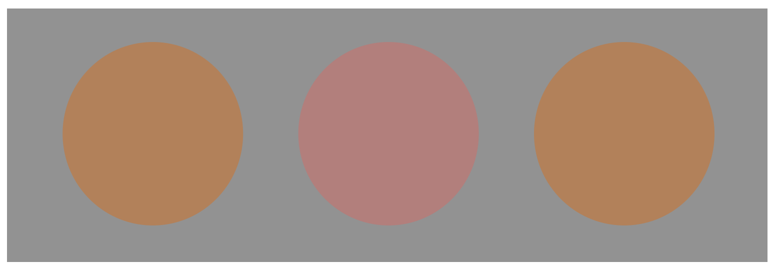
- Crowding varies across the visual field (Greenwood et al, 2017):
  - Greater in the upper visual field than the lower
  - Greater on the horizontal meridian than the vertical

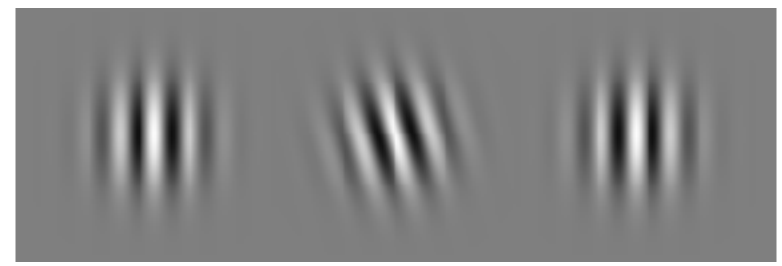
Crowding ruins everything

Orientation
(Wilkinson et al 1997)

Letters
(Bouma, 1970)

Colour
(van den Berg et al, 2007)





Motion
(Bex & Dakin, 2005)

Faces
(Louie, Bressler & Whitney, 2007)

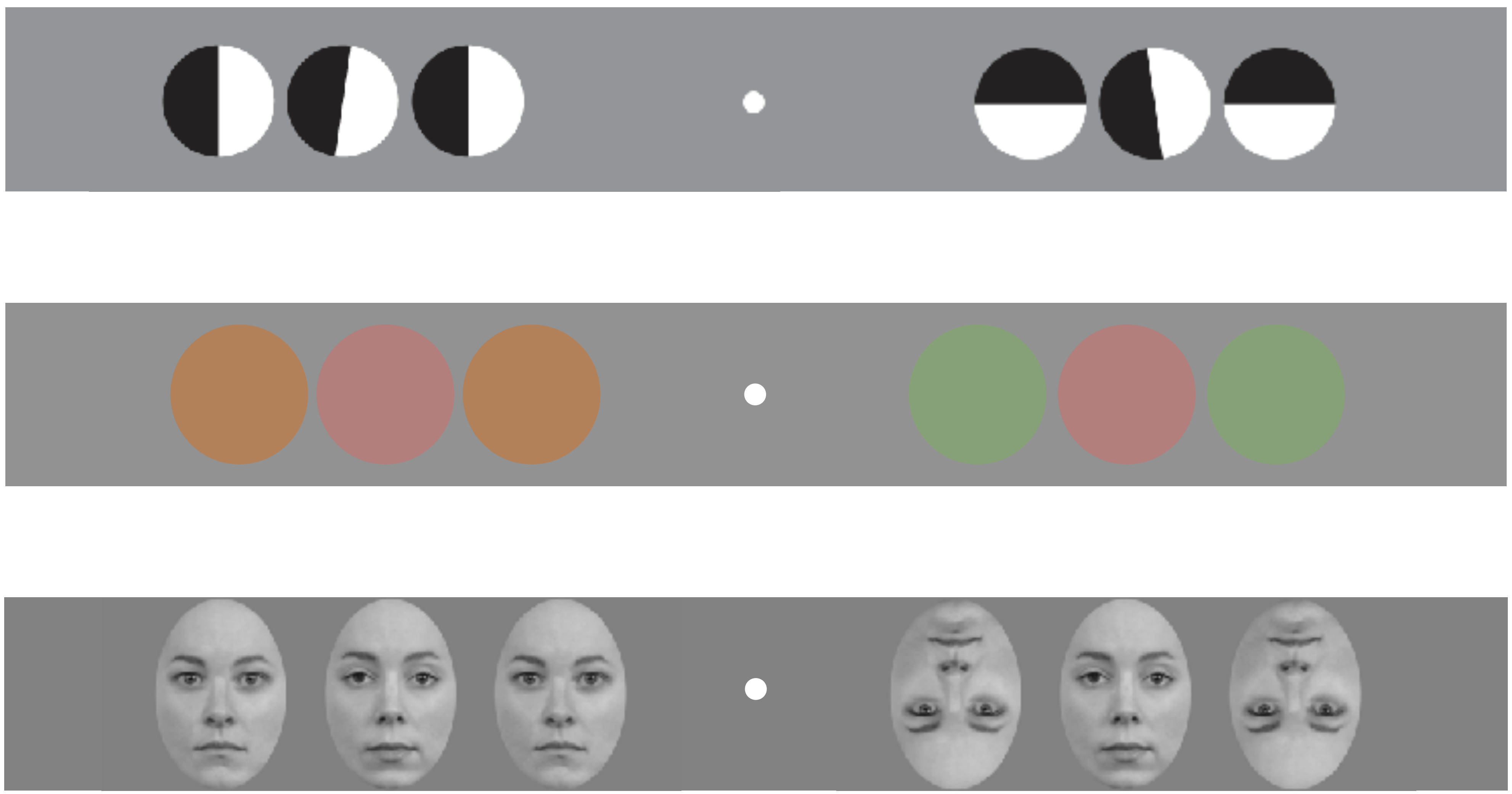
Natural scenes
(Freeman & Simoncelli, 2011)

- Crowding is:
  - ‘the most important factor in peripheral vision’ (Rosenholtz, 2016)
  - ‘a fundamental limit on conscious perception’ (Whitney & Levi, 2011)
  - ‘an essential bottleneck for object recognition’ (Levi, 2008)

