Motion:

Displays and Perception

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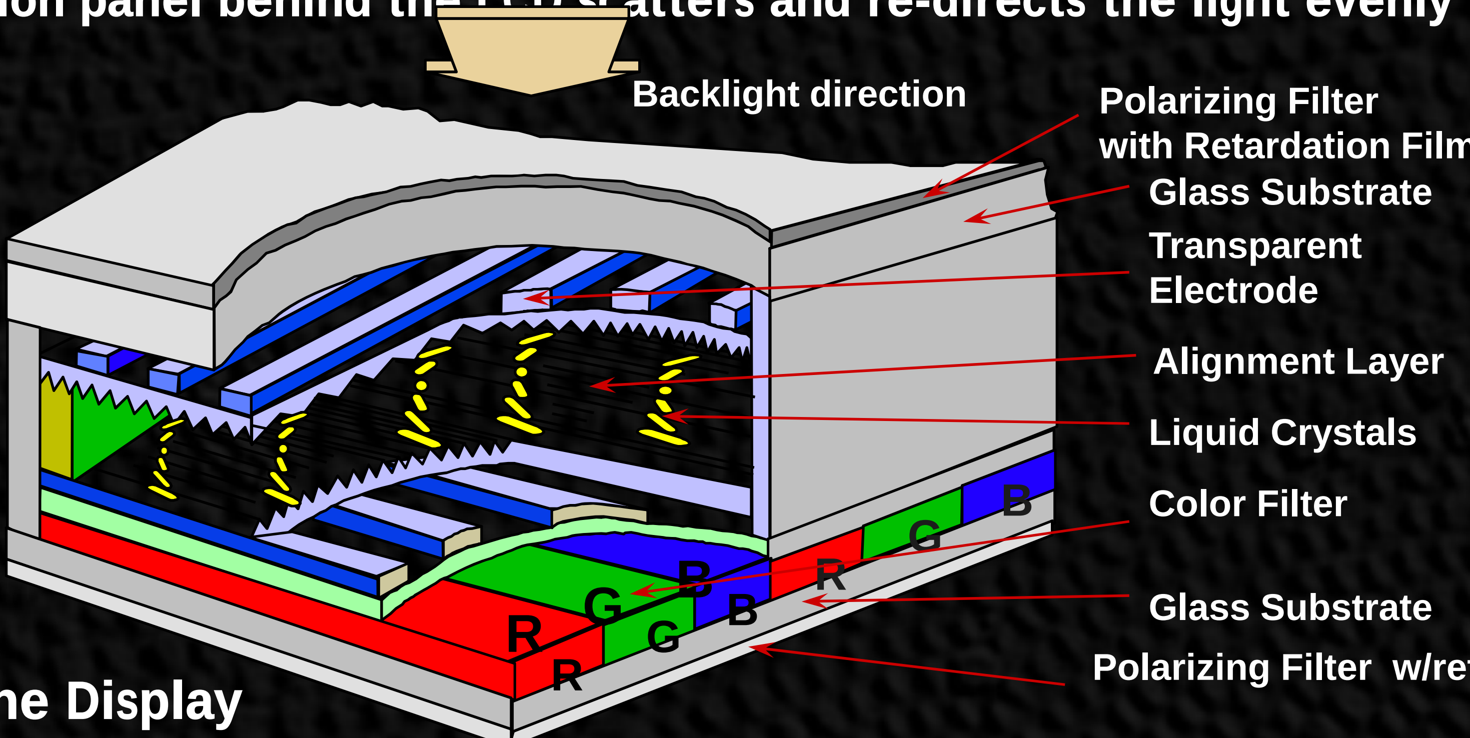
Outline

- **LCTV Basics**
  - Transmission modulation, Spatial , Color, etc.
- **Basics of Spatiotemporal vision**
  - Motion
  - Eye movements
  - Eccentricity
- **LCD Temporal Issues**
  - Overdrive
  - Dynamic Gamma
  - Display Temporal Rendering Function
  - Analysis of Temporal LCD approaches
- **Perceptual Appearance: Motion Sharpness Effect**
- **Standardized Metrics**
- **Conclusions/Summary**
- **What’s next:**
  - Other Temporal Artifacts
  - What Does Motion Really Look Like?

LCTV Basics

Light Modulation via Liquid Crystals

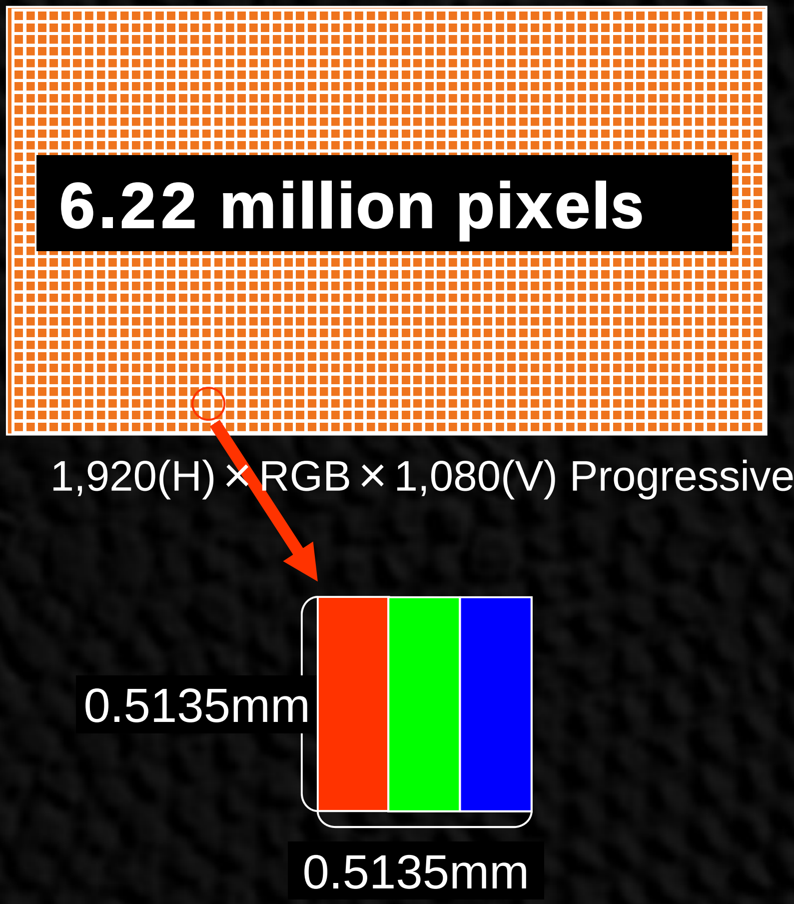
- LCD is a "transmissive" display
  - Light is not created by the liquid crystals themselves
  - A light source behind the panel shines through the display (CCFL, LED)
  - Diffusion panel behind the LCD scatters and re-directs the light evenly



- Driving the Display
  - 2 polarizing transparent panels (One Vertical , One Horizontal)
  - Liquid crystal solution sandwiched in between
  - Liquid crystals are rod-shaped molecules
    - Bend light in response to an electric current
    - Act like a shutter - allow light to pass through or block (or attenuate)

Pixels to resolution

45" LCD “full HDTV”

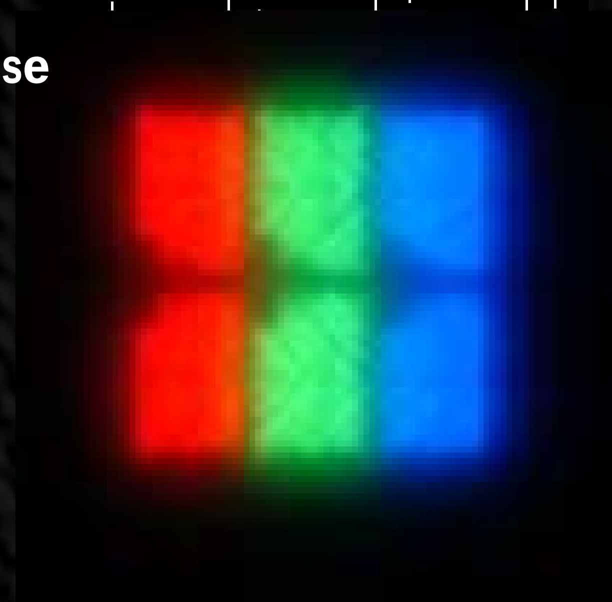


- Physical resolution vs. # Pixel Dimensions
- Full HD (1920 x 1080 progressive) achieved in 2003
- Full HD now shown up to 108” for LCTV
- 4k x 2k pixel resolution shown by several manufacturers (65”; 24 million pixels)
- Usually, pixel physical resolution for LCTV is near 45 ppi

Salient Characteristics of LCD: MTF & PSF

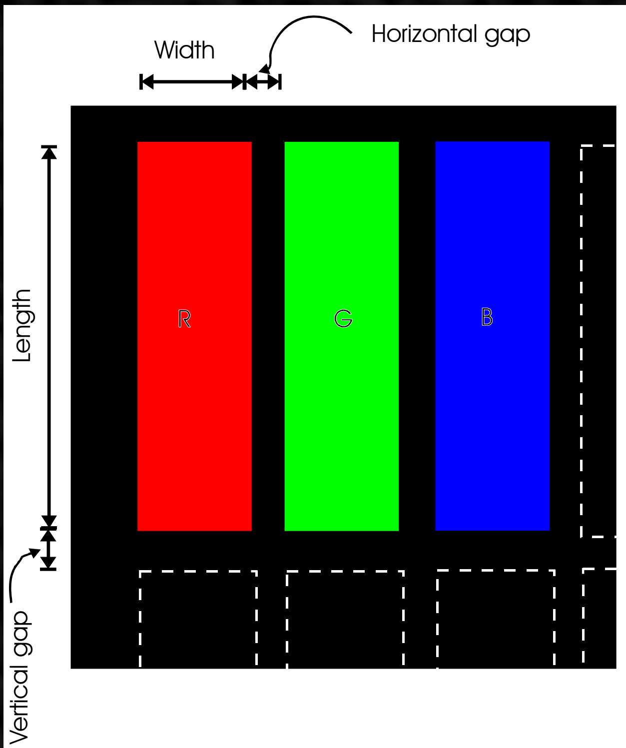
- LCD MTF does not vary with gray level or spatial neighbors
  - Rigid pixel via fixed aperture + steady Backlight
  - MTF is sinc function based on subpixel dimensions
  - color crosstalk correction sometimes needed

- CRT spatially nonlinear → MTF hard to assess & use
  - Spatial superadditivity in H direction :
  - Spatial sub-additivity if power supply not powerful enough



Salient Characteristics of LCD: MTF details

- **Comparison to visual system "MTF" = CSF**
  - Sinc is only a gradual LPF within HVS CSF "window"
  - Viewing distance = 2000 pix
  - ~2H for HDTV, ~4H for VGA



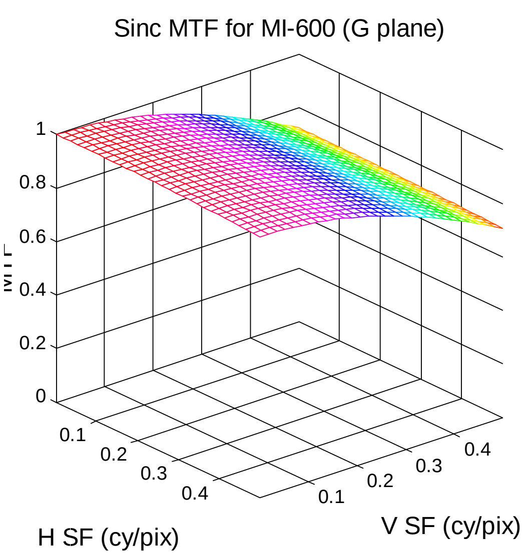


Figure 13A: Sinc MTF for MI-600

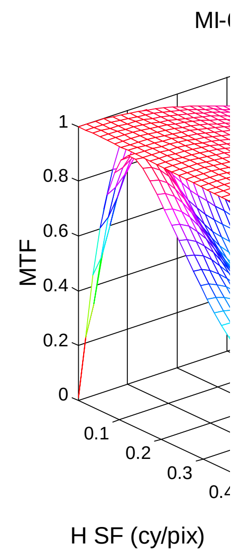


Figure 13B: MI-600 and CSF

Current Challenges for LC TV

- High Dynamic Range at consumer cost
- Wide Color Gamut at consumer cost
- Ultra high resolution 4k x 2k and up
- Achieving perfect motion fidelity :

1. Speeding up response time for pixels
   - How fast a pixel can change color without blurring
   - Currently <= 2-4 milliseconds cites, but not for all gray level transitions
2. Hold-response blur (problem with Plasma also)
3. Judder (frame rate issue, problem with CRTs and Plasma also)

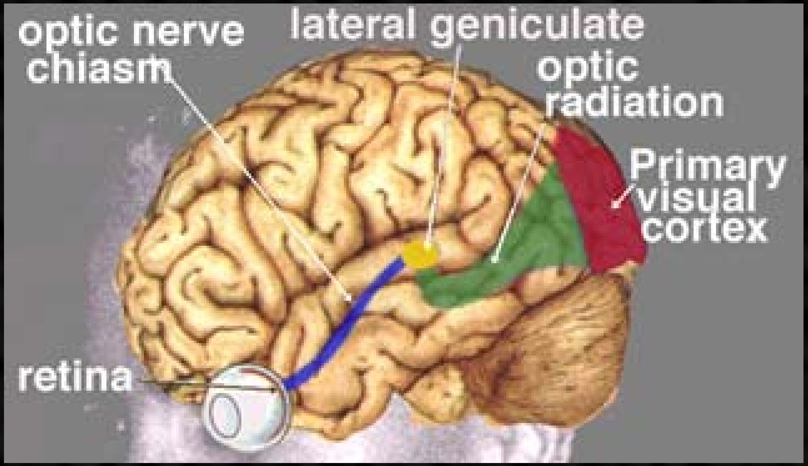
- Human visual perception plays a role in performance

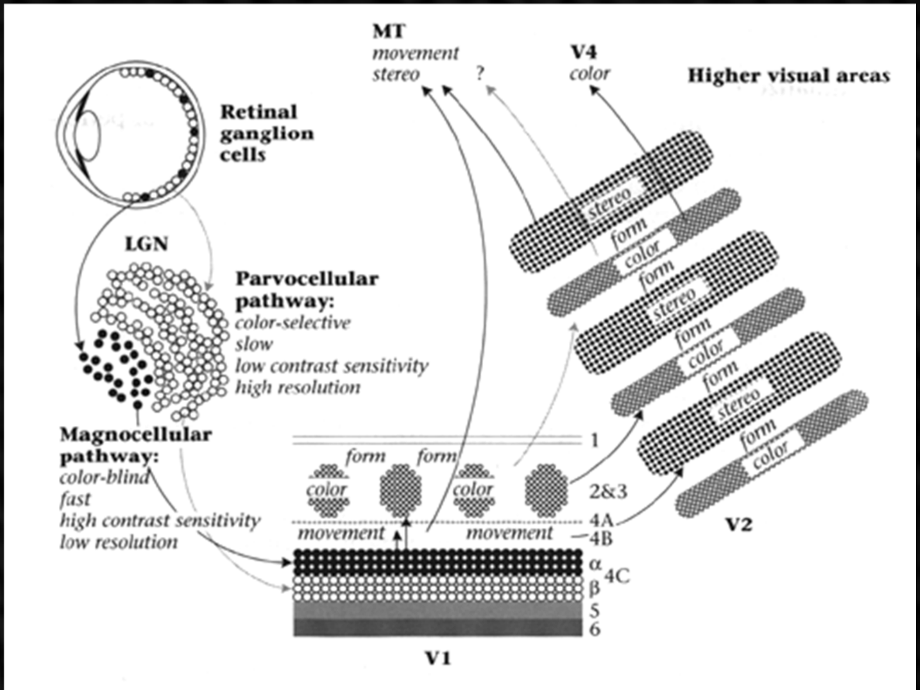
Some Basics in Spatiotemporal Vision

Properties of the Visual System

Properties generally dissected along these dimensions:

- Luminance Level
- Spatial Frequency
- Local Spatial Content
- Temporal Frequency
- Motion
- Global Color
- Eccentricity
- Depth

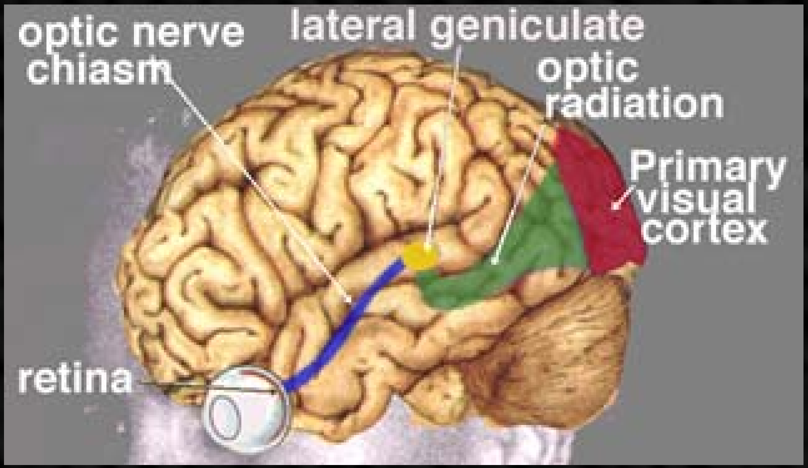




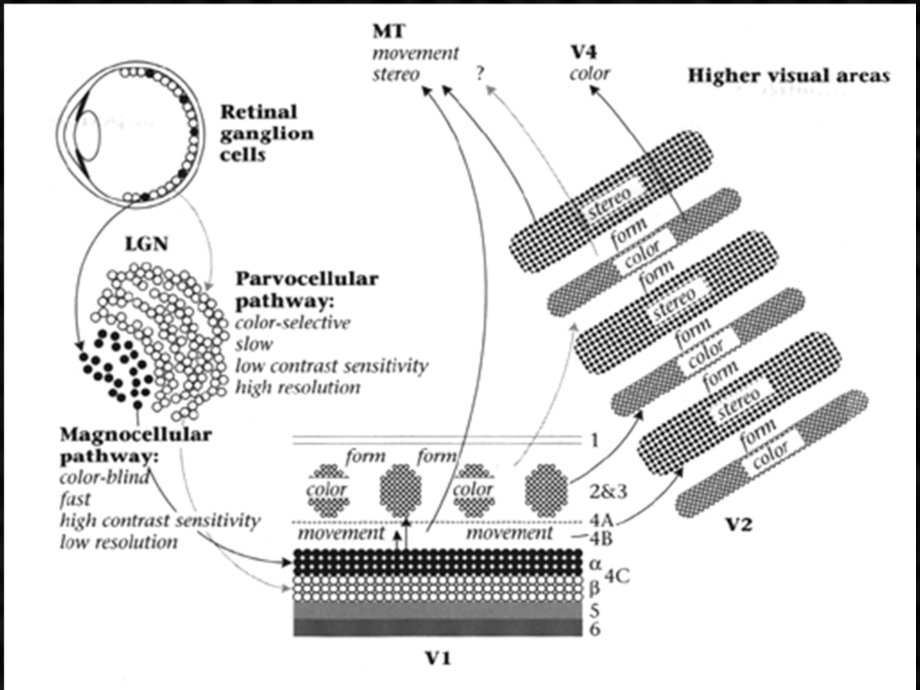
6.23 AN ANATOMICAL/PERCEPTUAL MODEL OF THE VISUAL CORTEX.

Properties of the Visual System

Properties generally dissected along these dimensions:



- Spatial Frequency
-
- Temporal Frequency
- Motion
-
-

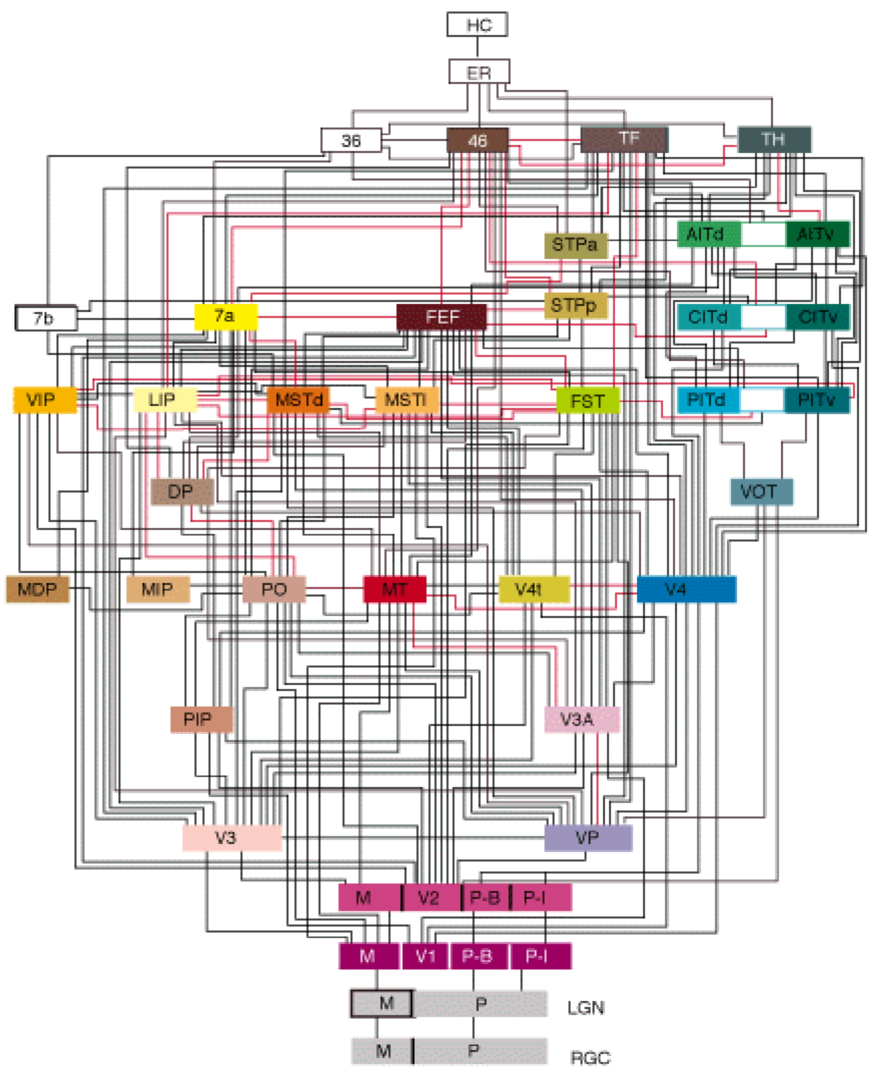


6.23 AN ANATOMICAL/PERCEPTUAL MODEL OF THE VISUAL CORTEX.

Engineering vs. Physiological Models of the Visual System

- Engineering Models of visual behavior aim for mathematical descriptions of key functionality
- Psychophysics and black-box modeling have gotten the most mileage for practical applications
- While physiological plausibility is helpful, simplification is desired
- No need to model down to the neurotransmitter
- How is more important than where

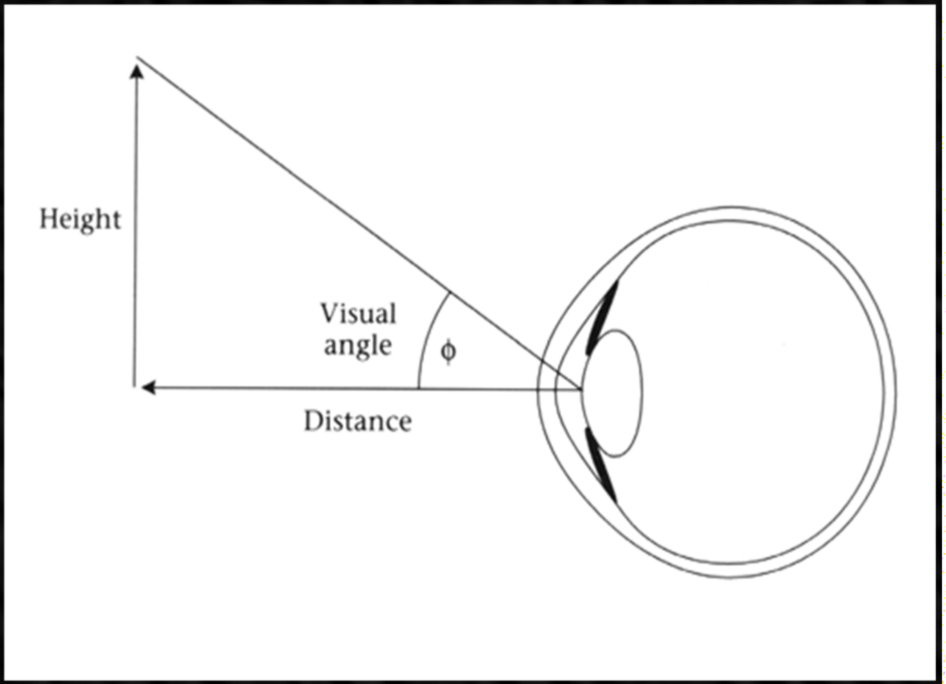
Circuit Diagram of Macaque Visual Areas

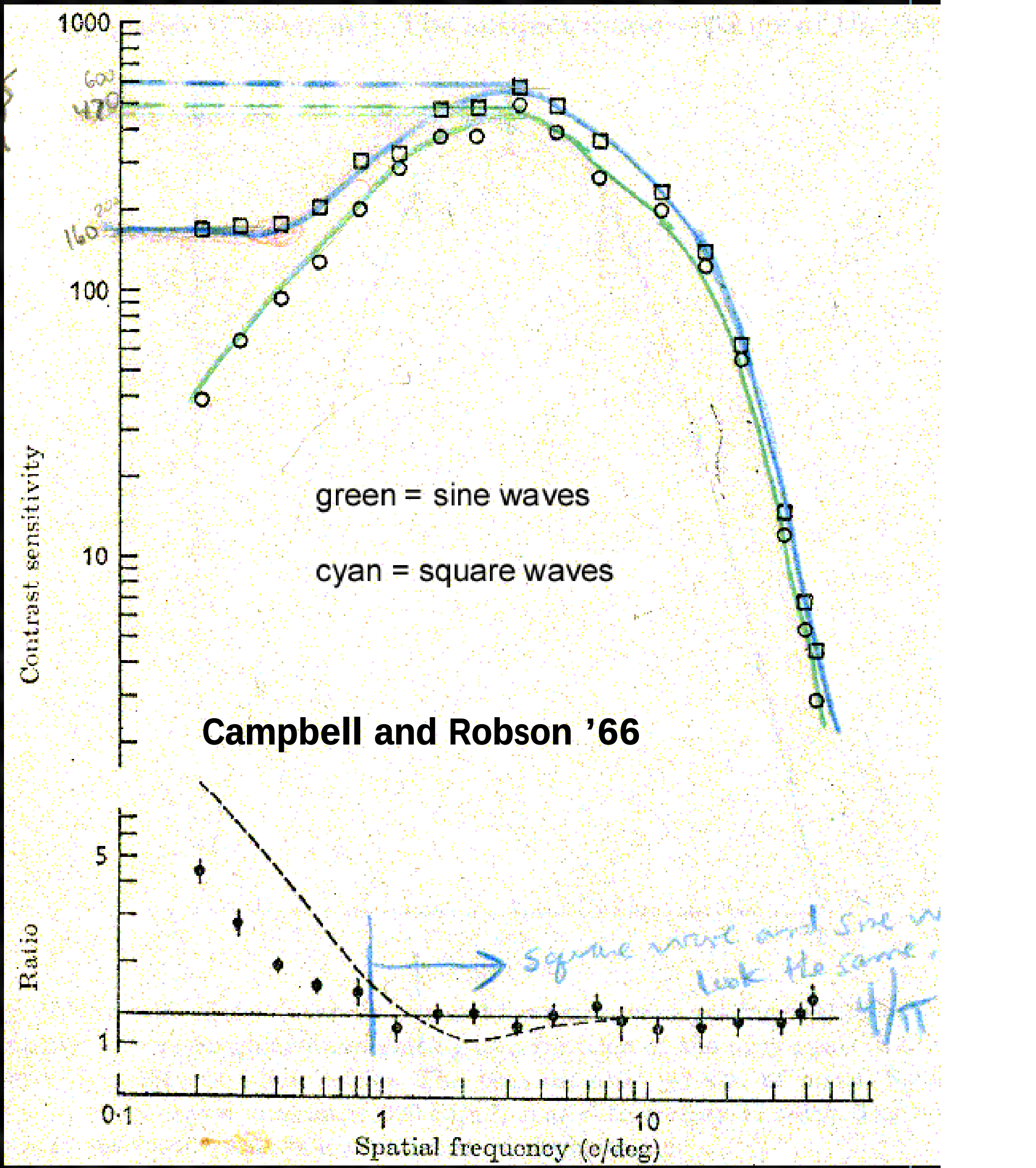


from Felleman, D. J. and Van Essen, D. C. (1991) *Cerebral Cortex* **1**:1-47.

