Spatial vision

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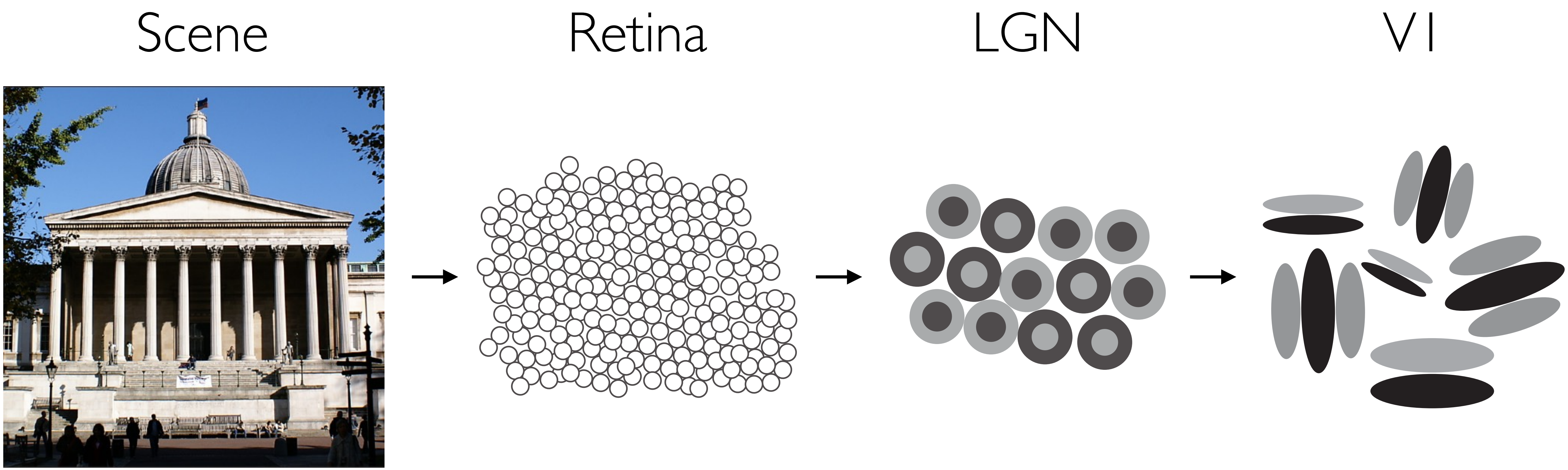
Today

- What is spatial vision?
- Orientation perception
- Spatial frequency perception
- Context effects in spatial vision

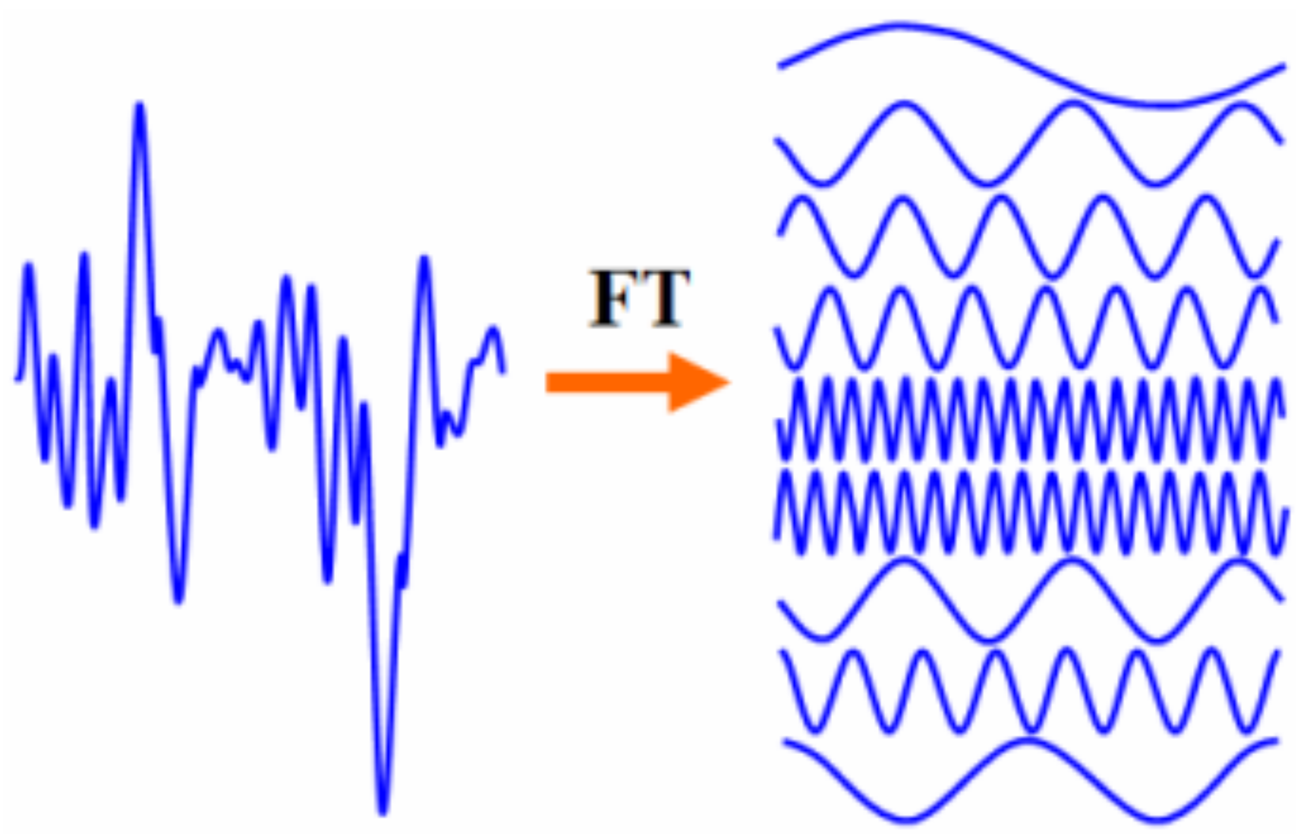
What is spatial vision?

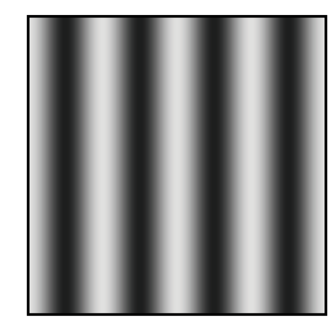


- Perception of the distribution of light across the visual field
  - The 'building blocks' of object perception in the early stages of visual processing
- What are the dimensions of spatial vision?
  - Fourier analysis gives us some clues

The Fourier Transform

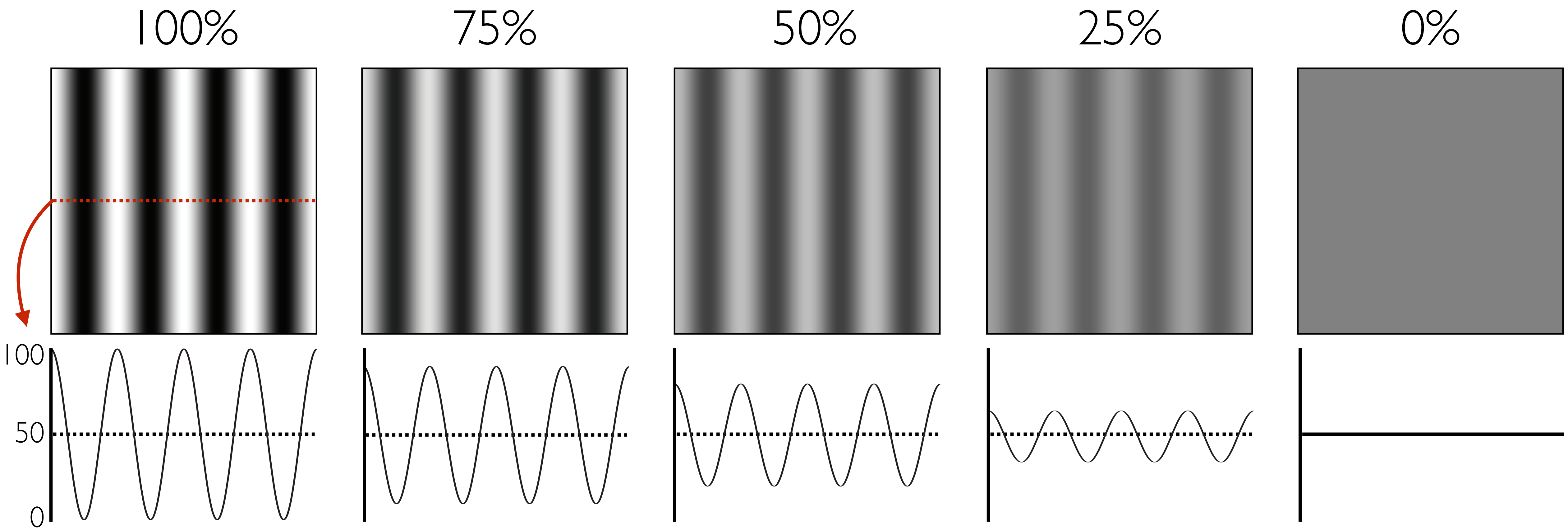
- Fourier (1822) showed that any signal can be characterised as the sum of sine waves at different frequencies, amplitudes and phases





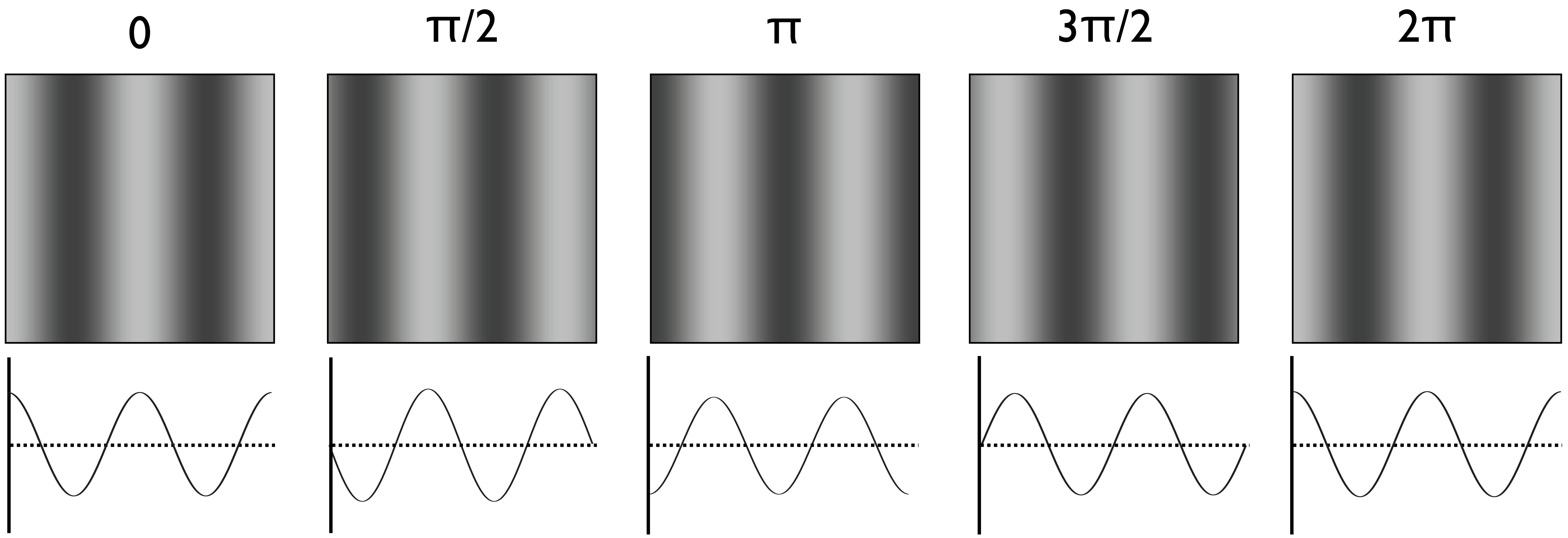
Sine wave amplitude

- Amplitude for a sine wave grating gives luminance contrast
  - The difference between light and dark regions in the scene



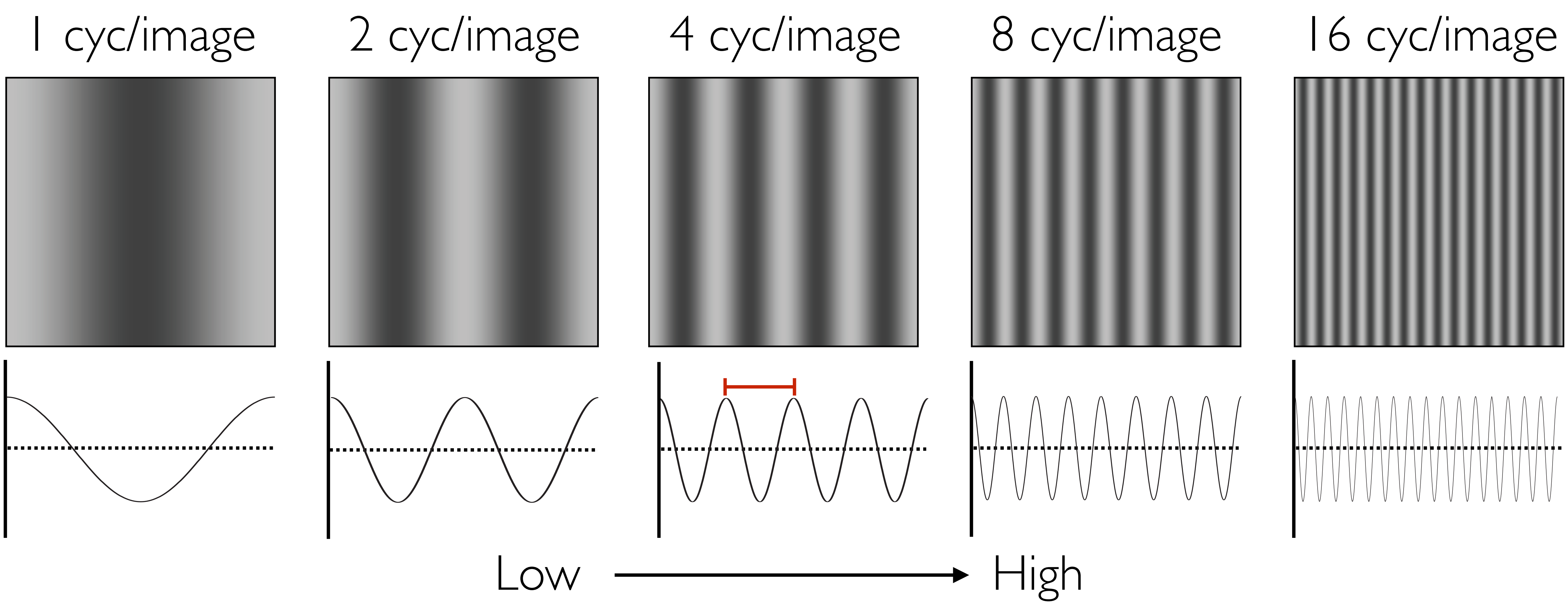
Sine wave phase

- Phase determines the point at which variations occur in space, e.g. the starting point of the cycle
  - Represented in radians with a cyclical structure
  - Determines the position of edges in the scene