But it’s not inevitable

- Modulated by target-flanker similarity (Kooi et al., 1994):
  - Strong crowding with similar elements; weak when dissimilar

strong *weak*



Orientation
Wilkinson, Wilson & Ellemberg, 1997

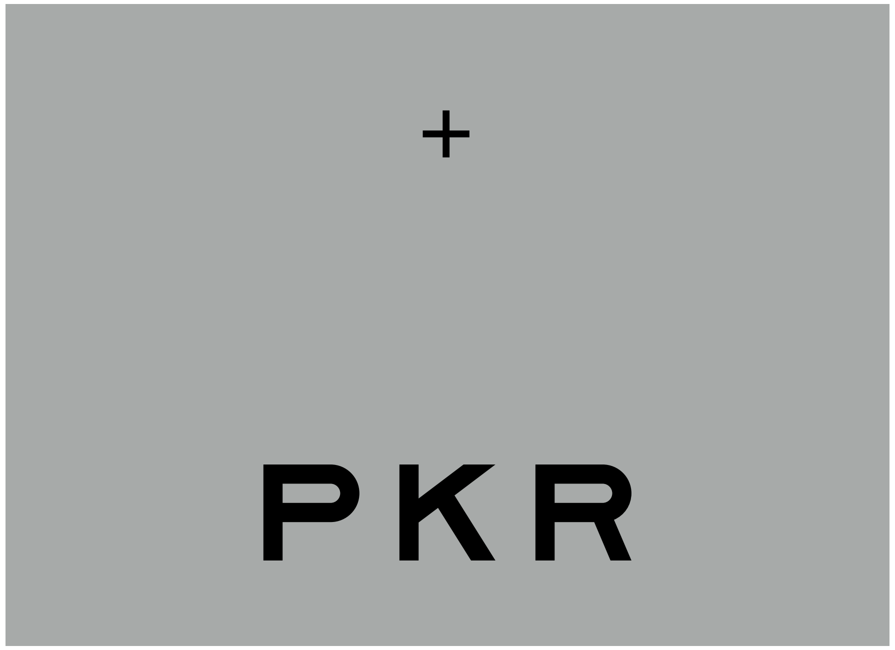
Colour
Kennedy & Whitaker, 2010

Face orientation
Louie, Bressler & Whitney, 2007

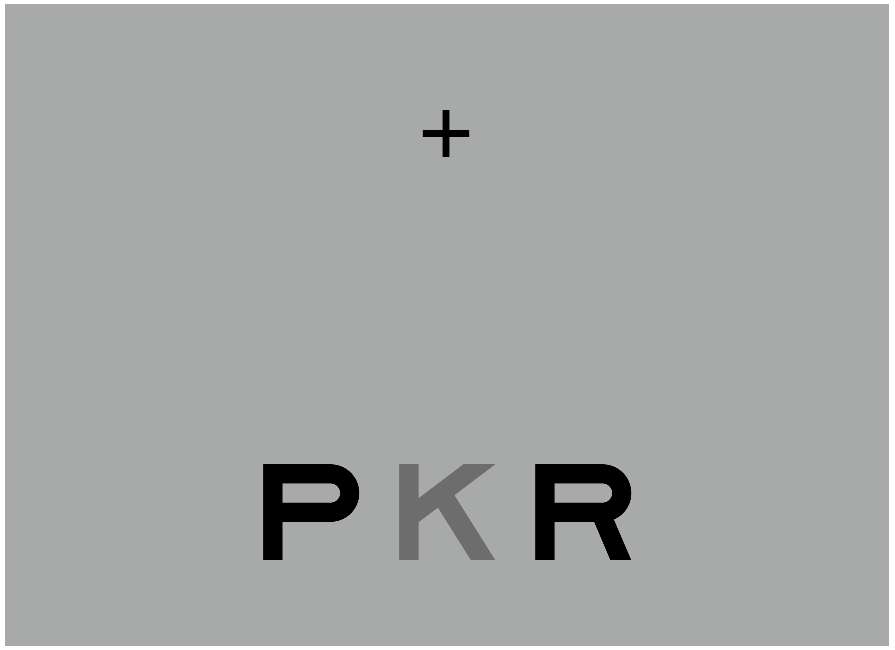
What does crowding do?

- An impairment in the *identification* of a target object
- But *detection* is unimpaired (Pelli, Palomares & Majaj, 2004)
  - i.e. you can see that *something* is present, but not *what it is* (unlike issues of resolution)

Identification:
What is the middle letter?

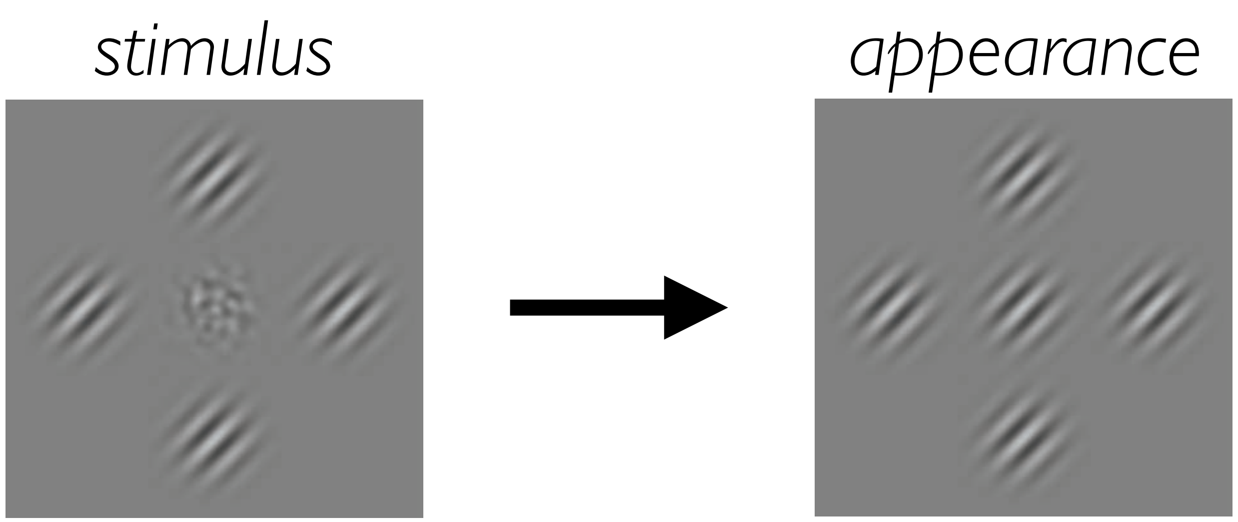


Detection:
Is there a middle letter?