Spatial Frequency

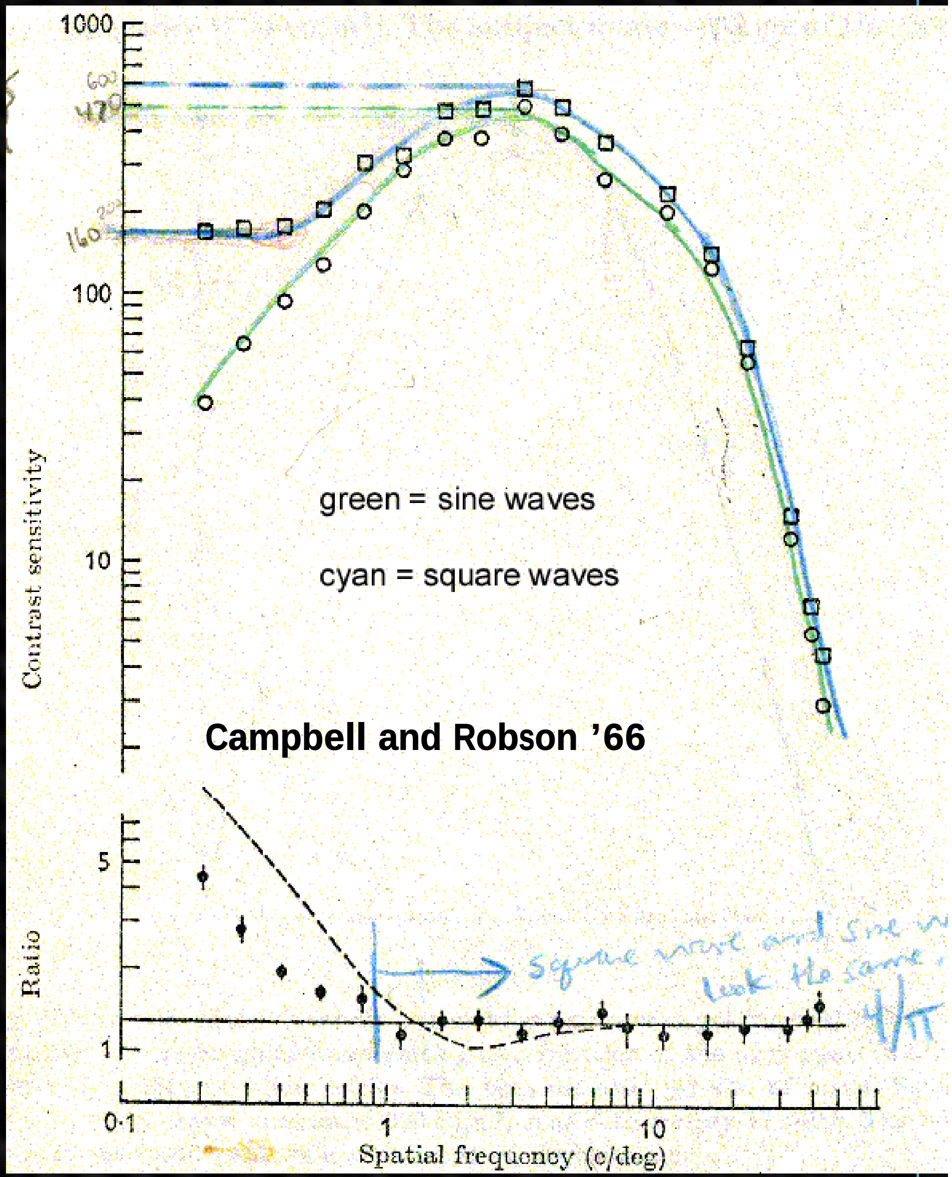
- Spatial behavior constant with visual angle (degrees)
- Spatial frequencies specified in cycles/degree (cpd, cy/deg)



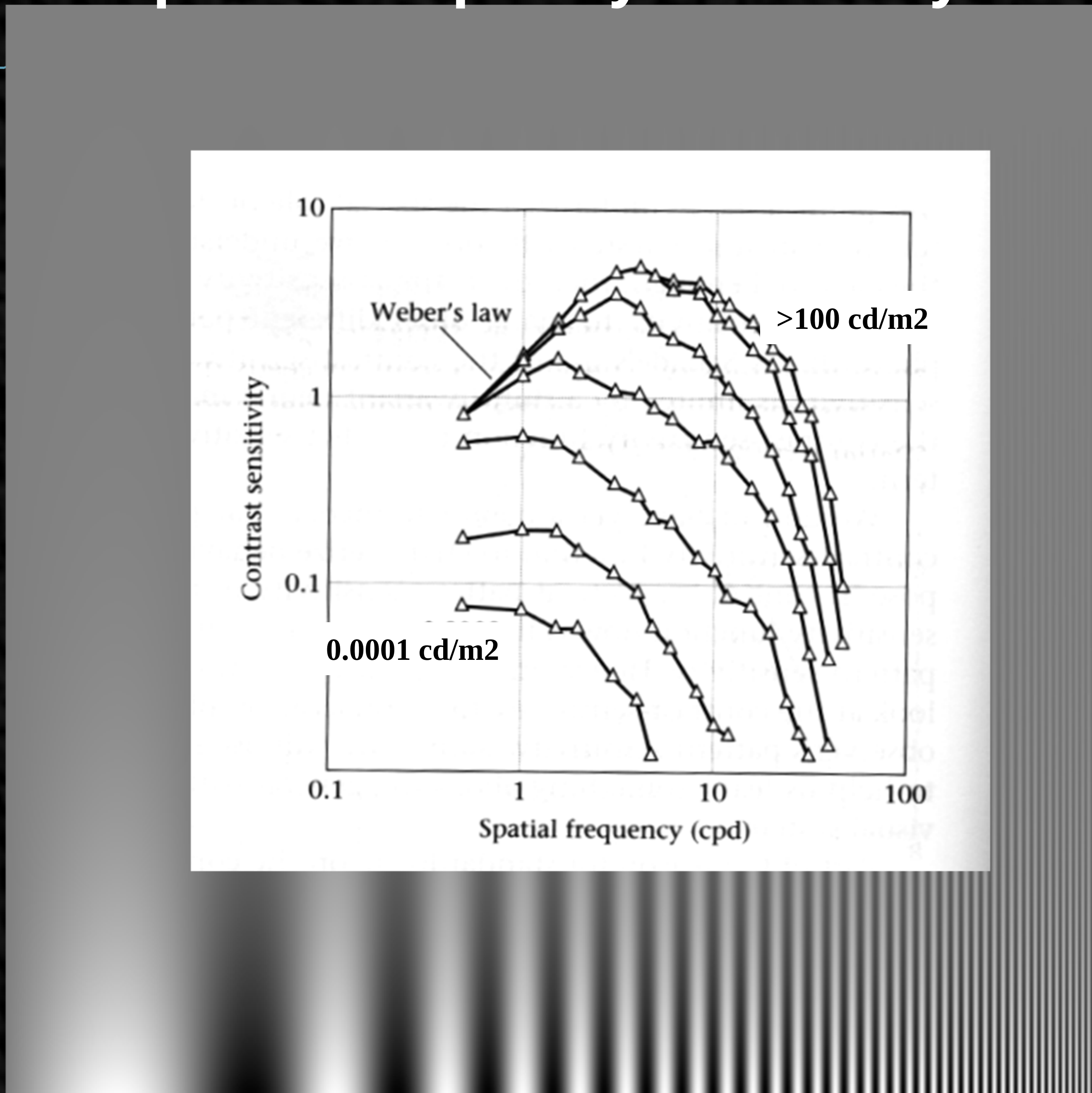


Spatial Frequency

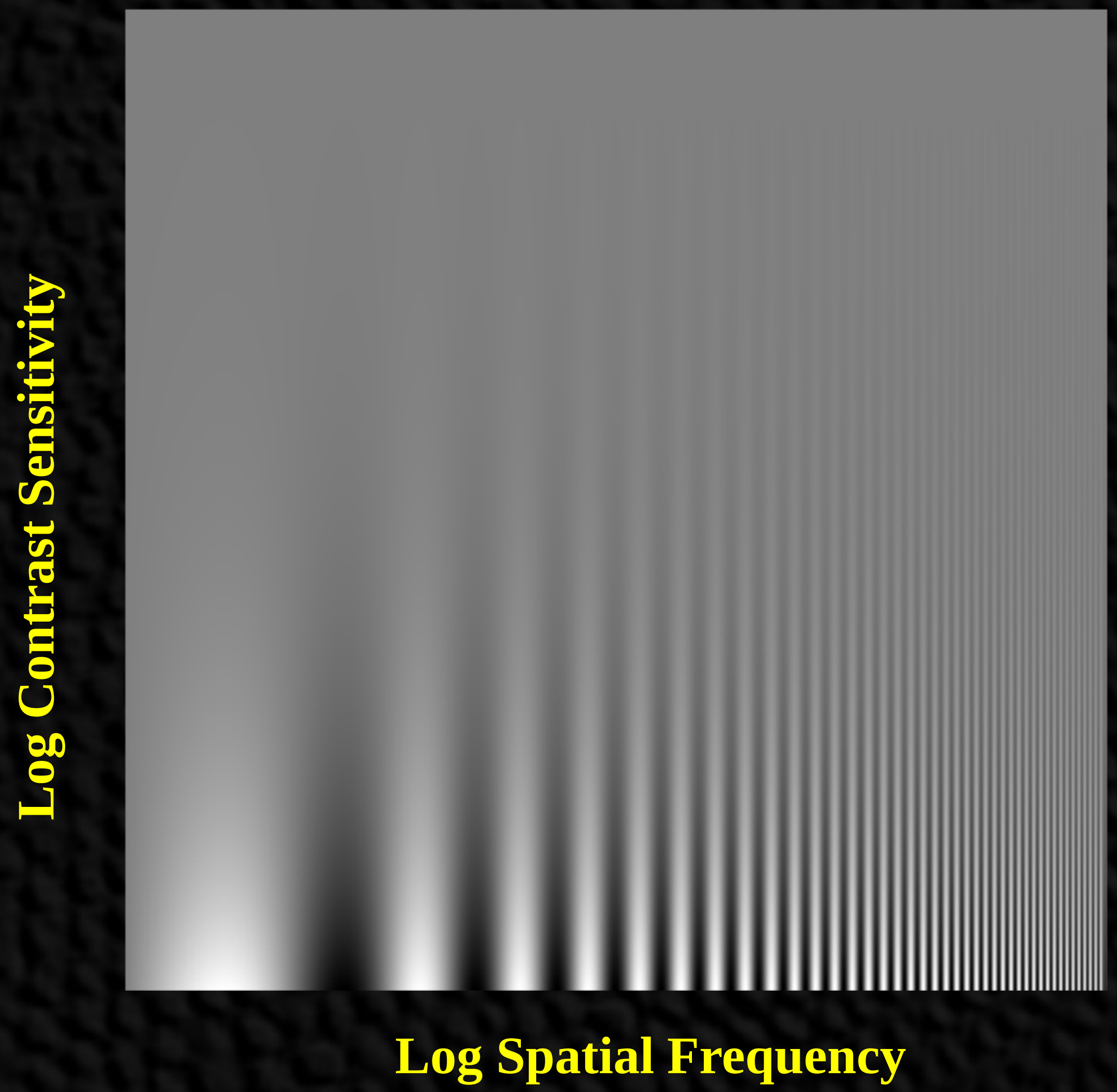
- **Spatial behavior constant with visual angle (degrees)**
- **Spatial frequencies specified in cycles/degree (cpd, cy/deg)**
- **Spatial frequency behavior described with** CSF
  (contrast sensitivity function)
  - Similar to OTF of optics, MTF of electrical systems, but it is nonlinear and adaptive
  - Measured with psychophysics
- **One of the most useful, and widely used properties of visual system**



Spatial Frequency Sensitivity



Spatial Frequency Sensitivity



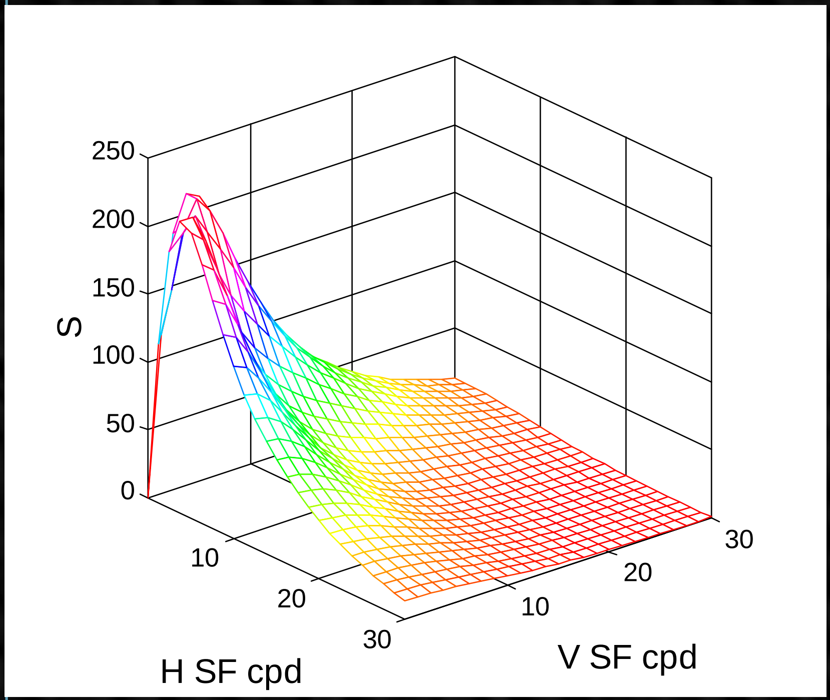
Spatial Frequency in Application

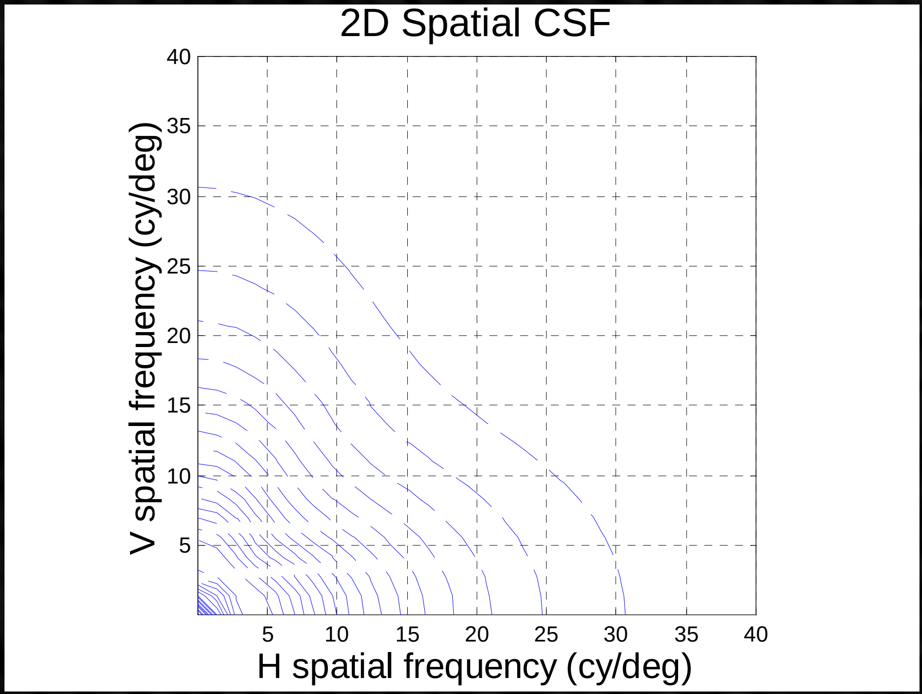
- **The max spatial frequency that can be displayed digitally is the Nyquist frequency**
- **It is ½ the sampling frequency (e.g., 500 pixels can display at most 250 cycles)**
- **Common max frequency seen by humans (I.e, CSF) is 30 cy/deg for medium brightness**
  - **Highest max ever seen is 60 cy/deg (very high brightness, Carlson @ RCA)**
- **Examples of visual Nyquist frequencies and viewing distances for common displays:**

NTSC (425 lines) at 6H	(2550 pixels):	22 cy/deg
NTSC (425 lines) at 3H	(1275 pixels):	11
XGA (1024x768) at 3H	(2304 pixels):	20
SXGA (1280x1024) at 1H	(1024 pixels):	9
1366 x 720 HDTV at 3H	(2160 pixels):	19
Full HDTV (1920x1080) at 6H	(6480 pixels):	57
Full HDTV (1920x1080) at 3H	(3240 pixels):	28
Full HDTV (1920x1080) at 2H	(2160 pixels):	19

2D Spatial Frequency

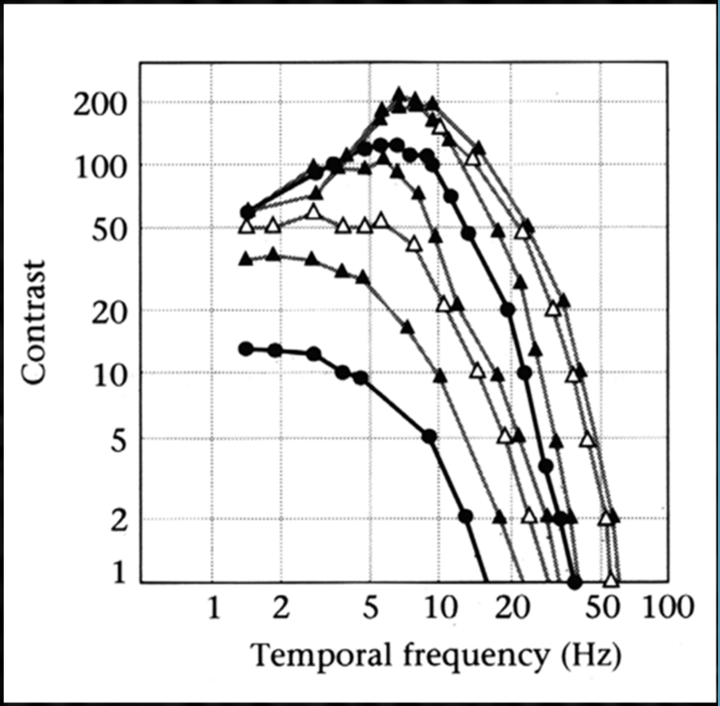
- **2D frequencies important for images**
- **2D CSF is <u>not</u> rotationally symmetric (isotropic)**
- **Lack of sensitivity near 45 degrees, called the oblique effect**





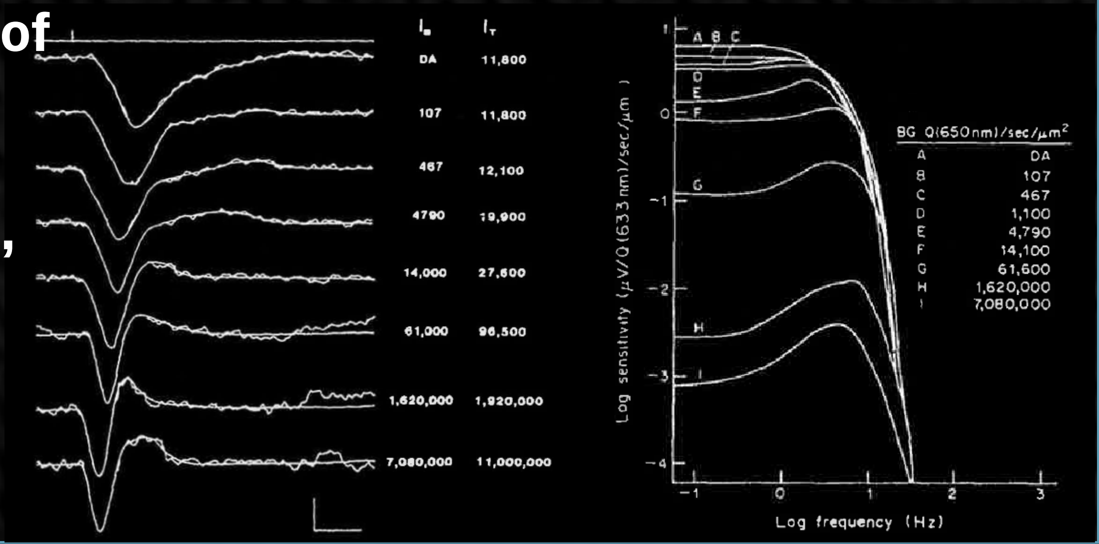
Temporal Frequency

- **CSF for temporal frequencies also has been measured and modeled**
- **Temporal CSF for different light adaptation levels for luminance →**
  - Top curve is best for mid-bright display applications



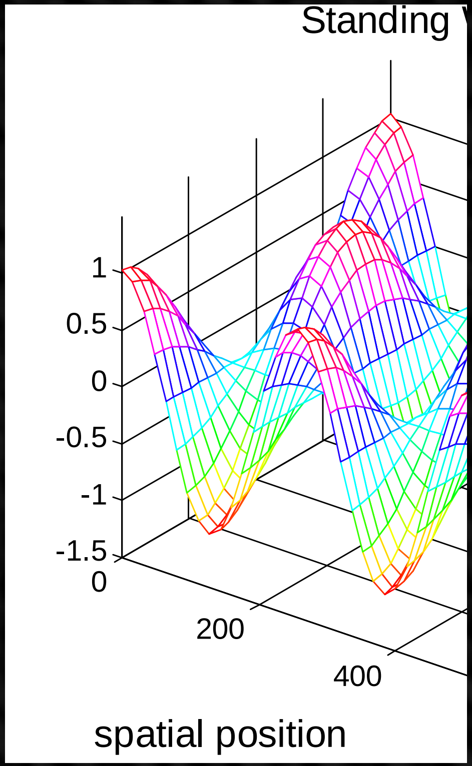
- **Opponent Color temporal CSF also has about 1/2 the bandwidth and sensitivity of the luminance**
- **DeLange 52, Kelly 60s-70s, Watson 80s**

Cone impulses vs. LA & calculated frequency response in amplitude → sensitivity format



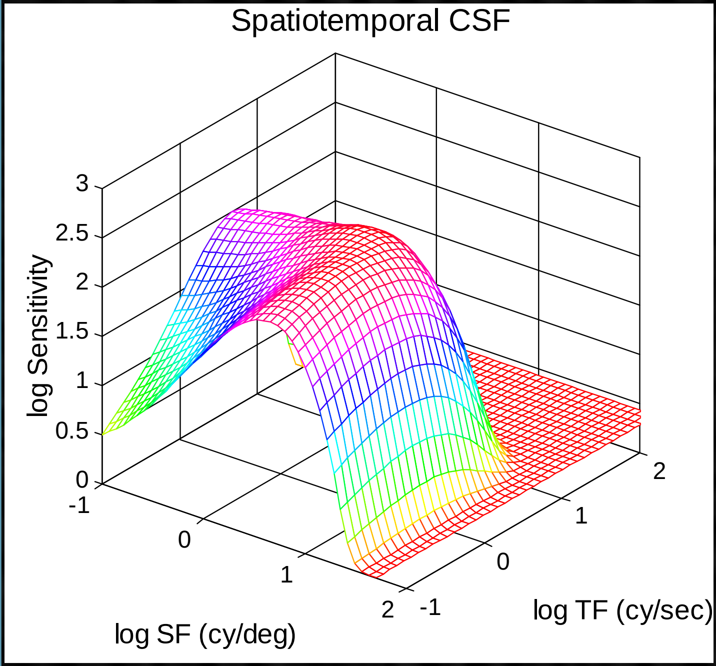
Spatiotemporal Frequency

- **Psychophysical data measurement of spatio-temporal CSF is common**
  - Robson 66
  - Van Nes, Koenderinck, Bouman 67
  - Kelly 79
  - Kelly and Burbeck 80
- **Test signal is product of spatial and temporal frequency modulation**
  - Standing Wave
  - Counterphase flicker

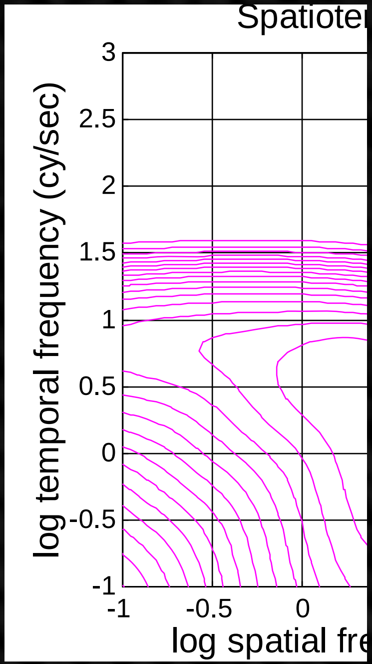


Spatiotemporal CSF

- Spatiotemporal CSF (measured with counterphase flicker)
- Window of visibility
- Data shows max visible temporal frequency (CFF) near 50 cy/sec
  - CFF = Critical Fusion Frequency = max temporal frequency that can be seen



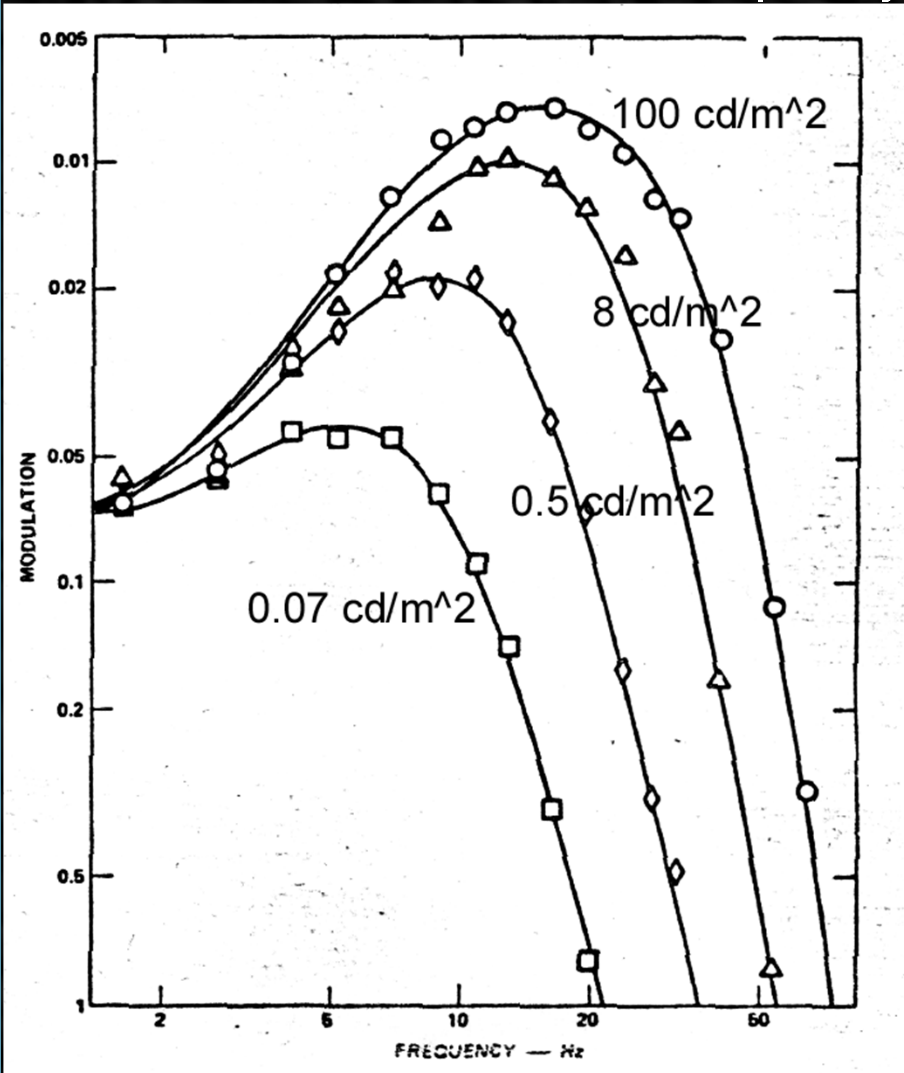
- D.H Kelly 79
- Koenderinck & van Doorn 79 (bimodal)
- Burbeck & Kelly 80 (excitatory-inhibitory separable version)