Sine wave spatial frequency

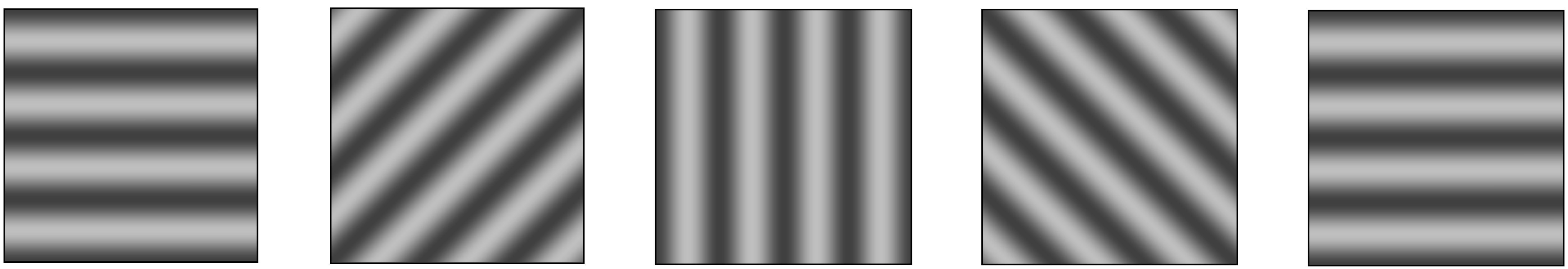
- Spatial frequency determines the variations across space
  - Reported as the number of cycles in a spatial region (peak to peak)
  - Captures the fine vs. coarse detail in an image



Sine wave orientation

- For two-dimensional images we also need to consider the orientation of the sine wave

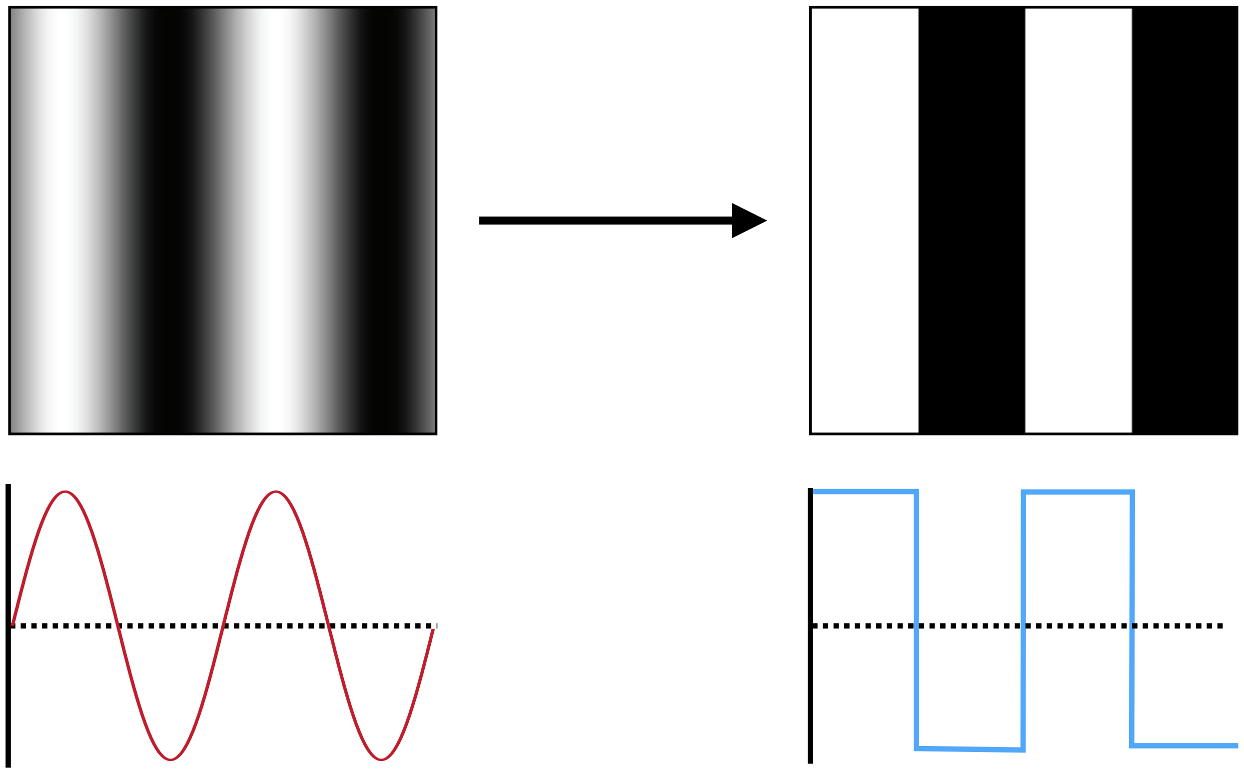
0° 45° 90° 135° 180°



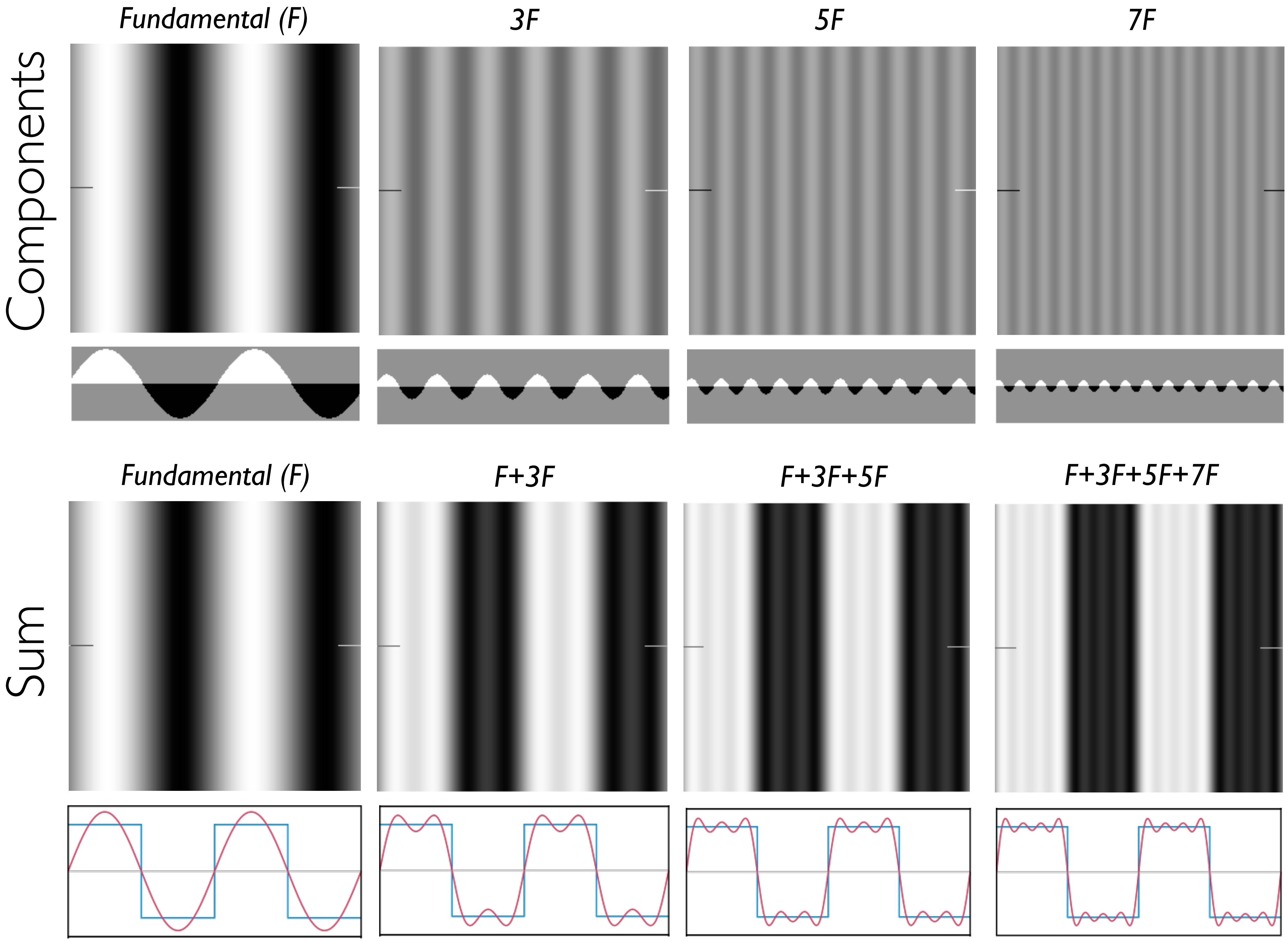
- Orientation is certainly a key dimension for visual processing and we'll return to this shortly

Making images from components

- How do we make an image using sine waves?
  - Sum all of the component sine waves together
- Easiest example: a square wave
  - How do you get a square wave from sine wave components?



From  to 



- Start with a sine wave with matched SF: the fundamental
- Add the odd harmonics (increasing SF) with decreasing amplitude

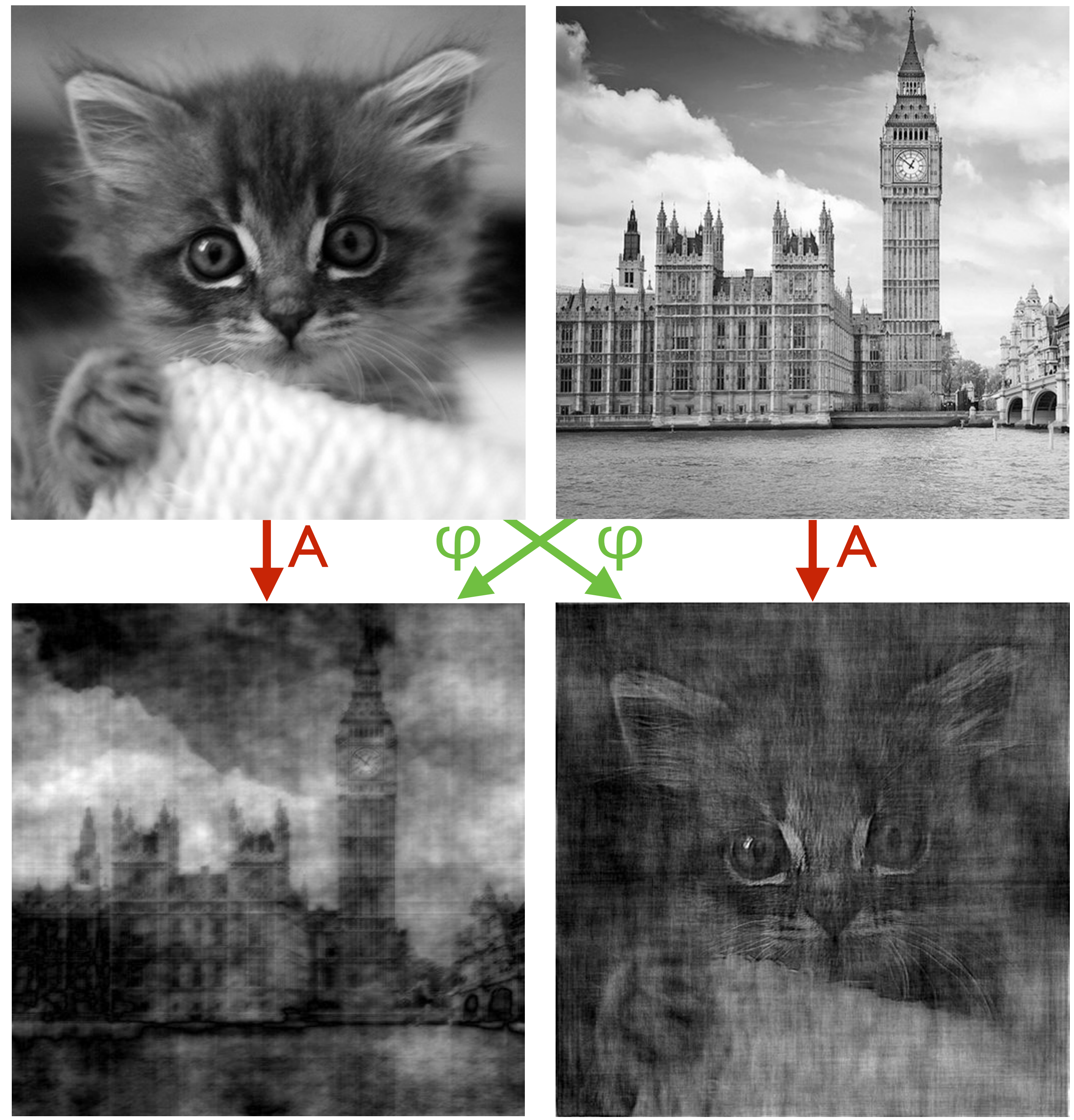
SF in natural scenes

- Filtering natural scenes reveals both low (coarse, 'blobby') and high (edges, fine detail) spatial frequency content

Image = Low SF + High SF

Phase in natural scenes

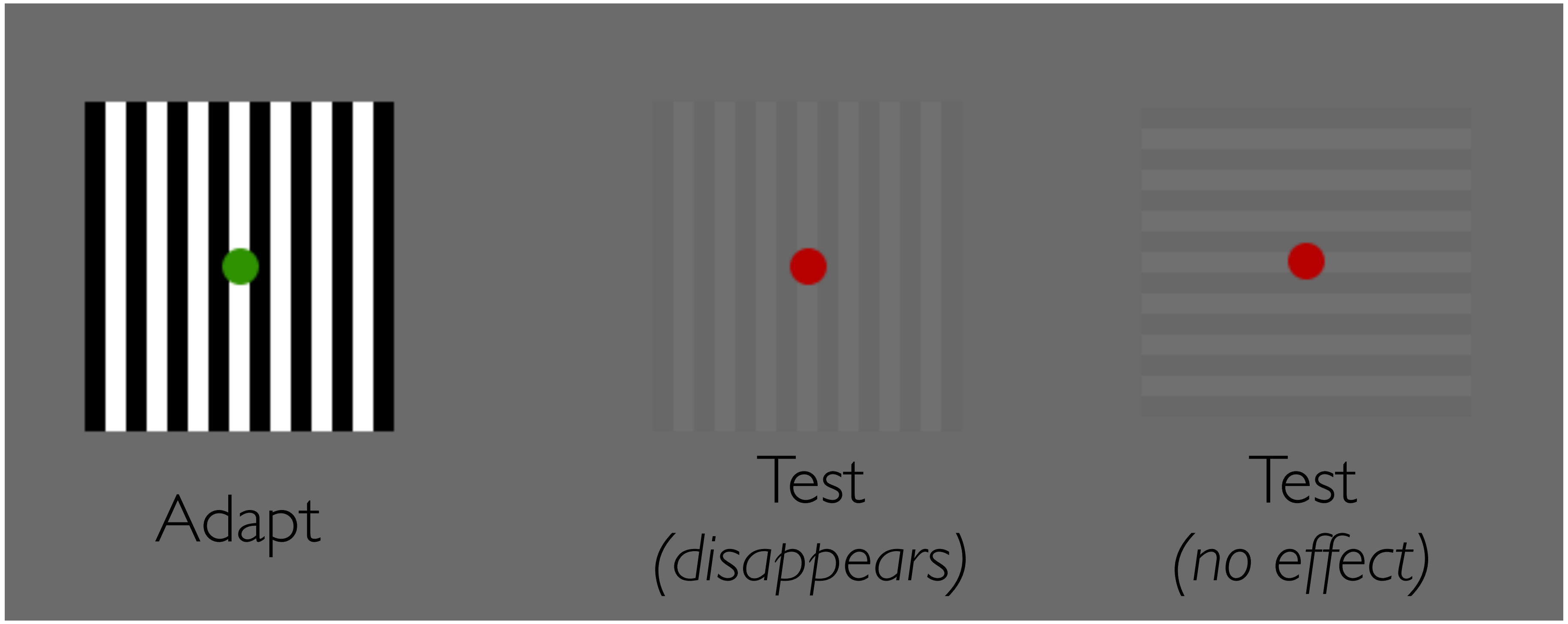
- Combine the kitten's amplitude (at each spatial frequency) with the building's phase spectrum
  - Makes a blobby parliament
  - The opposite combination is an edgy kitten
- The phase of edges is very important for objects (Oppenheim & Lim, 1981)



Are we Fourier analysers?

