POVS
Basic Vision Science Core
Spatial Vision I: Contrast Sensitivity
Spatial Vision

• The ability to resolve or discriminate spatially defined features
• The ability to detect and analyze changes in brightness across space
• The perception of borders, lines, edges, etc.
• Two primary measures are visual acuity and contrast sensitivity

Salamanca & Kline “Visual Development”
Steven Schwartz “Visual Perception”
Linear Systems Analysis

- To quantify spatial vision, we must first be able to describe the visual stimuli

- Linear systems analysis
  (Baron Jean Fourier (1822))
  - First applied to the heat equation
    - describes the distribution of heat in a given region over time
  - Often used to describe waveforms in time (sound, hearing)
  - Can be applied to vision by describing a waveform in space
Fourier Transform

- Any complex waveform can be decomposed into a series of sinusoidal components: **Fourier Analysis**.

- Composing a complex waveform from various sinusoidal components: **Fourier Synthesis**.
For Example

Measurements of accommodative microfluctuations can be analyzed by Fourier transform to determine the frequency components of the microfluctuations.
Fourier Transform

This complex, repetitive waveform can be described by several sinusoidal waves of differing amplitudes, frequency, and phase.

Thus we can have a universal representation for a complex waveform.

De Valois RL & Devalois KK “Spatial Vision”
Sine Wave Characteristics

- **Frequency**
  - Oscillations across time (sound wave)
  - Oscillations across space (ripples on water)
    - Used for spatial vision
    - Often referenced to the visual angle (cyc/deg)

- **Amplitude**
  - Height of the sine wave
  - Related to the contrast of the visual pattern
    - (more explanation later...)

- **Phase**
  - The position of the wave with respect to a reference point
Spatial Frequency

Period or cycle

2.5 cycles

2.5 c/deg

1 degree

20 cycles

20 c/deg

1 degree
Spatial Frequency (SF)

Low SF -> wide bars

High SF -> narrow bars
Amplitude & Phase

Phase: position of a sinewave grating with respect to a reference point or another grating.

This red grating has a 90° phase shift with respect to the green one.

Phase: position of a sinewave grating with respect to a reference point or another grating.
Sinewave Grating

This red grating has a 180° phase shift with respect to the green one.

Phase: position of a sinewave grating with respect to a reference point or another grating.
Back to Fourier Transforms...
Fourier Transform

Any repetitive stimulus can be represented as a sum of sinusoids, of appropriate amplitude & “phase”

– even a stimulus with sharp edges (square wave)
Fourier Transform

Square Wave = sum of infinite odd harmonic sine waves with decreasing amplitude. The fundamental sine wave \((f)\) has an amplitude of \(4/\pi\) times that of the square wave.

\[
\begin{align*}
\text{Square Wave} &= f + 3f + 5f + 7f \\
&\quad+ \ldots
\end{align*}
\]
Fourier Transform

Non-repetitive stimuli can also be represented as the sum of a fundamental SF and higher SF components.
Fourier Transform

• Wave forms can also be combined in multiple meridians (i.e. horizontal and vertical)

Horizontal square wave
Multiplied horizontal and vertical square waves
Summed horizontal and vertical square waves

De Valois RL & De Valois KK “Spatial Vision”
Fourier Transform

- Multiple sine waves in multiple orientations can sum together to represent any visual stimulus

De Valois RL & De Valois KK “Spatial Vision”
Application to Spatial Vision

• Now that we know how to define the stimuli, we proceed to quantifying the visual system’s response to these stimuli...
Major Assumptions

1. The visual system behaves linearly, i.e., if you know an observer’s sensitivity to sinusoidal gratings of various spatial frequencies, then you can predict the observer’s response to other complicated waveform.

1. The visual system is uniform in its properties (we know this is not true for the retina, i.e. fovea is much different from peripheral retina)
The Modulation Transfer Function (MTF)

The MTF evaluates the quality of an optical system by comparing contrast in the image to contrast of the object, for various SFs. MTF is usually plotted on linear axes.
Human’s Sensitivity

Adjust the amplitude of the modulation of the sinewave grating until you can just detect the presence of the grating: psychophysically determined contrast threshold.

\[
\text{contrast sensitivity} = \frac{1}{\text{contrast threshold}}
\]
Contrast Sensitivity

• In order to determine a person’s contrast sensitivity, we need to know the contrast of the stimuli...

• Remember that contrast is related to amplitude of the sine wave grating – they are both measures of the height of the waveform.
Contrast of a Sinewave Grating
Michelson Contrast

\[ C_M = \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})} \]

\[ = \frac{L_{\text{mod}}}{L_{\text{ave}}} = \frac{\Delta L}{L_{\text{ave}}} \]

Usually applied to targets that are repetitive across space or time.

