What is the lowest contrast spatial frequency you can see?
What is the lowest contrast temporal frequency you can see?
Spatial vs. Temporal Contrast

Lum changes across space

Lum changes across time

L changes across both
Temporal Contrast Sensitivity Function (TCSF)

**Temporal** (time varying, flickering)

**Contrast** (luminance ratio of bright to dark)

**Sensitivity Function** (inverse of threshold plotted against flicker rate).

Peak Sensitivity is typically above 100, meaning less than 1% contrast is visible.

The highest visible flicker rate, when contrast is 100%, is called the Critical Flicker Frequency or **CFF**

**CFF** is analogous to acuity in the spatial contrast sensitivity function. It represents temporal resolution, instead of spatial resolution. Acuity is limited by optics, receptor spacing, and spatial integration. CFF is limited only by temporal integration.

*Waugh & Bedell, 1992*
Spatial Frequency & the TCSF

The shape of the TCSF changes from bandpass to low pass as the spatial content of the target shifts from lower to higher SFs.

Robson, 1966
Luminance and TCSF

The shape of the TCSF changes with decreasing luminance. As luminance goes down:

Critical Flicker Frequency (CFF) goes down.

The peak (our sensitivity to the best frequency) goes down and moves to lower TF.

Our contrast sensitivity to low TF stays about the same (Weber’s Law), until we drop below photopic levels into scotopic vision.

At scotopic levels, sensitivity is lower at all TFs.
Factors influencing the CFF

CFF increases linearly with log luminance over much of the photopic range, the Ferry-Porter Law:

\[ \text{CFF} = k \log L \]

Each log unit increase of luminance raises CFF by about 20 Hz. CFF tops out at around 100 Hz no matter how bright.

CFF also depends on stimulus size, up to a point. For small to medium size patches, CFF increases linearly with log area, the Granit-Harper Law:

\[ \text{CFF} = k \log A \]
Flicker in Daily Life

Generally, light sources that are driven by Alternating Current (AC) will flicker, and sources driven by Direct Current (DC) are steady. Most video displays flicker. We don’t see these as flickering because the rate is above the CFF.

TV frame rate: 30 frames/s x 2 scans per frame = 60 Hz (or 50 Hz depending on the country’s AC rate.)
Movies: 24 frames/s x 3 flashes/frame = 72 Hz.

CRT Computer monitors: 60 to 140 Hz, depending on resolution. 75 Hz is common.
LCD Computer monitors: 60 Hz frame rate, but may or may not flicker at all if image is not changing. Newer LCD TVs flicker at 120 Hz to allow for stereoscopic displays where each eye gets a 60 Hz flicker.

Incandescent bulbs: 120 Hz, and very small amount of modulation. (Twice the AC rate of 60 Hz because they flash for both directions of current flow. Low modulation because they stay hot while current is switching direction.)
Flourescent bulbs: 120 Hz, with much more modulation. Old bulbs sometimes flicker at 60 Hz, producing high modulation, visible flicker. Newer compact fluorescent bulbs flicker much less because of the phosphor coatings used.

Some laser pointers flicker, some do not. Many LEDs on electronics, new car taillights, etc. will flicker. Most headlights, taillights, traffic signals and flashlights do not flicker because they are driven by direct current.
“Laws” describing perceived flicker

1. Ferry-Porter Law
   CFF is directly proportional to the log of stimulus luminance.

2. Granit-Harper Law
   CFF is directly proportional to the log of stimulus area.
“Laws” describing perceived flicker

3. Talbot plateau Law
For flicker rates well above CFF, the perceived brightness of a flickering light is the same as the brightness of a constant light set to the average luminance of the flicker. At these rates, the visual system averages the luminance of high and low levels.

4. Brucke-Bartley Effect
At the peak of the TCSF (e.g. 8 Hz) there is a brightness enhancement. The flickering light looks even brighter than a steady light set to the high luminance value of the flicker.

The curve plots the perceived brightness of a flickering patch for a range of temporal frequencies. When the light is on steady, it is rated as “100” by the subject. When the light is off, it is rated as “0”. When it flickers at very high rates, it is rated as “50,” the average of on and off (Talbot Law). When it flickers at around 10 Hz, it is rated as “200” (Brucke-Bartley effect).
Eccentricity and CFF

CFF depends on both retinal location and target size. For small patches (1/2°) the CFF declines with eccentricity. For larger patches, (3°, 10°) CFF increases with eccentricity to a maximum at about 40° eccentricity.