- Fourier analysis allows us to break an image down into component wave forms characterised by:
  - Amplitude (contrast)
  - Phase (position)
  - Spatial frequency (size)
  - Orientation (orientation…)
- Are these dimensions specifically encoded by *our* visual systems, and (if so) how is this achieved?
- Physiological and psychophysical evidence for two aspects:
  - Orientation
  - Spatial frequency

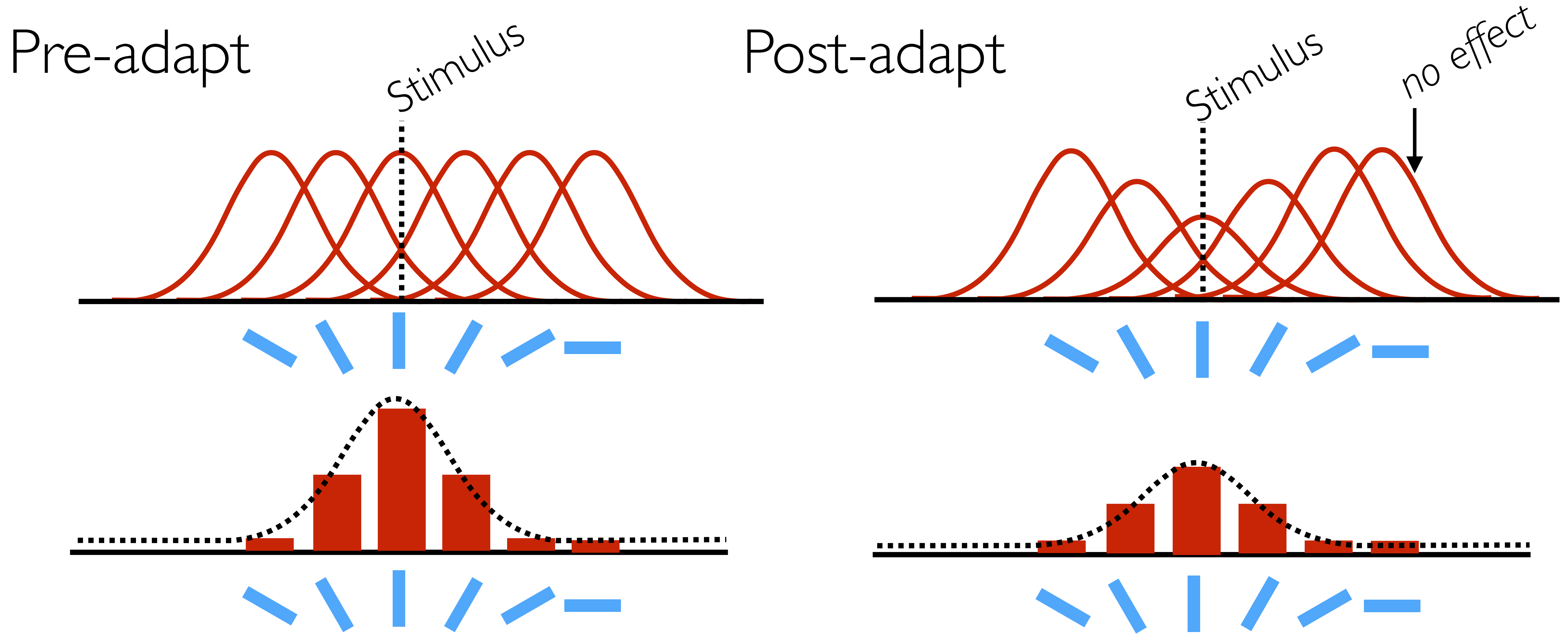
Orientation perception



- How do we perceive the orientation of an edge or line?
- One way to examine this: adaptation
- Gibson (1937): prolonged viewing of one orientation reduces sensitivity to that orientation (but not others)

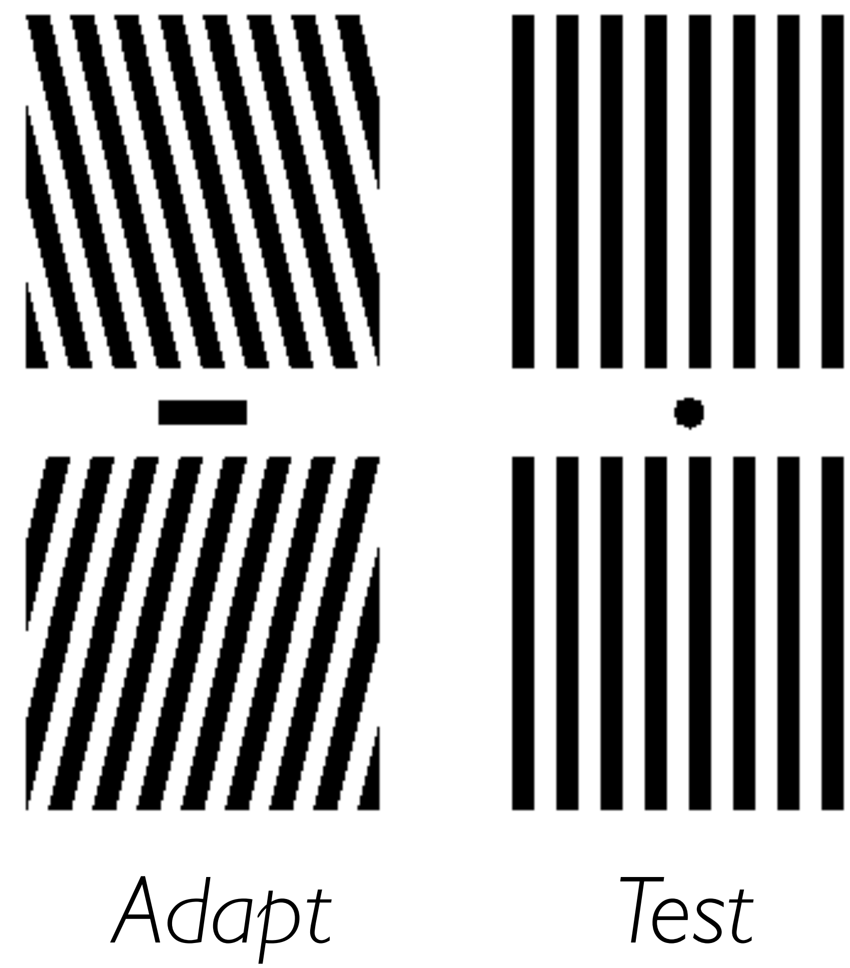
Orientation adaptation

- Adaptation reduces sensitivity to the adapting orientation
  - e.g. higher contrast required for detection
  - Can be attributed to reduced sensitivity of the underlying neurons



Local orientation

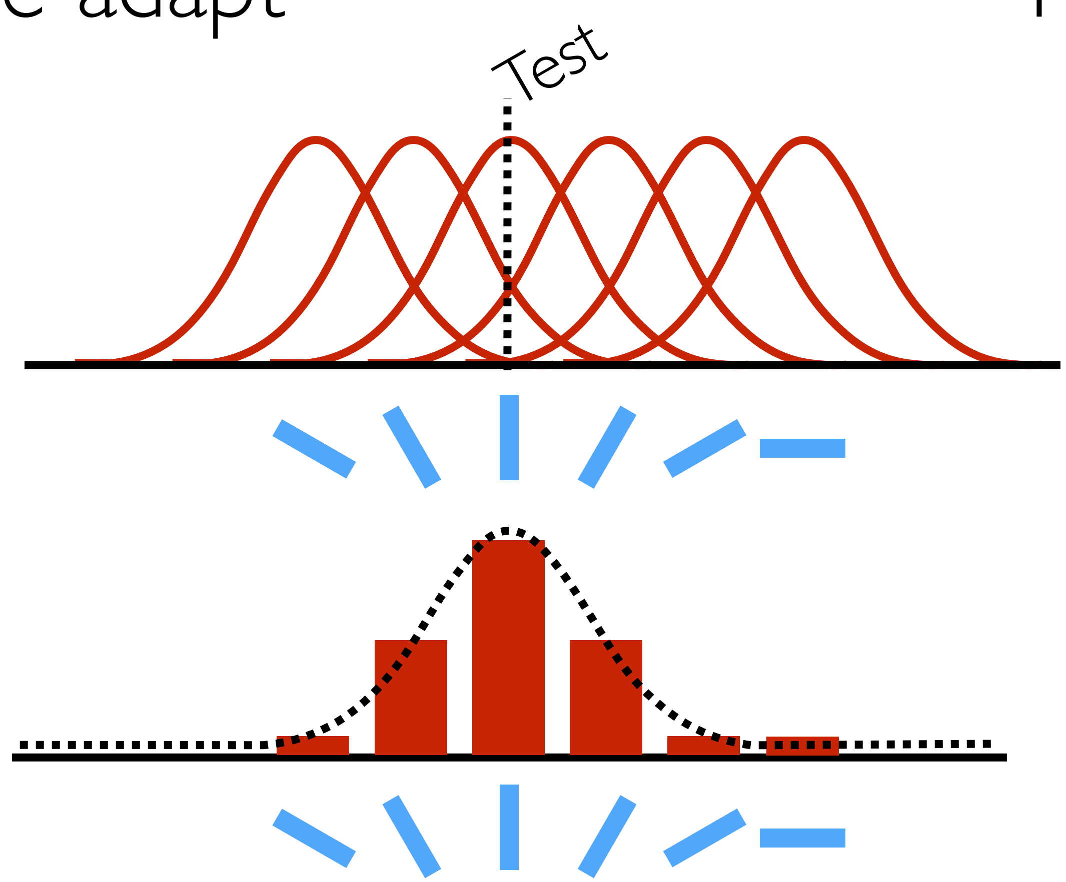
- Gibson (1937): adaptation reduces sensitivity to the adapting orientation
  - ie. adaptation alters performance
- But it also produces repulsion in the perceived tilt of dissimilar gratings
  - ie. adaptation alters perceived orientation (appearance)
  - We call this the tilt aftereffect



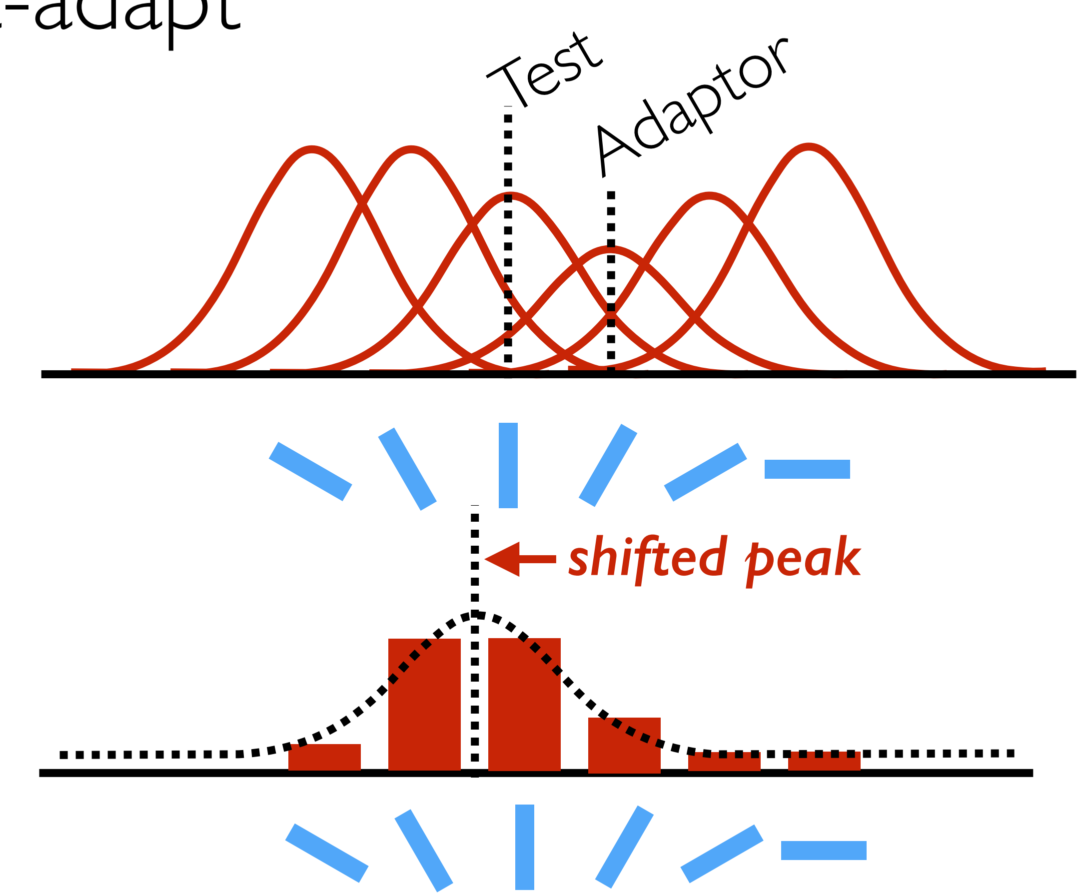
Tilt aftereffect

- Subsequent dissimilar orientations appear repulsed away
  - Produces a shift in the peak response away from the adaptor
  - Suggests population coding of orientation (Blakemore et al., 1971)

Pre-adapt

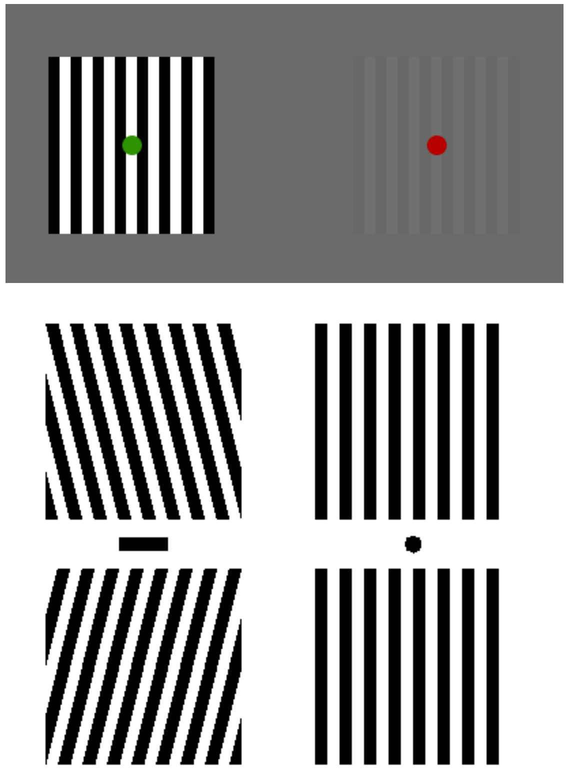


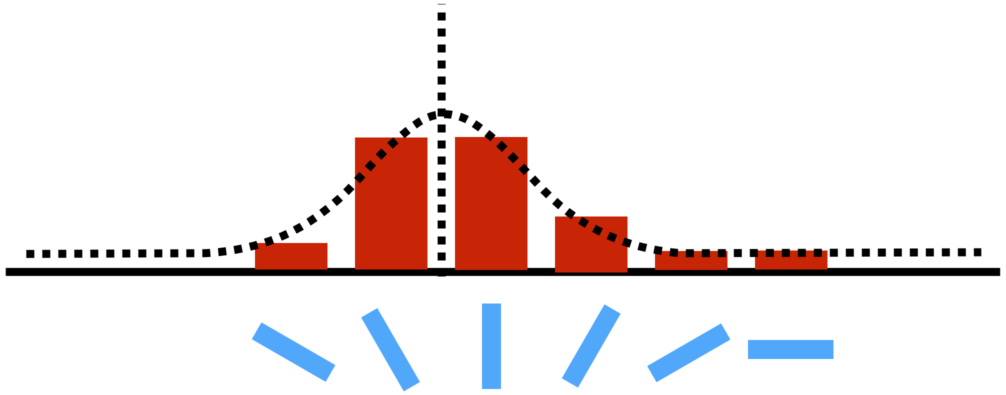
Post-adapt



Two key principles

- Adaptation
  - Reduces neural responses to continued stimulation and enhances responses to novel stimuli (redundancy reduction)
  - Suggests existence of orientation detectors within the visual system
- Population coding
  - Adapting to one orientation influences the perception of others
  - Our perception of orientation is inferred from the population of neural responses, e.g. as the peak