Range: 0 to 100%
Example

Calculate the contrast of a sinewave grating if the maximum and the minimum luminances are 80 and 15 cd/m², respectively.

Solution:

Michelson Contrast

\[ \text{Michelson Contrast} = \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})} \]

\[ = \frac{(80 - 15)}{(80 + 15)} \]

\[ = \frac{65}{95} = 68.4\% \]
Weber Contrast

\[ C_W = \frac{(L_{\text{target}} - L_{\text{background}})}{L_{\text{background}}} = \frac{\Delta L}{L} \]

Usually applied to isolated targets on a homogeneous background.
Weber Contrast

Range: $-100\%$ (black on white) to infinity (white on black).

\[ C_W = \frac{(0 - L)}{L} = -100\% \]

\[ C_W = \frac{(L - 0)}{0} = \text{infinity} \]
Example

Calculate the contrast of a letter ‘E’ if the luminance of the letter measures 80 cd/m$^2$ and that of the background is 10 cd/m$^2$.

Solution:

Weber Contrast
= \( \frac{(L_{\text{target}} - L_{\text{background}})}{L_{\text{background}}} \)
= \( \frac{(80 - 10)}{10} \)
= 7 = 700\%
Contrast Sensitivity

- Now that we know how to calculate the contrast of a stimulus, we can return to discussing the determination of contrast sensitivity in an observer.

- Remember we are determining the threshold contrast for the detection of different spatial frequencies...
Example of Determining Contrast Sensitivity

• First - Adjust the amplitude of the modulation of a sinewave grating until you can just detect the presence of the grating: psychophysically determined contrast threshold.

• http://vcstest.com/
Determining Contrast Sensitivity

- If we determine threshold detection for a variety of spatial frequencies, we can derive the contrast sensitivity function for a given observer by converting threshold measures to sensitivity and plotting as a function of spatial frequency.

\[
\text{contrast sensitivity} = \frac{1}{\text{contrast threshold}}
\]
CS Test Using Gratings: A Demo

Contrast Sensitivity (1/contrast threshold)

low medium high

Spatial Frequency (c/deg)
Contrast Sensitivity Function (CSF)

- The CSF plots CS vs. SF on log-log axes, where CS = 1/contrast threshold.
- Photopic CS is best for middle SFs (e.g. about 4 c/deg).
Shape of CSF

- Affected by a lot of stimulus and non-stimulus parameters, but a typical CSF is an asymmetric inverted U-shaped function.
- Peak at mid-SF (~2 – 6 c/deg).
- High-SF fall-off.
- Low-SF roll-off.
CSF for Various Species

Relative Contrast Sensitivity

Spatial Frequency (cycles/degree)

Goldfish, Cat, Owl Monkey, Macaque, Falcon
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Luminance and CSF

- Peak CS improves and shifts to higher SFs as luminance increases.
- In addition, the high-SF cut-off (acuity) improves with luminance.
- Low SF roll-off is lost with scotopic levels of luminance.

De Valois, Morgan & Snodderly (1974)
Luminance and CSF

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De Valois, Morgan & Snodderly (1974)
Luminance and CSF

For a decrease in luminance, four main changes:
1. Peak CS decreases.
2. SF at which peak CS occurs shifts toward lower frequency.
3. High SF cut-off decreases (acuity decreases).
4. Loss of low SF attenuation.
Contrast Sensitivity vs Sensitivity to Luminance Differences

- Contrast is relative (amplitude related to the mean luminance)

- If someone has a constant contrast sensitivity at two different light levels, it means sensitivity to absolute luminance differs.

- The opposite is also true – someone with constant sensitivity to luminance changes at two different light levels has different contrast sensitivity at those light levels.
Example

• Let’s say a person has constant contrast sensitivity of 50% at a mean luminance of 0.5 \( \text{cd/m}^2 \) and also a mean luminance of 500 \( \text{cd/m}^2 \)

• Using \( \text{CS} = \frac{\Delta L}{L_{\text{ave}}} \)

For mean luminance of 0.5 \( \text{cd/m}^2 \):

\[
0.5 = \frac{\Delta L}{0.5} \quad \text{Thus} \quad \Delta L = 0.25 \text{ cd/m}^2
\]

For mean luminance of 500 \( \text{cd/m}^2 \):

\[
0.5 = \frac{\Delta L}{500} \quad \text{Thus} \quad \Delta L = 250
\]

This subject with constant contrast sensitivity is 1000x more sensitive to luminance differences at the lower light level.
**Weber’s Law**

- A situation in which contrast sensitivity is constant (as shown in the previous example) is in agreement with Weber’s Law

- Weber’s Law: \( \Delta L/L = \text{constant} \)

- The just noticeable difference (JND) differs in luminance conditions, but the ratio of the JND to the background luminance is constant.
Luminance and CSF

- At low SFs, Weber’s Law is observed ($\Delta L/L = \text{constant}$)
- At high SFs, CS depends on absolute luminance modulation.