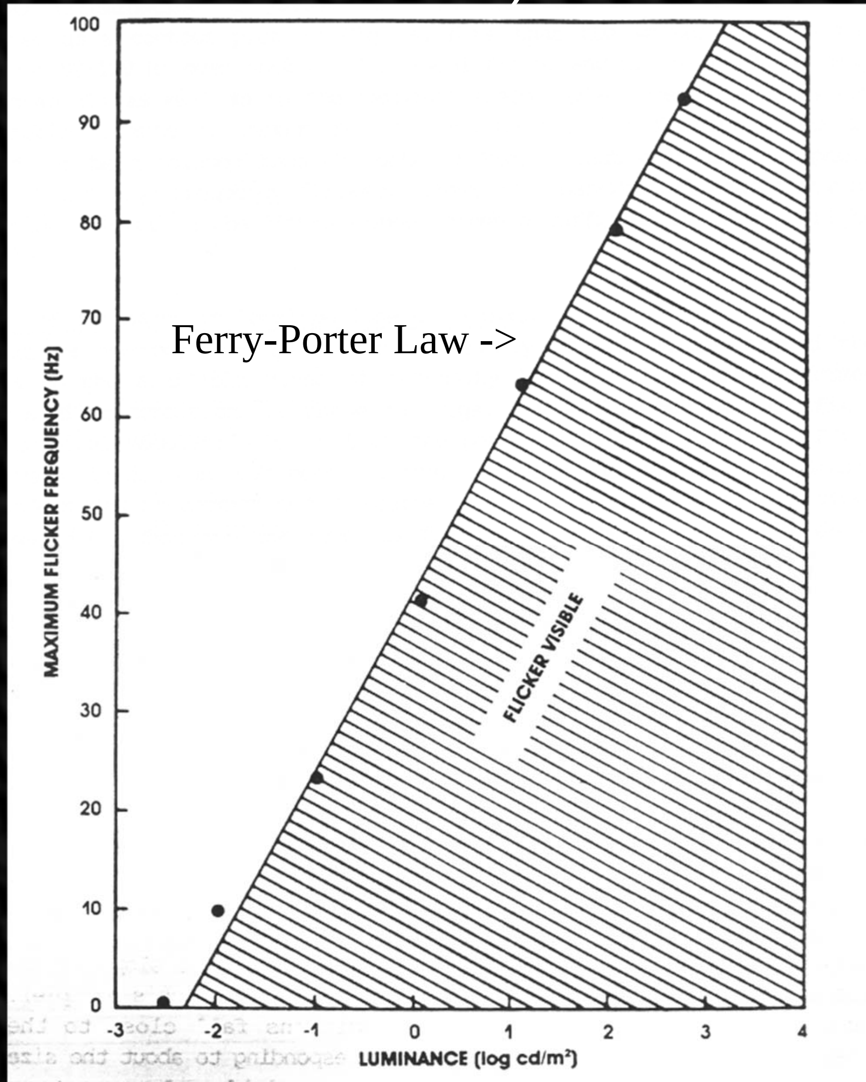


- Thus 60 fps usually causes no visible flicker (foveal)
- Movie film at 24 fps causes visible flicker, so projectors shutter each frame 2 or 3 times to increase fundamental temporal frequency
  - Before the 1920s , movies were called “the flickers’

Brightness and Light Adaptation effects on T-CSF

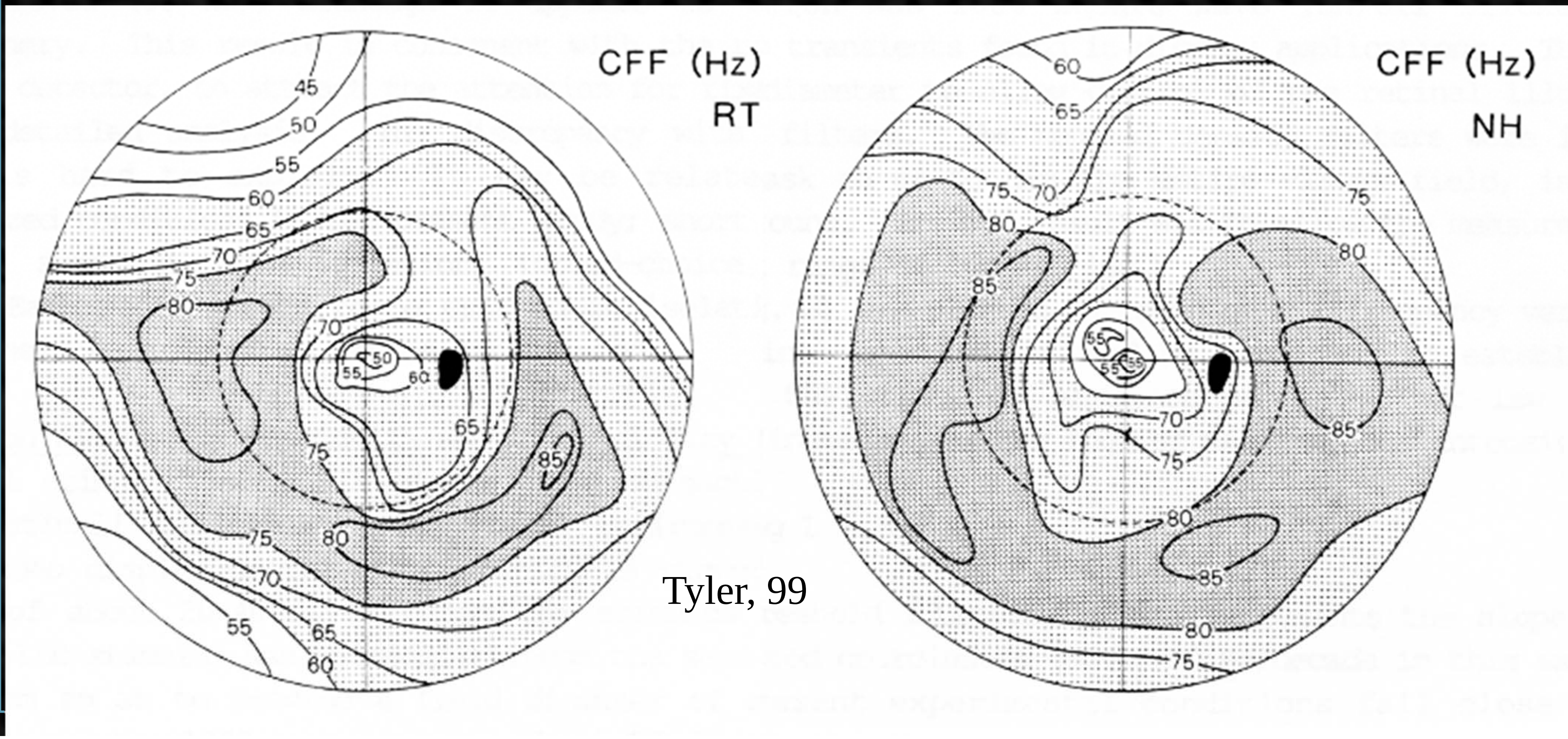
- Higher brightness → Increase in peak sensitivity of temporal CSF
- Higher brightness → Increase in bandwidth of temporal CSF
- CFF = Critical Fusion Frequency (CSF bandwidth cut-off)





CFF and Eccentricity

- **CFF= critical fusion frequency.**
  - Defined as frequency when 100% modulation signal looks identical to flat-field
  - Viewer does not see any flicker
- **For fovea and typical display light levels, CFF around 55 Hz**
- **For periphery at same light levels, it can increase to over 80Hz**



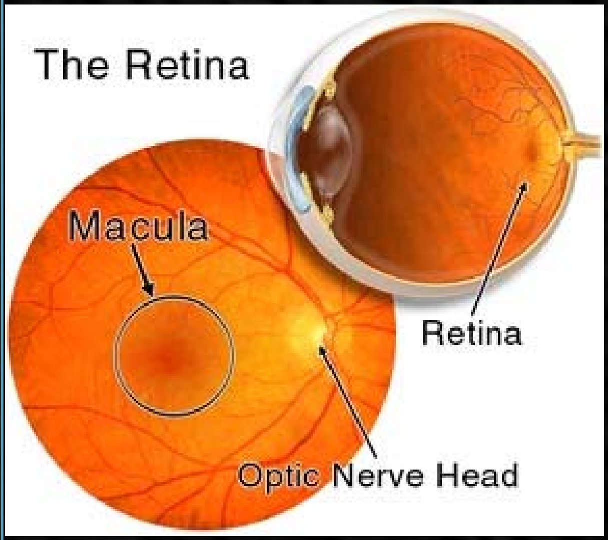
Tyler, 99

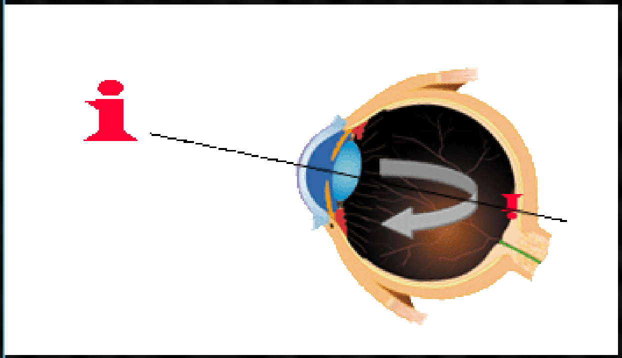
Spatiotemporal Spectra Demos

Constant RMS Contrast

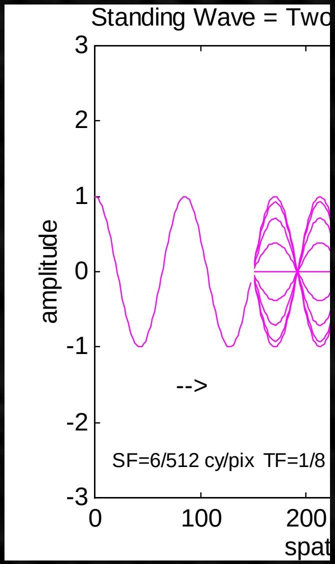
Motion

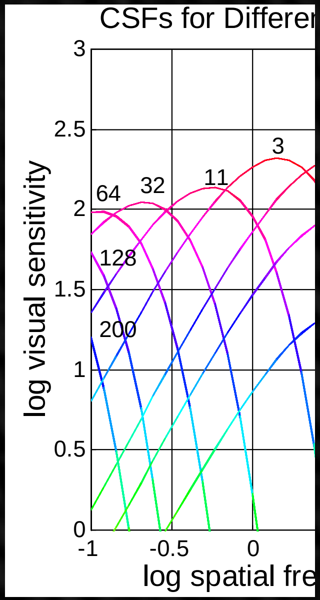
Motion and Retinal Velocity





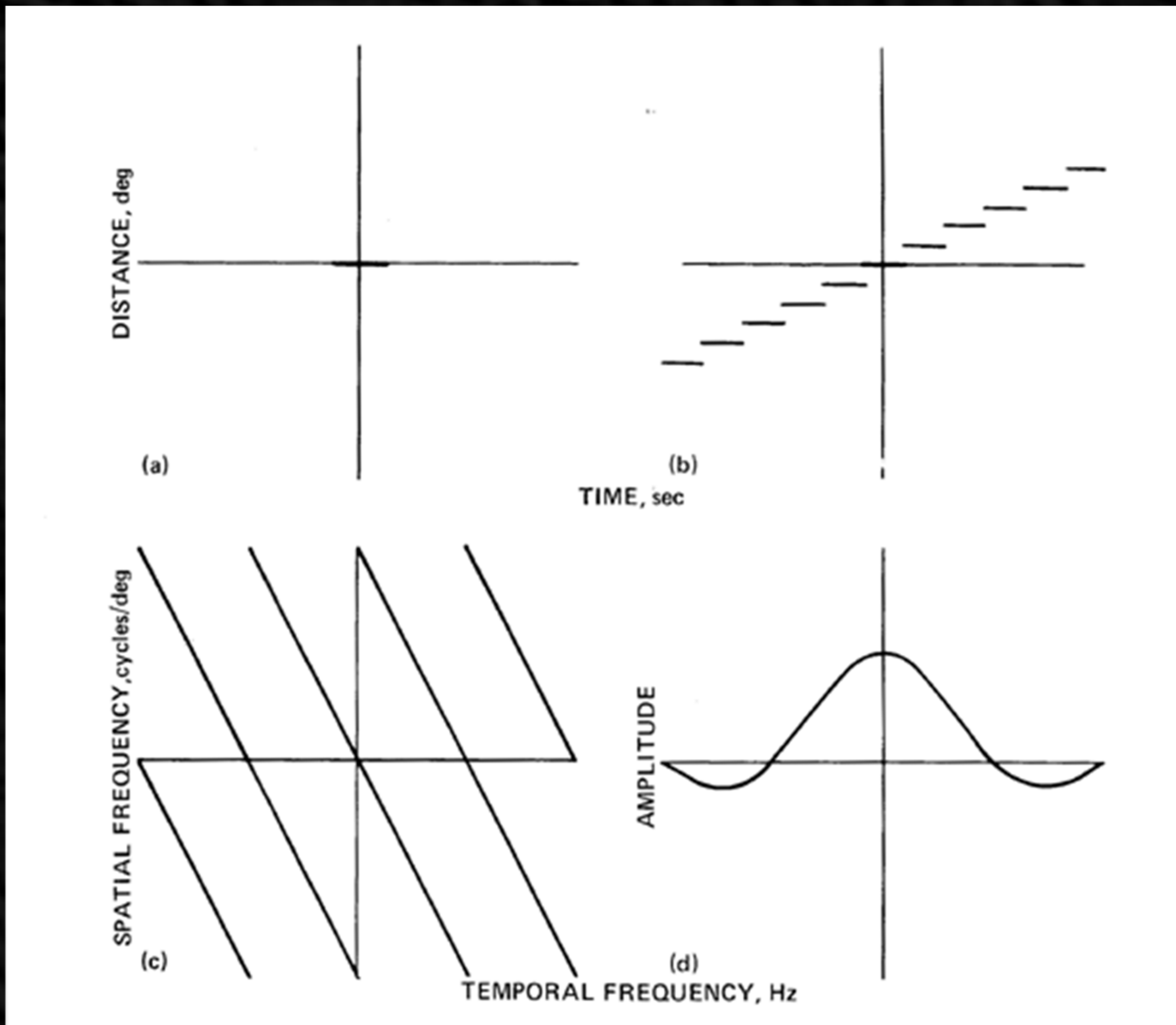
- For objects in real world, Velocity more important than flicker
- Standing waves can be de-composed into traveling waves
- Smooth tracking eye movements can reduce image velocity on the retina
- Spatiovelocity CSF by Watanabe '68
- Retinal Velocities & stabilization
- Retinal Velocity CSFs by Kelly from Motion & Vision series 79





Sampled Motion and the Window of Visibility

Watson, Ahumada, Farrell 86



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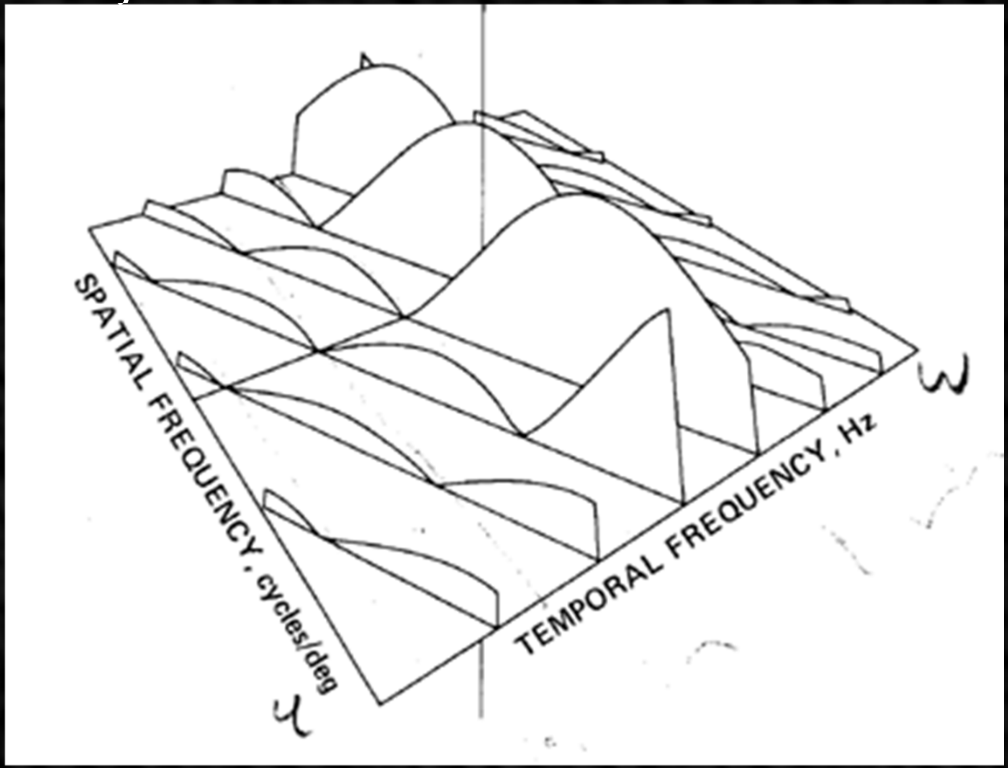


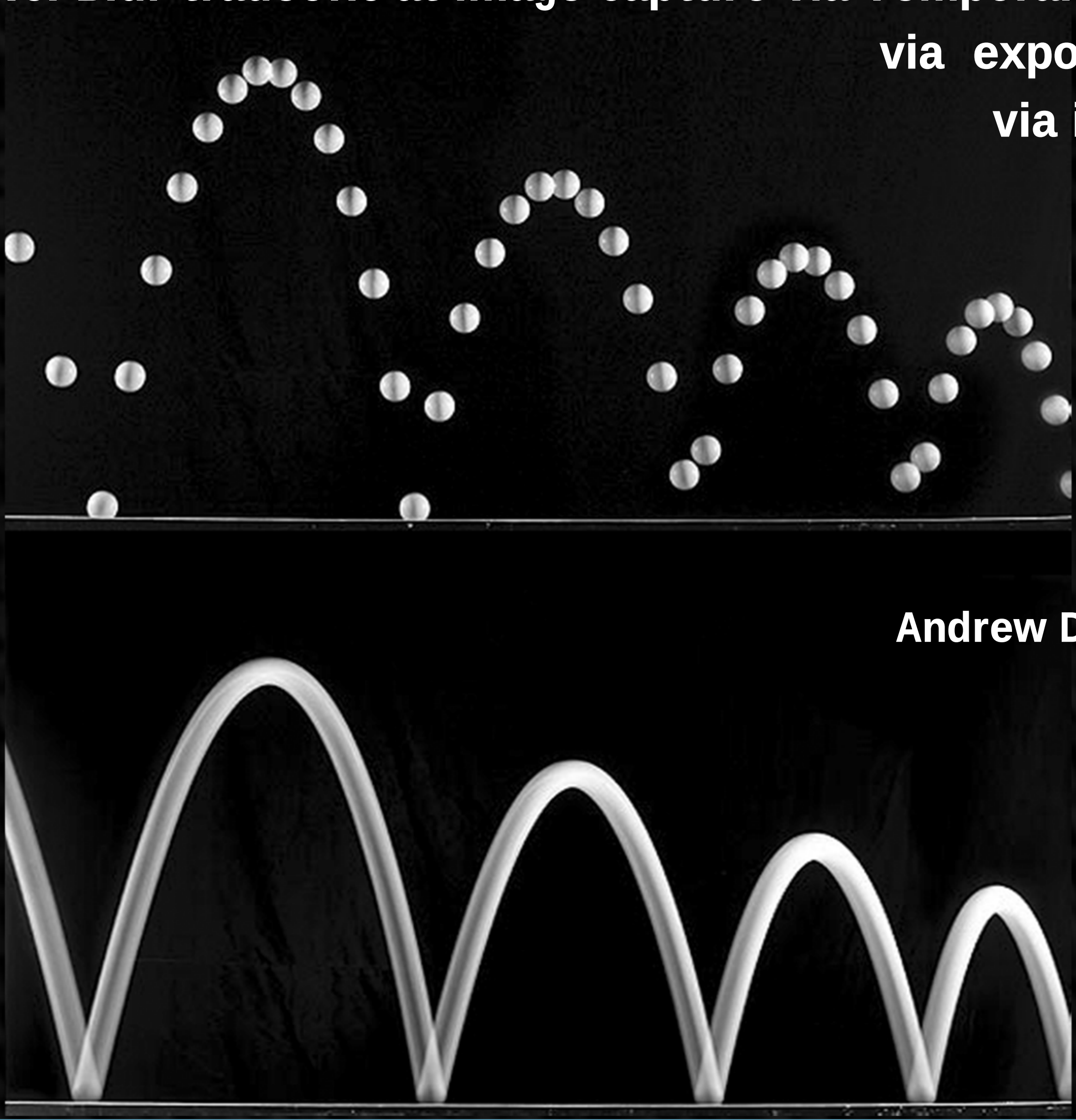
- **Rectangular support shown is window of visibility (idealized separable version)**
  - Max spatial = 50 cy/deg (depending on conditions, well studied)
  - Max temporal = 30 cy/sec (depending on conditions and visual eccentricity, well studied)
- **Undersampled motion**
- **Replications due to sampling = temporal aliases**
- **Note: this would look awful**

Sampled Motion and the Window of Visibility

- Camera constrained window of visibility (not HVS)
- Aliasing vs. Blur tradeoffs at image capture via Temporal LPF prefilter

via exposure aperture length

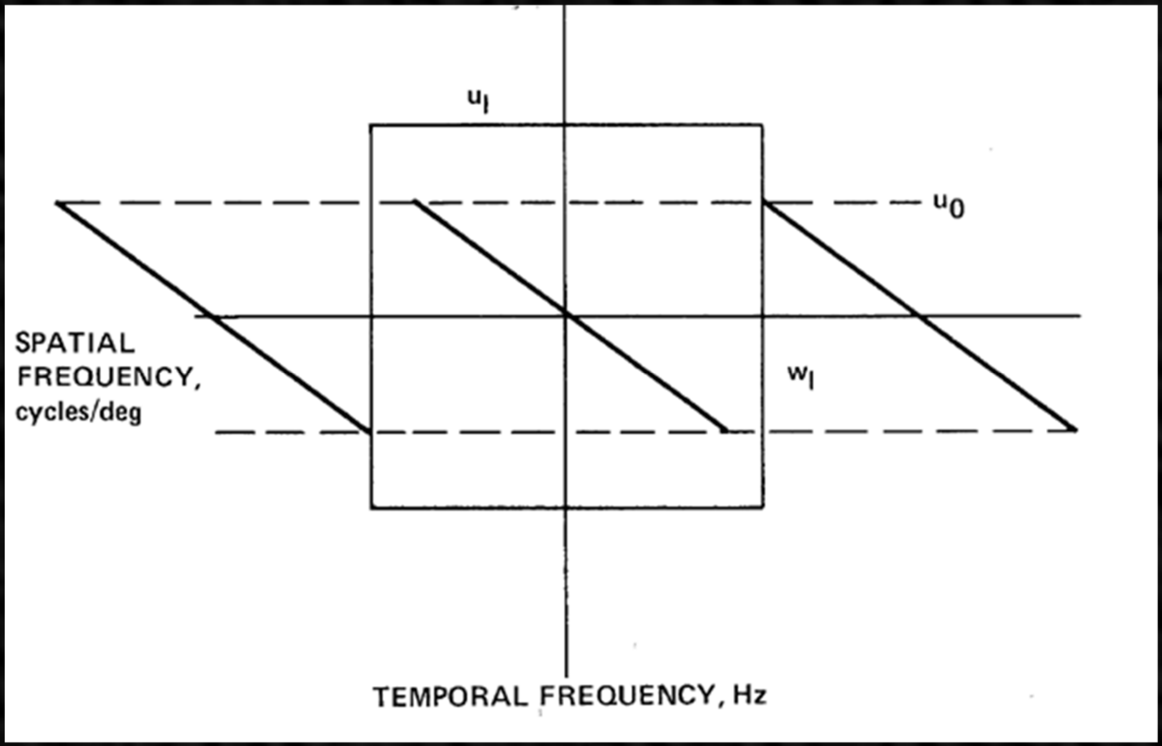
via illumination duration



Andrew Davidhazy @ RIT

Sampled Motion and the Window of Visibility

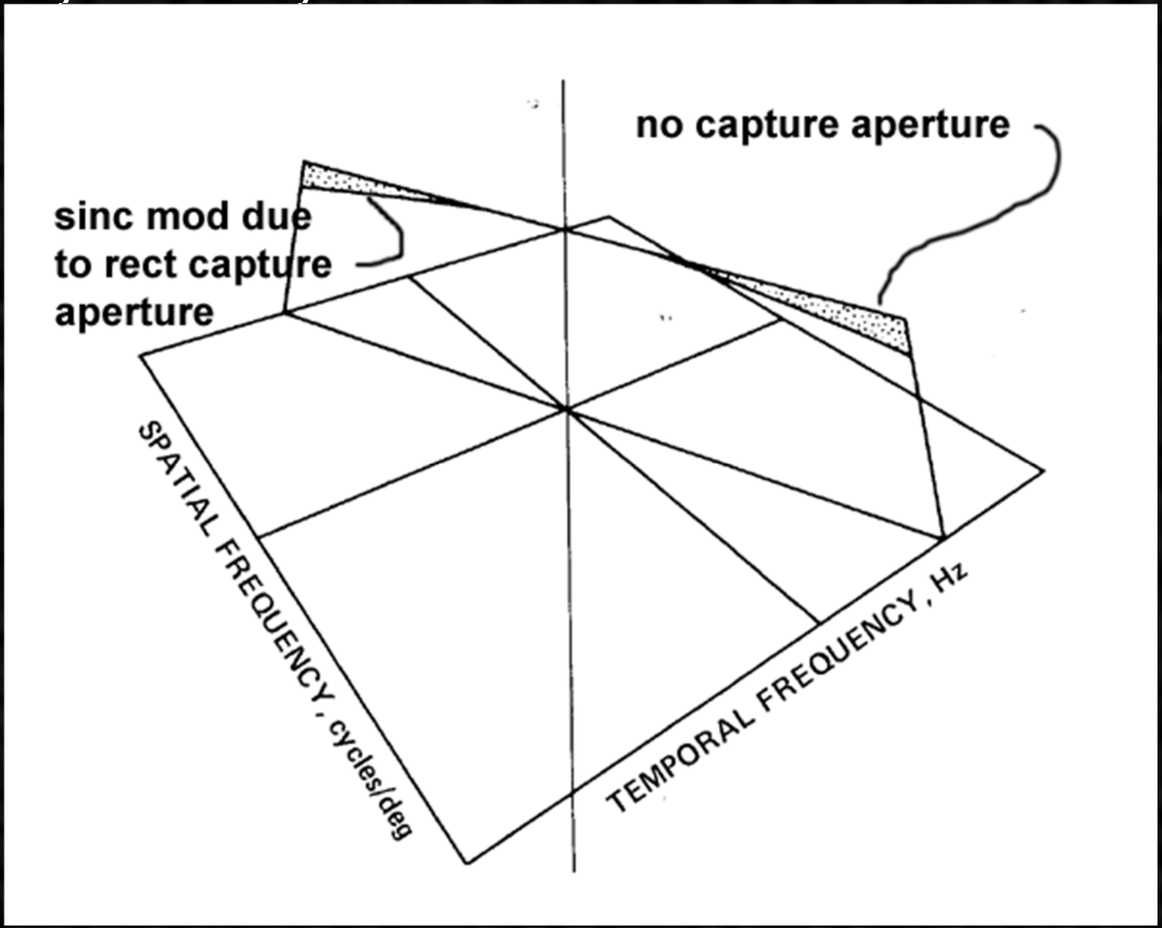
Watson, Ahumada, Farrell 86



- **Example of smoothly perceived motion**
- **Sampling rate increases spreads out replications**
- **Preventing aliases in window of visibility results in smooth true motion**
- **Sampling rate depends on object speed and spatial content**
  - (I.e., bandwidth)

Sampled Motion and the Window of Visibility

- **Watson, Ahumada, Farrell 86**



- **Now that we have smooth motion by keeping aliases out of the window of visibility……**
- **We still need to worry about motion blur due to capture aperture**
  - Thus the use of shorter capture time than the frame duration

Relations between Temporal, Spatial, and Motion

- Translational motion can be defined as

$$l(x,y,t) = l(x-\upsilon_x t, y-\upsilon_y t, 0)$$

- Its 3D Fourier spectrum is given by

$$L(f_x, f_y, f_t) = L(f_x, f_y)\delta(f_x\upsilon_x + f_y\upsilon_y + f_t)$$

$L(f_x, f_y, f_t)$ is non zero only on the plane defined by

$$f_x\upsilon_x + f_y\upsilon_y + f_t = 0$$

- The motion of an object causes temporal component in the spatiotemporal spectrum.
- The temporal component is proportional to spatial frequency and velocity

Relations between Temporal, Spatial, and Motion and MTF

Spatio-temporal spectrum is low pass filtered by the ST CSF , as well as display MTF (combined ST system MTF: T)

$$L_s(f_x, f_t) = L(f_x)\delta(f_x\upsilon_x + f_t)T(f_x).T(f_t)$$

When eye accurately tracks the motion, the retinal image is purely spatial

$$L_s(f_x) = L(f_x)T(f_x)T(\upsilon_x f_x)$$

Spatial transfer function due to display spatio-temporal MTF

$$T_d(f_x) = T(f_x)T(\upsilon_x f_x)$$

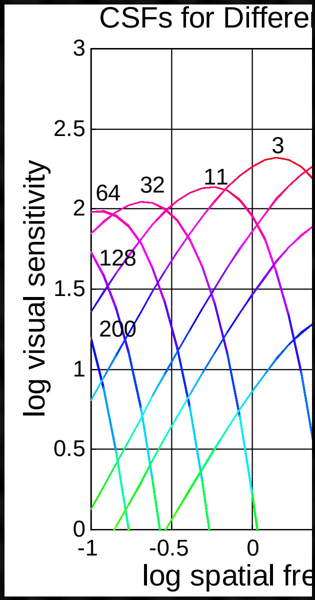
Spatial MTF

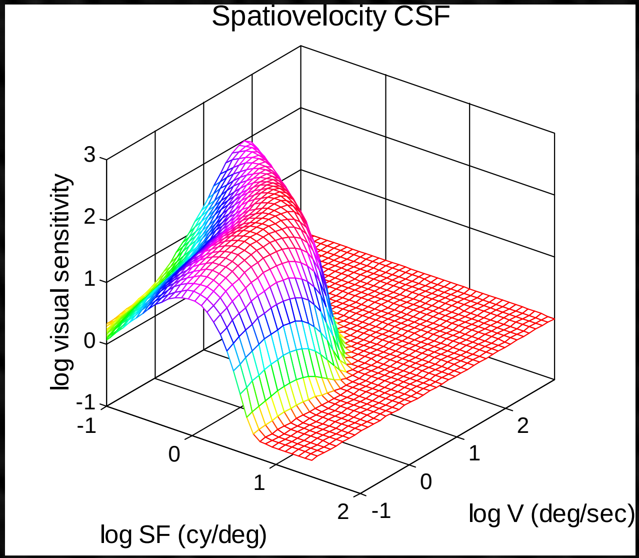
Temporal MTF

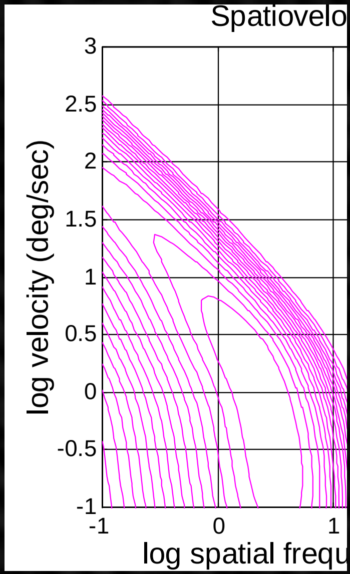
Advanced Issues in Spatiotemporal Vision