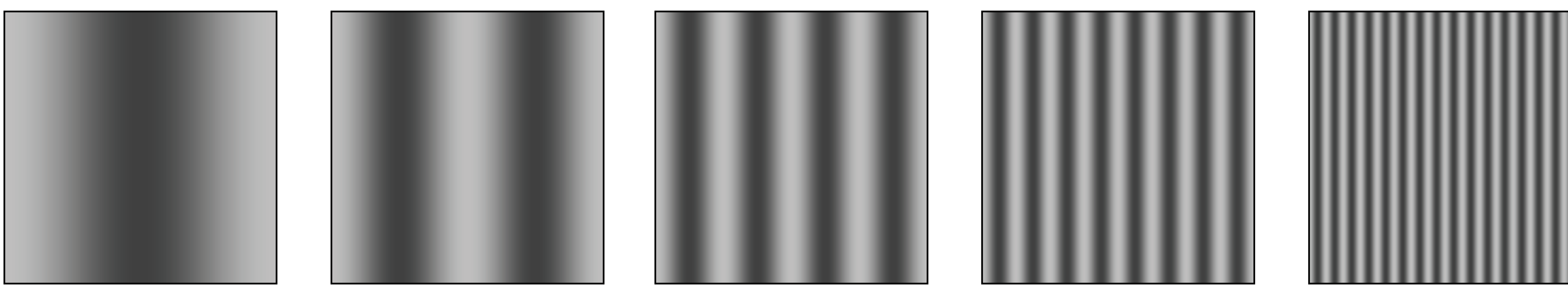




Spatial frequency

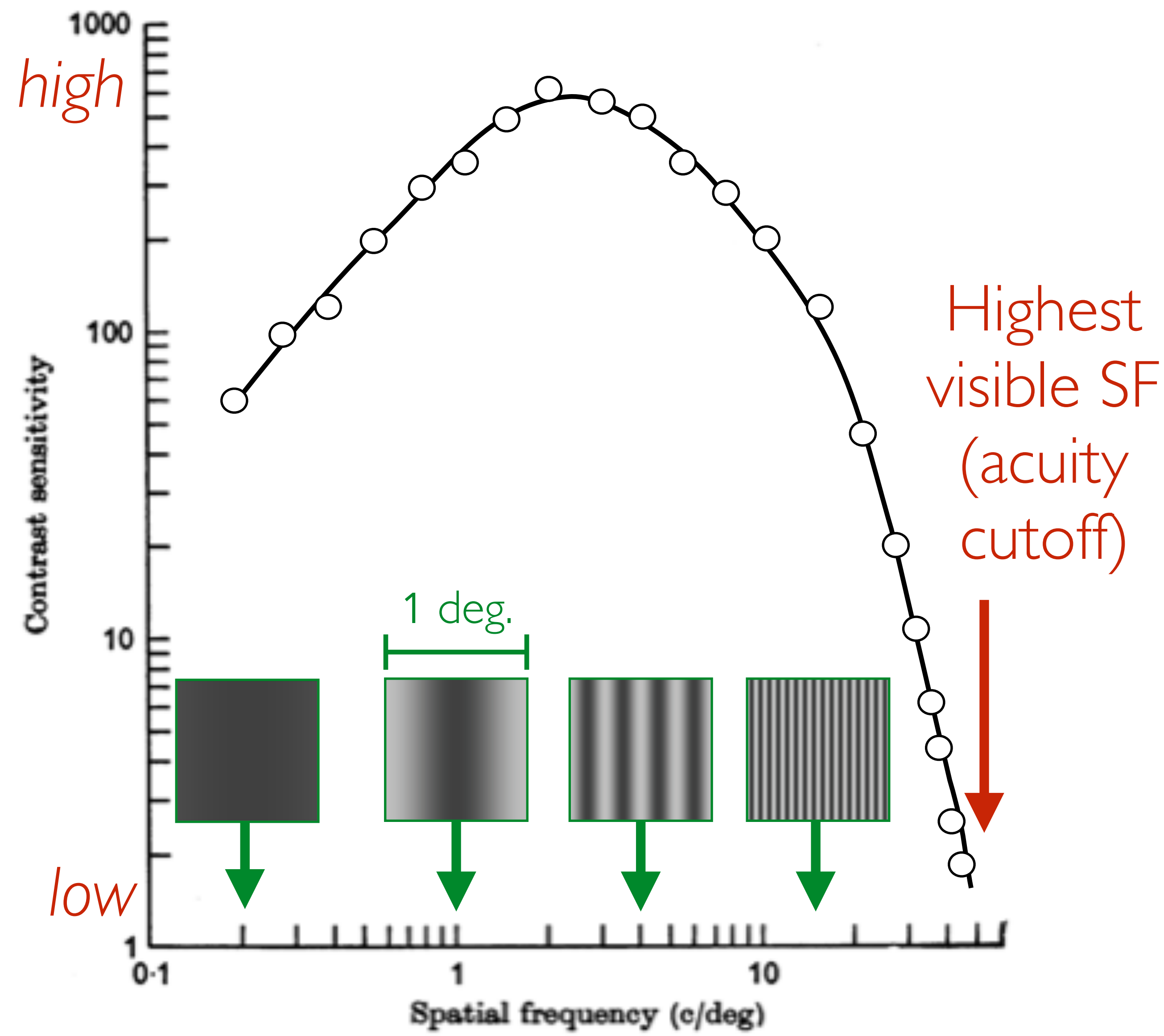
- Fourier analysis gives us a way to think about scale (or *size*)
  - Images contain information at different spatial frequencies
- Are there dedicated neurons for spatial frequency?
- Which of these components is visible to an observer?
  - With Fourier analysis we can take a broader view of the image content that is visible to a given observer

1 cyc/image 2 cyc/image 4 cyc/image 8 cyc/image 16 cyc/image



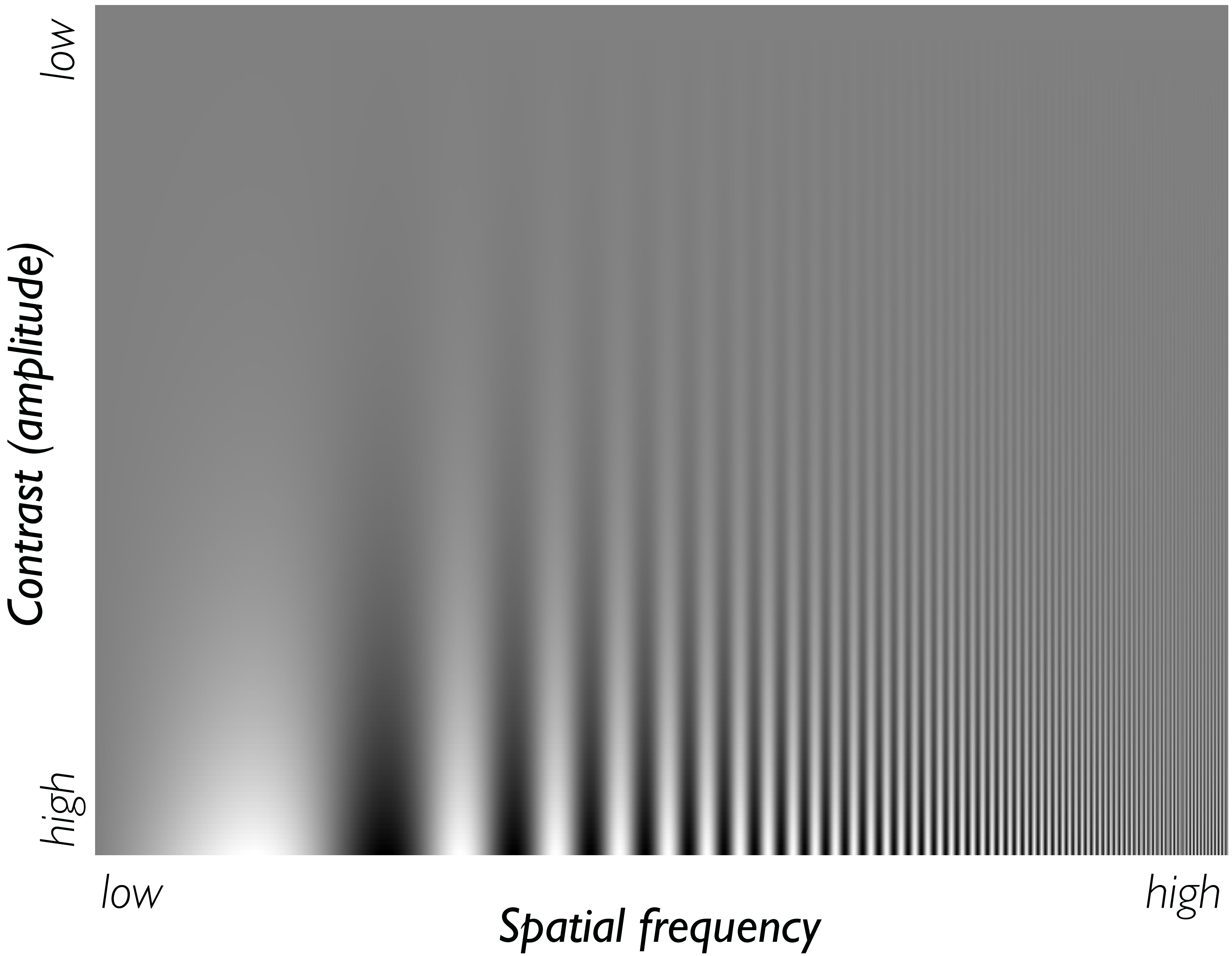
Contrast sensitivity functions

- Campbell & Robson (1968):
  - Measured contrast sensitivity at a range of spatial frequencies
  - Contrast sensitivity function (CSF) peaks around 4 c/deg
  - Sensitivity is not greatest for uniform regions (low SF)!
  - Sensitivity also drops for high SFs - highest visible spatial frequency is our acuity cutoff
  - Defines our 'window of visibility' in spatial vision



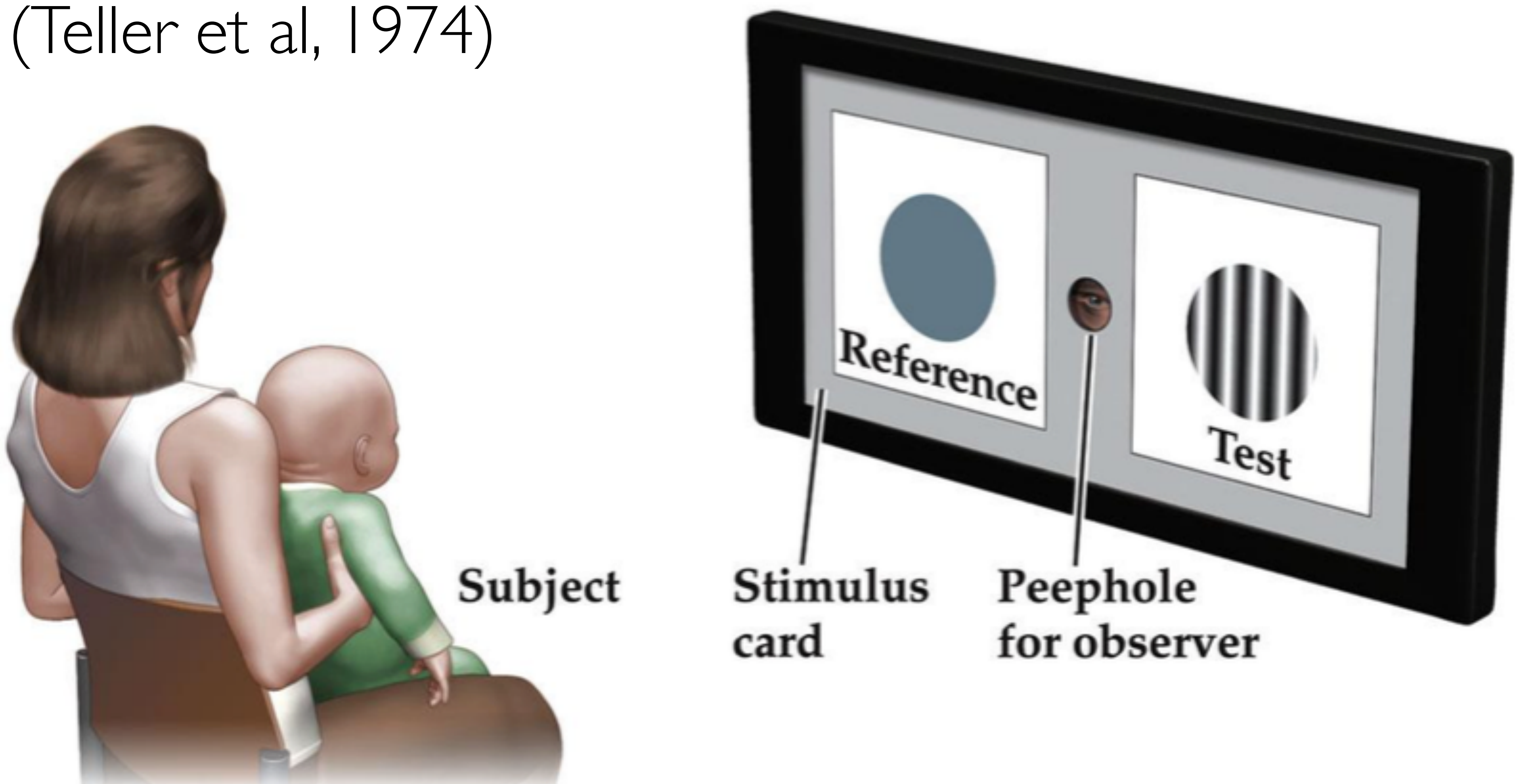
A depiction of the CSF

- We visualise the CSF by plotting contrast against spatial frequency
- Note: peak in the middle & the drop in visibility on either side



What does a baby see?