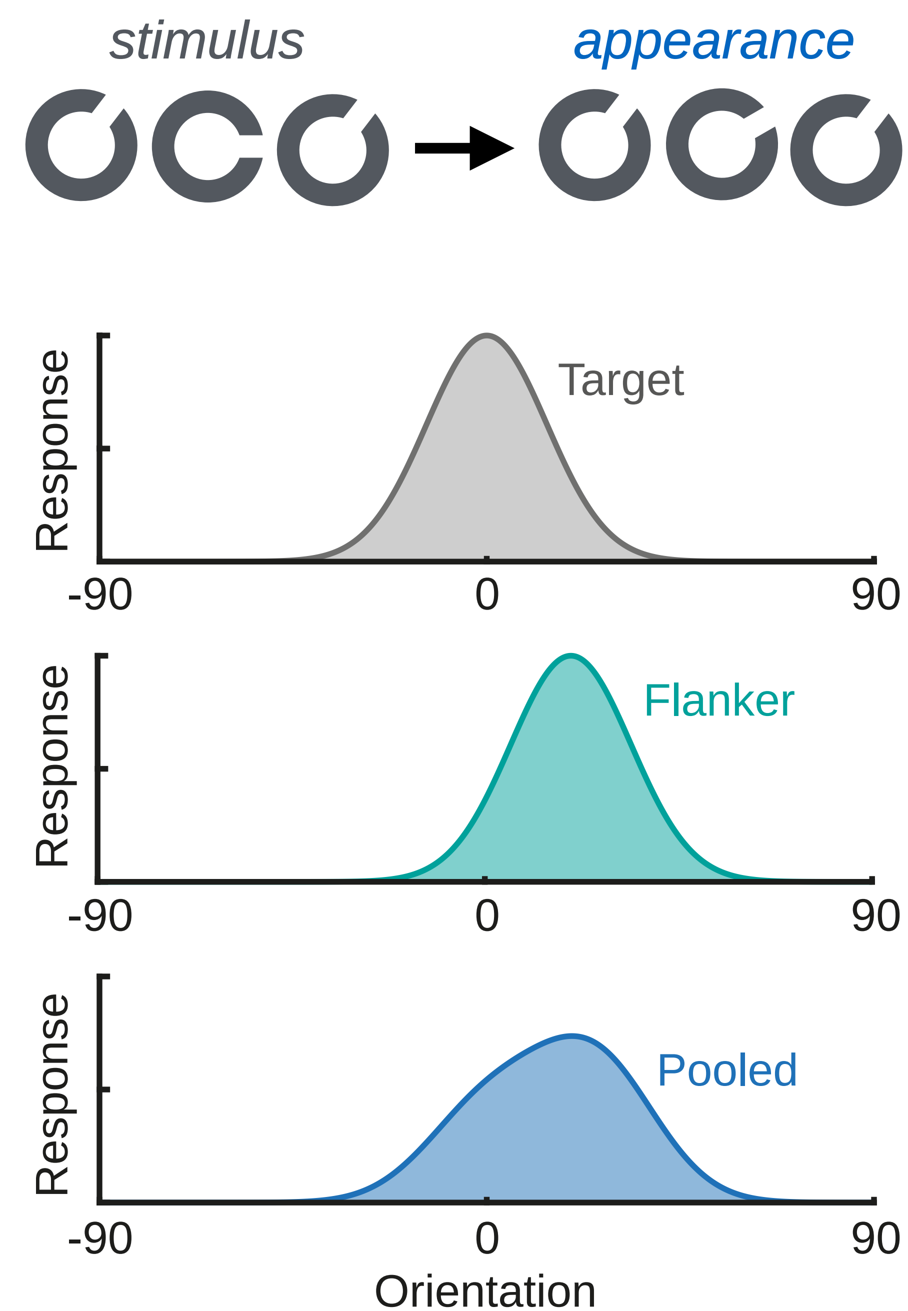
And how does it do it?

- Observers can't report target orientation but can report the *average* orientation in the scene (Parkes et al., 2001)
- A target patch of crowded noise appears identical to a physically oriented stimulus (Greenwood, Bex & Dakin, 2010)
- Adjacent objects become 'pooled' such that the target appears more similar to flankers