De Valois, Morgan & Snodderly (1974)
Luminance Modulation

In terms of modulation sensitivity (difference in luminance), it is higher at low than high luminance.

not contrast sensitivity

De Valois, Morgan & Snodderly (1974)
CS for Low SFs

- CS for low SFs remains constant for photopic luminances, consistent with Weber’s law.
- CS for low SFs and high SFs are poorer at scotopic luminances.

De Valois, Morgan & Snodderly (1974)
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Eccentricity and CSF

- Effect of eccentricity on CSF depends on stimulus size.
- If you use a fixed (and small) size stimulus, CS drops in the periphery.
- If you scale the stimulus in the periphery, peak CS can be the same as in the fovea.
Eccentricity and CSF

Contrast sensitivity falls outside the fovea, particularly for a stimulus of constant (small) size.

Rovamo & Virsu (1979)
Eccentricity and CSF

For fixed-size stimuli, with an increase in eccentricity, four main changes:
1. Peak CS decreases.
2. SF at which peak CS occurs shifts toward lower frequency.
3. High SF cut-off decreases (acuity decreases).
4. Loss of low SF attenuation.
Cortical Magnification Factor (CMF)

- CMF: The amount of cortical area devoted to representing a certain fixed visual angle in the periphery.
- Rovamo & Virsu (1979) scaled the stimulus size and spatial frequency such that equal number of ganglion cells were stimulated.
Scaling Stimulus Size

When target size is increased peripherally, peak CS is nearly unchanged, but shifts to lower SFs.

Rovamo & Virsu (1979)
For targets scaled appropriately in size, CS is approximately constant across eccentricity when expressed in cortical units (cycles/mm of cortex).
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Optical Blur and CSF

- Blur decreases CS, especially at high SFs.
- Not much effect of blur at low SFs.

Campbell & Green (1965)
MTF of the Eye

dioptic blur: attenuates high SFs
Optical Blur and CSF

Campbell & Green (1965)
Optical Blur Attenuates CSF

Blur can also introduce “notches” in the CSF.
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Pupil Size and CSF

Campbell & Green (1965)
MTF of the Eye

• The MTF is highest at low SFs and declines as SF increases; best when pupil size ≈ 2.0 - 2.5 mm.
• The MTF is degraded by diffraction when the pupil is small and by aberrations when the pupil is large.
MTF vs. CSF

- At high SFs, the MTF and foveal CSF are similar, indicating that the primary limitation on CS for high SFs is optical.
- Peripherally, CS for high SFs drops faster than the MTF, indicating a neural limitation for high SFs outside the fovea.
Interference Gratings “Bypass” Optics of the Eye

Gratings formed directly on the retina by 2-beam interference minimize the influence of the eye’s MTF on CS.
CS Improves Using Interference Gratings

- CS is better using interference than gratings imaged by the eye’s optics.
- Interference gratings are sometimes used to test vision in patients with ocular opacities.

Campbell & Green (1965)
**Effect of Blur: Fovea vs. Periphery**

- Blur has less effect on CS in the periphery than in the fovea.
- Blur has little effect on high SFs in the periphery because the high-SF cut off is not limited by optics.

Wang, Thibos & Bradley (1997)
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Age and CSF

CS is initially very low in infants.
Infant Vision

1 month

2 months
Infant Vision

3 months

6 months
Adult Vision
Age and CSF

In adults, CS at high SF declines gradually with age.
Factors Affecting CSF

- Luminance
- Eccentricity
- Optical blur
- Pupil size
- Age
- Temporal modulation
Temporal Modulation

- Luminance of a target can modulate in time.
- Frequency at which a periodic stimulus changes over time: temporal frequency (TF), usually measured in Hertz (Hz) or cycles per second (cps).
Temporal Modulation and CSF

With temporal modulation, the low spatial frequency roll-off is lost.

Robson (1966)
Temporal frequency and spatial frequency are related as follows:

Velocity (deg/s) = \frac{TF \ (c/s)}{SF \ (c/deg)}
Image Motion and CSF

Spatial Frequency

Contrast Sensitivity

Drifting stimulus

Normal CSF (careful fixation, stationary stimulus)

Partial retinal stabilization

(almost) complete retinal stabilization
Image Motion and Vision

• All contrast are virtually invisible without retinal image motion (cannot see shadows of retinal vessels).
• Slowing retinal image motion makes low SFs disappear (Troxler fading).
• Introducing fast retinal image motion makes high SFs disappear (try reading text on a moving page, motion blur).
Troxler Fading
Phenomena Related to CS Loss at Low TFs

- Fading of stabilized retinal images.
- Troxler fading of peripheral targets during steady fixation.
- Fading of afterimages on steady background.
Contrast Detection versus Absolute Luminance Detection

- At low SFs, Weber’s Law is observed ($\Delta L/L = \text{constant}$)

- At high SFs, CS depends on absolute luminance modulation.