- How could you possibly measure a CSF for a baby?
- Preferential looking with two-alternative forced choice (Teller et al, 1974)

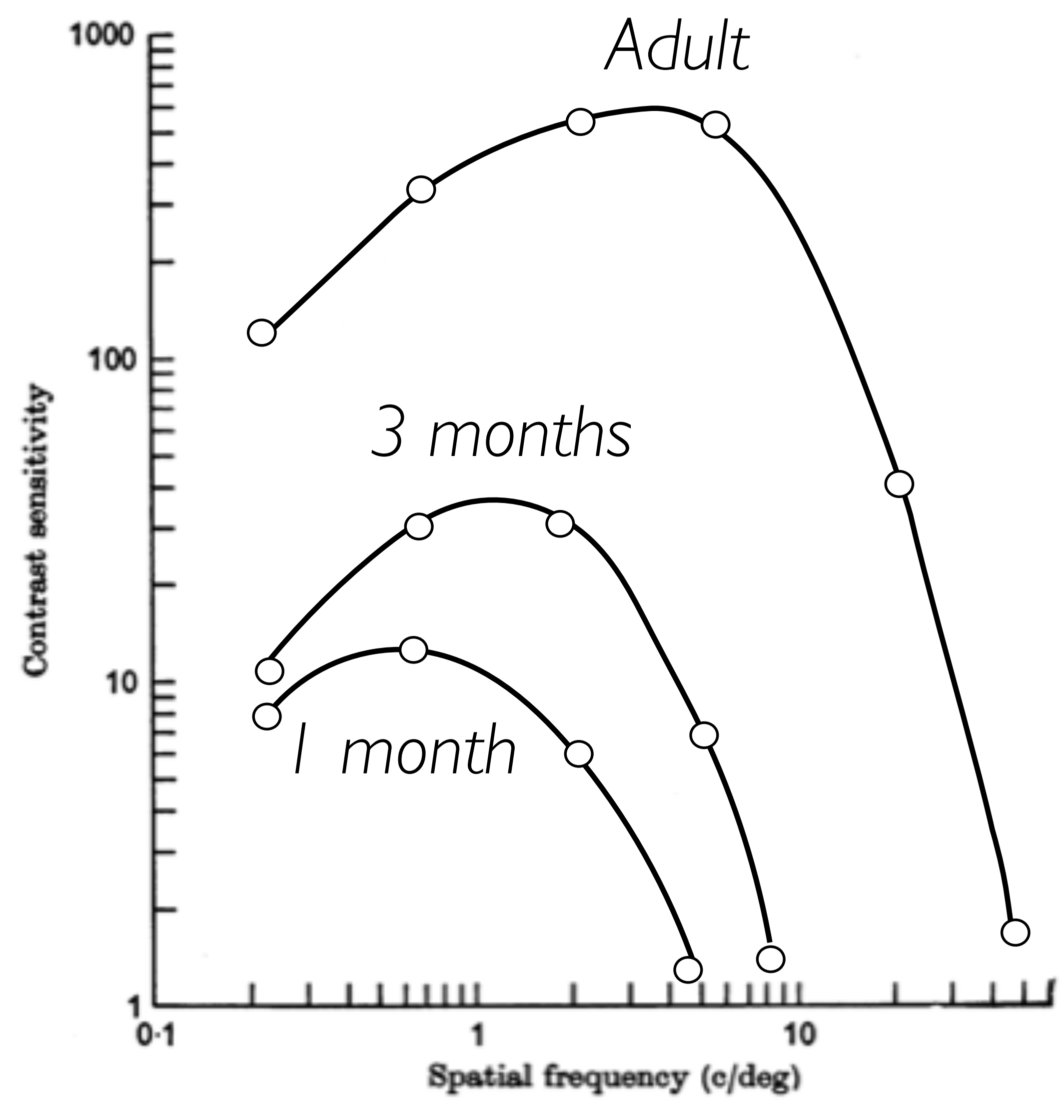


CSF: development

- CSF can capture our visual experience across the lifespan
- Infants not only have poor acuity (the upper cutoff) but are also less able to see lower spatial frequencies

1 month *3 months* *Adult*

Teller (1997)



Norcia, Tyler, & Hamer (1990)

Visibility in other species

- We can use this to characterise vision in other species
- What does a cat see? (Bisti & Maffei, 1974)
  - Present gratings on a monitor
  - Present/absent task
  - Cats trained to press a lever when grating is seen
  - Grating contrast and SF varied along Method of Constant Stimuli

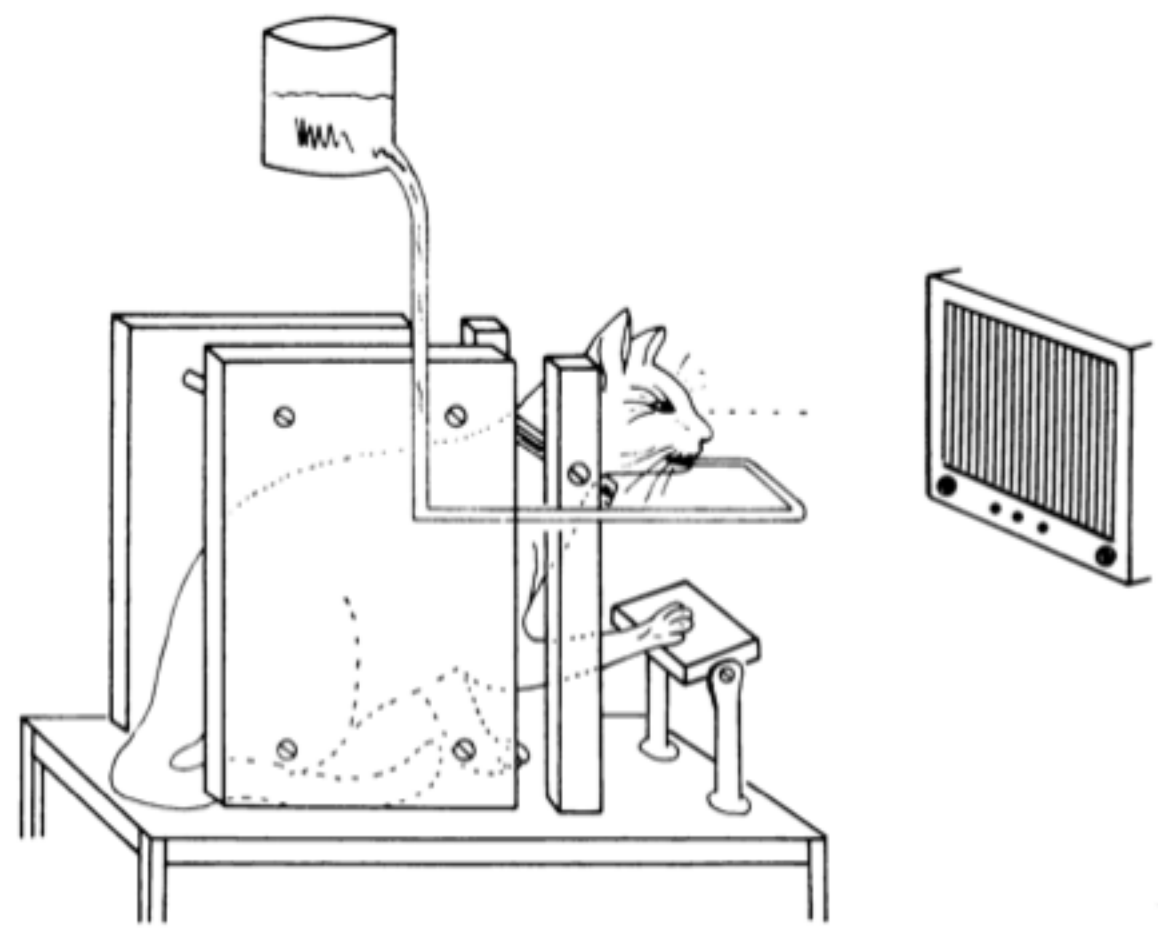


Fig. 1. Schematic diagram of the experimental set up (for explanations see text).

CSF of cats

- Feline sensitivity:
  - Has a lower cutoff point (i.e. worse acuity limit)
  - Peaks at a lower SF (0.3-0.4 cyc/deg)
  - But sensitivity much higher than ours in the low SF range
  - Do cats see strange shadows on the wall?

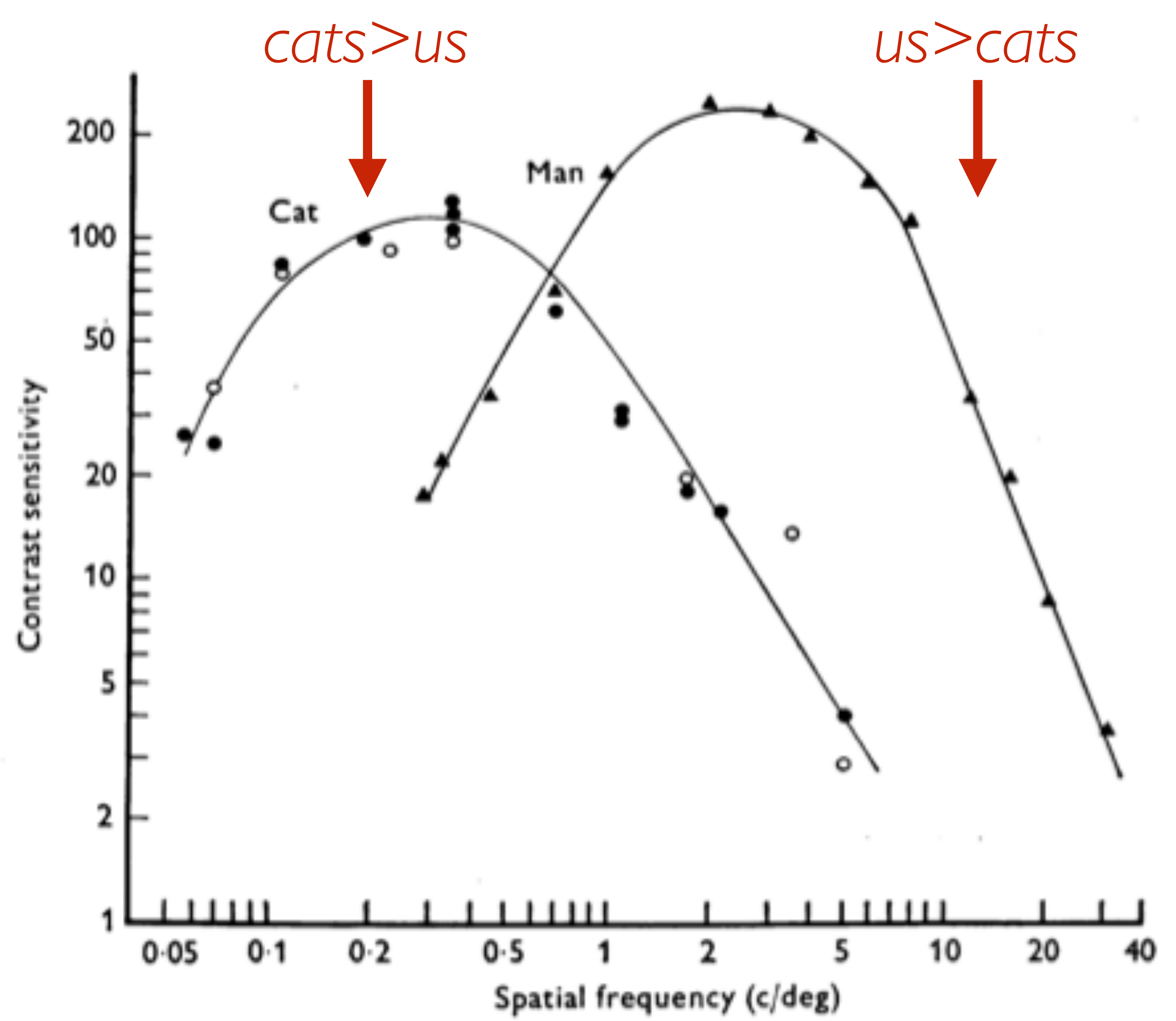
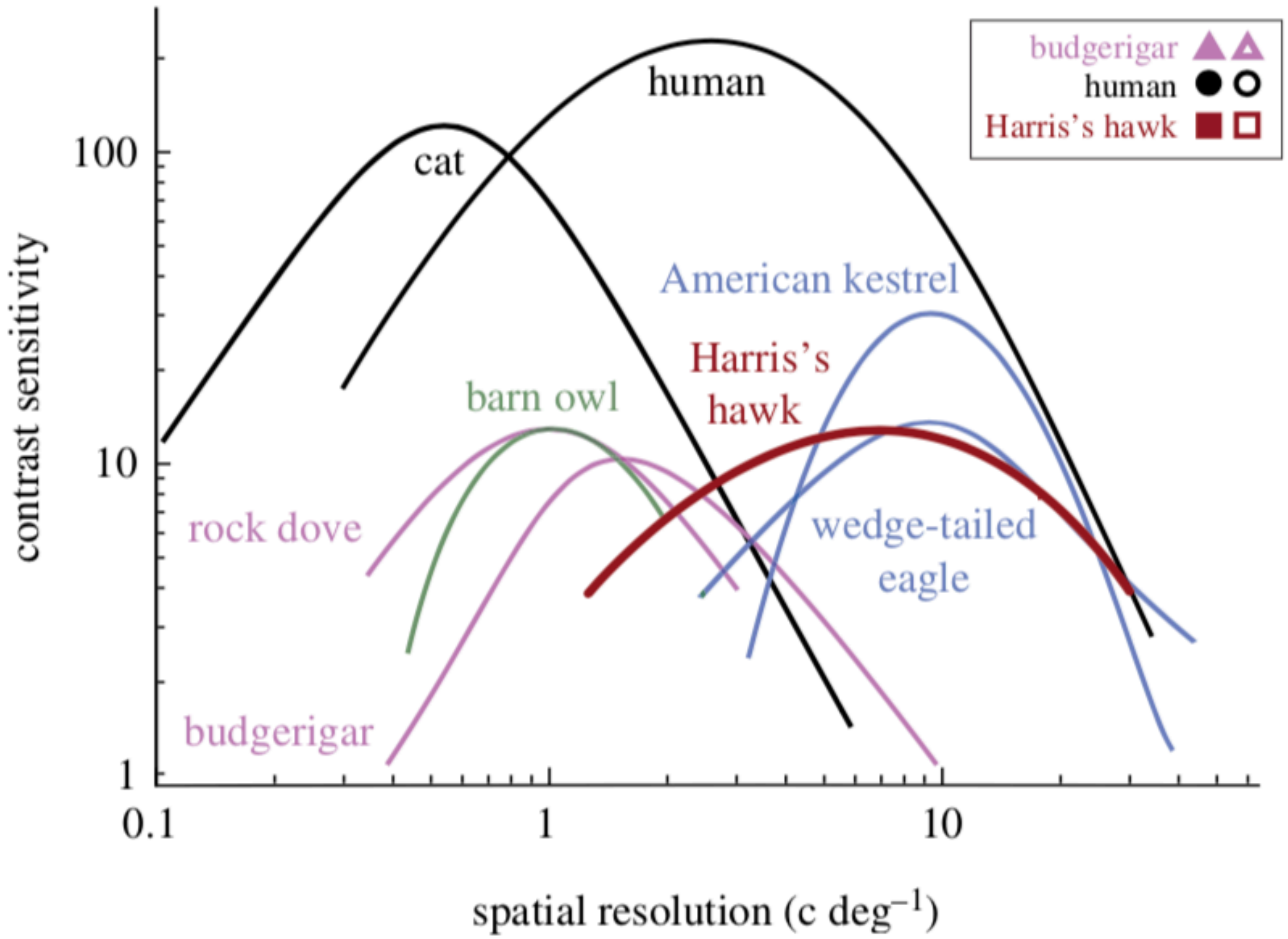


Fig. 4. Comparison of the contrast sensitivity curves of the cat and of a human subject (L.M.) in similar experimental conditions.