Properties of Visual System: Motion: retinal velocity

- Retinal Velocities
- No Eye Movements Occur
- Image velocity = retinal velocity
- Spatiovelocity CSF
  (stabilized retina)

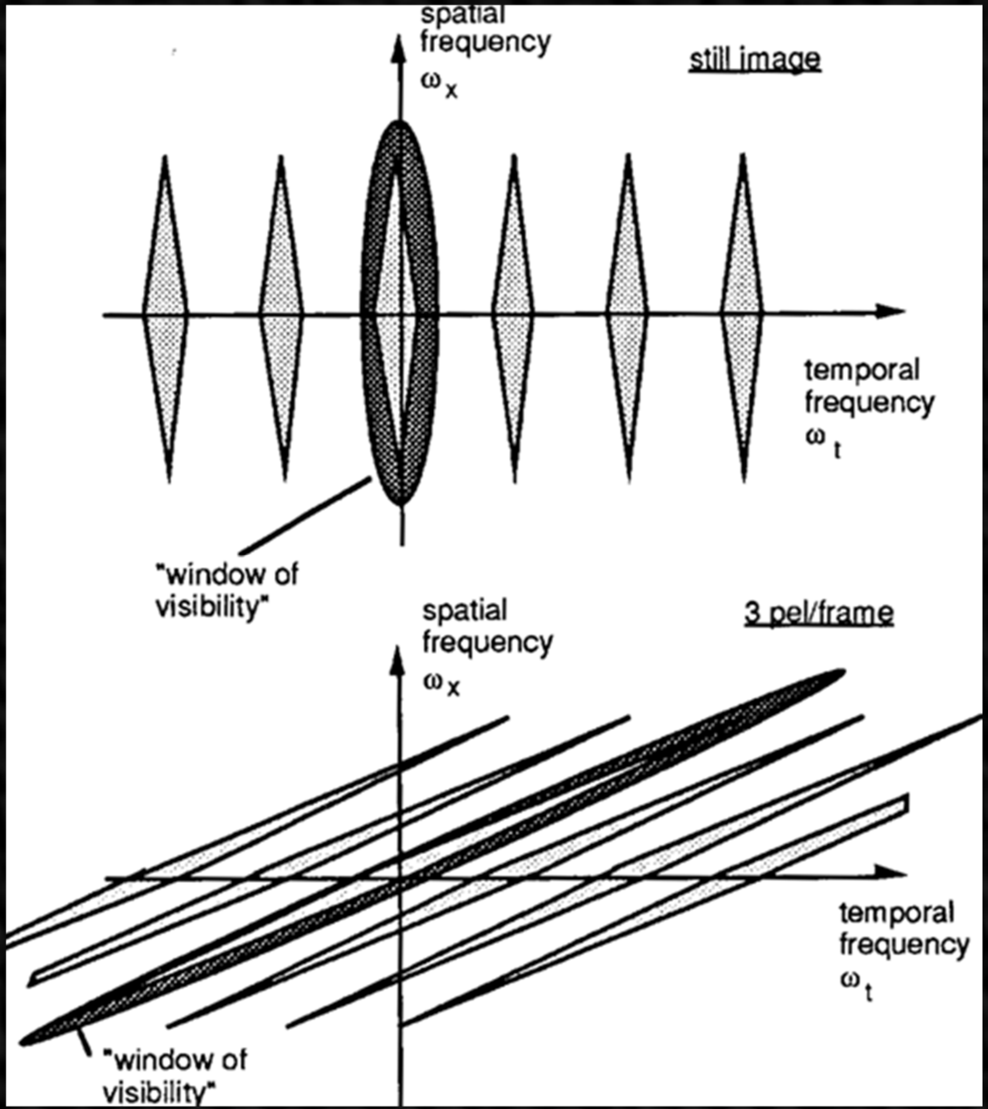






Properties of Visual System: Motion: Eye Movements

- Eye movement's tracking changes the window of visibility

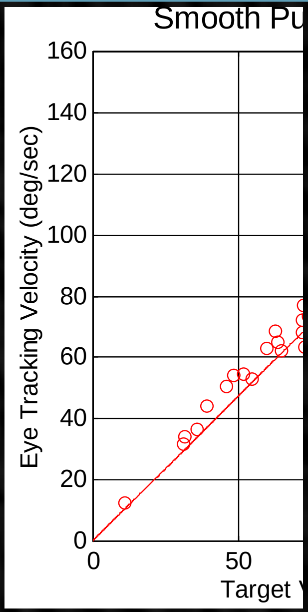


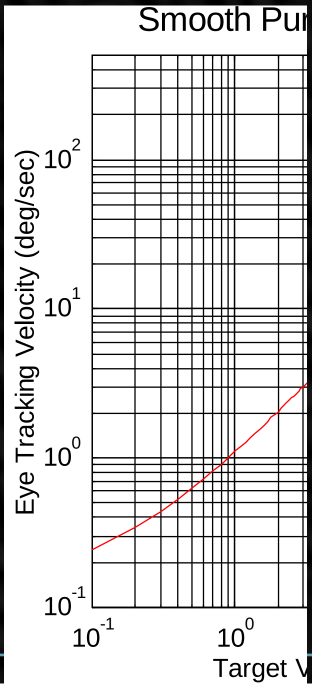
- B. Girod 93, Perfect (and mandatory) object tracking

Properties of Visual System: Motion: Eye Movements

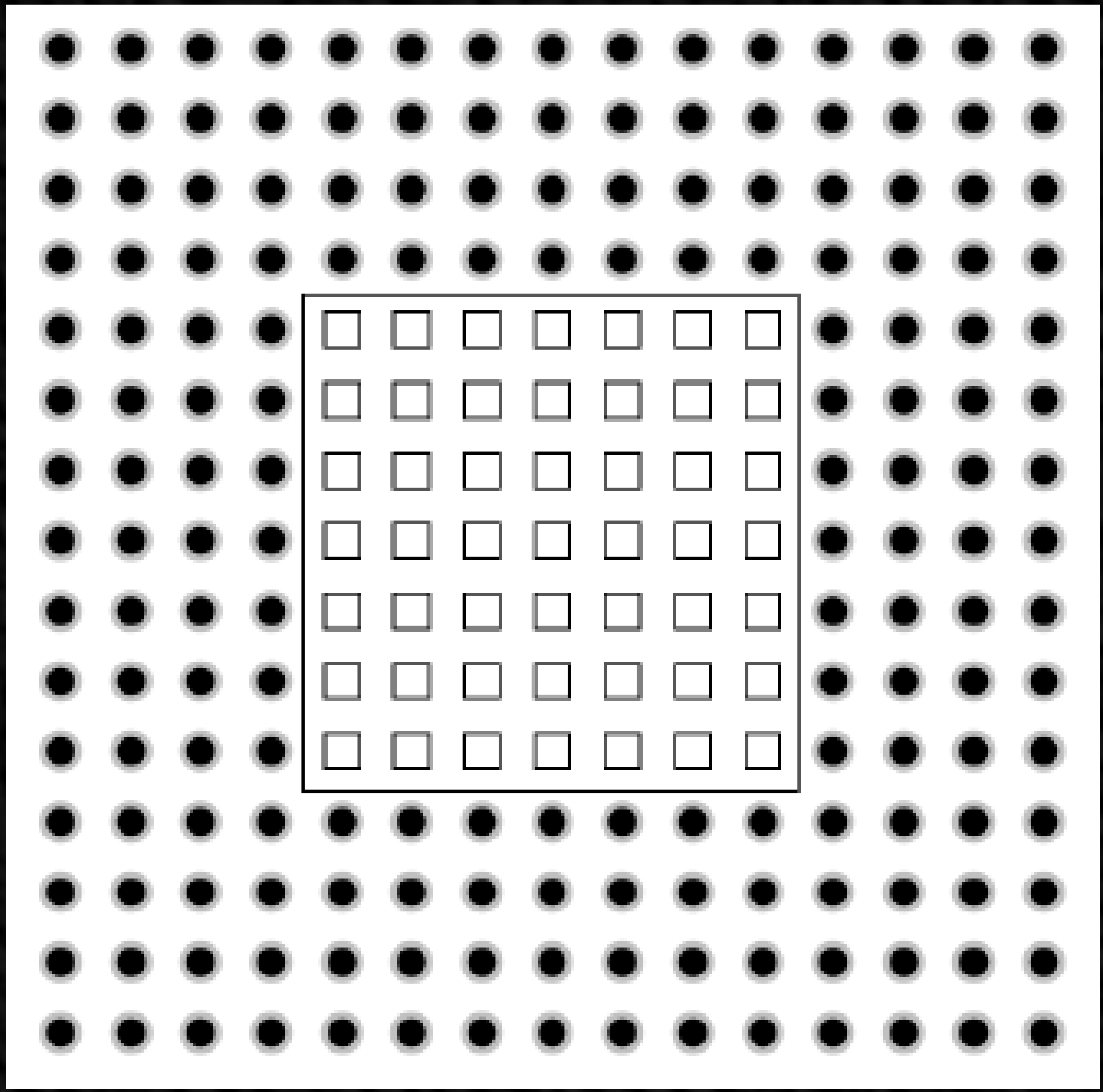
Types of eye movements:

- **Saccadic Eye movements (jumps)**
  - Usually > 160-300 deg/sec
  - With larger display, larger saccades will still fit on screen, giving more of a feeling of being in real world
- **Smooth Pursuit Eye Movements (tracking)**
  - 80 deg/sec for 90 degree field of view (+-45 deg)
  - 30 deg/sec for 30 deg field of view
  - Some retinal slippage (slope= 0.9)
- **Drift Eye movements (very small)**
  - responsible for the prevention of image fading due to low S of spatial & temporal CSFs
  - No expected consequences of large screen on these
  - Approx 0.10 to 0.15 deg/sec
  - Other small eye movements: **Tremor, Microsaccades**
- **Data from Meyer 85 : Smooth tracking data**
  - Red line is model we use for eye movements
  - -smooth pursuit + baseline drift as minimum



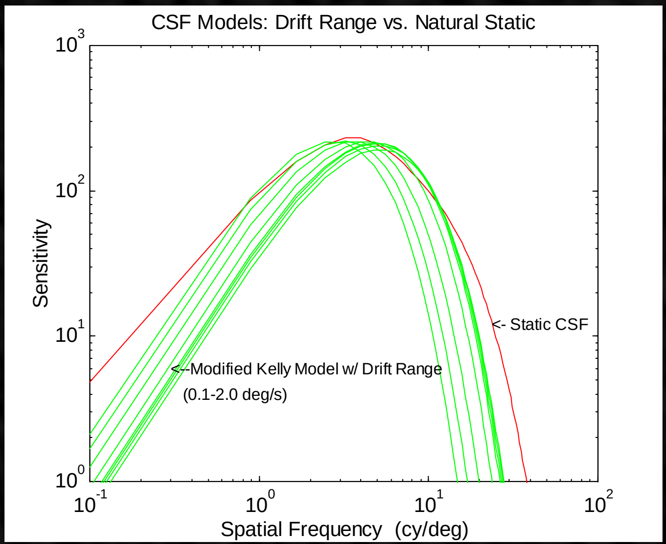


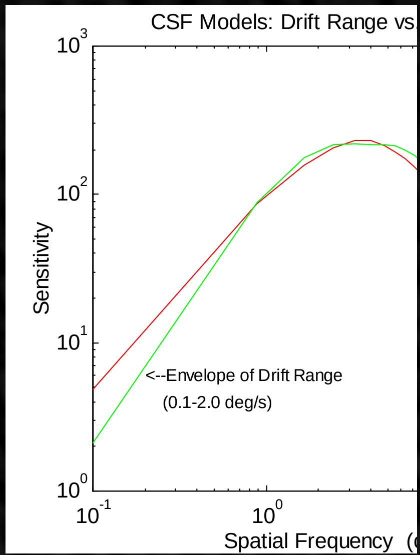
Demo of Microsaccades and Tremor



Properties of Visual System: Motion:

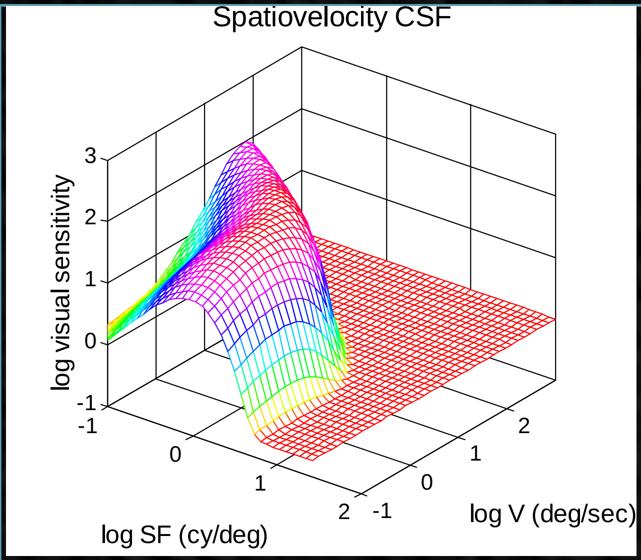
- Problem: spatial CSFs vs. velocity are narrower than usual CSF
- Static CSF viewing does not result in stabilized image on retina
- Eye drifts and small pursuit movements cause retinal velocities during CSF examination

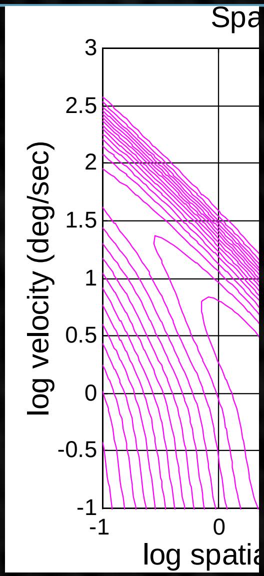




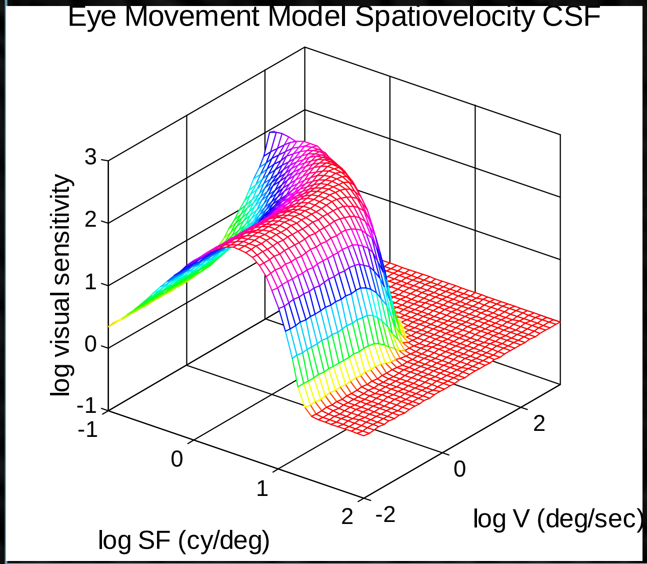
- This gives us more confidence in the model for spatial attributes

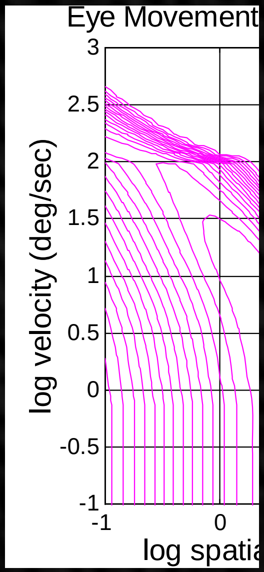
Eye Movement Model Spatiovelocity CSF



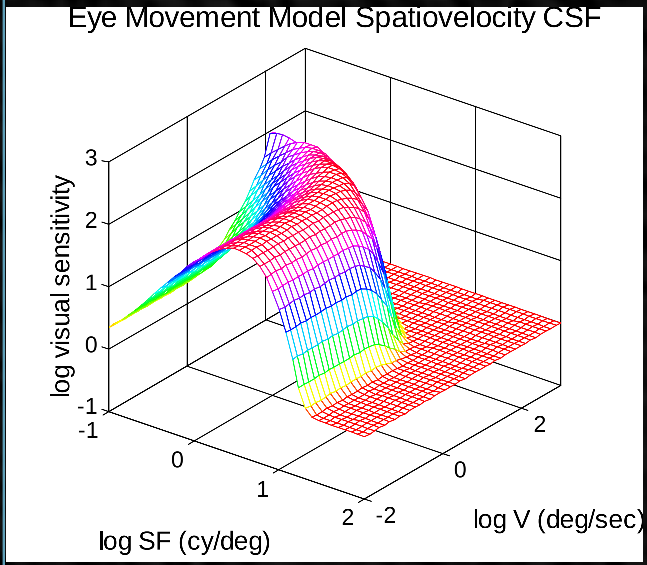


- Use best case eye movements for detection of moving targets
- Eye Movement Model
- Shifts image velocities to retinal velocities that are low
- Daly '98 (SPIE HVEI)





Eye Movement Model Spatiovelocity CSF



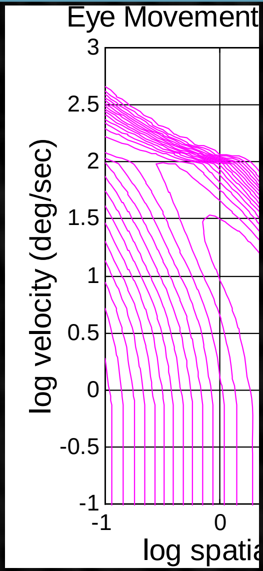
- **Spatiovelocity CSF using Eye movement model**
- $\omega = v\rho$

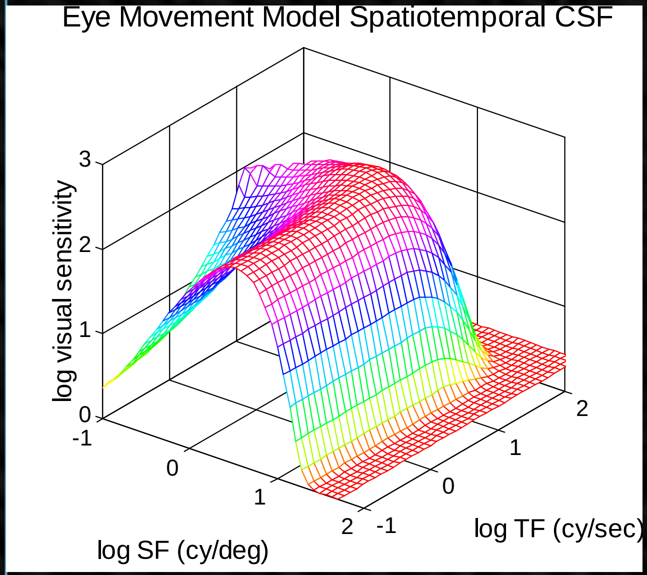
(cy/sec) = (deg/sec)(cy/deg)

ω = **temporal frequency**

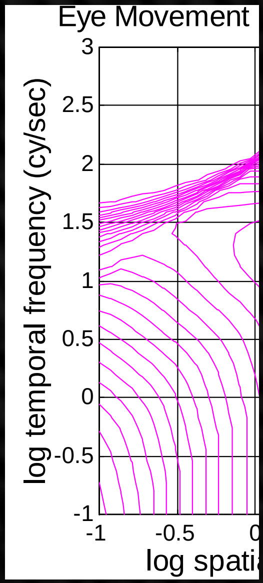
v = **velocity**

ρ = **spatial frequency**





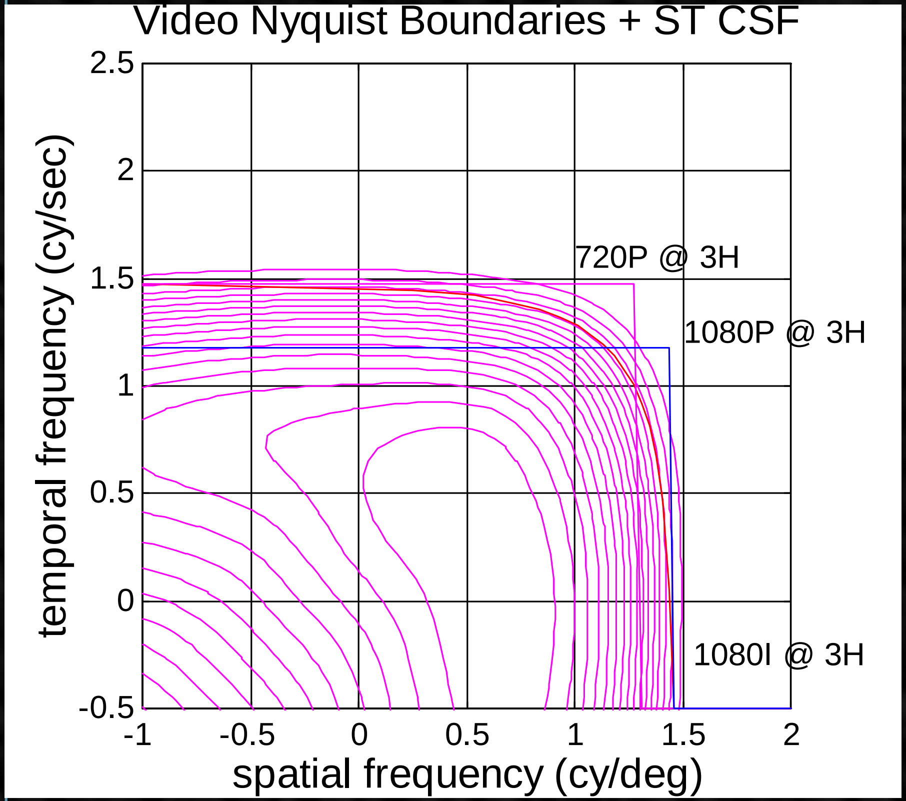
- **Rotation back into spatiotemporal CSF including effects of eye movements**
  - Can be used to assess smoothness of motion

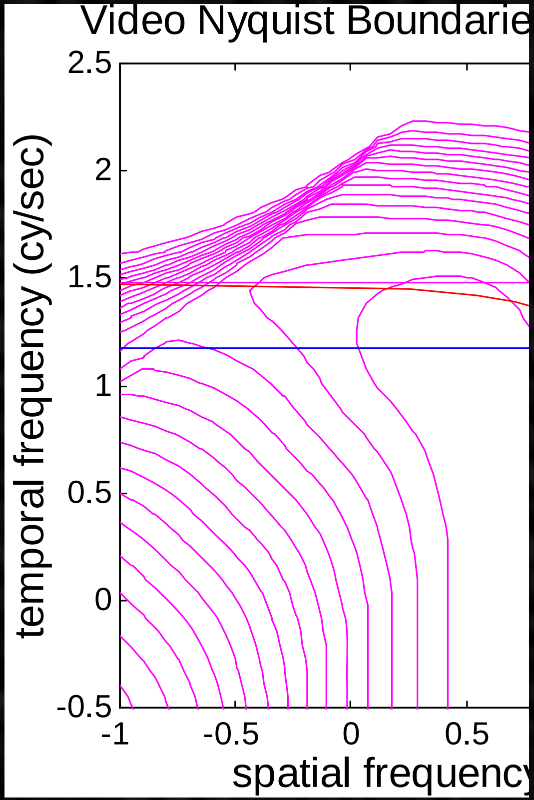


Spatiotemporal and Spatiovelocity Visibility Demos

Application of SV EMM model : Analysis of Digital Video Formats

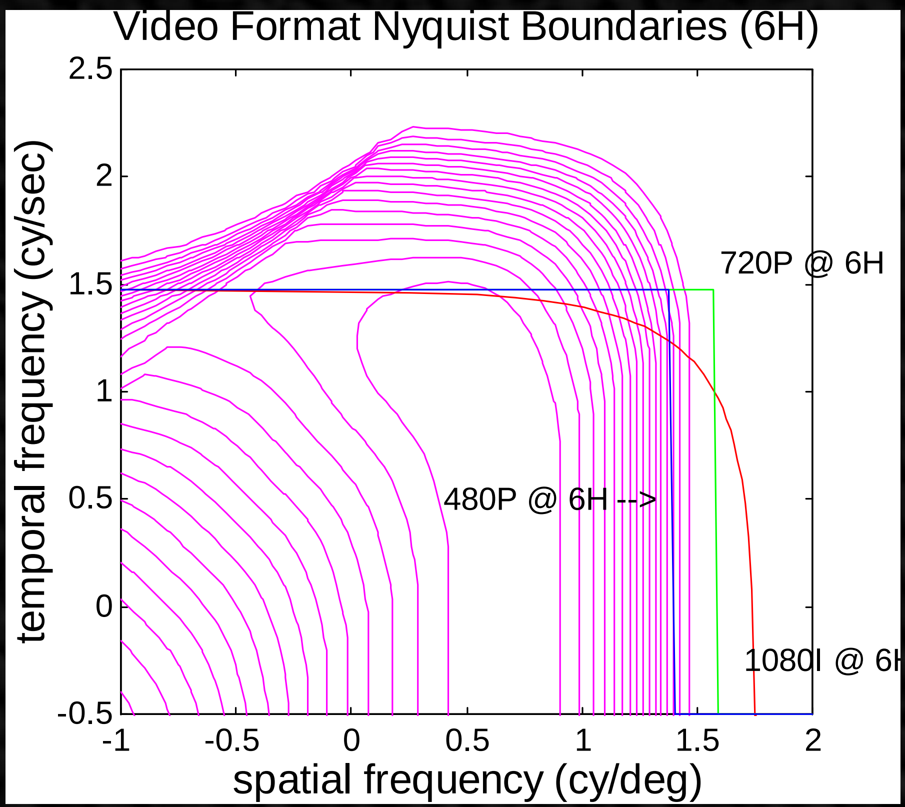
- **Analysis of interlace, flicker and resolution issues**
- **Use spatiotemporal CSF to analyze progressive and interlace parameters**
  - 720 lines progressive @ 60 fps, 1080 lines progressive @ 30 fps, 1080 lines interlace @ 60 fps
  - all have similar uncompressed data rates
- **Viewing distance = 3H**

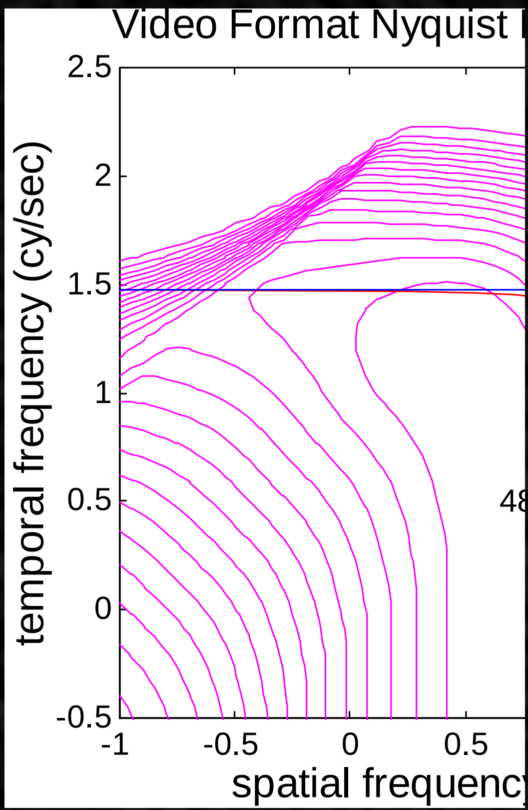




Different Viewing Distances

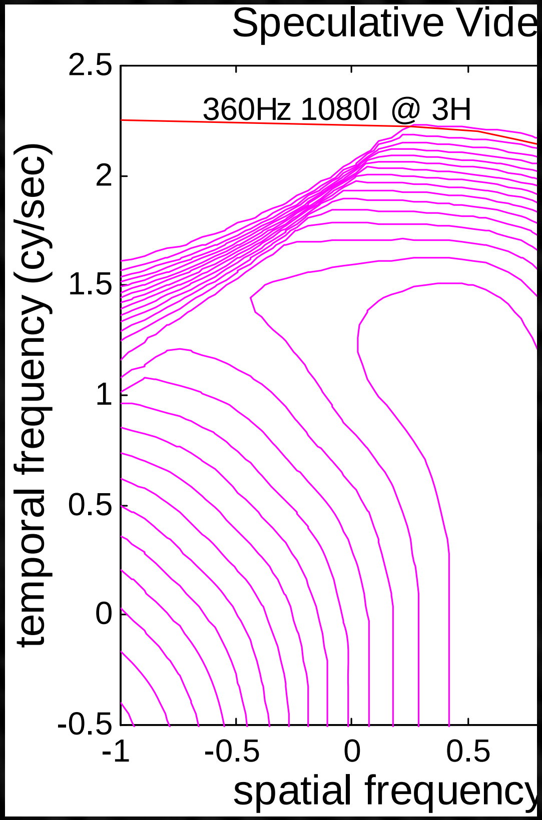
- **Analysis of interlace, flicker and resolution issues**
- **Use spatiotemporal CSF to analyze progressive and interlace parameters**
  - 720 lines progressive @ 60 fps, 1080 lines progressive @ 30 fps, 1080 lines interlace @ 60 fps
  - SD signal of 480P also considered (some DVDs)
- **Increase Viewing distance to 6H and 9H -> Interlace advantage lost**