Fusion frequency in the horizontal meridian of the visual field. Four different sizes of the test-fields: 10°, 3°, 1½°, ½°.

Subject: B. S. H.
Eccentricity and CFF

For small dim targets, CFF is highest in the fovea.

For large targets, CFF is highest peripherally.

If targets are scaled with eccentricity, CFF is highest at about 40 degrees.

CFF shows high variability across the visual field.

Fig. 4. Visual-field contour maps of CFF for square-wave modulation (in cycles per second) as a function of eccentricity and meridian, with the field sizes scaled to stimulate a constant number of cones at each eccentricity, for two observers. The field boundary is 60°, with 30° eccentricity indicated by a dashed line and the blind spot indicated by a black ovoid. Contour lines are shown in 5 Hz steps, with light shading above 60 Hz (NH) and 65 Hz (RT). Dark shading occurs above 75 Hz (NH) and 80 Hz (RT). Note particularly the high CFF's in a band encircling the lower field at about 40° eccentricity.
If our two eyes were simply averaged together, out of phase flicker would be invisible. We have better binocular sensitivity to in-phase than out-of-phase flicker, but out-of-phase is still visible.
Retinal responses to pulses

The rods and cones respond different to brief flashes of light. Rods respond in a sustained way for a long fraction of a second.

Cones respond in a biphasic way, with an initial positive lasting about .1 seconds and then a negative.

Baylor, 1987
Physiological Basis of TCSF

Magno-cellular (M) and parvo-cellular (P) neural pathways in primates have different SF and TF sensitivity. Magno cells are more sensitive to high flicker rates. Lesions of M and P pathways yield selective TF losses.
Physically, Motion = \Delta \text{Position} / \Delta \text{Time}

Physiologically, is the perception of motion based on comparing perceived changes in position & time?
Motion sensitivity over space and time

Matlab demo QuickPhi
Motion models: comparing visual activity across space and time

The earliest model is from Reichardt, called a **Reichardt Detector**, meant to describe motion sensitivity in the fly.

A neuron compares activity from one position to **delayed** activity from a second position.

Delta ($\Delta$) refers to the delay of detector 1. The unit $M$ combines the two signals.

This setup also responds to flickering gratings, though.
Elaborated Reichart detector

By subtracting two Reichart detectors, one can make a motion detector that doesn’t respond to flicker.
Motion sense is adaptable
Motion breaks camouflage
Motion is detected “locally”, then combined “globally”.
The “aperture problem”

The “Aperture Problem”:
The individual parts of the moving diamond are seen by neurons in the cerebral cortex as isolated line segments moving through the cell’s “receptive field”: that part of the visual field that activates the particular cell. Seen through this small aperture, the motion always appears to be going perpendicular to the line. Only by combing the activity of many such cells can the brain extract the whole pattern motion.
Motion of a grating is a lot of local flicker
Spatial Frequency, Temporal Frequency, and Velocity

The velocity of a drifting grating is given by the ratio:

\[ V \text{ (deg/s)} = \frac{\text{TF} \text{ (cyc/s)}}{\text{SF} \text{ (cyc/deg)}}. \]
"Motion Energy" theories

A simple neuron like a ganglion cell has a receptive field over space and a temporal impulse response. It responds to motion in more than one direction, and also to flicker.
By combining receptive fields of different neurons, a directionally selective cell can be built. In 1985, three different groups published models of how this might be done: Adelson & Bergen, Watson & Ahumada, Van Santen & Sperling. Later papers have shown that they all are the same model, with minor differences.
Motion sensitive areas

Motion processing in cortex:
Area V1 (also called “Area 17”) in cortex is the primary visual area, and has cells with motion selectivity, but they cannot solve the aperture problem. The **Middle Temporal** area (“area MT”) in the Temporal lobe collects the responses of all those V1 cells and has cells that respond to the whole pattern, rather than small pieces. Experiments suggest that this area has the closest association to our perception of motion in complex displays.

Damage to this part of the brain leads to a condition of “motion blindness” or **Akinetopsia**. Patients with this condition will see objects clearly, and be able to indicate position, but are unable to smoothly follow moving objects or judge their speed.

A nearby, related area called the **Middle Superior Temporal** area (MST) has similar sensitivity to global motion, but also includes information about the rotation of the eyes to help us track moving objects.
If there’s time:

Referenced/unreferenced
$1^{st}$ $2^{nd}$ $3^{rd}$ order
quadmixadjust