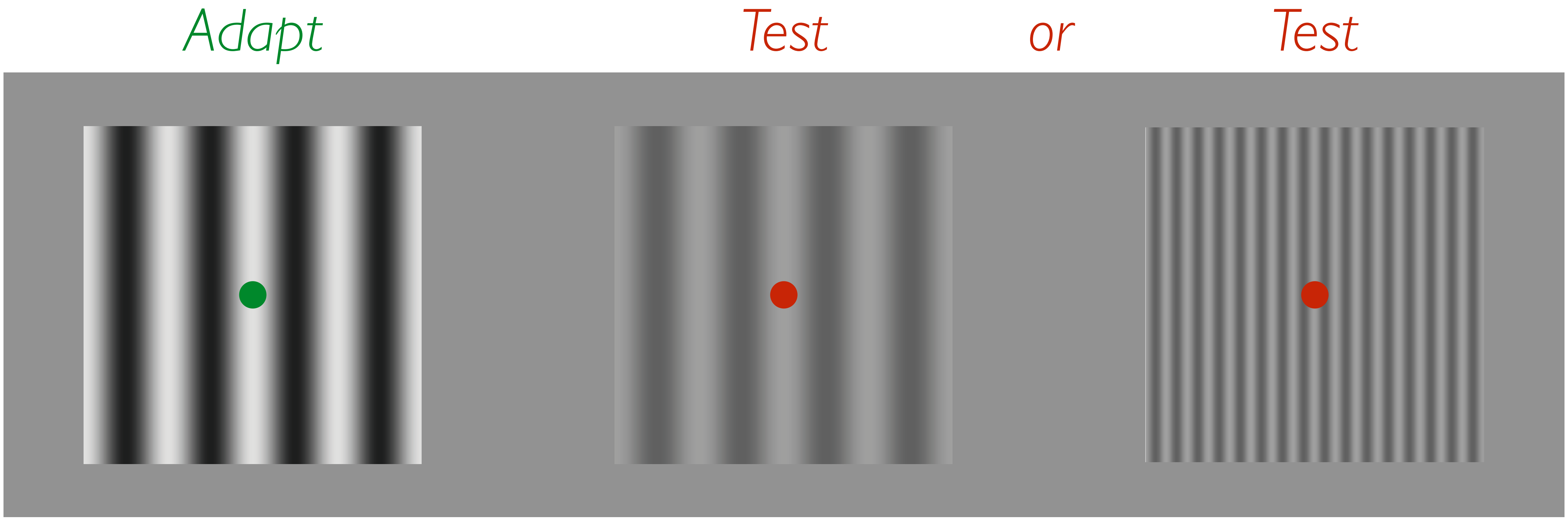
Other species



- Some birds of prey show sensitivity to very high SFs (Potier, Mitkus & Kelber, 2018)

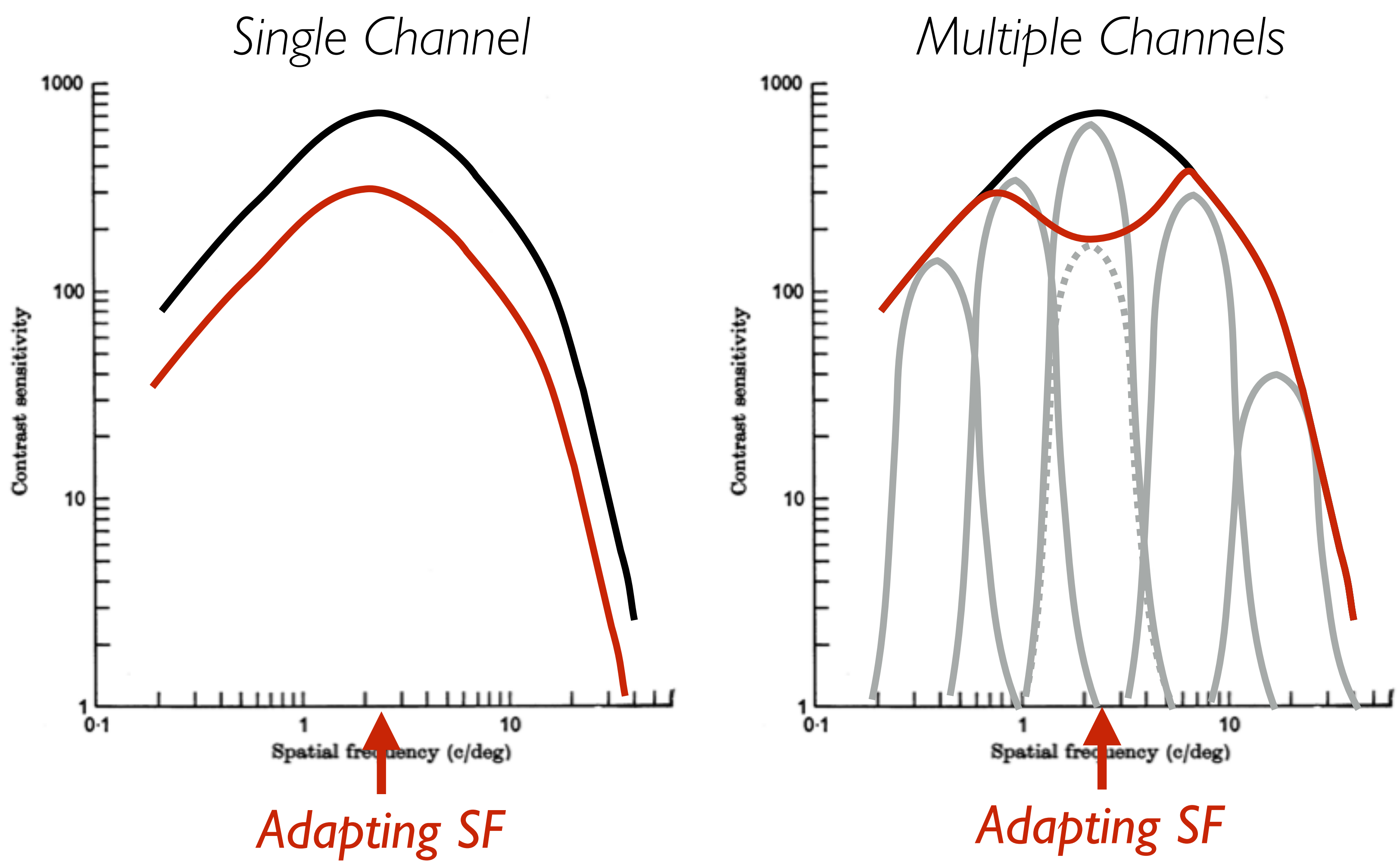
What produces the CSF?

- Why do we show this pattern of sensitivity?
- Campbell & Robson (1968) hypothesised that the visual system is composed of spatial frequency channels, each sensitive to a restricted range of SFs
- Blakemore & Campbell (1969) tested this using adaptation



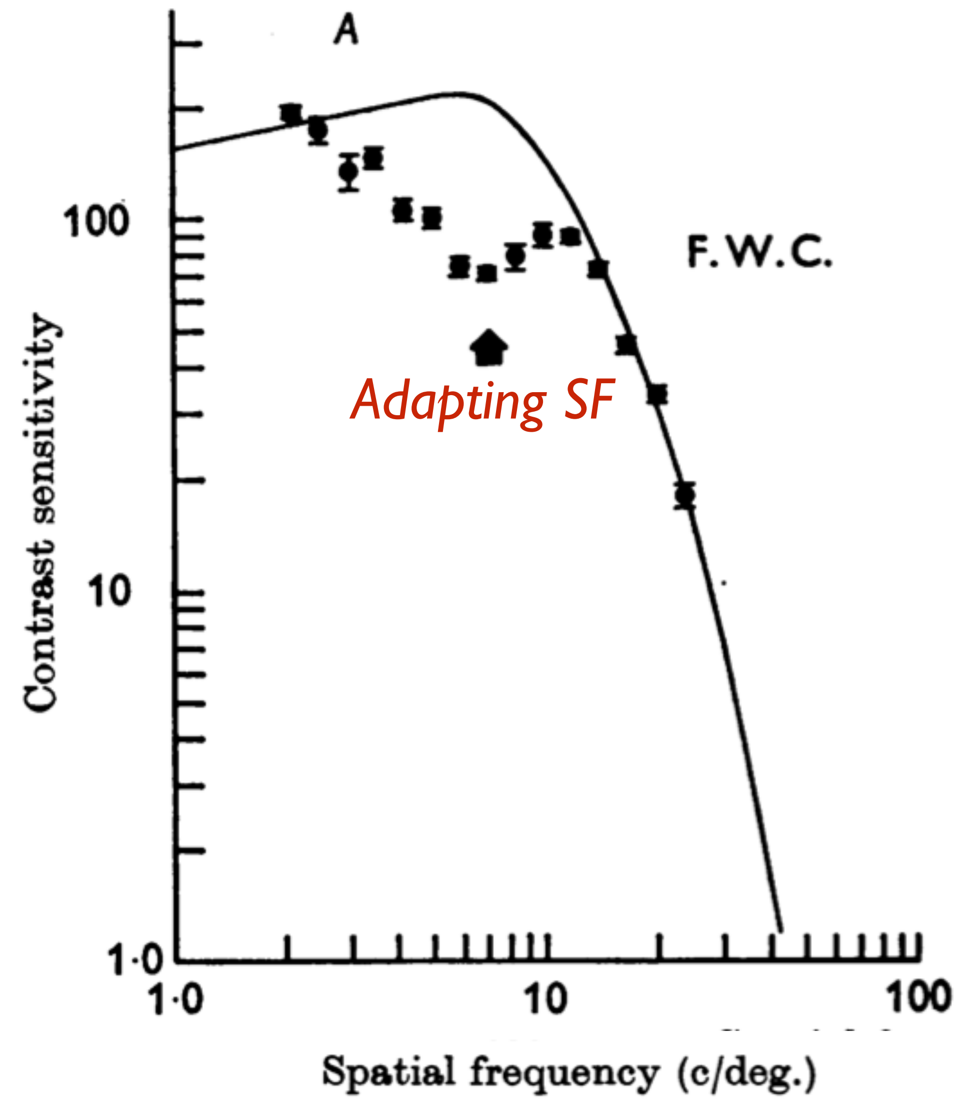
CSF adaptation: predictions

- Adaptation reduces sensitivity to contrast
- But does it affect all SFs or just those of the adaptor?



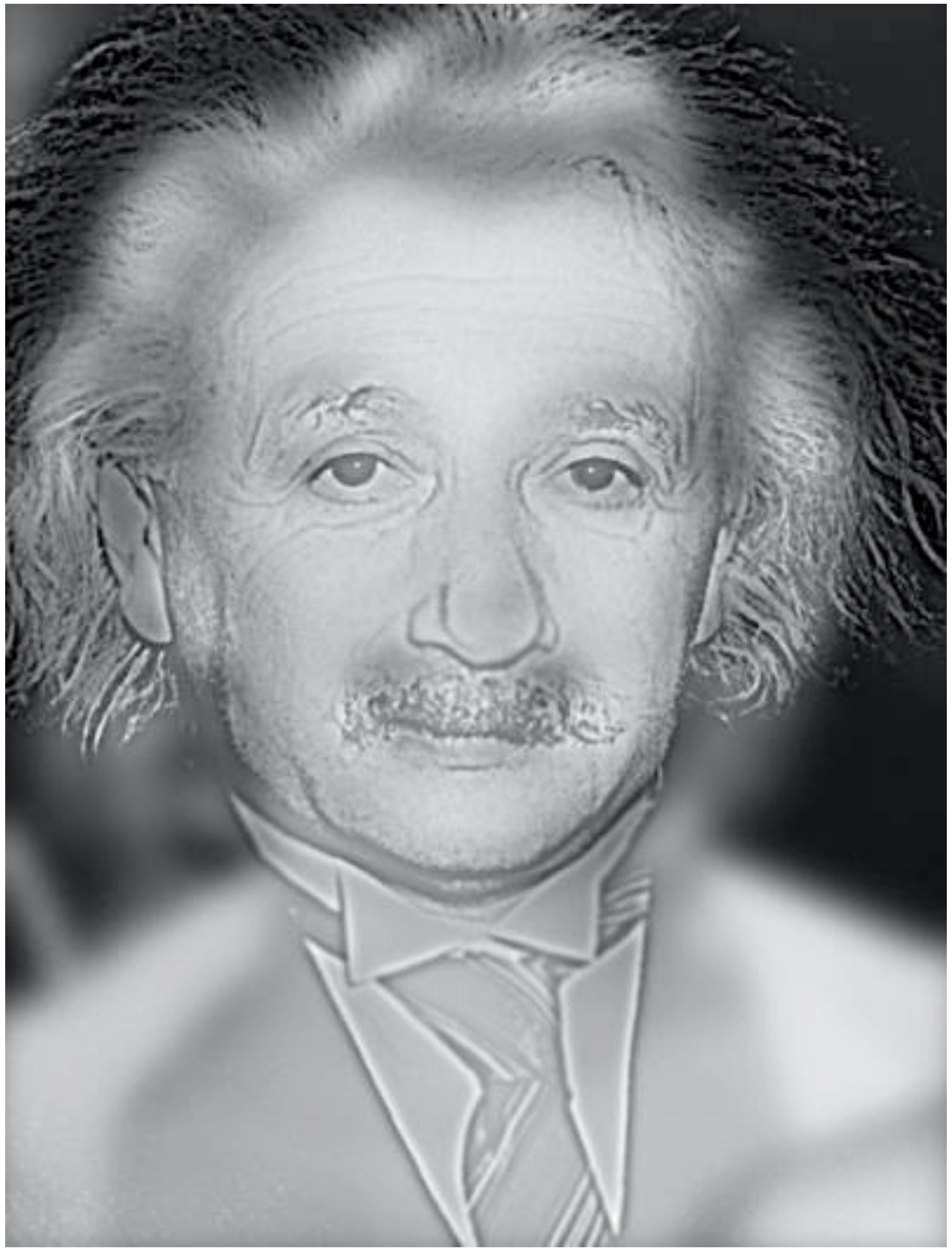
Multiple SF channels

- Adaptation to a sine grating with 7.1 cycles per degree
  - Sensitivity strongly reduced at the adapted spatial frequency
  - Decreased effect for adjacent SFs
- Consistent with multiple channels for spatial frequency
  - Evidence that we separate the visual scene into its Fourier components (at least for SF)



Independent access?

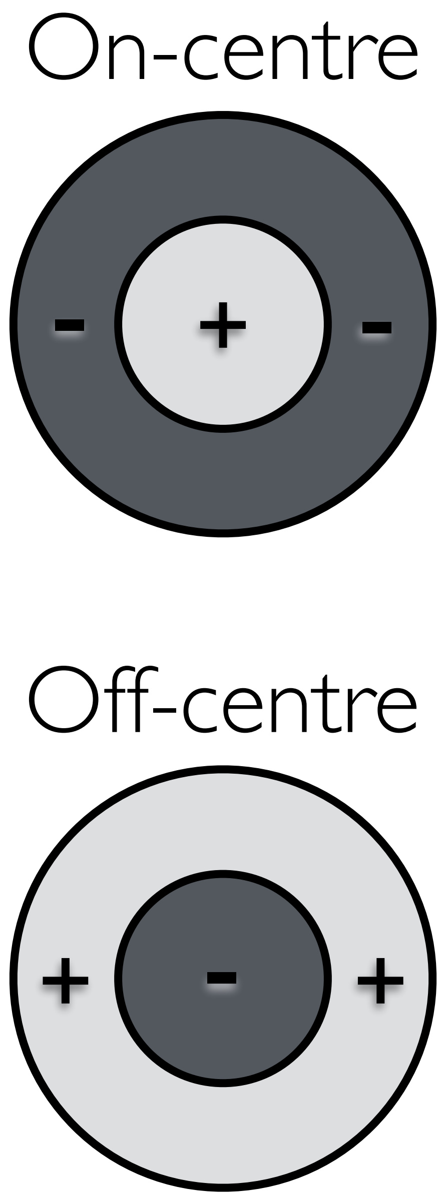
- Does independent channels mean independent access to each frequency band?
- No: Pairing high SF image with low SF image shows high SFs are difficult to ignore
  - Low SFs can appear by squinting/defocusing/shrinking the image
- High spatial frequency channels dominate the lower SFs in object recognition



Schyns & Oliva (1999)