- Object constancy will be maintained for the lower spatial frequencies which have constant contrast sensitivity.
Spatio-Temporal CSF

Kelly (1979)
Factors Accounting for the Shape of CSF

- Optics of the eye.
- Spatial sampling.
- Lateral inhibition.
- Spatial summation.
Evidence for Optical Limitation of Sensitivity to High SFs (Foveal CSF)

- Blur affects primarily the high spatial frequencies

Campbell & Green (1965)
Evidence for Optical Limitation of Sensitivity to High SFs (Foveal CSF)

- Fall-off of high SFs similar between MTF and CSF.
Evidence for Optical Limitation of Sensitivity to High SFs (Foveal CSF)

- Interference gratings only improve sensitivity at high but not low SFs.
Impact of Pre-neural Factors on the Sensitivity of Mid to High Spatial Frequencies

De Vries / Rose Law: \( \Delta I / \sqrt{I} = \text{constant} \)
Where \( \Delta I \) is the signal/noise ratio

Quantal fluctuations account for the separations of curves at the different luminances and a significant portion of the high-freq roll-off.

This curve takes into account quantal fluctuations, ocular media transmittance, and photoreceptor quantum efficiency. The primary contributor was quantal fluctuations.

This second curve takes into account cone aperture size.

The third adds effects of defocus.

Banks, Geisler & Bennett (1987)
Impact of Spatial Sampling on the High Spatial Frequency Cut-Off

Spatial sampling by the receptors set an upper limit to the extent to which the nervous system can transmit high SF information.
Spatial Sampling

- Photoreceptor can only faithfully sample sinusoidal waves with period $= 2 \times$ detector’s separation.
- In human fovea, cone-separation $\sim 0.5$ min, thus minimum resolvable period is 1 min, or 60 c/deg.
- Above 60 c/deg, will see alias if high frequencies present in stimulus.
Nyquist Limit

- Nyquist frequency: the critical frequency in c/deg above which aliasing occurs.
- In human fovea, Nyquist frequency is about 60 c/deg.
Cone Aperture Limitation

Miller & Bernard (1983)
CS Determined by Laser Interferometry

POVS: Spatial Vision I

Williams (1985)
Sampling Artifacts: Aliasing

Williams (1985)
Aliasing in the Periphery

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Thibos, Walsh & Cheney (1987)
Aliasing

- **Fovea**: Nyquist limit is ~60 c/deg, optical limitation is about 50 c/deg, therefore, human fovea is not limited by sampling.
- **Parafovea**: visual resolution is limited by photoreceptor density.
- **>10 – 15° eccentricity**: resolution limited by retinal ganglion cell density.
Lateral Inhibition

• Retinal (and post-retinal) receptive fields (RFs) have antagonistic center-surround organization.

• E.g. on-center off-surround receptive field:

  + + +
  + + +
  - = inhibition

  + = excitation

POVS: Spatial Vision I
Therefore, this is a “center-surround” receptive field with lateral inhibition.
Receptive fields have spontaneous firing activities.

Excitatory region (+): loves light. When a light is shone on it, firing rate increases.

The larger is the spot of light in the excitatory region, the higher is the firing rate.

When a spot of light is shone on the inhibitory region (−), firing rate decreases.
Receptive Field (RF) Structure and SF Tuning

- Optimal responses occur for the SFs that match each neuron’s RF profile.
- Responses are reduced for higher SFs due to reduced excitation, and for lower SFs due to increased lateral inhibition.
Low-SF Roll-Off of CSF not due to Lateral Inhibition

Lateral inhibition can account for low-SF roll off in the CS of individual neurons but not the overall CSF.
Low-SF Roll-Off: Spatial Summation

- Decreased spatial summation contributes to low-SF roll off of CSF.
- CS improves with number of grating cycles ≤ 10.
Suprathreshold Contrast Perception

• Above threshold, perceived contrast increases faster for low and high SFs than middle SFs.

• Consequently, different SFs with physically equal supra-threshold contrast appear about the same.

Georgeson & Sullivan (1975)
CSF and Acuity

Contrast Sensitivity

Spatial Frequency (c/deg)

High SF cut-off (hi-C acuity)

High CS = low contrast

Low CS = high contrast

High SF cut-off (lo-C acuity)
Clinical Measures of Contrast Sensitivity
Clinical Measures of Contrast Sensitivity
Clinical Measures of Contrast Sensitivity
Myths Regarding Acuity

• High contrast acuity is the best way to test everyday vision.

• A patient who has 20/20 acuity has perfect vision.