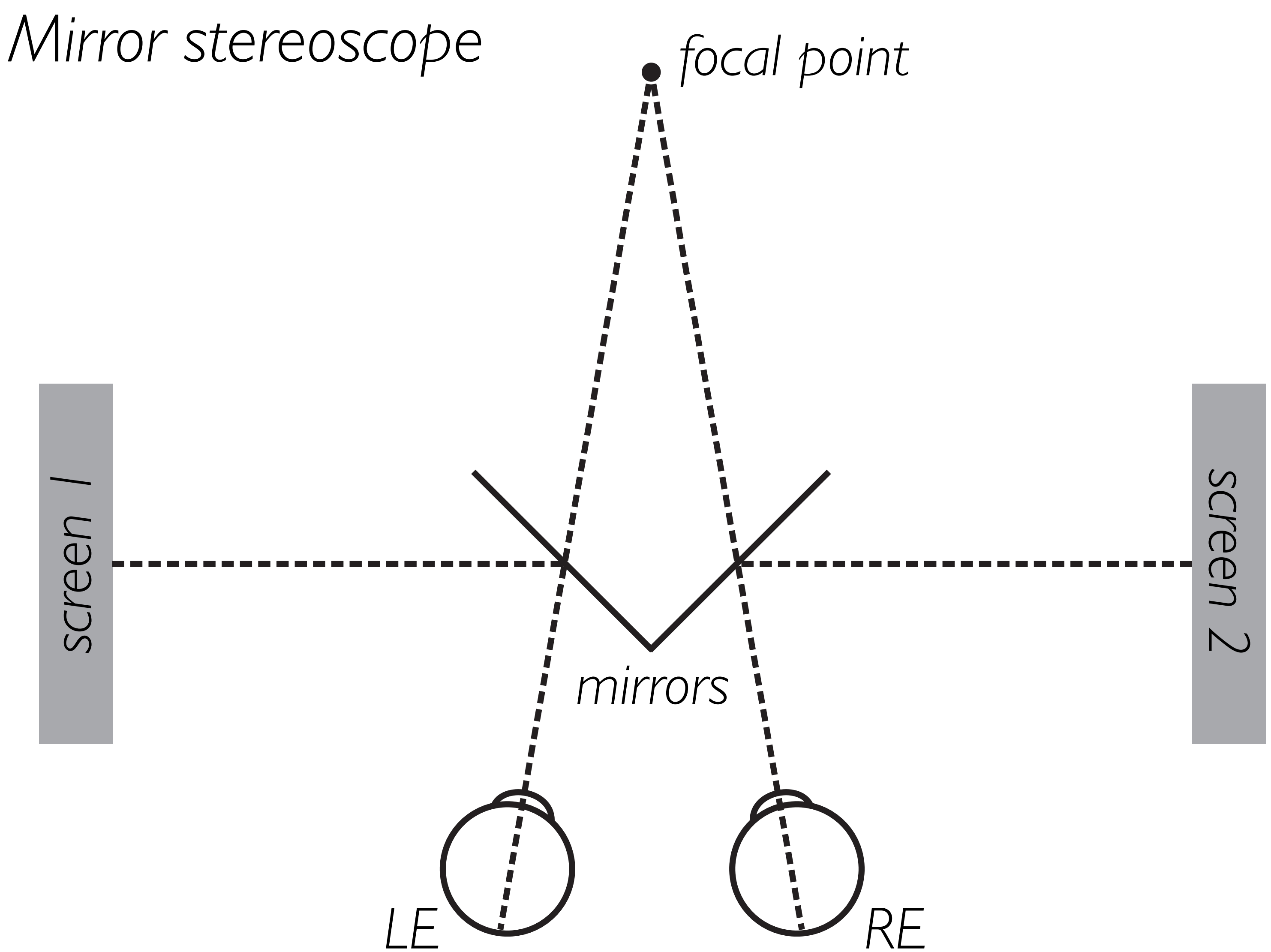
Population-based pooling

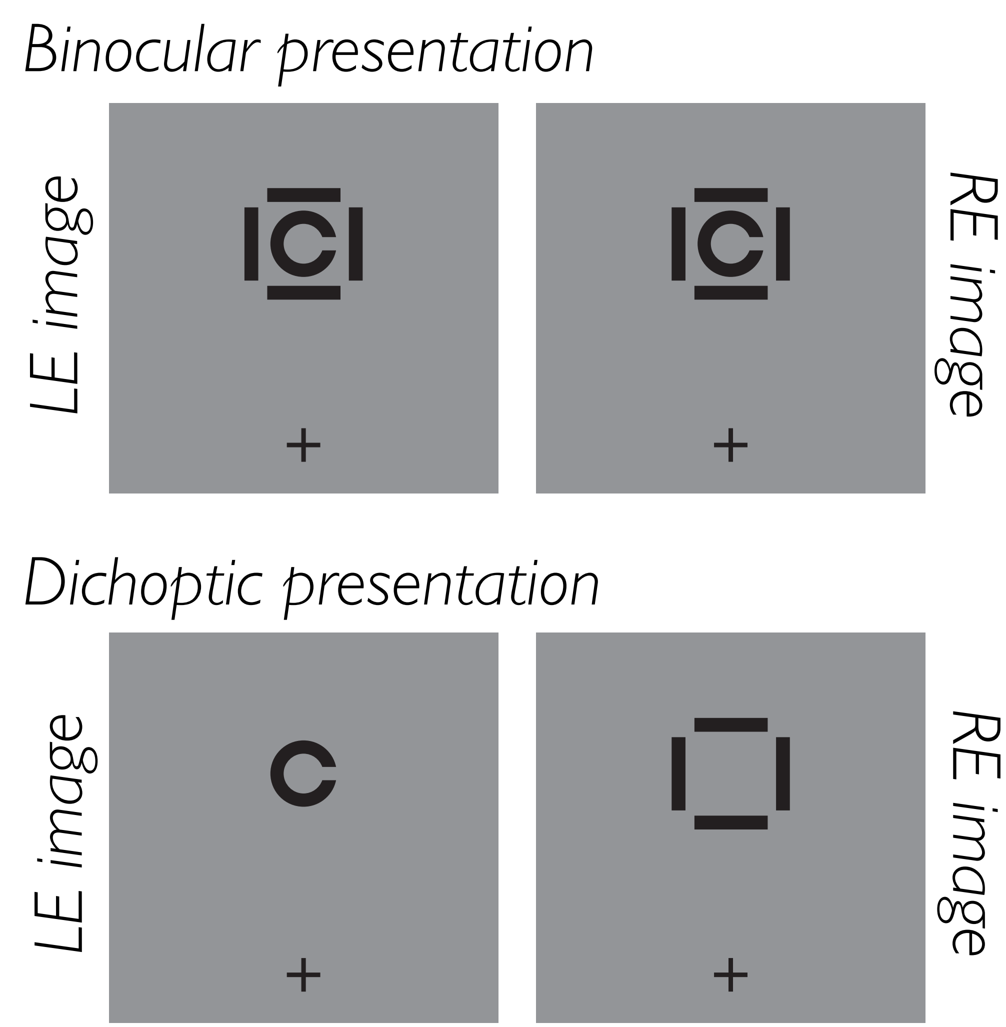
- Pooling models: crowding is an unwanted combination of target and flanker signals
- Harrison & Bex (2015):
  - Pooling occurs in the population responses to the elements
  - Unwanted combination of target and flanker population responses gives a pooled population response
  - The peak of this distribution gives the altered percept for the target



Is crowding in the brain?