Speculative Video Format

360 Hz 1080I @ 3H

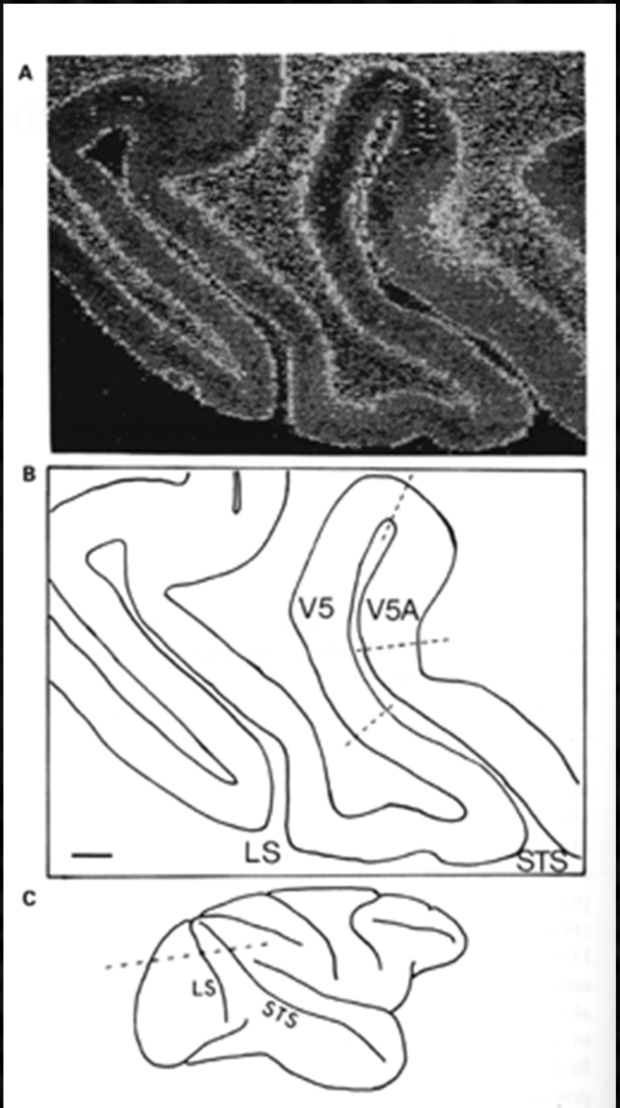


- **Auxiliary issues:**
  - Interlace is more difficult to compress
  - 2H becoming more common with large displays, so 1080 not enough
  - Cost
  - Trumbull's Showscan (explored up to 100 Hz): some considered too realistic and not cinematic ; BBC desires ~300 fps capture

Closer Examination of Spatiovelocity CSF via Eye Tracking

Verification of Eye Movement Model & SV CSF

- Laird, Pelz, Rosen, Montag and Daly (2006)
- Spatiovelocity Model based on Kelly's experiments
  - Using retinal stabilization to control velocities on the retina
  - No directed eye movements
- However, in real image viewing applications,
  - eyes will actually be in motion,
  - And generally be directed as well
- The Spatiovelocity model may not be valid when the eyes are actually in motion…
  - … if auxiliary signals from eye control circuitry to V5, the motion area, affect …..??
- Build/optimize 2D spatio-velocity CSF model
  - Further refine Daly (Kelly+EMM) model
  - Incorporate calculated retinal velocities
  - Study effects of eye movements on retinal velocity sensitivity



Experimental Setup

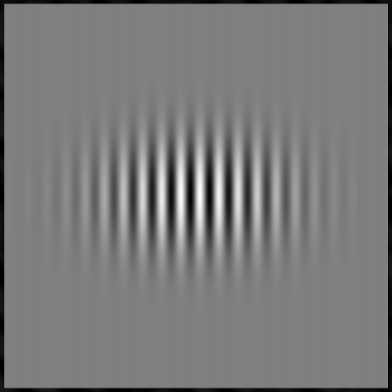
- **Equipment & Methodology:**
  - Sony Trinitron MultiScan G420 CRT
  - ASL Series 504 Remote Eyetracker
  - 2IFC

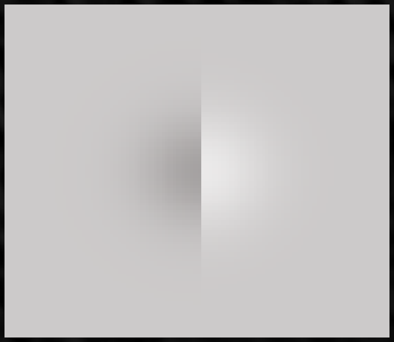
Mean Lum. of screen	**60 cd/m^2**
Dist Obs. from Screen	**84 cm**
Horiz. Deg span of screen	**23.95º**
Size of stimulus	**2.46º x 2.46º**

- **Stimuli:**
  - Gabor

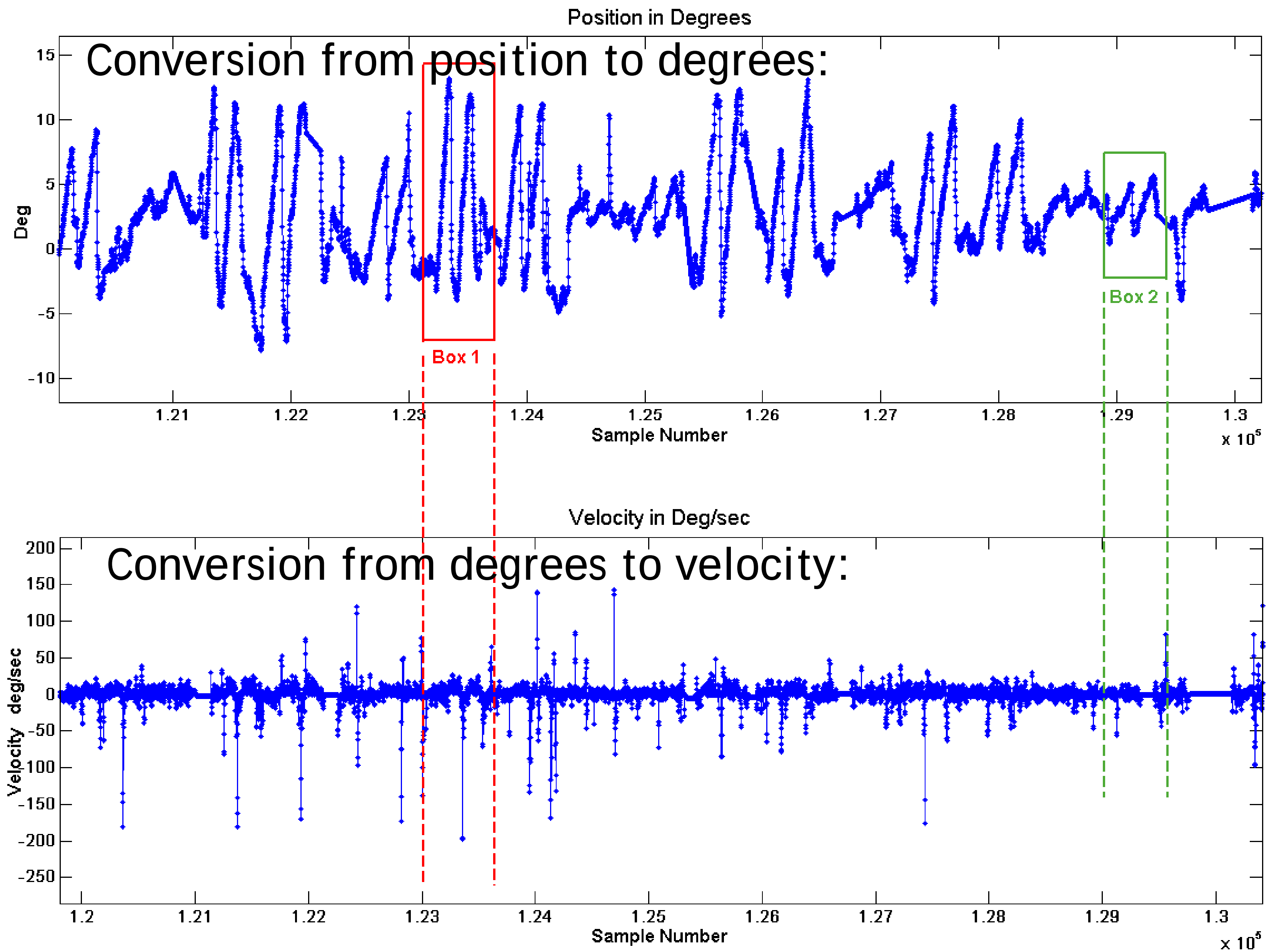
    (contrast, frequency, velocity)
  - Disembodied Edge

    (contrast, velocity)





Eye tracking velocity calculations



Tested spatiotemporal frequencies

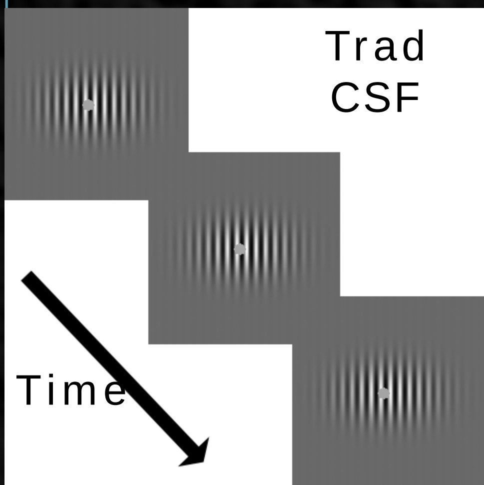
	Temporal Freq (Hz)			
		10	20	30
Spat Freq (Cyc/Deg)	4	**2.5**	**5.0**	**7.5**
	8	**1.25**	**2.5**	**3.75**
	16	**0.625**	**1.25**	

$$\nu = \frac{\omega}{\rho}$$

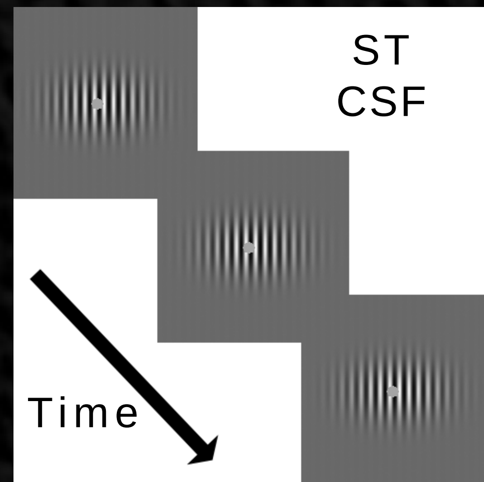
$$\frac{\text{deg}}{\text{sec}} = \frac{\text{cycles}/\text{sec}}{\text{cycles}/\text{degree}}$$

Retinal velocities with and without directed eye movements

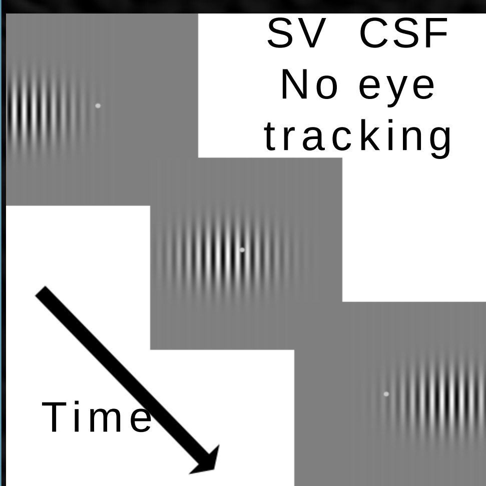
- **Experiment tests 4 cases:**
  - mixtures of Gabor velocity, fixation points, and envelope:



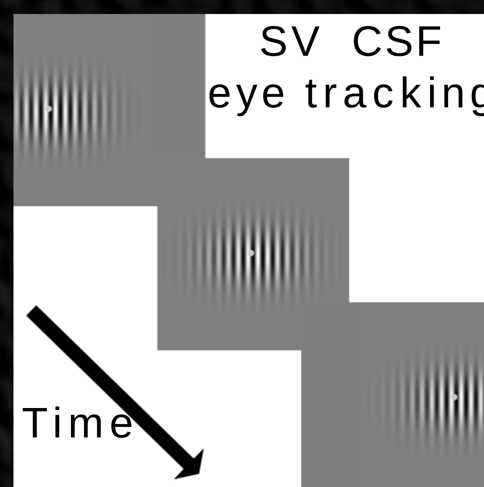
Gabor does not move



Sine moves, but envelope & fixation do not: Retinal velocity



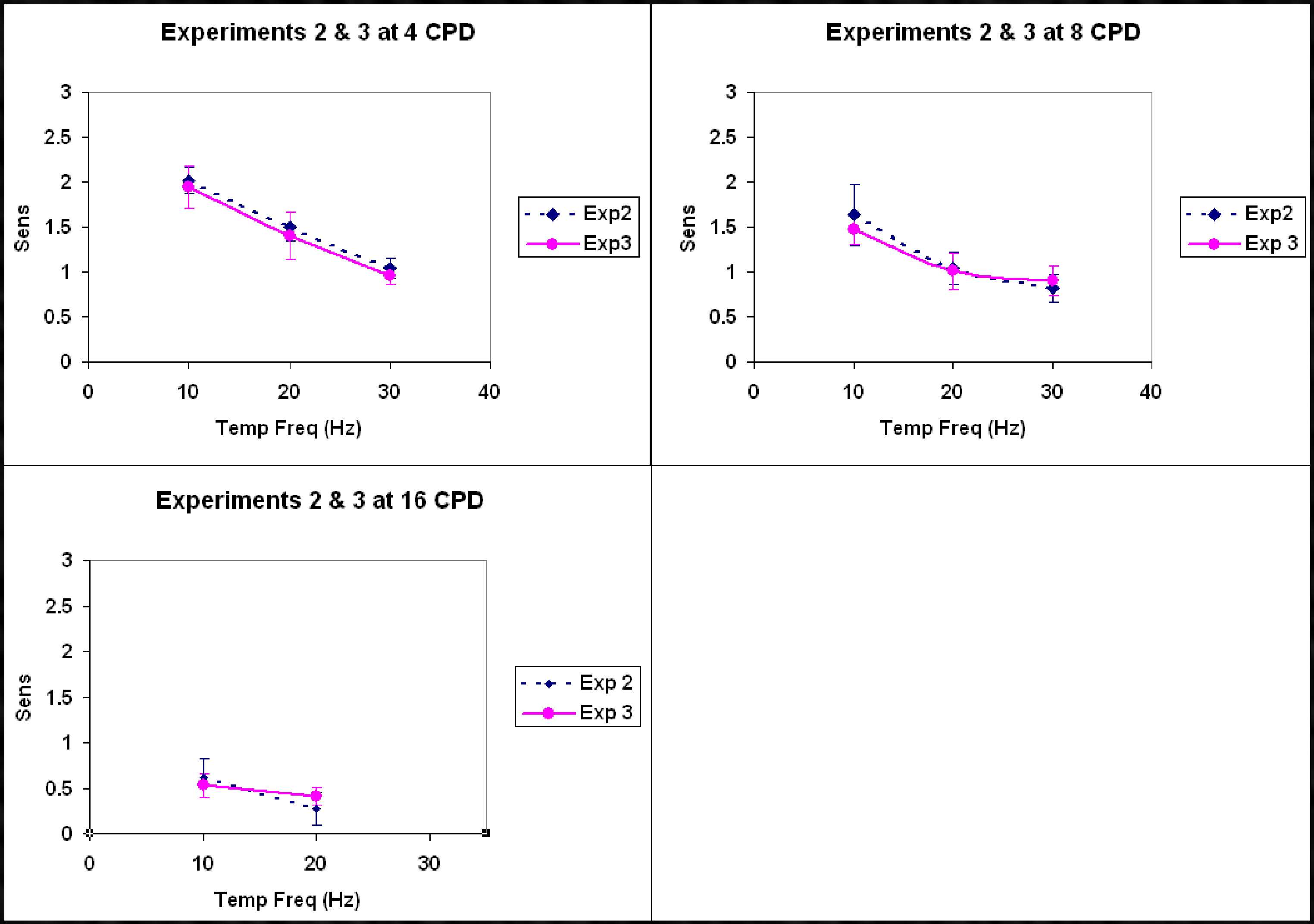
Gabor moves, but fixation does not: Retinal velocity if observer can ignore envelope?



Fixation moves with Gabor: Retinal velocity depends on eye tracking

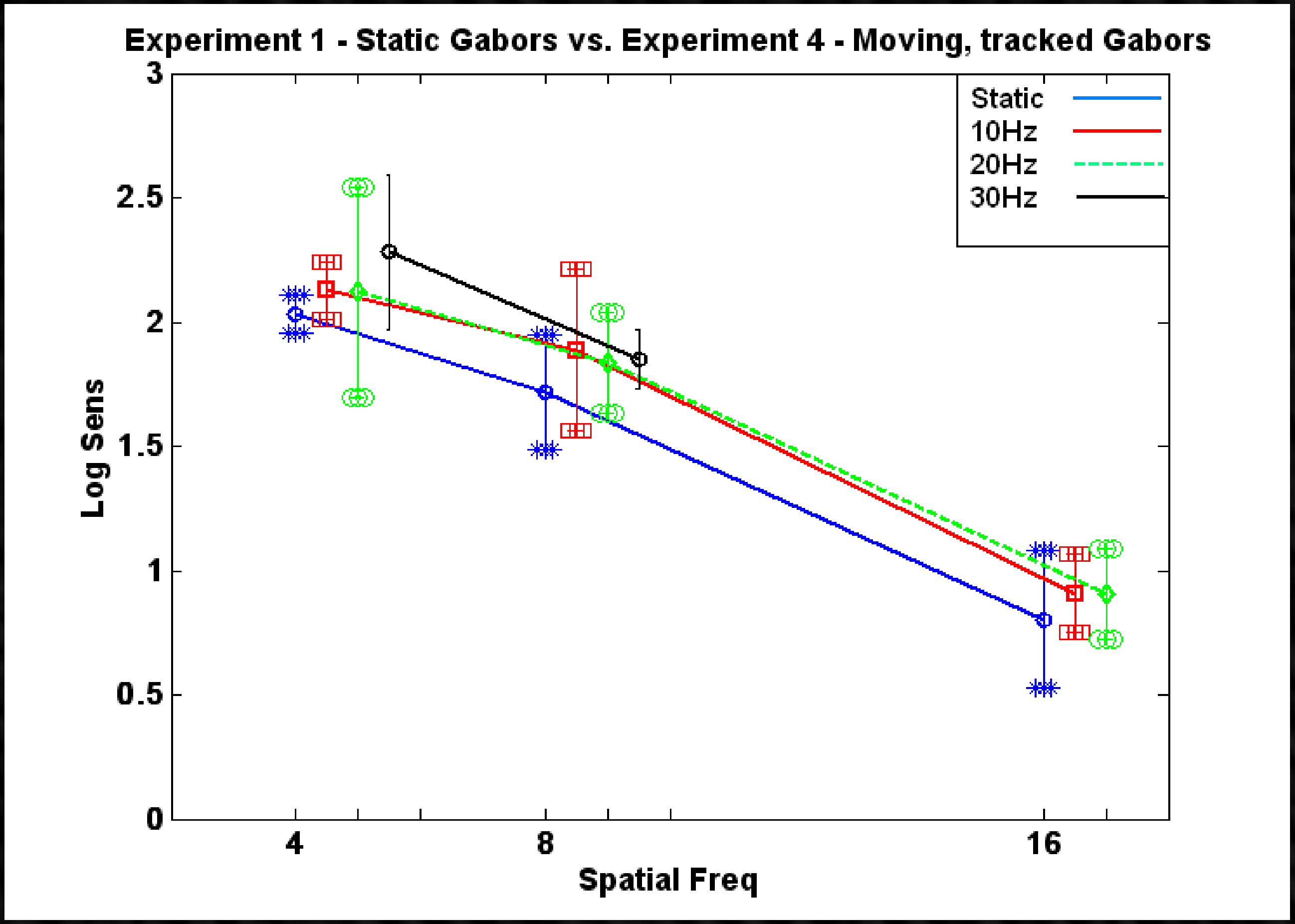
Retinal velocities without directed eye movements

- **Eye fixation is good (able to ignore moving object, if requested)**
- **Moving sines (fixed envelope) = moving gabor (moving envelope)**



Retinal 'stasis' with and without directed eye movements

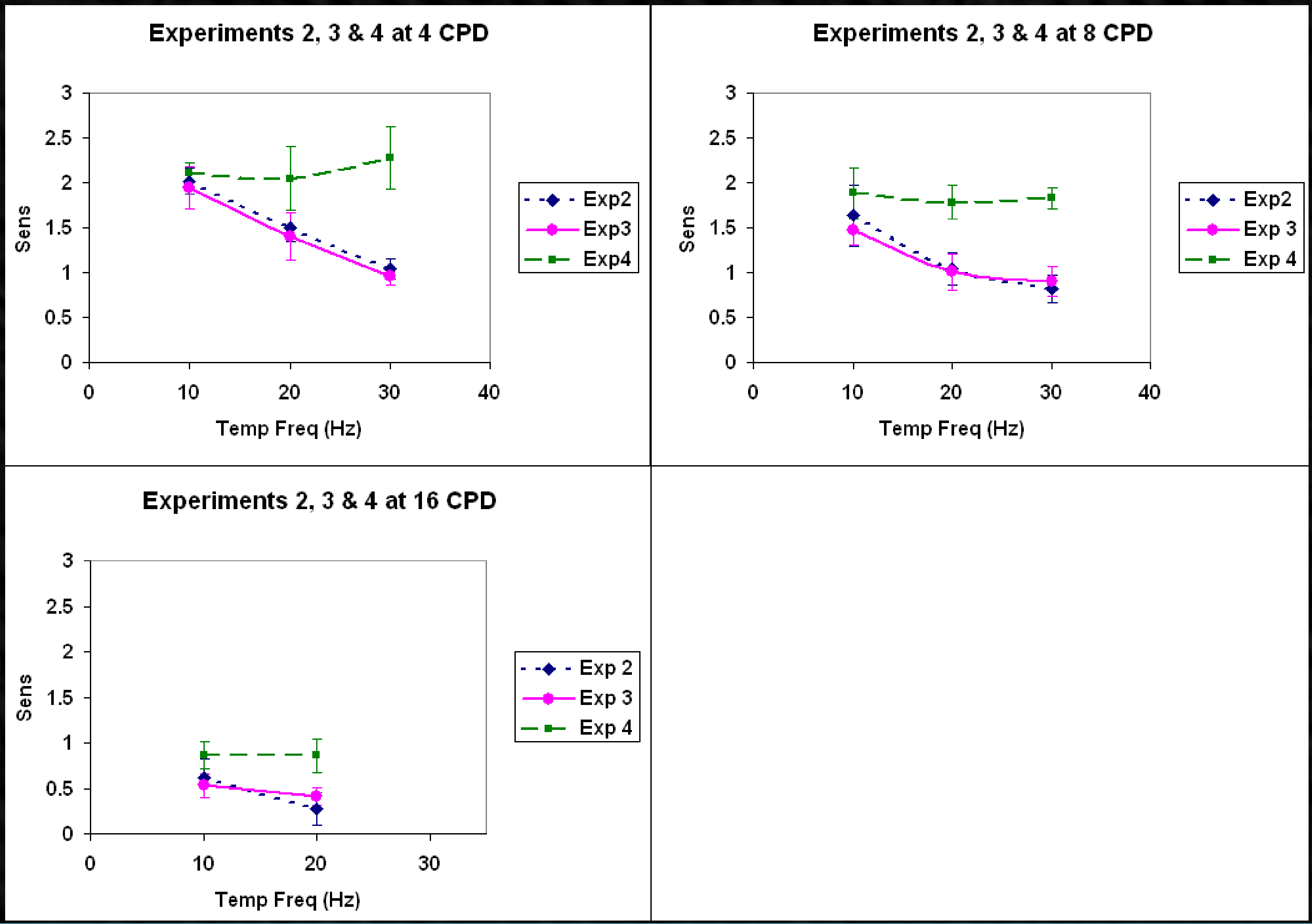
- Eye tracking is good, results similar to static
- No signals related to eye motion affect neural processing (no intercedent)



- Data shifted horizontal for separability, since they superimpose closely

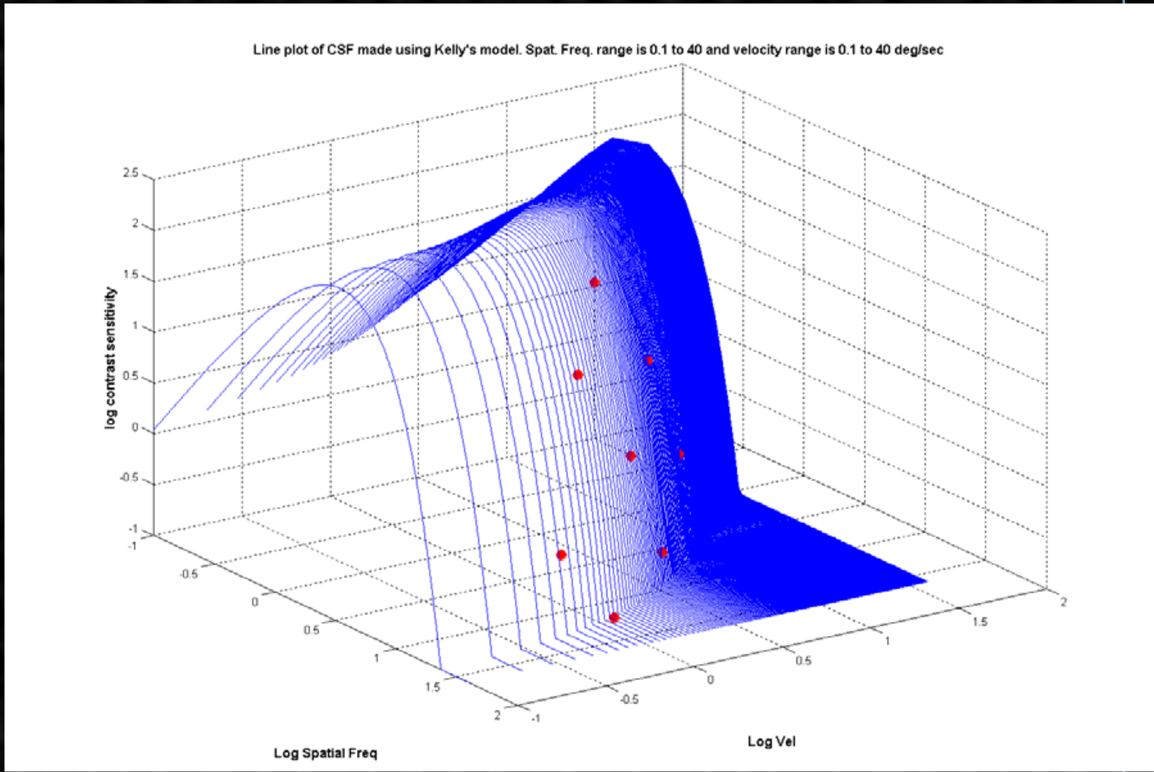
Retinal velocities with and without directed eye movements

- Eye tracking removes the decrease in Sensitivity with increasing temporal frequency , for all tested spatial frequencies
- Maybe motion sharpening at 4 cpd?



Sensitivity results on Spatiovelocity CSF model

- The red dots correspond to the points in the table



- The velocities result from the particular spatial and temporal frequency combination.