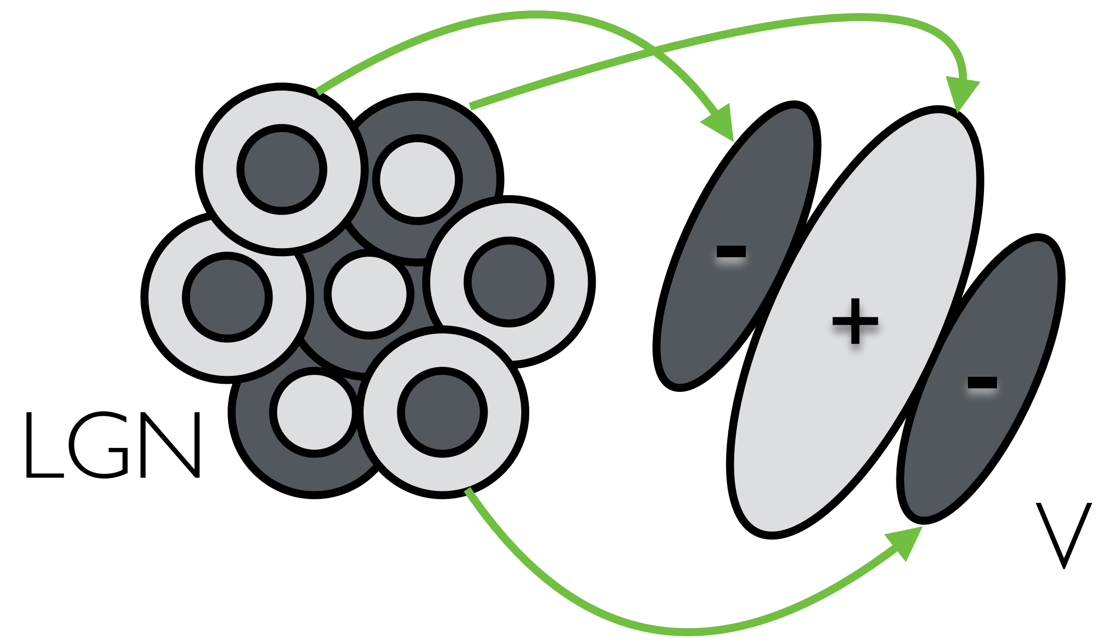
Spatial vision: LGN

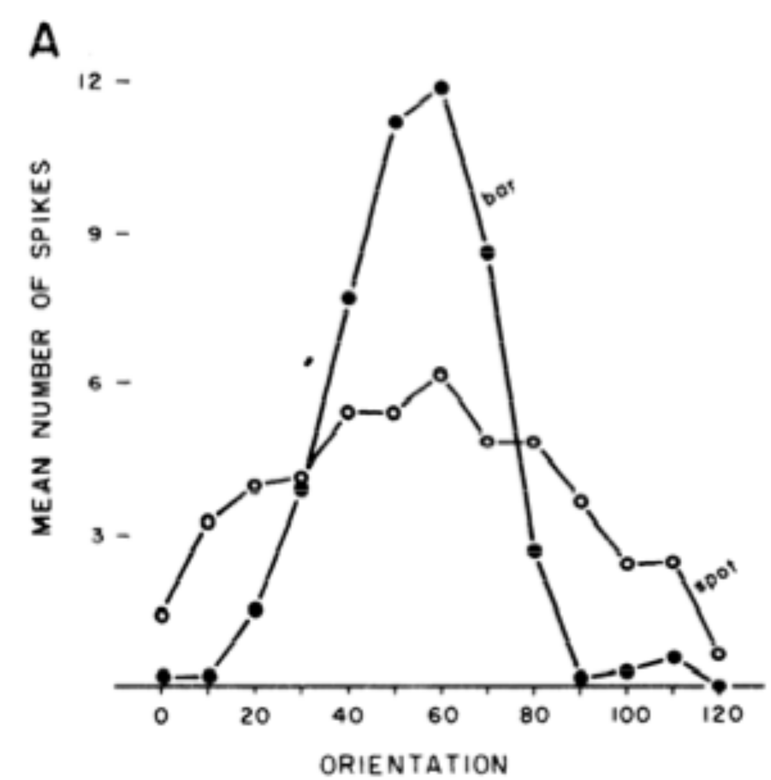
- Where in the visual system do these selectivities for orientation and spatial frequency arise?
- Retinal ganglion cells and neurons in the Lateral Geniculate Nucleus have centre-surround receptive fields
    - Can highlight regions of change, ie. transitions from light to dark or vice versa
- But this does not give selectivity to the *orientation* of edges



Spatial vision: V1

- Hubel & Wiesel (1962) found orientation selectivity in the primary visual cortex (V1)
    - Cells respond to particular orientations of edges & lines
    - Have a preferred orientation that produces maximal spike/firing rate (Schiller et al., 1976)
    - Likely built from particular combinations of centre-surround LGN neurons (Hubel & Wiesel, 1968)

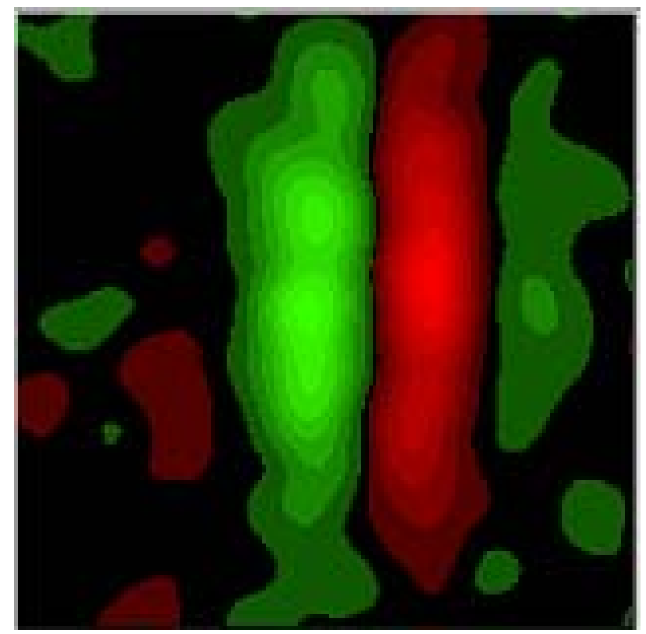




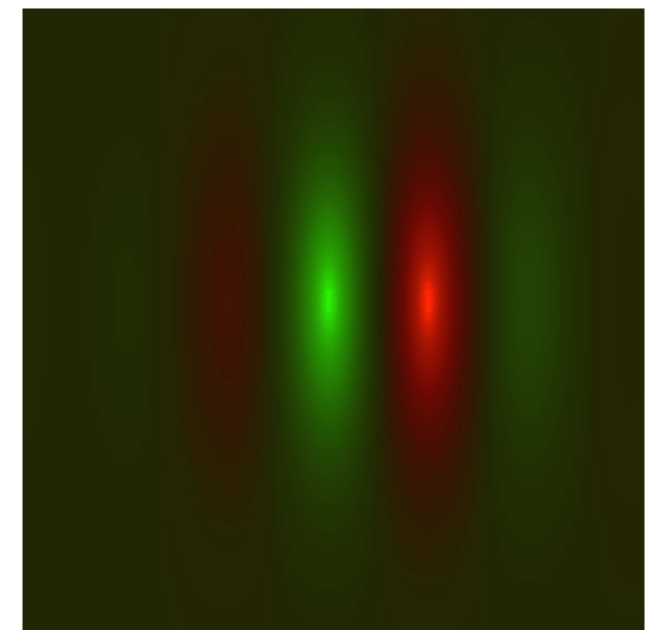
V1 cells as Fourier analysers

- Present white noise in the receptive fields of V1 cells and correlate cell responses with pixel values
- For most V1 cells the preferred stimulus looks like a 'Gabor'
  - The multiplication of a sine wave with a 2D Gaussian profile

V1 receptive field

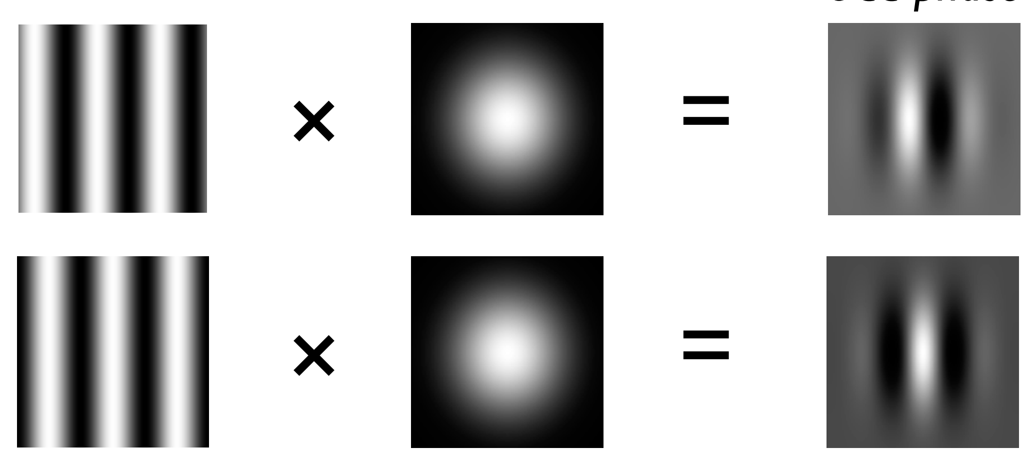


Gabor model



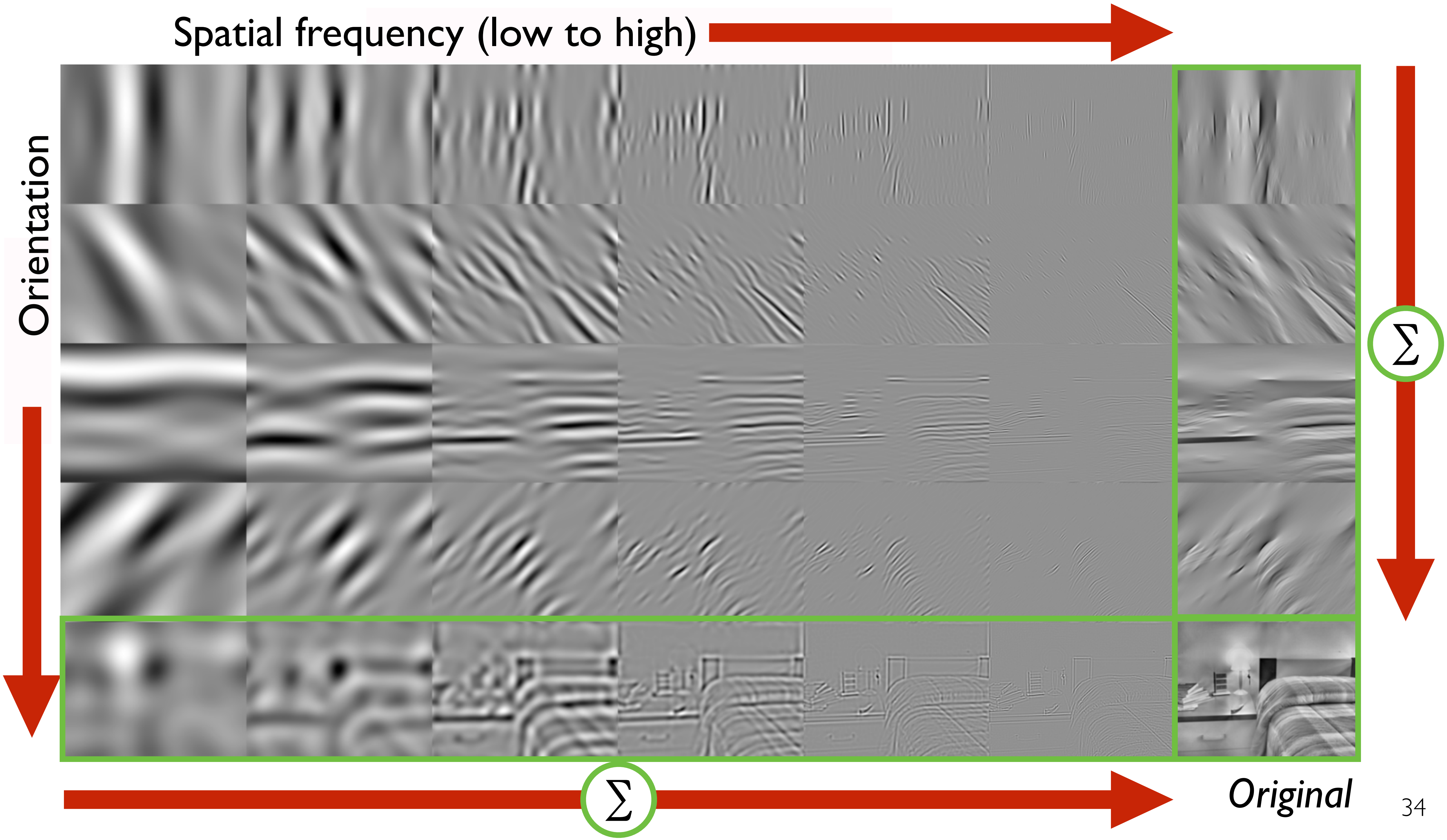
De Angelis, Ohzawa & Freeman (1995)

Odd-phase



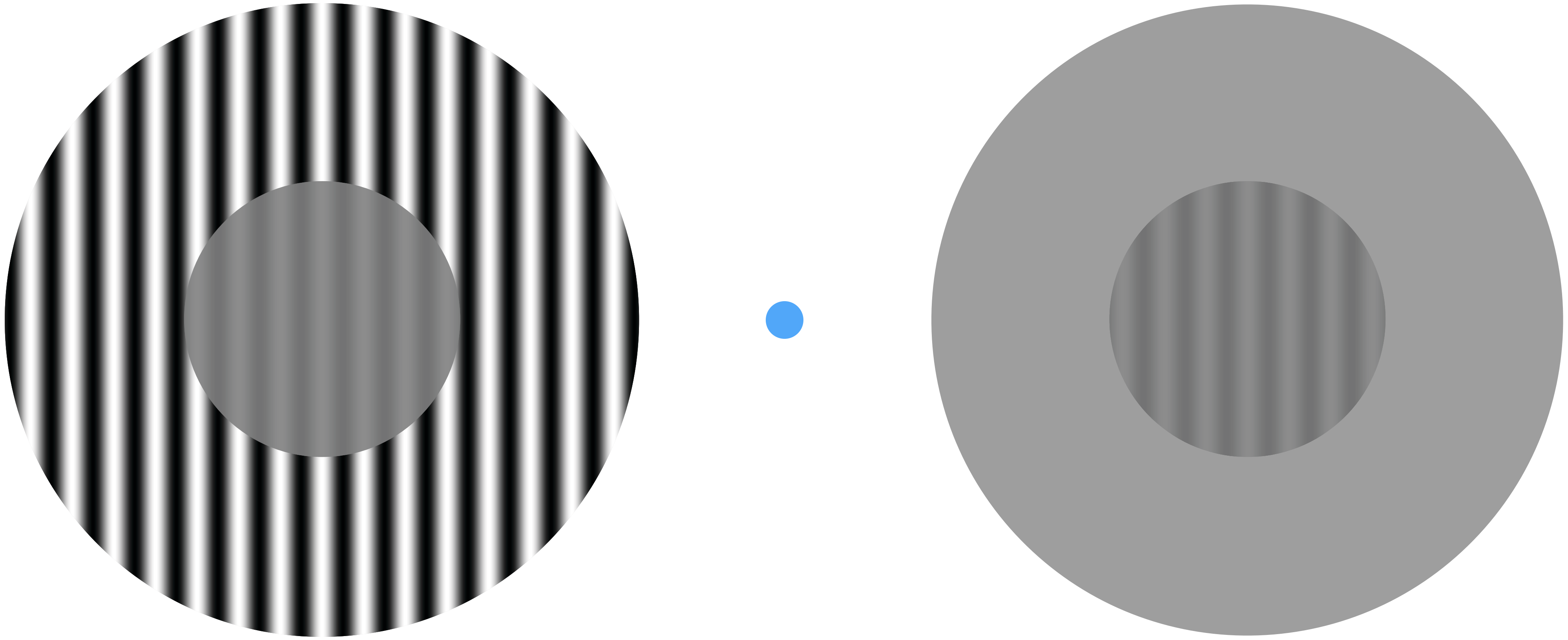
Even-phase

Filtering an image with filters similar to the receptive fields of V1 cells gives us orientation energy at a range of spatial frequencies