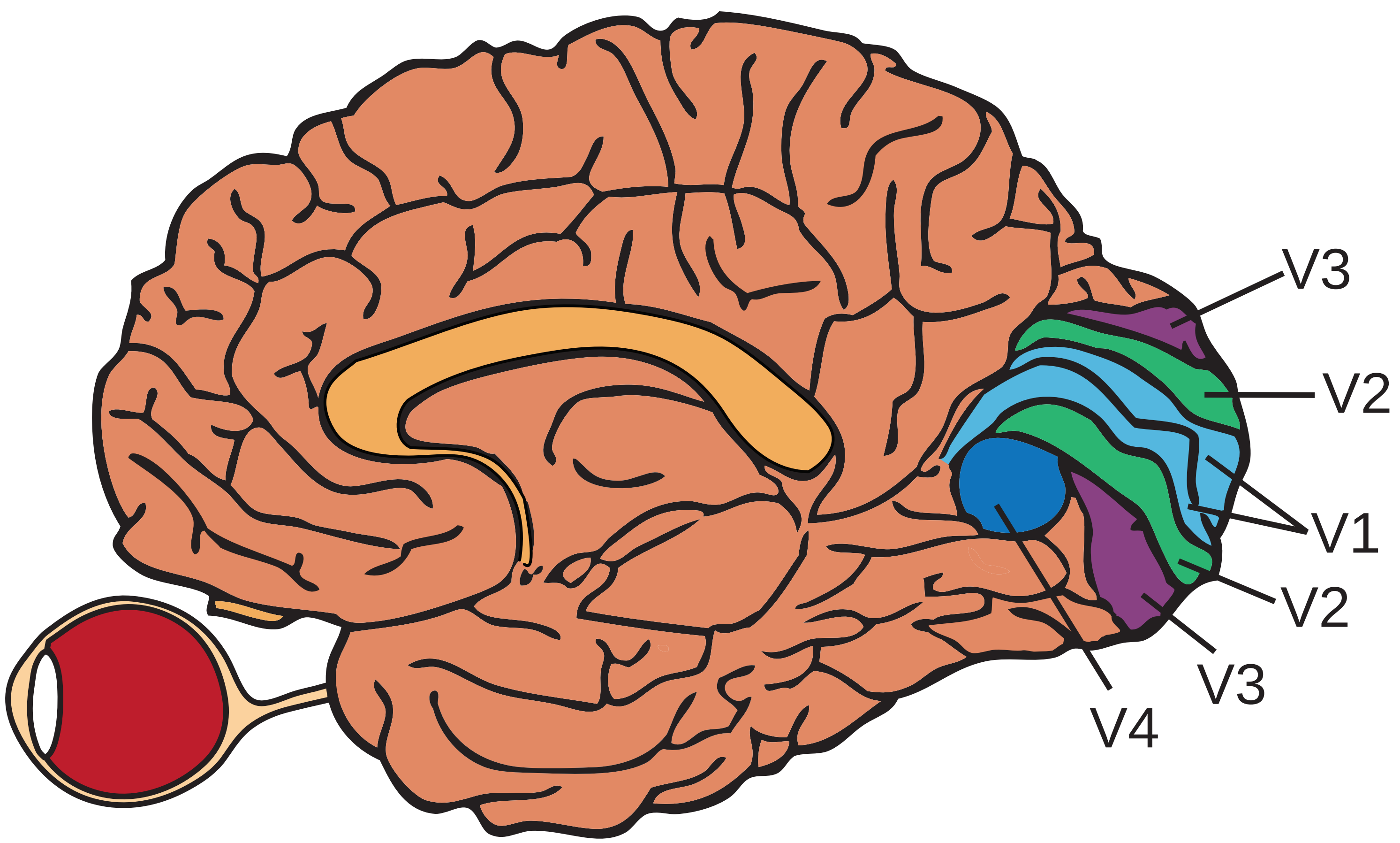
- Dichoptic crowding effects (Flom, Heath & Takahashi, 1963):
  - Magnitude is unchanged when target and flankers are presented to both eyes (binocular) vs. to different eyes (dichoptic)
  - Effects must be at least V1 (where binocular signals first combined)





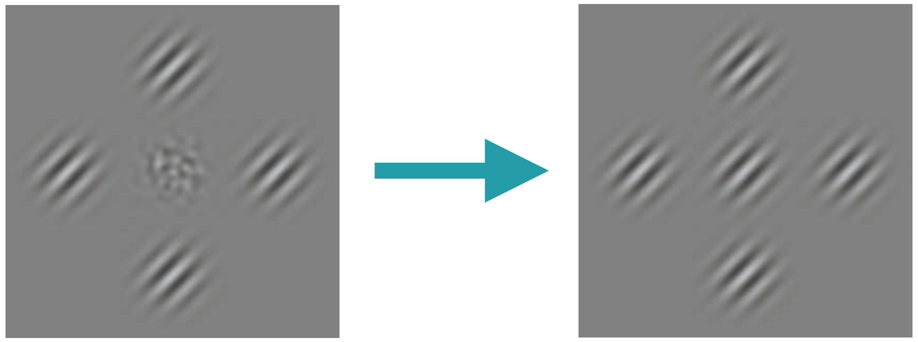
Where in the brain?

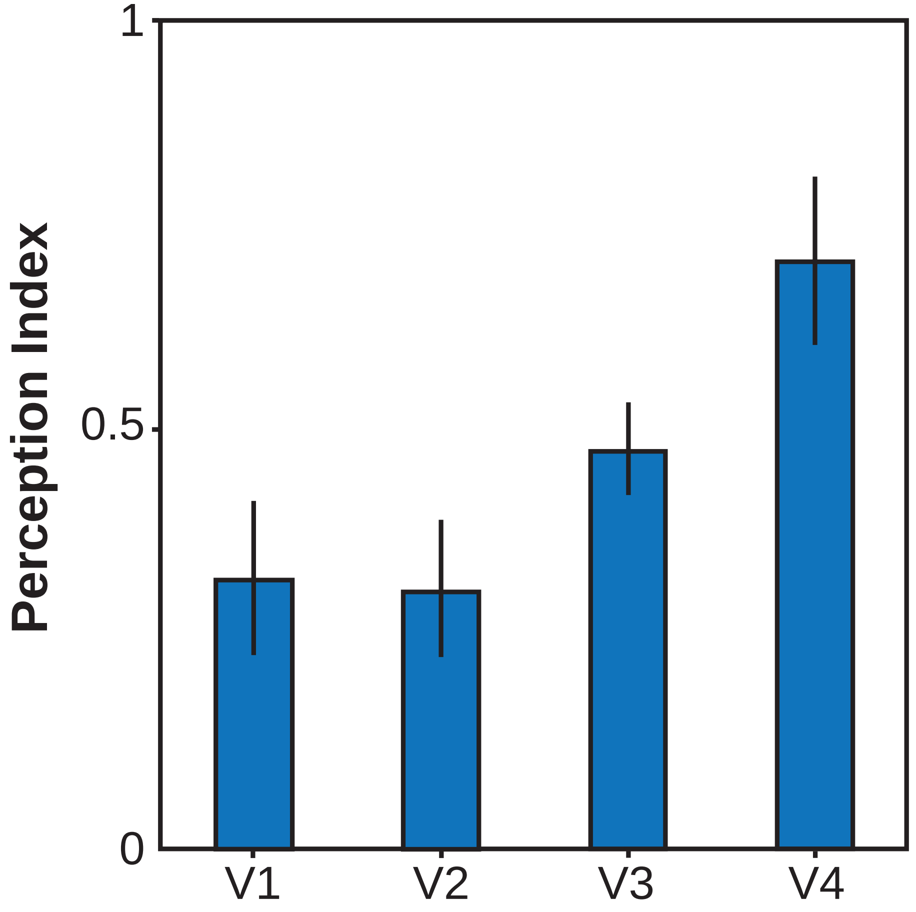
- The precise neural locus of crowding remains unclear
- Neuroimaging evidence gives us some clues



Changes in the brain

- Which region(s) respond to the perceptual changes of crowding? (Anderson et al., 2012)
  - BOLD responses in visual areas converted to a 'Perception Index'
  - Higher values mean greater change in response when crowded stimuli look different vs. the same
  - Some modulation in the earliest visual areas (including V1)
  - Increased modulation in higher areas V3 & V4





Why crowd?