	10Hz	20Hz	30Hz
4 cpd	2.5 deg/sec	5 deg/sec	7.5 deg/sec
8 cpd	1.25 deg/sec	2.5 deg/sec	3.75 deg/sec
16 cpd	0.625 deg/sec	1.25 deg/sec	

Fine tuning parameters of SV model

- SV CSF in retinal velocities, v_r, and spatial frequency ρ

$$CSF(\rho, v_R) = k \cdot c_0 \cdot c_1 \cdot c_2 \cdot v_R \cdot (c_1 2\pi\rho)^2 \exp\left(-\frac{c_1 4\pi\rho}{\rho_{\max}}\right)$$

Where:

$$k = s_1 + s_2 \cdot \left|\log\left(c_2 v_R / 3\right)\right|^3$$

$$\rho_{\max} = \frac{p_1}{(c_2 v_R + 2)}$$

Kelly model modified to fit data

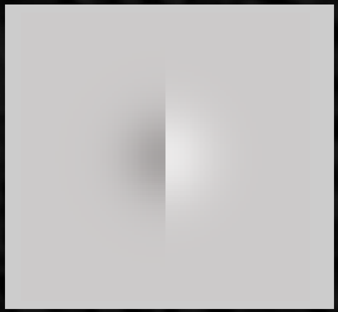
- (Kelly model only at low LA level, and noisier displays of the past)

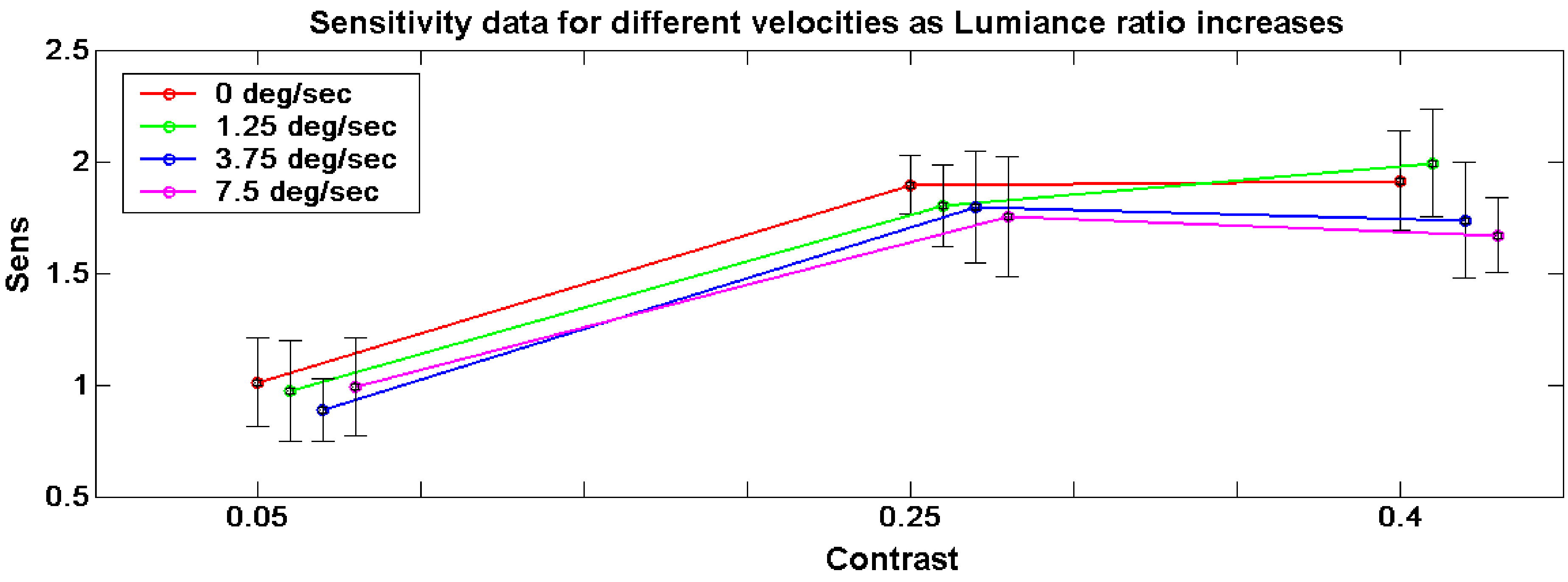
Non-linear least squares routine:

- Sensitivity values from model fit to experimental results

Test of model on combined frequencies

- **Experiment 5**
  - Moving edge results
  - Sensitivity to blurring of edge
  - As a function of edge contrast

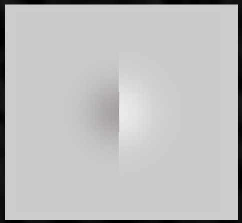




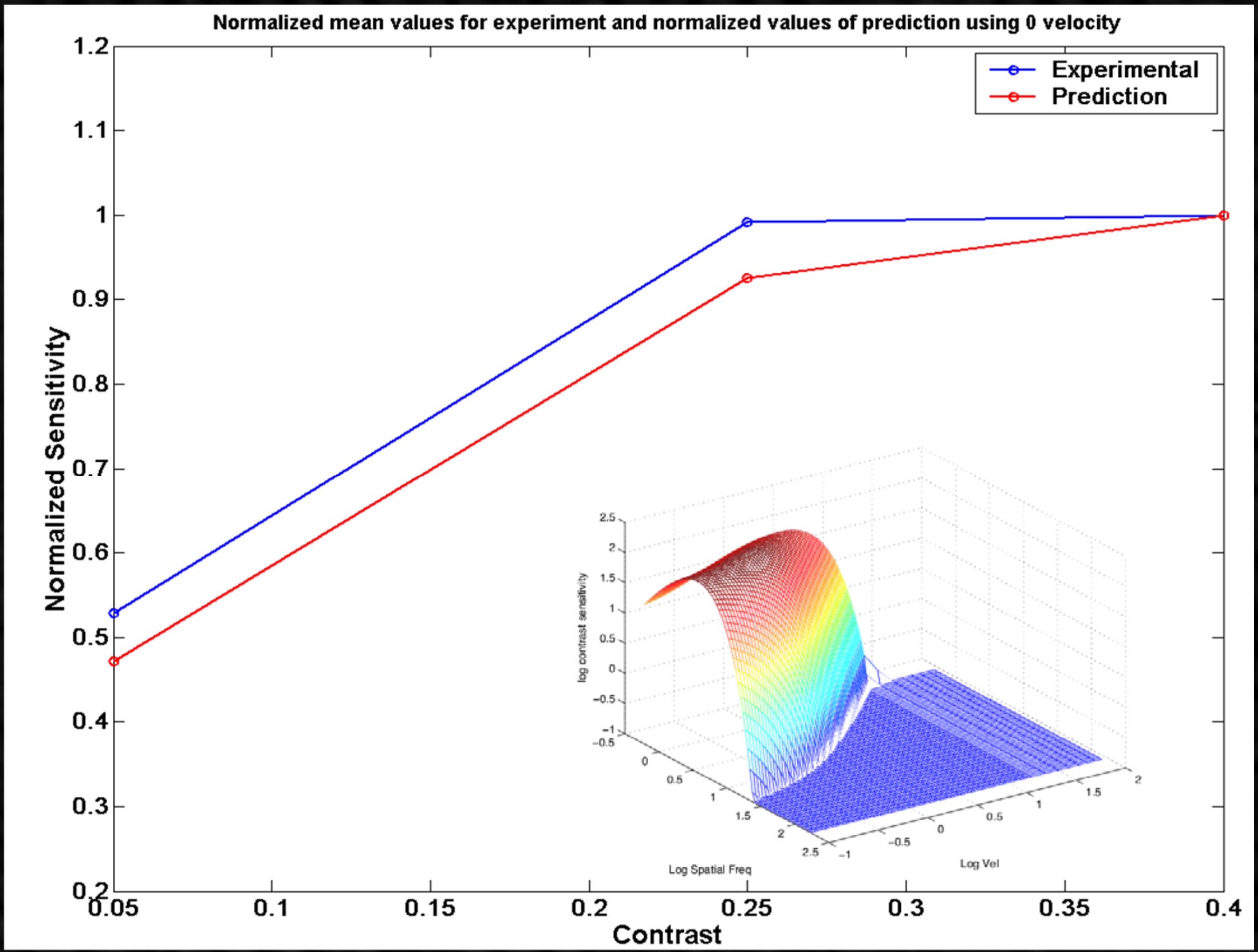
Data is shifted horizontally , due to overlap

Test of the SV model

- **Revised SV CSF model based on new parameters (inset)**
- **Prediction results of moving edges via model :**



  - Based on Watson & Ahumada JOV 2005
  - Use 2D integral of CSF x signal spectrum to model sensitivity
  - Perfect eye tracking assumed
  - Channels not needed since no masking ??
  - OK, but could be better (facilitation?)



Verification of Eye Movement Model & SV CSF - Summary

- Sensitivity determined by retinal velocity
  - Not affected by eye movements
- Sensitivity similar for 2 types of motion
  - Moving sinusoids within Gabor
  - Gabor moving across field of view
- Optimized 2D spatio-velocity CSF model
  - More applicable to TV imagery
  - Use of retinal velocity and unstabilized stimuli

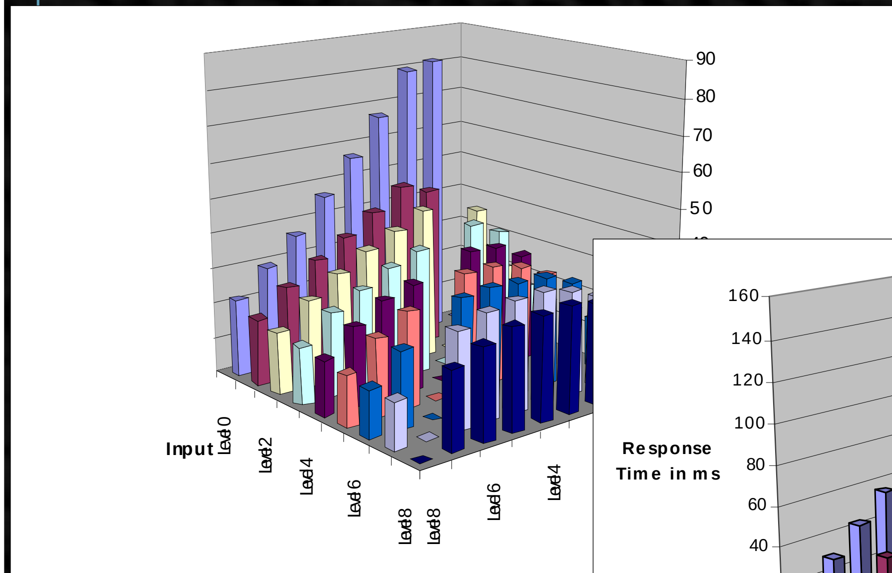
LCD Temporal Basics

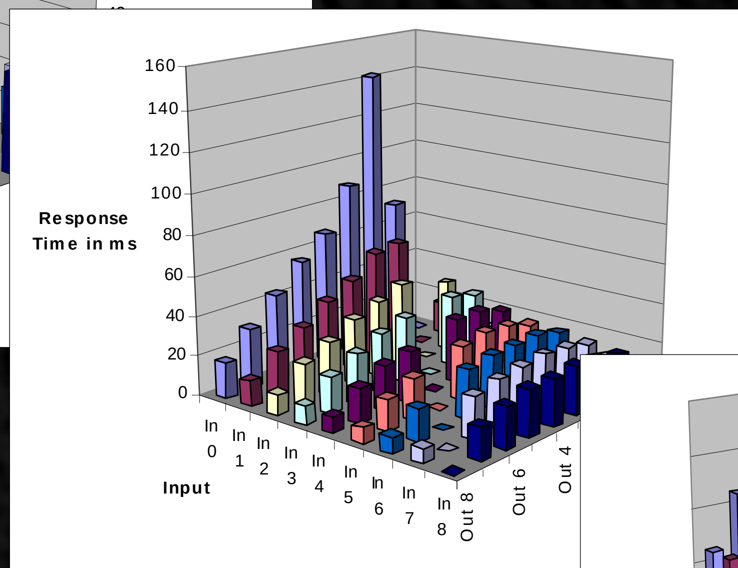
LCD Temporal Basics

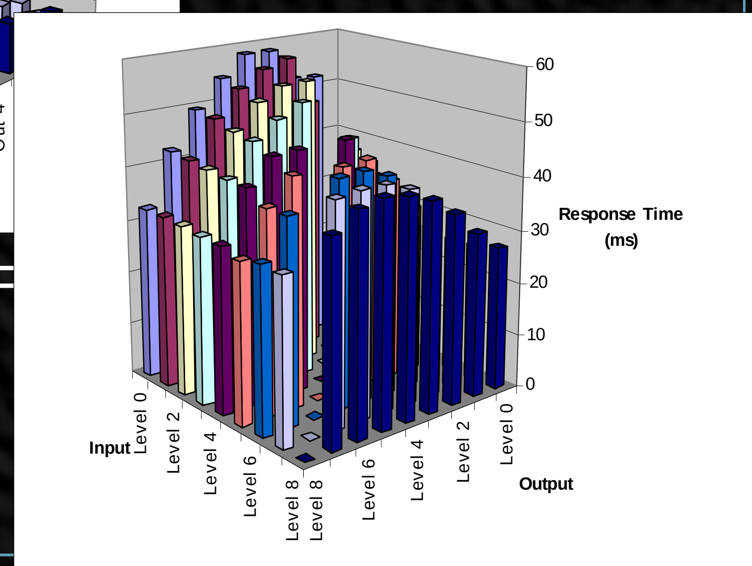
- Why does LCD motion blur happen?
- LCD Temporal MTF components
  - Temporal-response blur &
  - Hold-type blur (temporal rendering function)
- LCD motion blur modeling
- LCD motion blur analysis
  - Slow-response blur vs. hold-type blur
  - Analysis of Proposed solutions

Slow-response blur : **LCD Temporal Characteristics**

- Input vs. Output temporal responses shown
- Overall speed and asymmetry are important

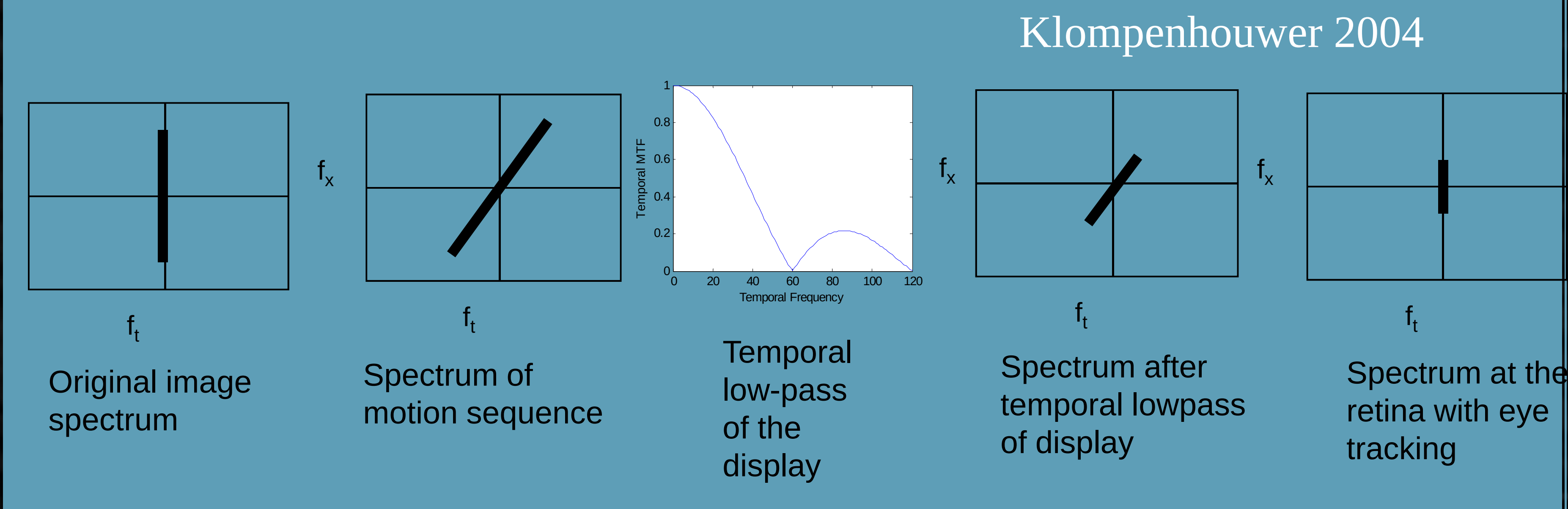






- Slower responses have more temporal LPF and lead to motion blur
- Asymmetric responses lead to HSF flicker
- Overdrive

Spatial consequences of Temporal LPF

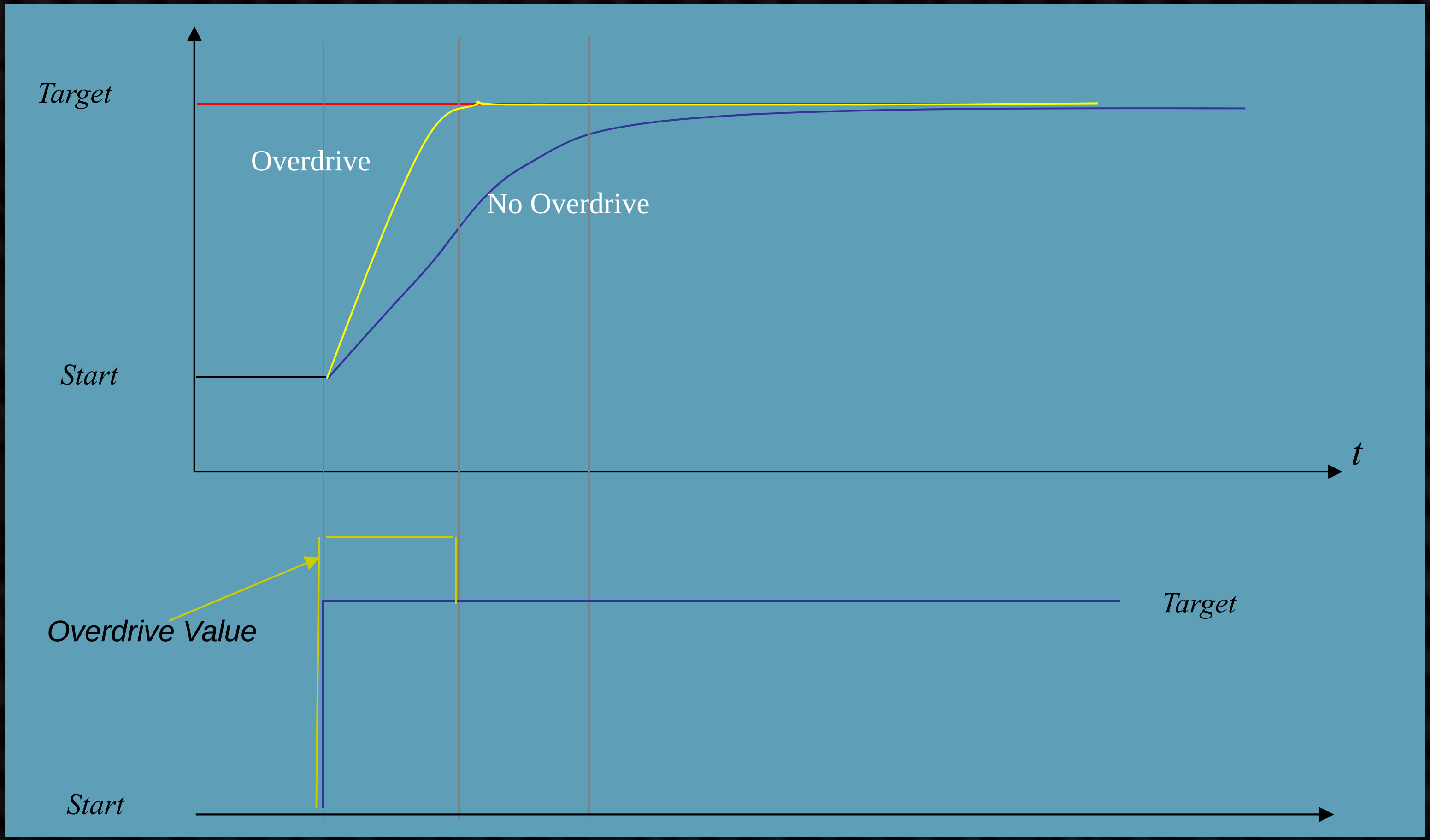


- The motion of an object causes temporal component in the spatial/temporal spectrum.
- This spectrum is low-pass filtered by the display spatial/temporal transfer function.
- The eye tracking causes the retina image to have pure spatial component of spectrum without any temporal component.
- But the temporal low-pass filtering in the display reduces the spatial bandwidth of the retina image, which causes the perception of motion blur.

Overdrive

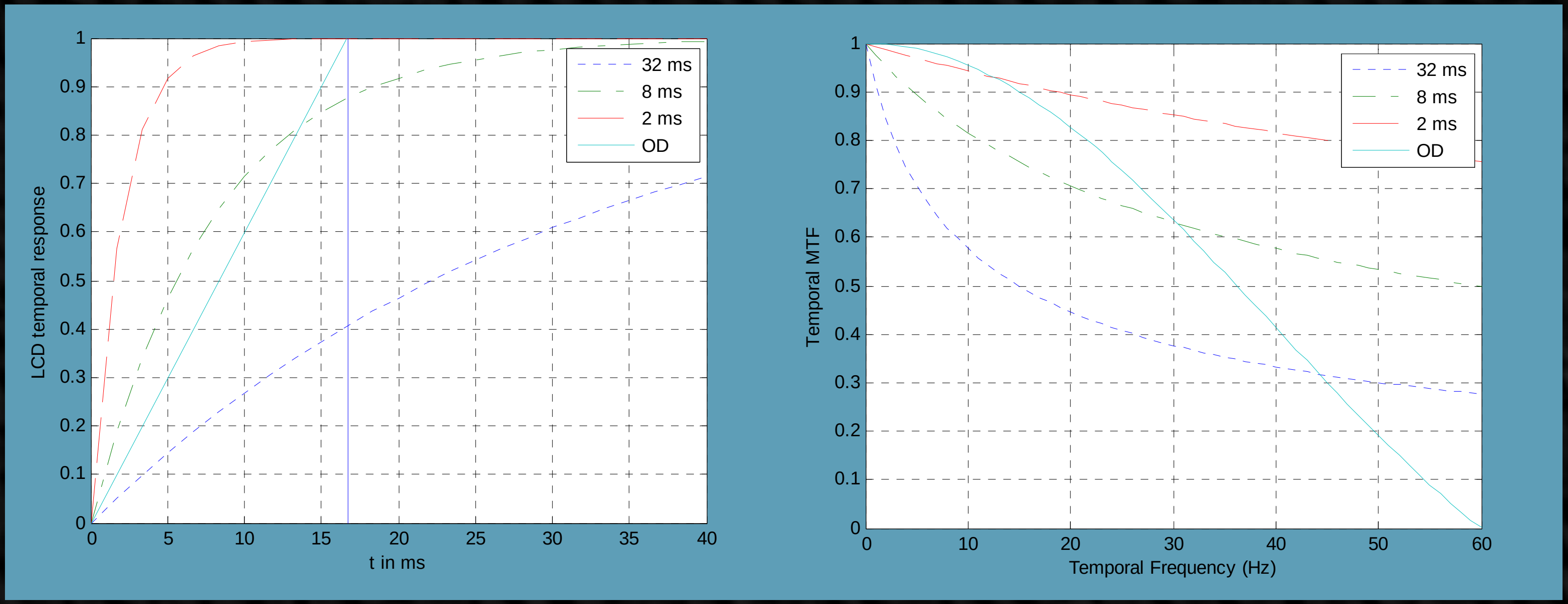
Improving LCD Temporal Characteristics with Overdrive

- Slower responses lead to motion blur
- Overdrive LUT - from gray level to gray level (intended to necessary map)



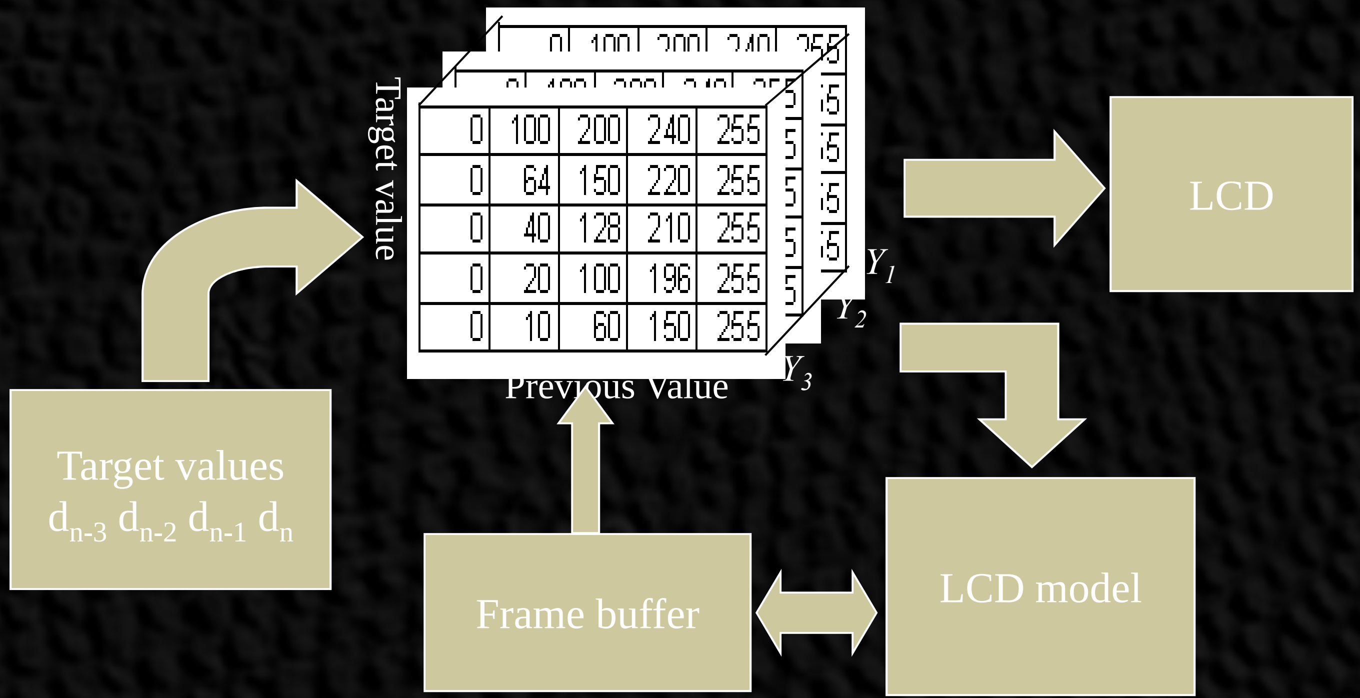
- Okumura 01, Sekiya 02

LCD Temporal Response and its Temporal MTF



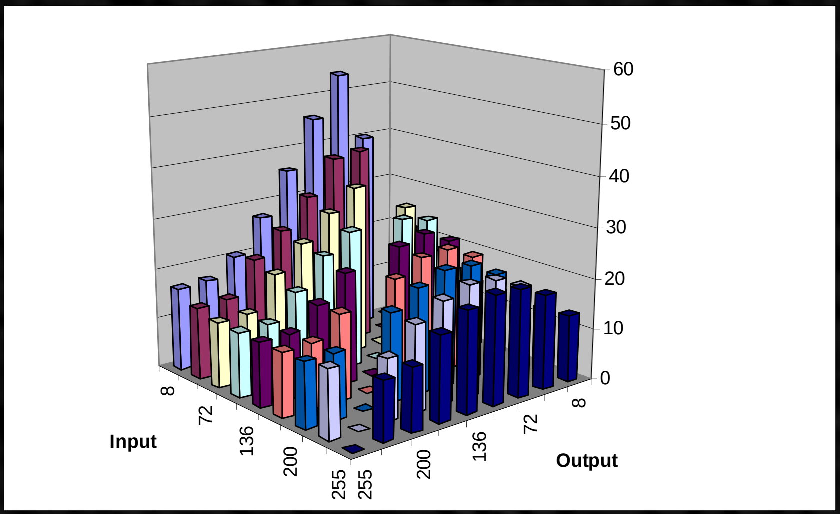
- Temporal overdrive can effective improve the temporal MTF ➔ thus reducing the motion blur
- At peak of HVS temporal CSF (8Hz), overdrive can even exceed a 2ms temporal response