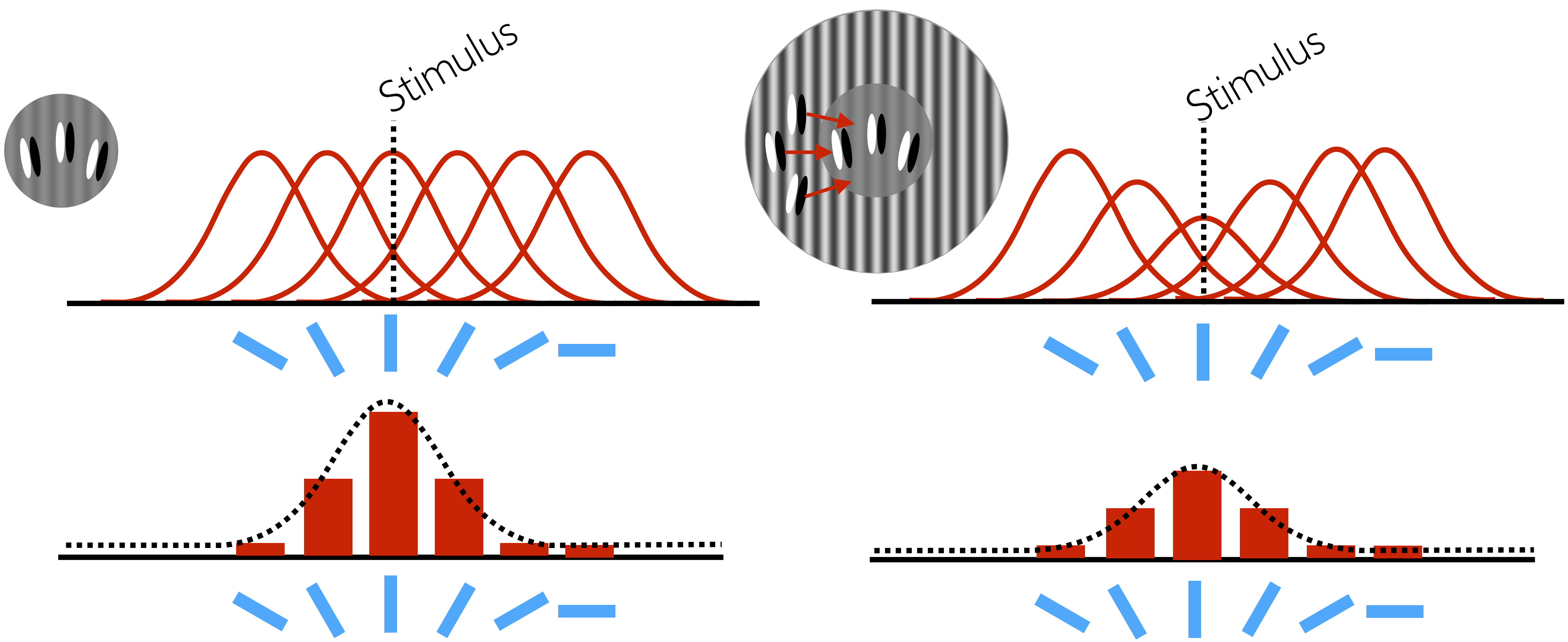
Context matters

- Interactions are also evident in SF and orientation across space
  - Surround suppression (Chubb et al., 1989): a central patch appears lower in contrast when surrounded by the same orientation
  - We can understand this via population coding with spatial interactions



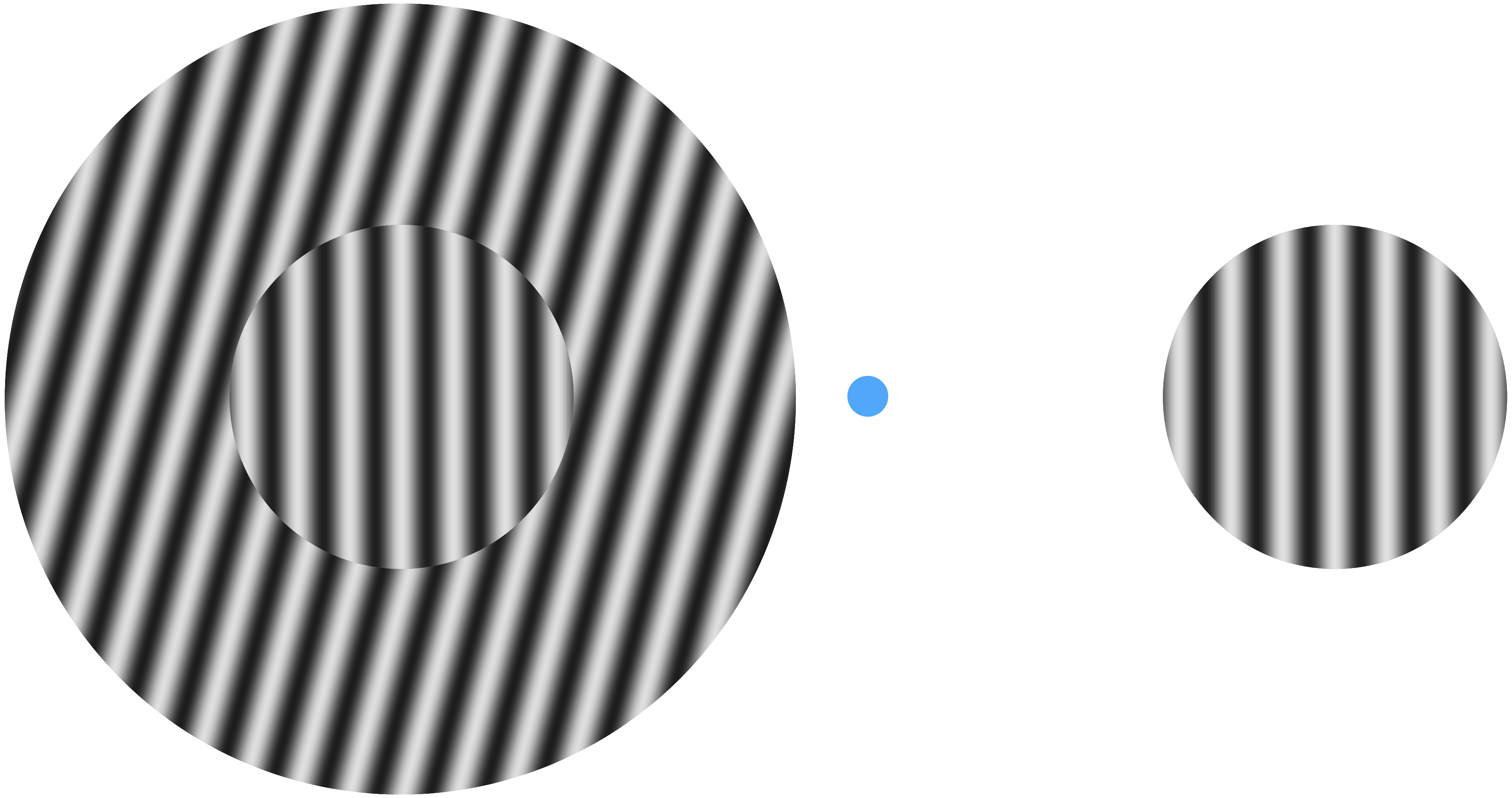
Surround suppression

- Can again be attributed to reduced sensitivity of the underlying neurons, via connections from adjacent neurons



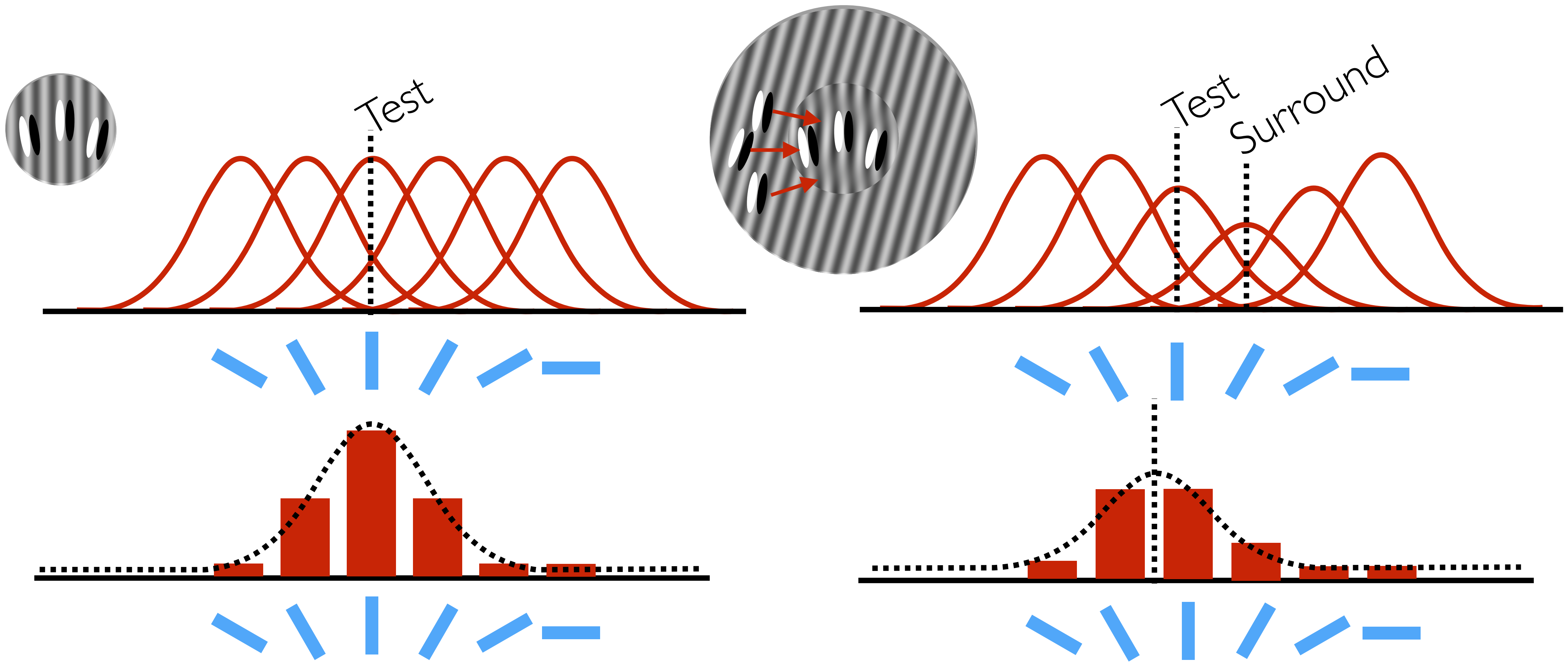
Simultaneous tilt contrast

- With dissimilar orientations can also see a shift in perceived orientation due to surrounding context
  - Similar to the tilt aftereffect (both noted by Gibson, 1937)



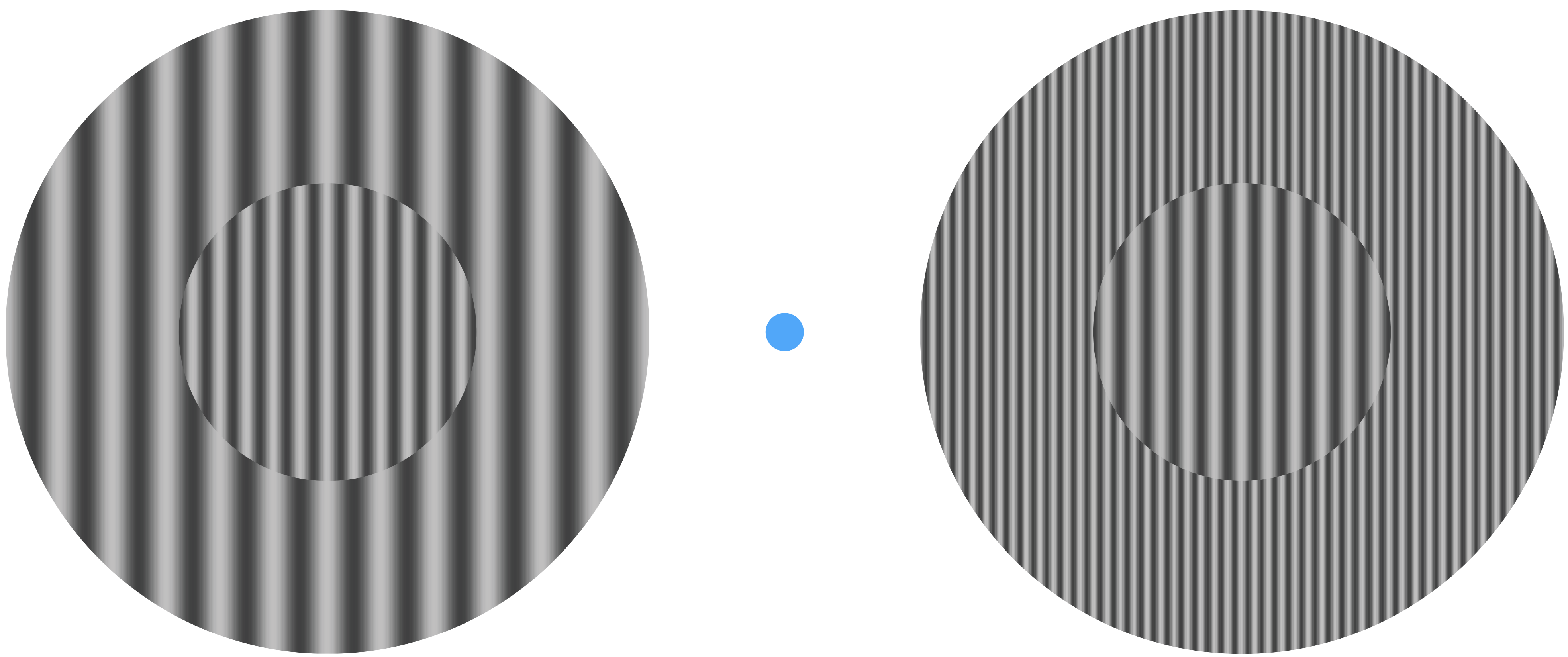
Population tilt contrast

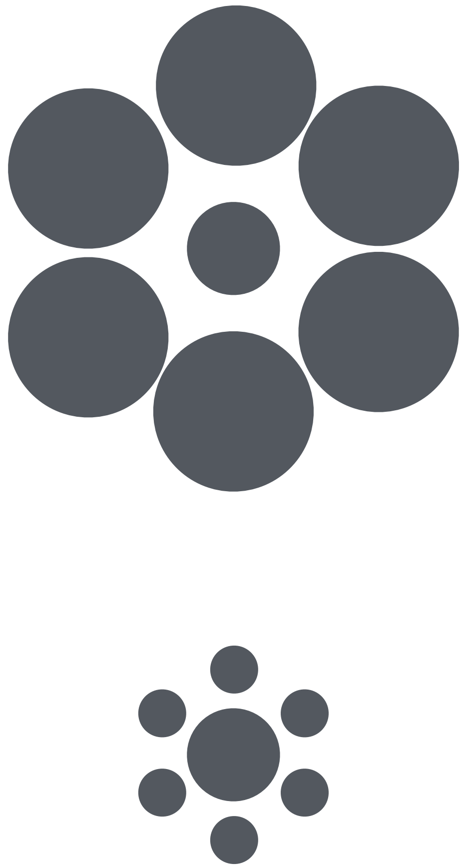
- Adjacent orientations appear repulsed from one another
  - Also accounted for by shifts in population response, induced by adjacent neurons (Blakemore et al., 1970)
  - Neurons compete across space to determine dominant orientation



SF surround effects

- We can also see surround effects for spatial frequency
  - e.g. simultaneous contrast illusions for spatial frequency and the Titchner / Ebbinghaus illusion for size
  - Likely similar mechanisms of population coding





Summary

- Fourier analysis gives us the dimensions of spatial vision
  - Contrast, phase, spatial frequency, and orientation
- Our visual system can be considered in similar terms
  - Orientation perception (e.g. within V1) follows principles of population coding, as seen with adaptation (e.g. the tilt aftereffect)
  - Spatial frequency perception is well described by the Contrast Sensitivity Function (CSF)
    - Allows us to characterise differences between species etc.
    - Similar evidence for population coding underlying our abilities
  - Surround/context effects show similar principles apply across space

Reading

- Chapter 3 of Wolfe et al. *Sensation & Perception* gives a good overview of these ideas
- Some further sources if interested or confused:
    - Surround suppression:
      Blakemore, Carpenter & Georgeson (1970) Lateral inhibition between orientation detectors in the human visual system. *Nature*.
    - Spatial frequency:
      Campbell, F.W., & Robson, J.G. (1968). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology*.