- Two points to consider about crowding:
  - It occurs when visual information exceeds our processing capacity
    - i.e. it disrupts peripheral vision, which is under-sampled relative to the fovea (fewer photoreceptors, larger receptive fields, etc.)
  - Its operation is to simplify visual input
    - Adjacent objects become more perceptually alike (Greenwood et al., 2010)
    - Although observers cannot report individual item orientations they can report the average orientation (Parkes et al., 2001)

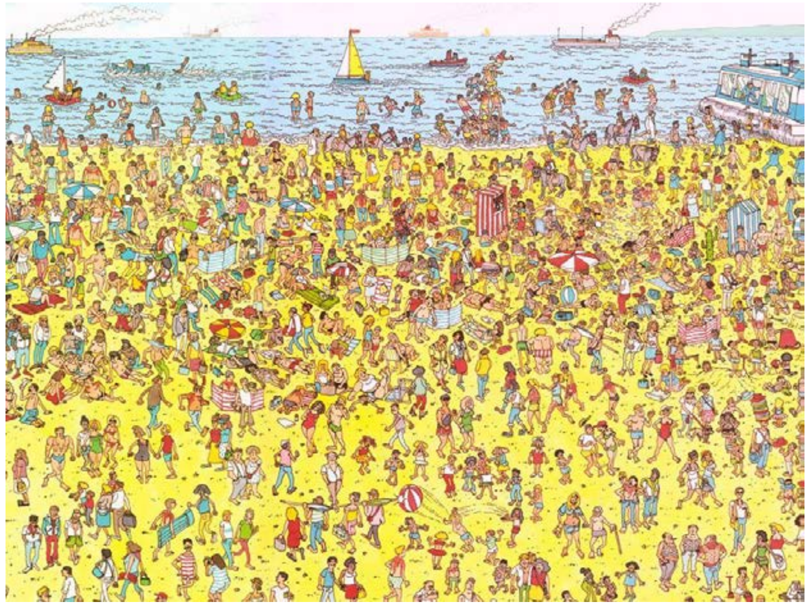
Why is this task difficult?

Is crowding useful here?

- Crowding gives us the 'gist' of the visual field rather than everything in fine detail (Freeman & Simoncelli, 2011)
  - Pooling across space gives us the average orientation, colour, etc.
  - May be an adaptive way to represent information-rich images simply with limited resources

The illusion of a 'rich' periphery





- The aforementioned studies combine to suggest the periphery is quite impoverished
  - Shows impaired acuity, low contrast sensitivity, high crowding, etc.
- But our subjective impression is of a 'rich and detailed' visual field (Cohen, Dennett & Kanwisher, 2016)
- Could this be due to crowding (Rosenholtz, 2016)?
  - Summary statistics in peripheral vision give a sense of 'richness' in the face of limited resources

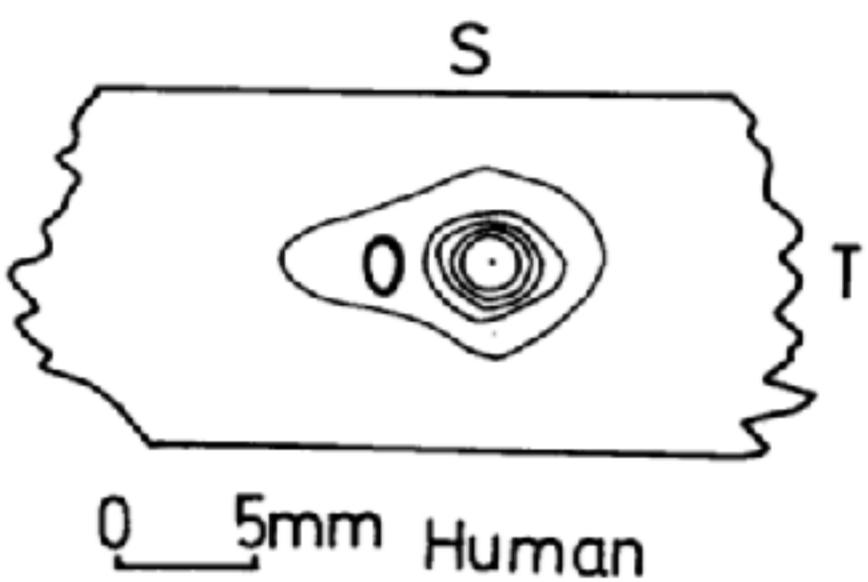
Context in fovea vs. periphery

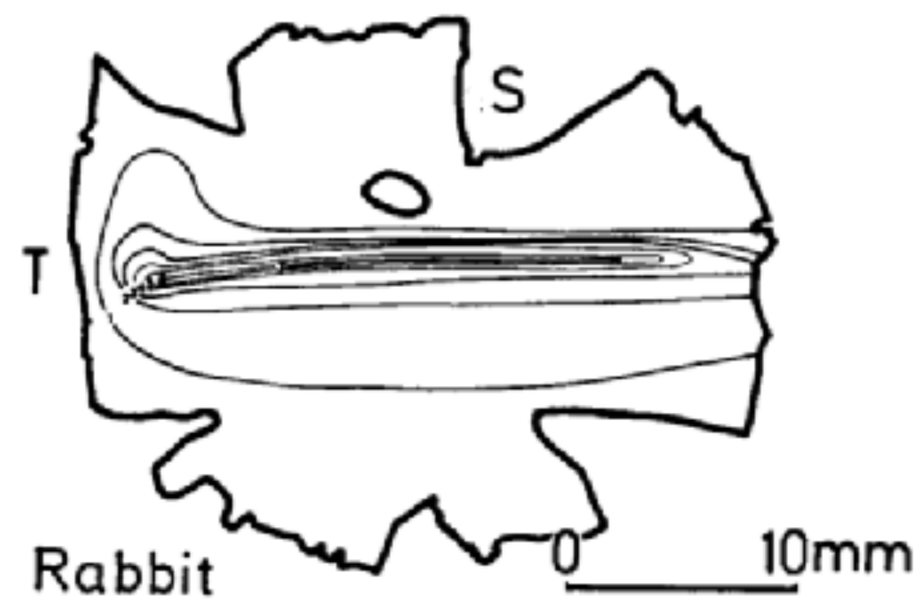
- Note that crowding differs from foveal processes like tilt contrast where differences are emphasised
  - Emphasising differences is a better strategy when the image is more finely represented, as in the fovea