Designing a temporal overdrive algorithm

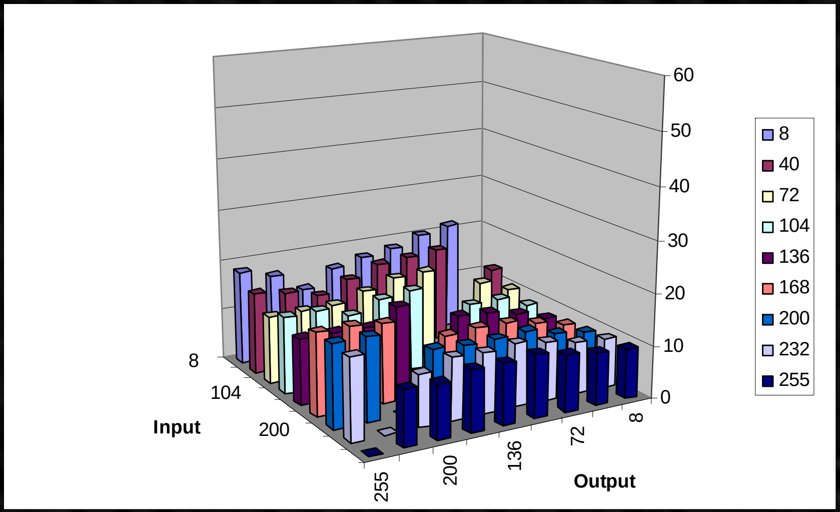


Overdrive algorithm results

No Overdrive



With Overdrive



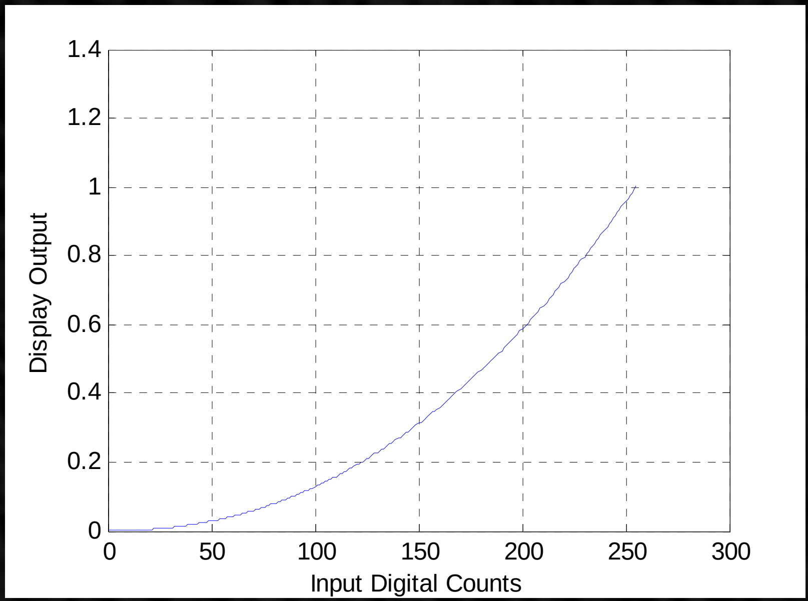
- **Note that overdrive makes temporal responses more symmetrical: this essentially eliminates the flickering artifacts**

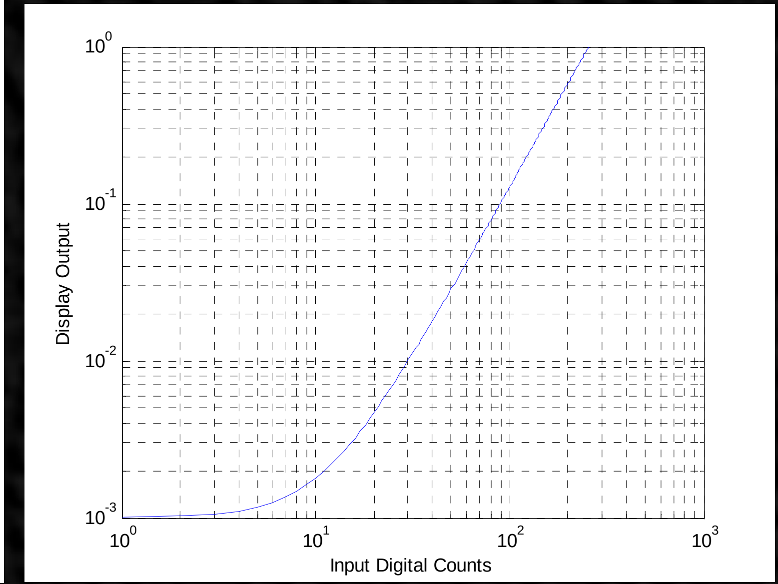
Temporal responses w/ OD are generally in range of 3-5ms

Dynamic Gamma Method for Overdrive Analysis

Dynamic Gamma Approach

- (Static) Display Gamma:

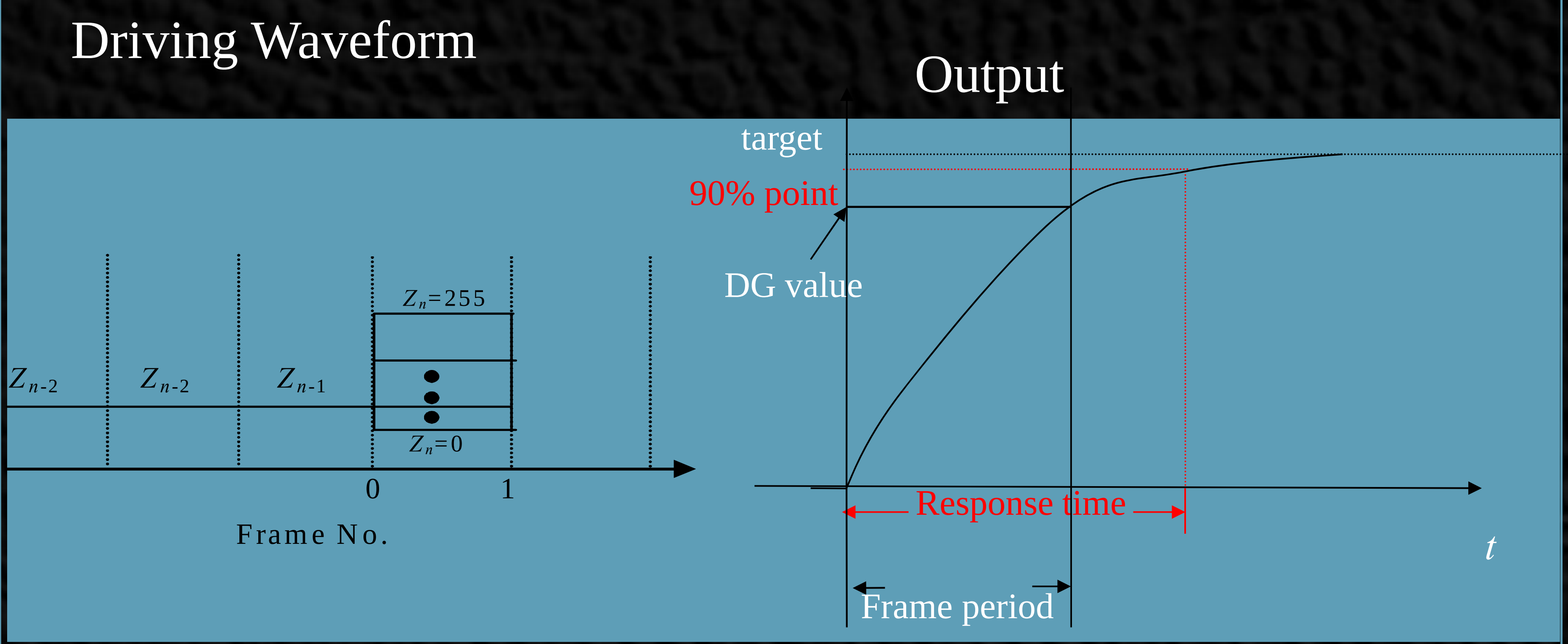




$$y = dc^{\gamma}$$

Feng et al 04 & 05

Definition of first order Dynamic Gamma



- The LCD input/output relationship changes with time when displaying motion
- Dynamic gamma value: the output value measured at the end of the first frame
- Can use the same equipment as response time measurement
- Advantages over use of response times

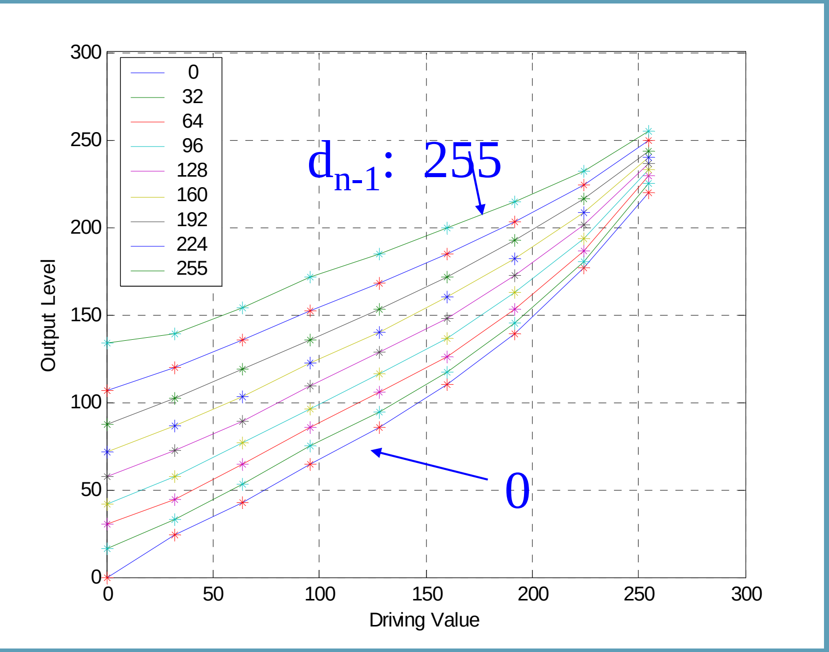
Representation: Table vs. Figure

$$d_n = f\left(d_{n-1}, z_n\right)$$

	0	32	64	96	128	160	196	224	255
0	0	22	39	61	82	111	140	155	220
⋮	⋮	Measured values						⋮	
25 5	135	141	15 5	175	186	203	214	236	255

Starting value

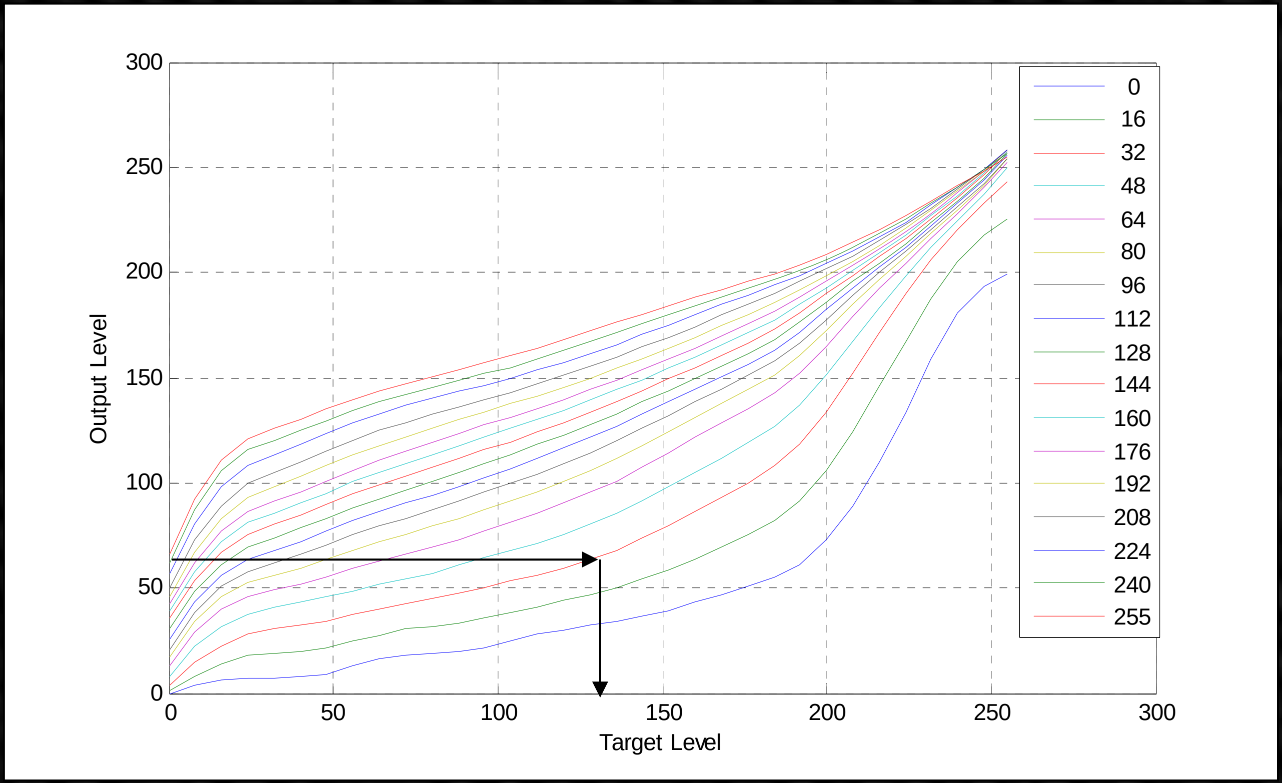
Target value



Each curve represents different previous value

- First order Dγ models the edge motion

Derivation of overdrive lookup table



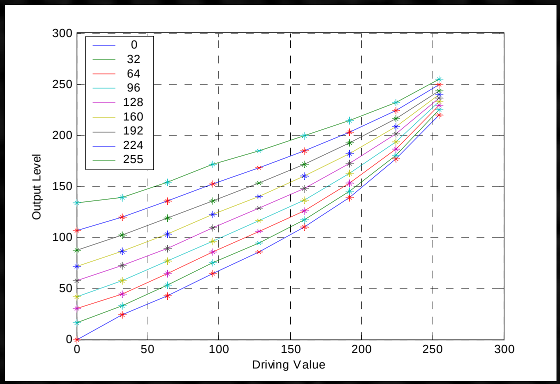
- To go from 32 (previous frame) to 64: needs OD value of 130

Application for comparing LCD systems

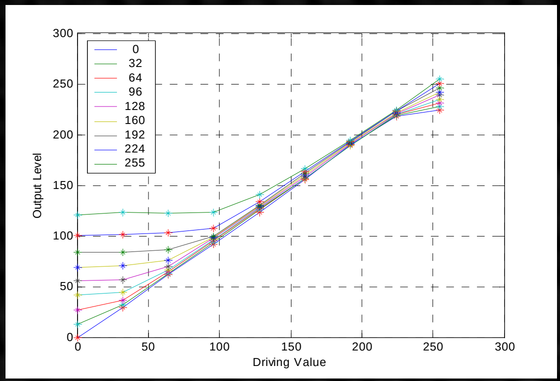
Dynamic Gamma useful for comparing LCD systems (overdrive + inherent temporal response)

Assessment of overdrive performance with dynamic gamma:

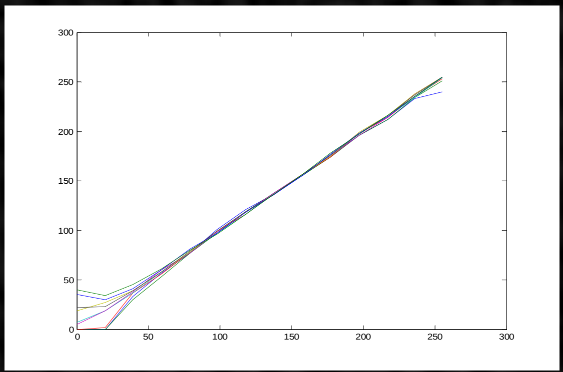
Slow LCD No OD



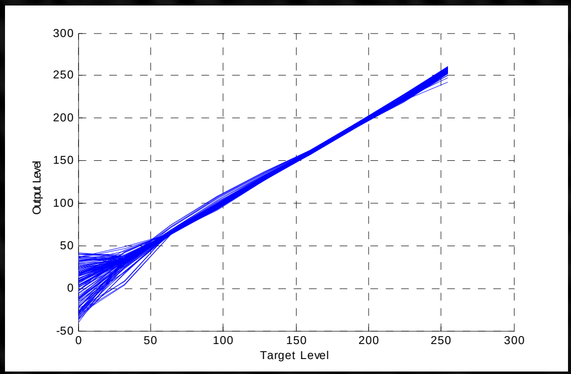
Slow LCD with OD



Fast LCD with OD

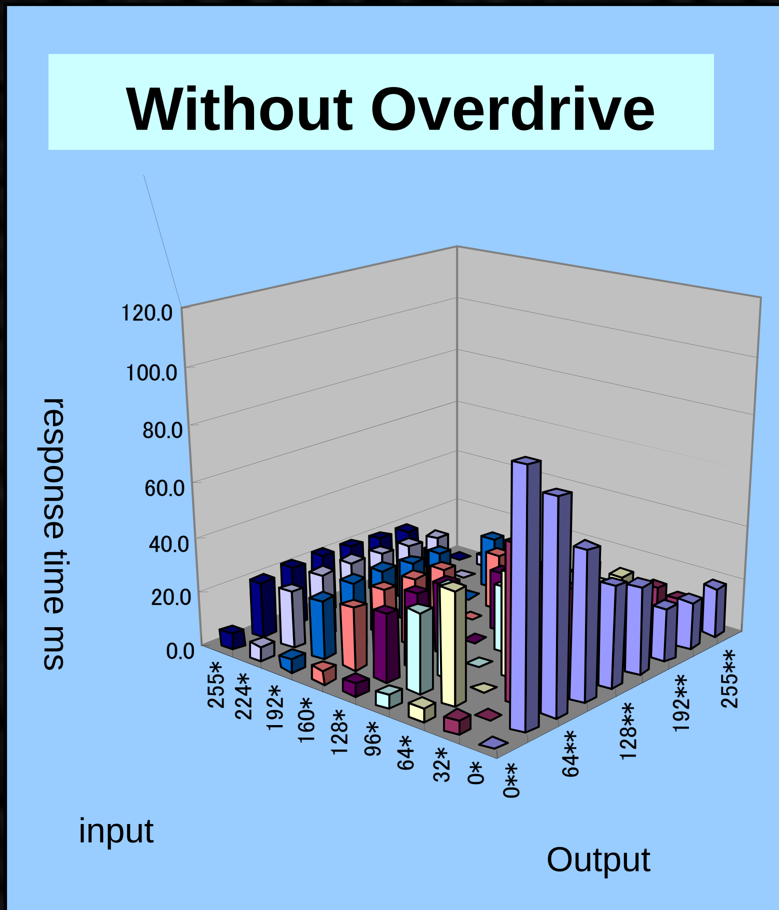


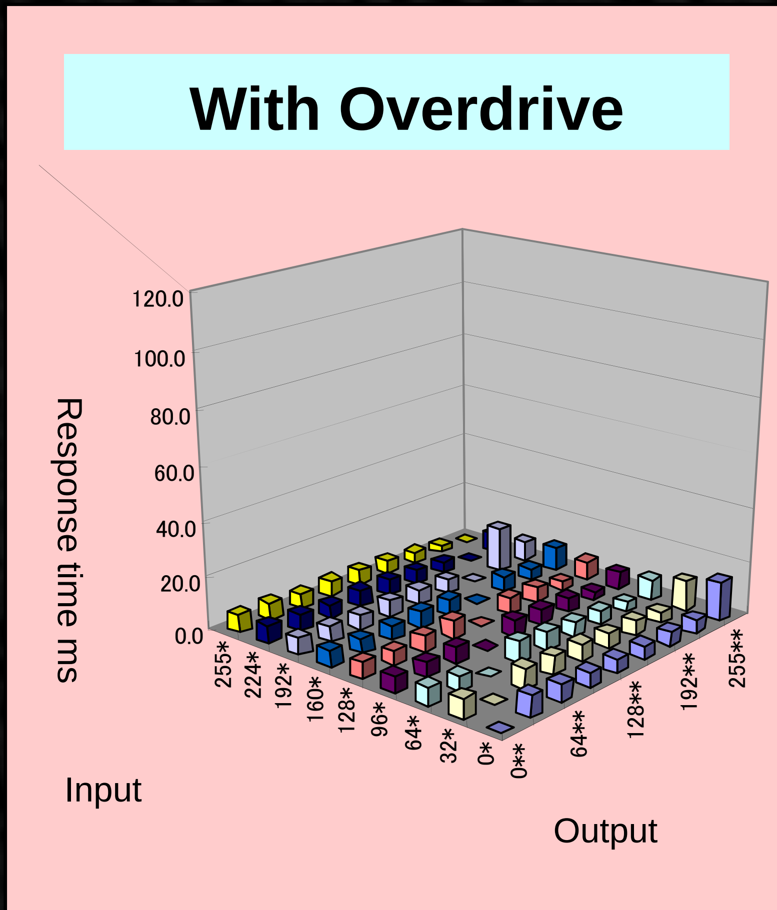
Fast LCD with OD (2^{nd}-order dynamic γ)



1^{st} order ➔ Edge 2^{nd} advantage ➔ real video

Current Overdrive algorithm results

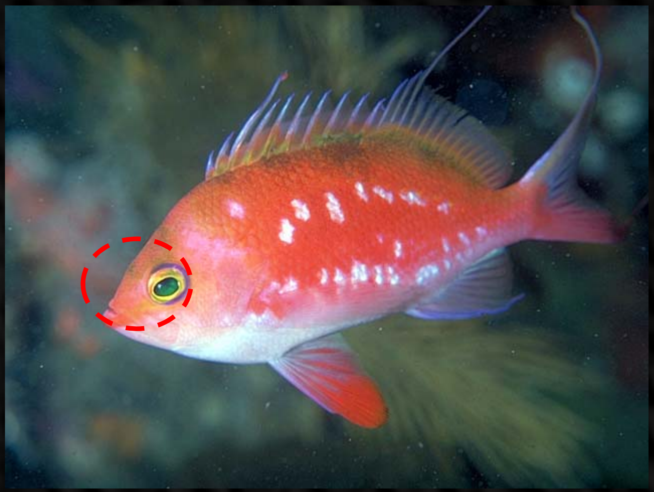




Current Overdrive algorithm results

Example of visual consequences:

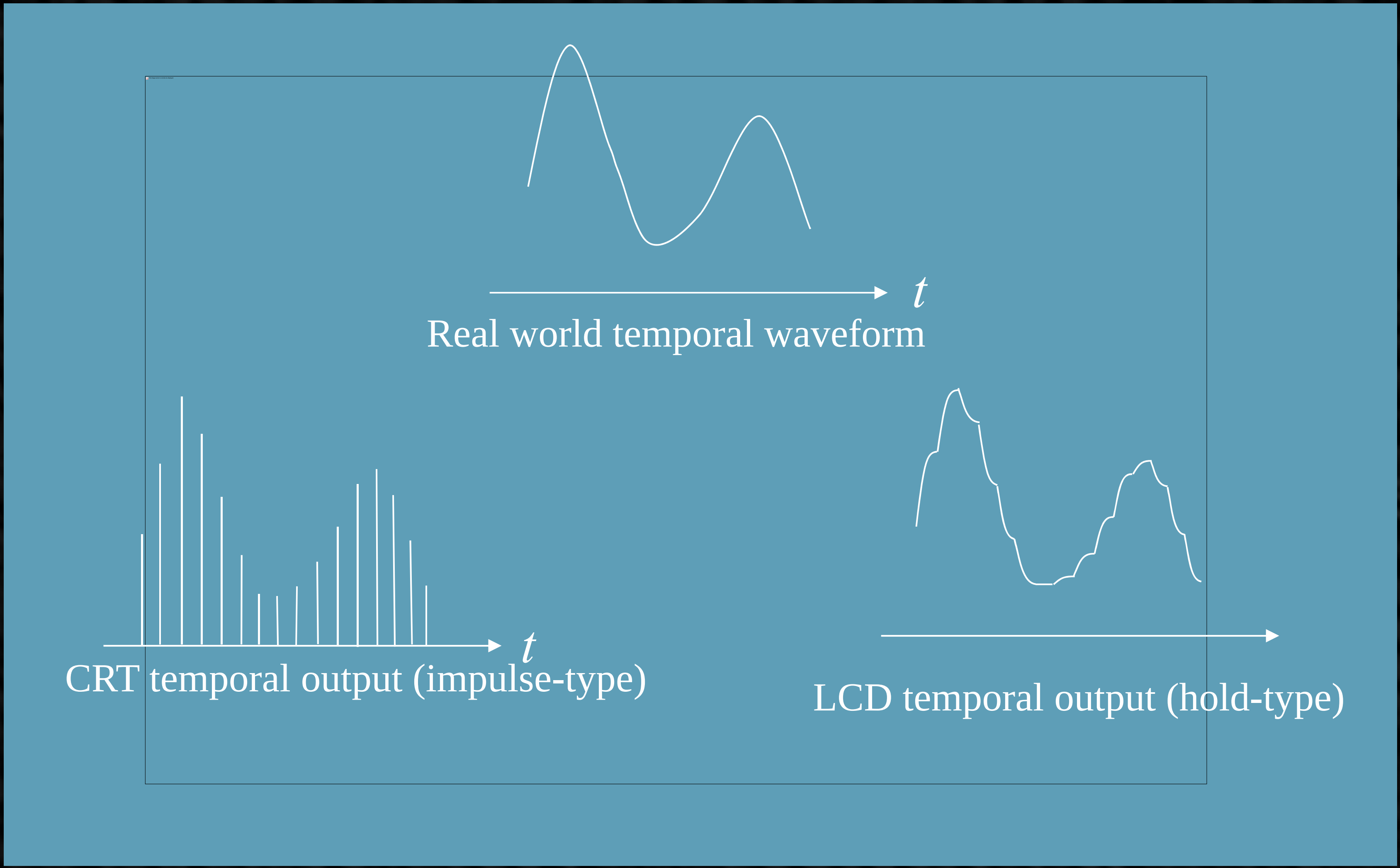
Conventional driver



High Performance Overdrive

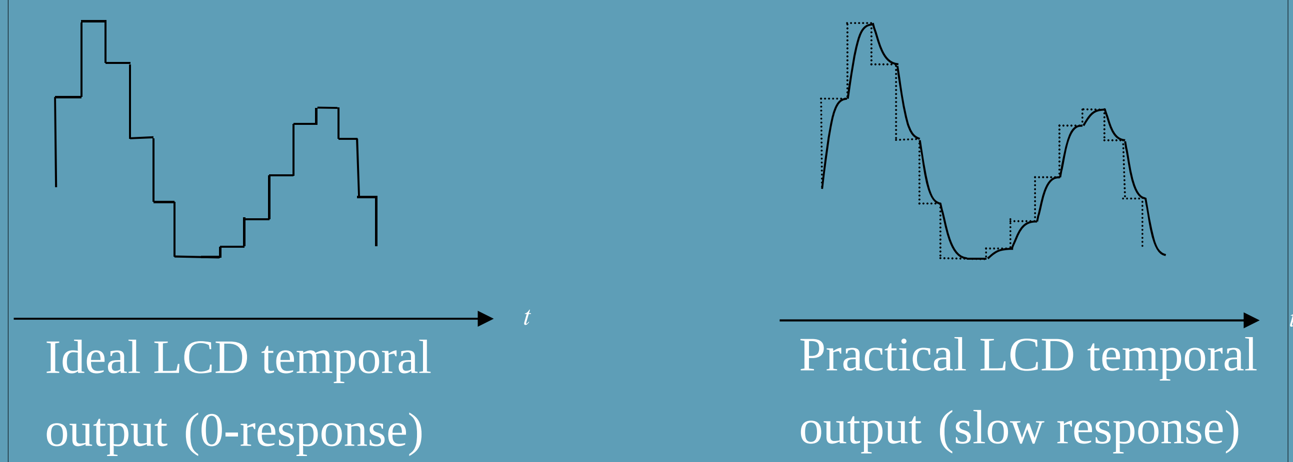
Display Temporal Rendering Function

Comparative Display Basics of Temporal Aperture



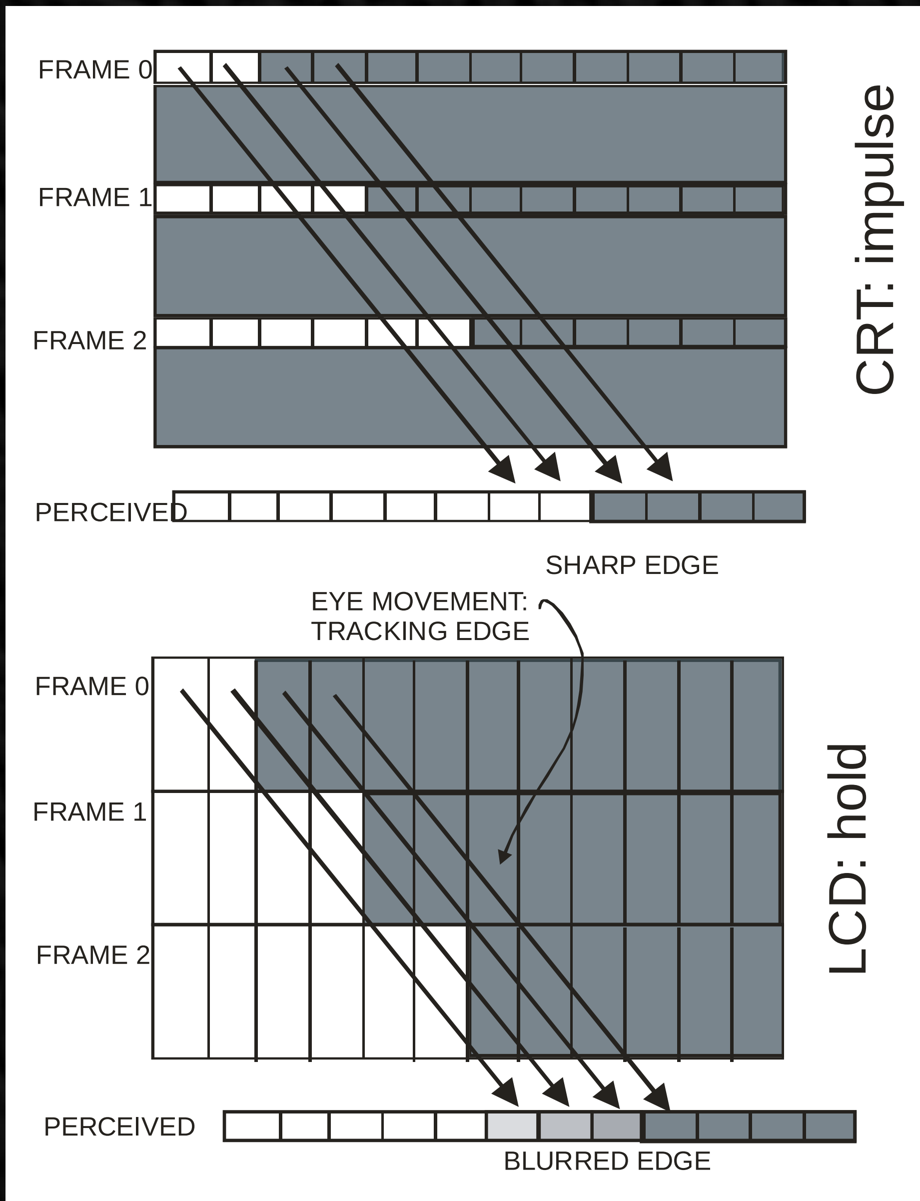
LCD Motion Blur

- **LCD's slow response:** ***slow-response blur***
  - physical;
  - can be captured by a fixed-position camera