Vision in other species

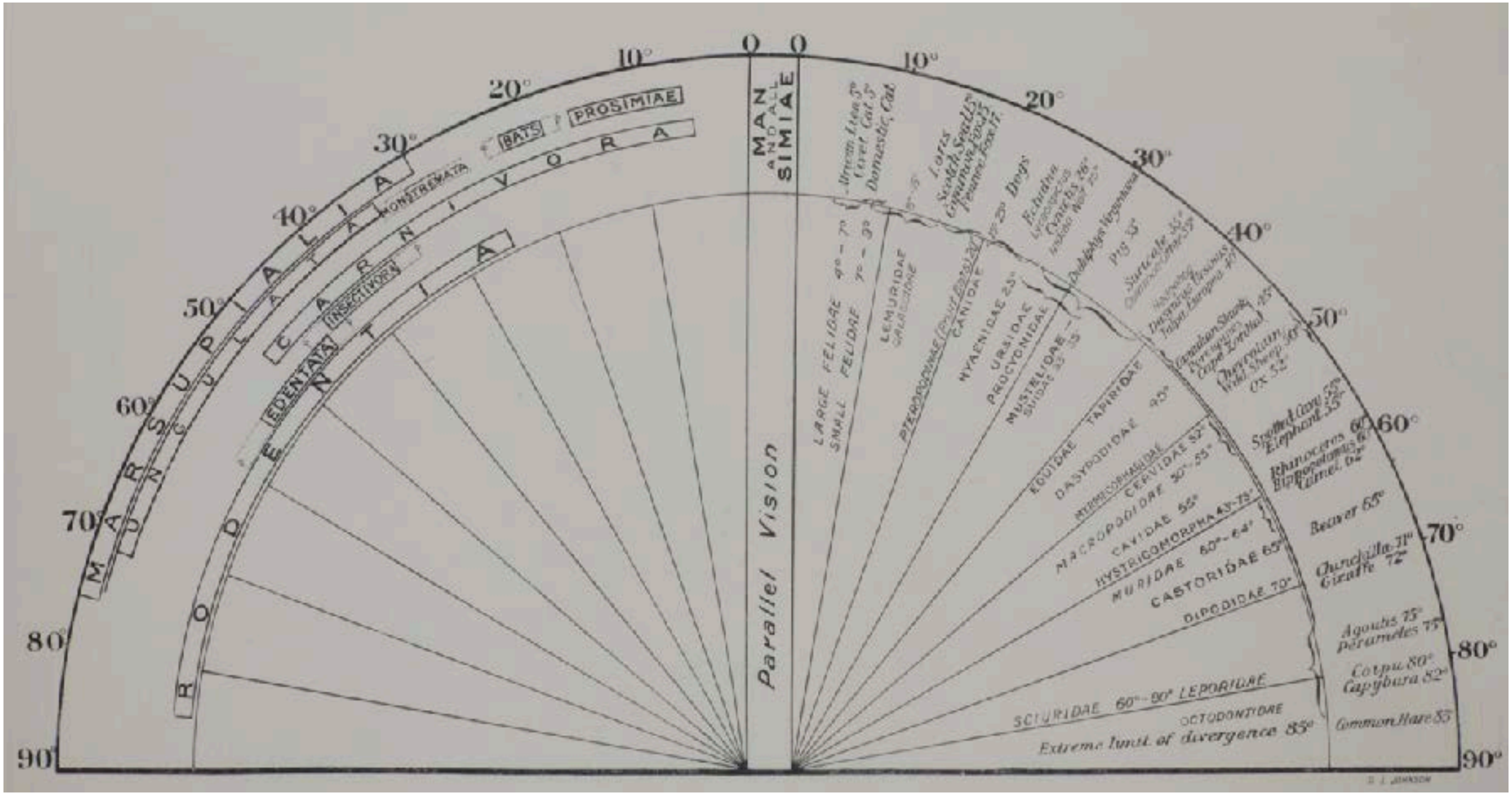
The retina in other species

- We have a foveated retina (with an 'acute zone')
- Many species don't (Johnson, 1901)
  - e.g. the rabbit retina shows a 'horizontal streak'
    - Highest concentration of retinal ganglion cells lies along the horizontal meridian, without a single point of focus





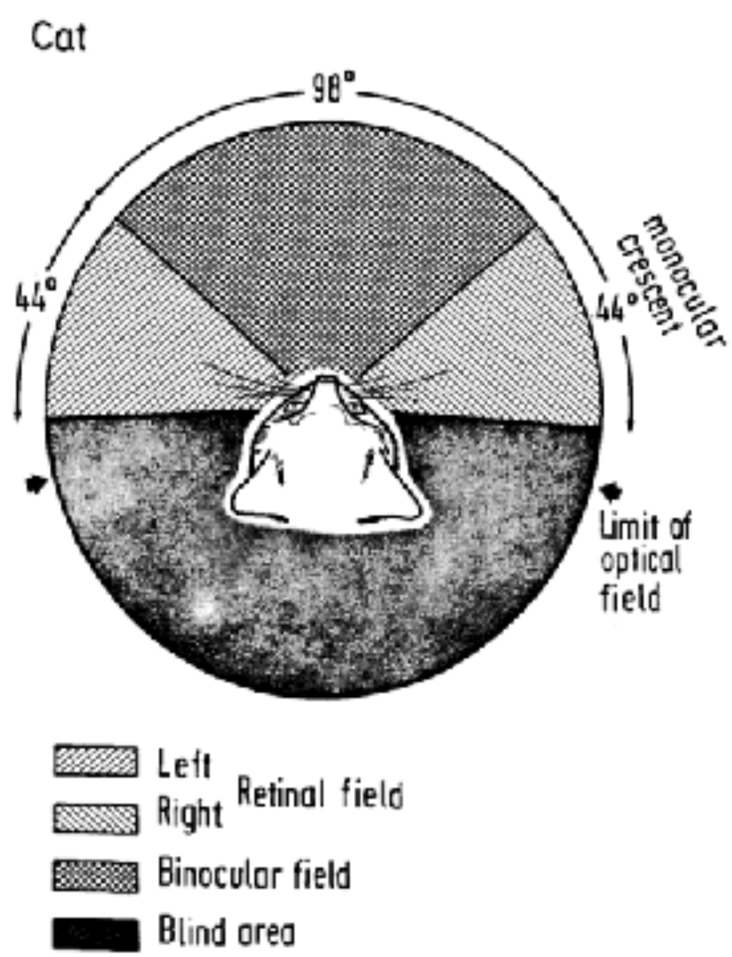
Predators vs. Prey?

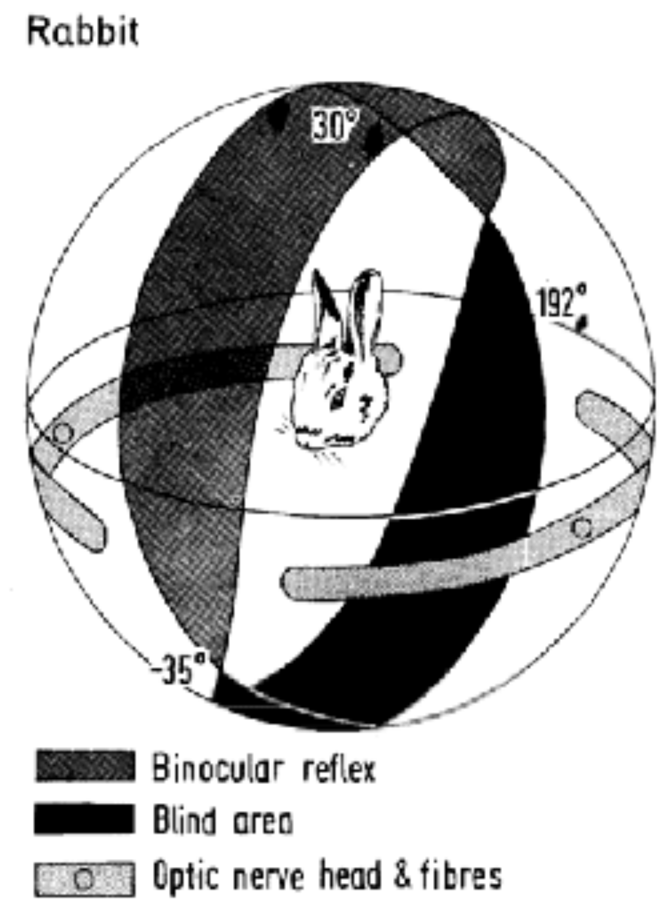


- Johnson (1901): Variation in 'optic axes' (direction of resting gaze) shows a separation between predators (frontal eyes) and prey (lateral eyes)

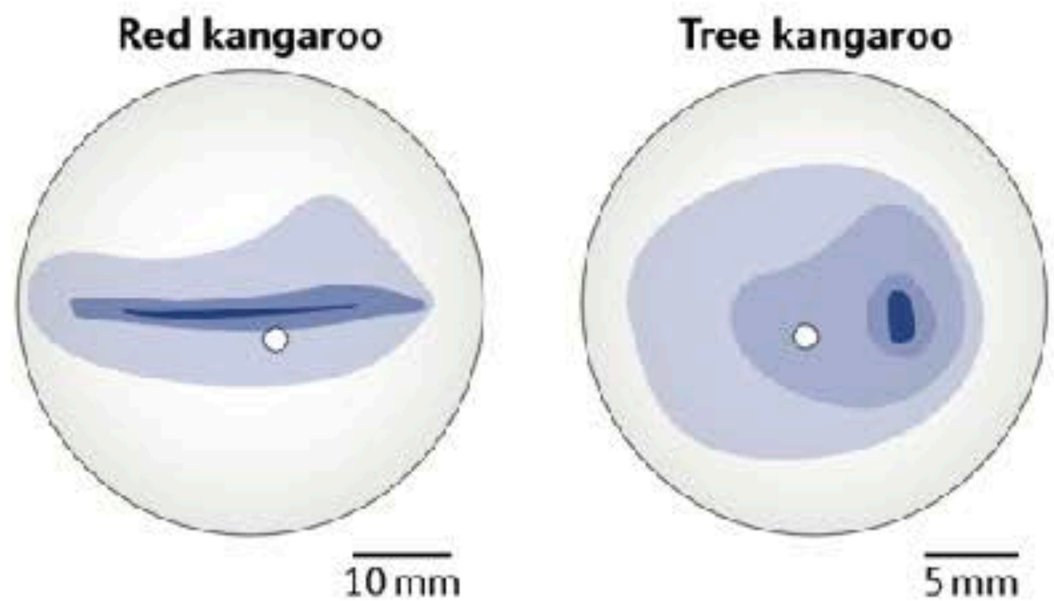
Visual field extent

- Johnson (1901): Retinal cell distributions and optic axes give differential sensitivity across the visual field
    - Predators: narrow field with high central acuity
    - Prey: wide field of view with distributed acuity





Ecological context matters



- Baden, Euler & Berens (2020): many species do not fit the predator vs. prey distinction, e.g. two species of kangaroo:
  - Red kangaroos live in open plain environments
  - Tree kangaroos live in dense forest
- Need to consider the 'visuoecological needs' of animals
- But efficient coding of visual input is still likely the driving factor in these distinct patterns of organisation

Summary

- Vision differs markedly between the fovea and periphery
- Acuity declines with eccentricity and the CSF shifts to lower frequencies
- Crowding disrupts peripheral vision, capturing 'gist' at the expense of fine detail
  - Occurs within an interference zone around the target
  - Affects a wide range of visual features (motion, colour, etc.)
  - Produces a *change* in the appearance of the target object
  - Likely an adaptive way to simplify rich visual environments
- These variations may reflect our 'visuoecological needs'

Reading

- Some further sources if interested or confused:
  - Peripheral vision:
    Rosenholtz (2016). Capabilities and limitations of peripheral vision. *Annual Review of Vision Science*.
  - Crowding:
    Whitney & Levi (2011). Visual crowding: a fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences.*
  - Variations across species:
    Baden, Euler, & Berens (2019). Understanding the retinal basis of vision across species. *Nature Reviews Neuroscience*.