- **LCD's hold-type rendition + HVS' smooth pursuit & lowpass filtering:** ***hold-type blur***
  - perceptual;
  - only happen when human eyes are tracking;
  - can NOT be captured by a fixed-position camera
  - Lindholm 96 , Parker 97, Kurita 98, Kurita 01

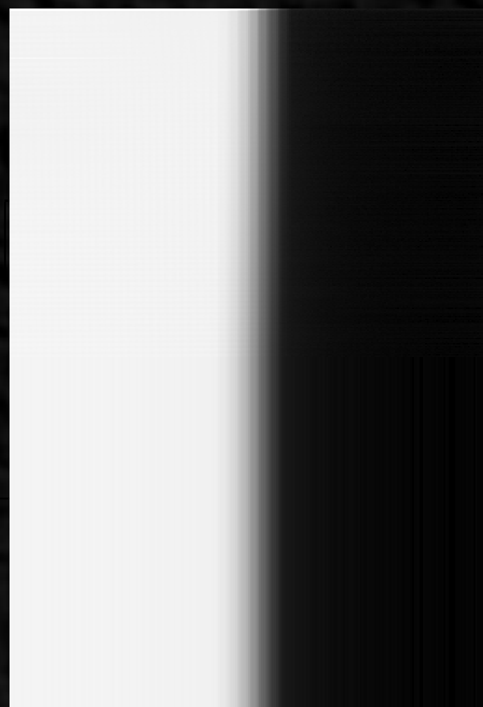
Role of eye tracking in LCD hold-type blur



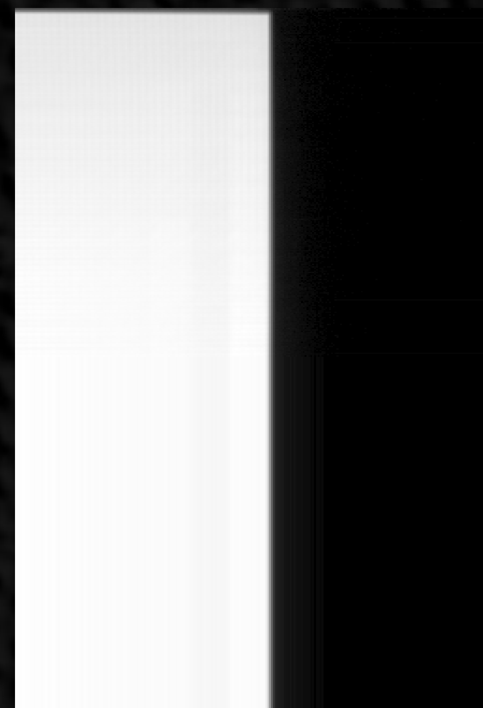
- Eye integrates along tracking path (10-50ms, LA)
- For CRT display, integration of eye tracking path causes no mixing of black and white displayed elements along path
- Result for CRT is sharp moving edge
- For LCD display, eye track path goes through regions of white and black displayed elements, so that mixing of signals occurs due to temporal integration of the eye
- Result for LCD (hold) is a blurred moving edge

Eye tracking Demo

Image examples



Retina image of a moving edge on hold display with eye tracking
➔ hold blur



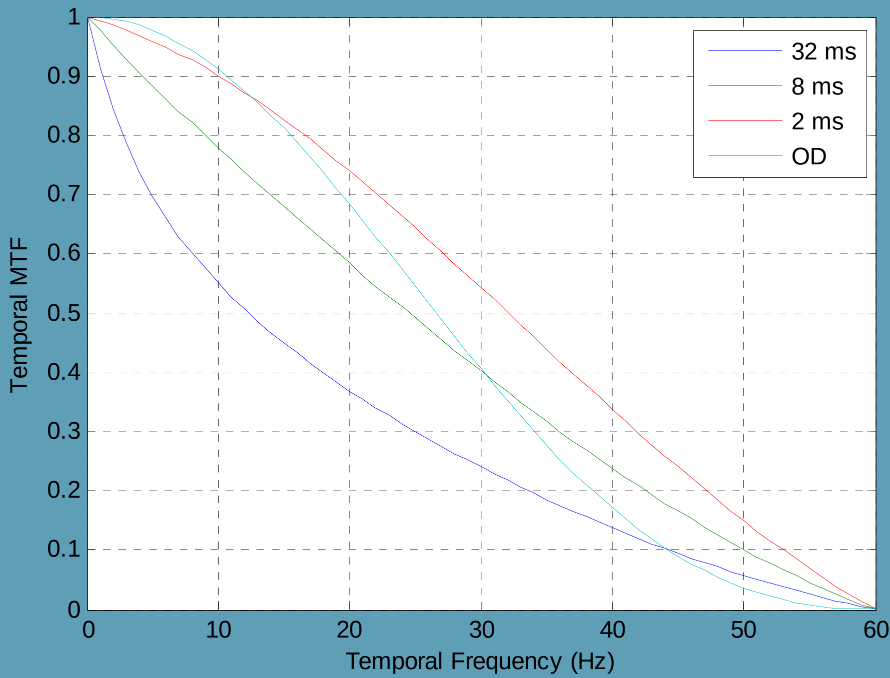
Retina image of a moving edge on impulse display with eye tracking
➔ No motion blur

Quantitative Simulation

Motion Blur Due to Hold: Temporal MTF

The effect of temporal hold is very similar to spatial aperture effect of CCD sensor. The temporal MTF is given by a *sinc* function.

$$T_h(f_t) = \sin c(f_t T)$$

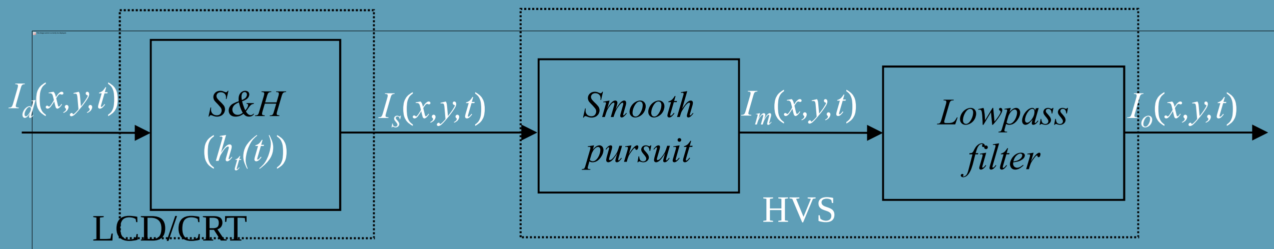


- For a faster LCD panel, the temporal MTF is limited by the hold effect. There is diminishing gain in further improving LCD temporal response.
- For a given temporal sampling, the only way to reduce hold blur is to reduce temporal aperture.
- Plot includes LCD temporal response + hold aperture

Analysis of Temporal LCD System Issues

Pan et al 05

Simplified display-perception chain



Input: assuming the dynamic discrete content $I_d(x,y,t)$ is an image $I_c(x,y,t)$ moving at a constant speed

$$I_d(x,y,t) = I_c(x + v_x t, y + v_y t, t)$$

(1) Sample-and-hold : $I_s(x,y,t) = I_d(x,y,t) * h_t(t)$

$h_t(t)$ is the temporal reconstruction function of an LCD or CRT

(2) Smooth pursuit eye movement: $I_m(x,y,t) = I_s(x - v_x t, y - v_y t, t)$

compensates motion to make the object still on retina.

(3) Lowpass filter: $I_o(x,y,t) = I_m(x,y,t) * \left(\Lambda_{xy}(x,y) * \Lambda_t(t)\right)$

$\Lambda_{xy}(x,y)$ & $\Lambda_t(t)$ are spatial & temporal impulse response functions of the filter

The general LCD motion blur model

- The input-output relationship of the chain:

$$I_o(x,y,t)=\int_{t'=-\infty}^{\infty}\iiint I_c(x-v_xt'-p,y-v_yt'-q,t-t'-t'')\Lambda_{xy}(p,q)\Lambda_t(t'')dpdqdt''h_t(t')dt'$$

- The spatial and temporal lowpass impulse functions ($\Lambda_{xy}(x,y)$ and $\Lambda_t(t)$) are unknown
- Assuming that HVS has the same lowpass impulse functions for LCD and CRT, and using image perceived on CRT as a reference

$$\boxed{I_o^{LCD}(x,y,t)=\int_{t'=-\infty}^{\infty}I_o^{CRT}(x-v_xt',y-v_yt',t-t')h_t^{LCD}(t')dt'}$$

The general LCD motion blur model

$$I_o^{LCD}(x,y,t) = \int_{t'=-\infty}^{\infty} I_o^{CRT}(x - v_x t', y - v_y t', t - t') h_t^{LCD}(t') dt'$$

- The LCD temporal reconstruction function $h_t^{LCD}(t)$ affects spatially and temporally.
- The reconstruction function $h_t^{LCD}(t)$ can be measured directly or derived from the temporal waveform.
- When $h_t^{LCD}(t)$ is δ-function, then LCD and CRT have the same result (motion blur does not exist)
- Generally, the model is not in the form of convolution.
- The motion speed v_x and the LCD reconstruction function jointly determine motion blur.
  - Faster the motion is, more blurred the perceived images are.
  - Wider the reconstruction function is, more blurred the perceived images are.

The reconstruction function is the key

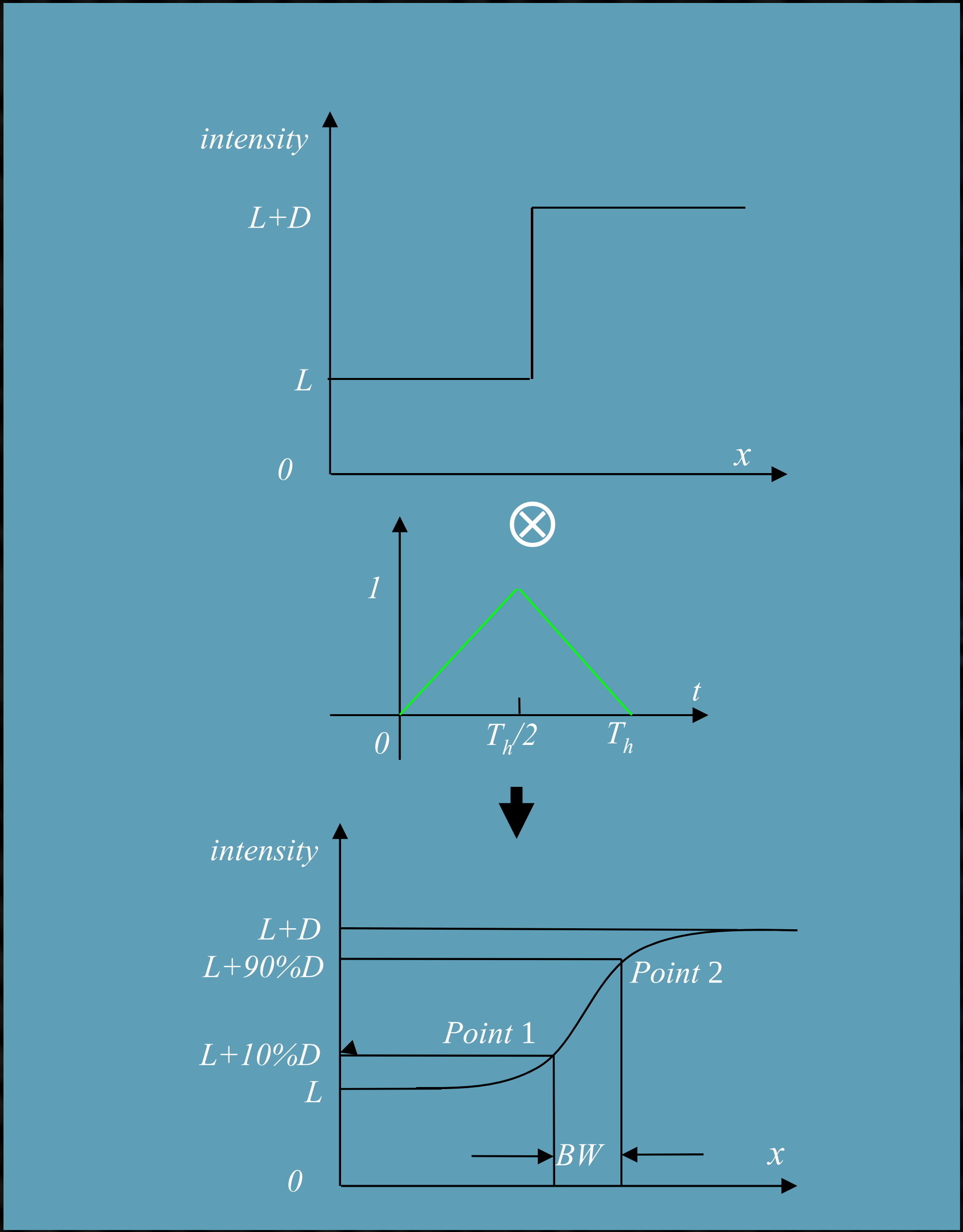
Blur width calculated by the model

1. Assume a virtual horizontally moving sharp edge perceived on CRT

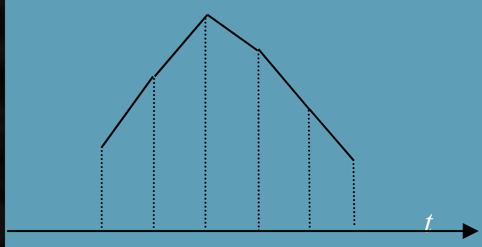
2. Calculate the perceived edge using the reconstruction function of the LCD

$$I_o^{LCD}(x) = I_o^{CRT}(x) * h_t^{LCD}(x / v_x)$$

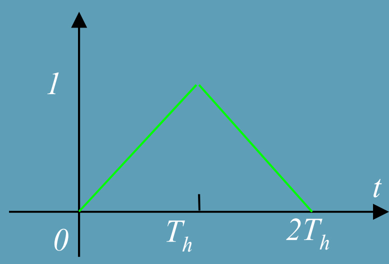
3. Calculate the blur width of the calculated perceived edge



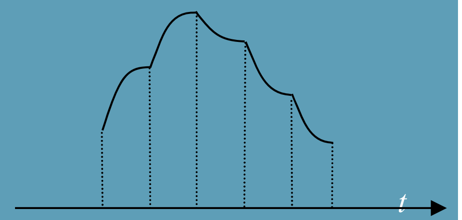
Traditional LCD (slow response blur + hold-type blur)



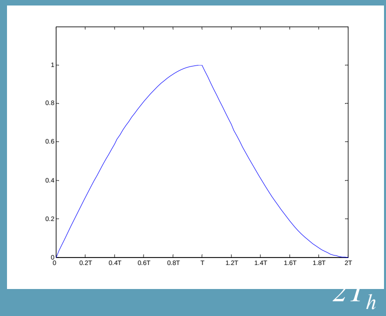
The temporal waveform (linear transition between frames)



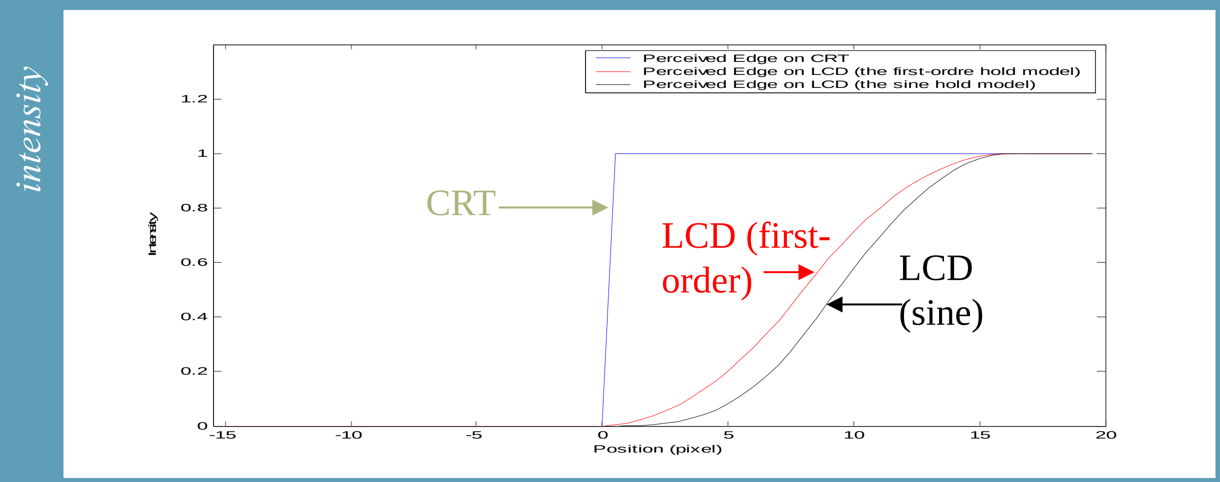
The reconstruction function (linear transition between frames)



The temporal waveform (sine transition between frames)

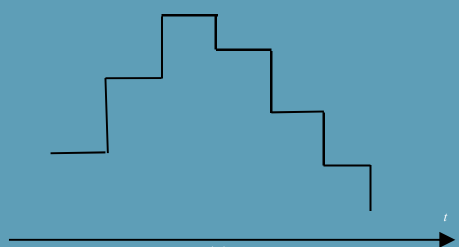


The reconstruction function (sine transition between frames)

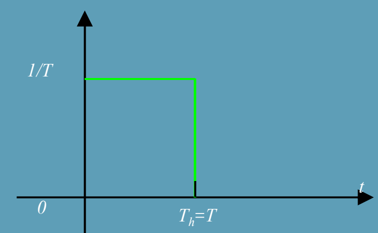


Blur width: 1.1 vT

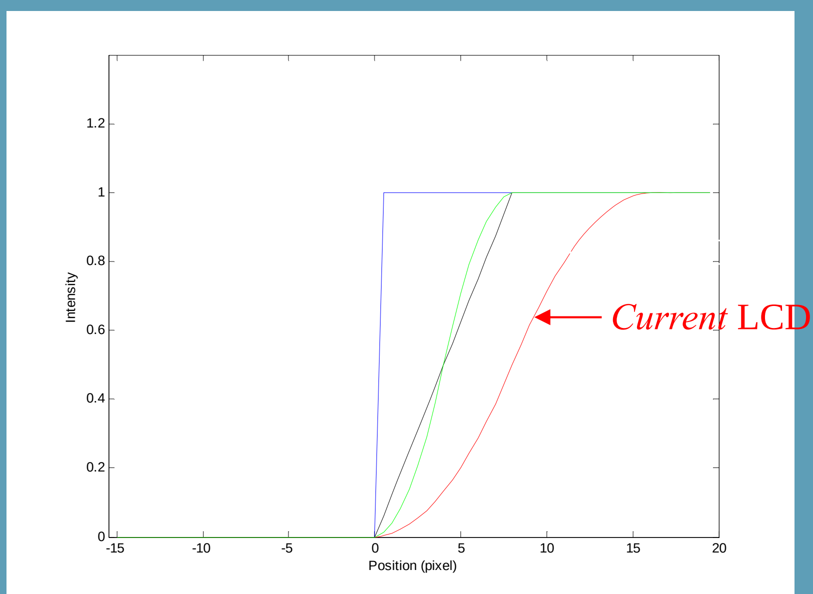
The ideal LCD temporal response (hold-type blur only)



(a)



(b)



Blur width: 0.8 vT

Hold-type blur vs. slow-response blur

- Hold-type +slow response blur: $1.1vT$
- Hold-type blur: $0.8vT$

- so slow response blur: $1.1vT-0.8vT=0.3vT$
  - 70% vs. 30%

- So, hold-type blur is the major factor

Four key proposed solutions

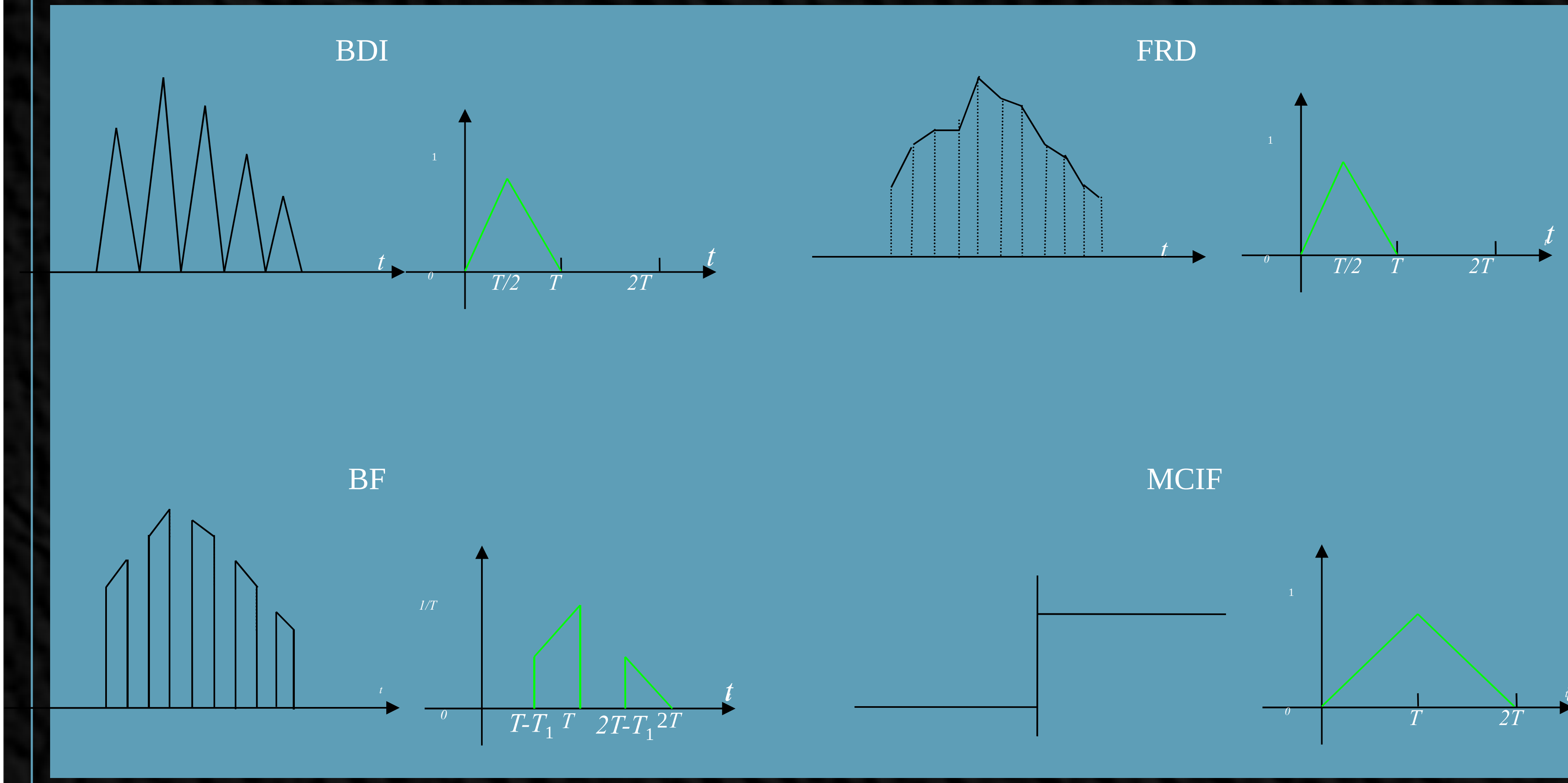
1) Black Data Insertion (BDI)
   - Hong 04, Kimura 05

2) Backlight Flashing and Scrolling (BF)
   - Fisekovic 01, Sluyterman 05
   - Adaptive backlight flashing (60 and 120 Hz), Feng 06

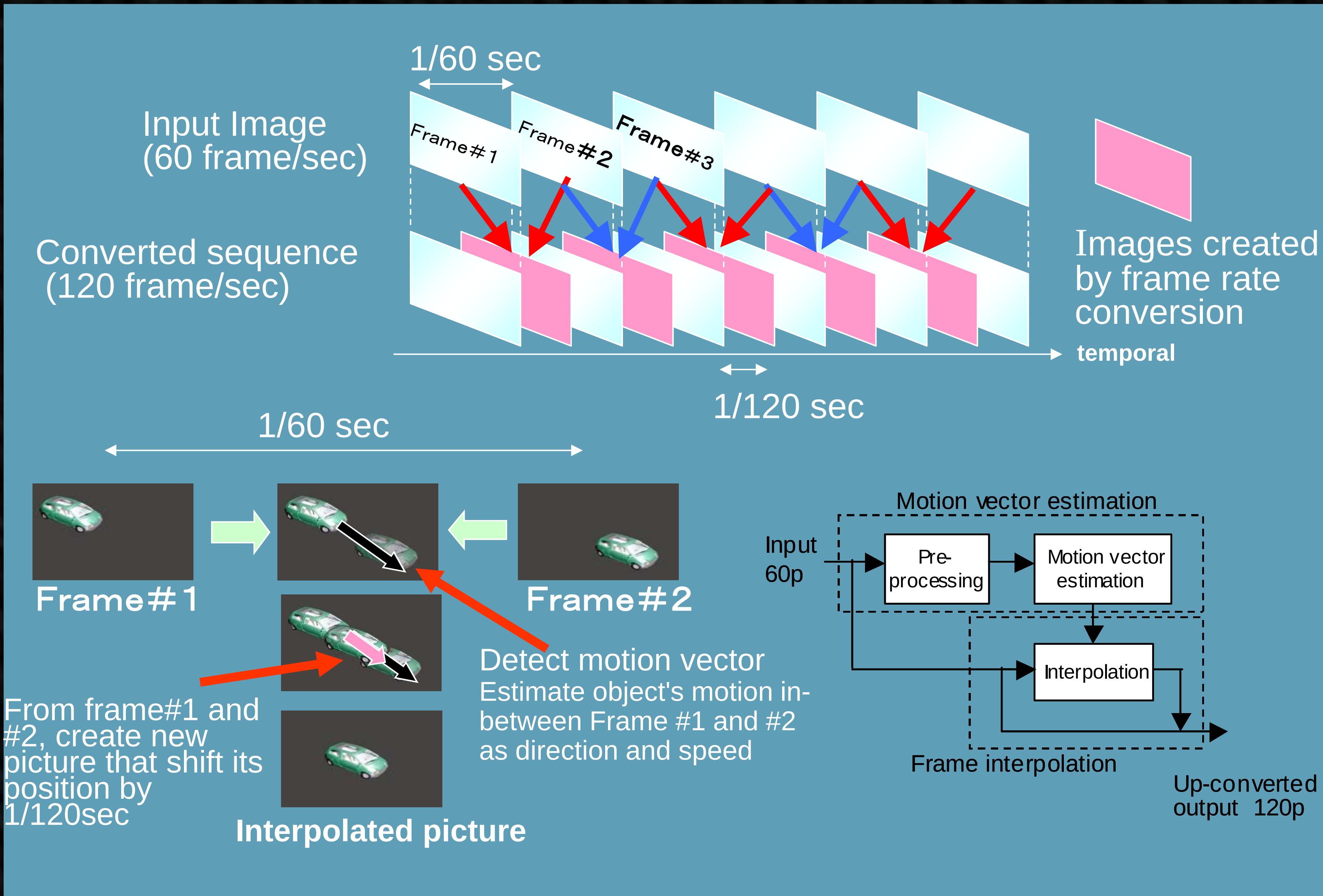
3) Frame Rate Doubling (FRD)
   - Sekiya 02, Kurita 05

4) Motion-Compensated Inversing Filtering (MCIF)
   - Klompenhauer 01, 05

Reconstruction functions of the four proposals



Frame Rate Conversion based on Motion Compensation



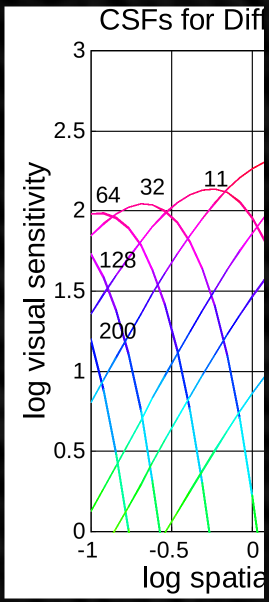
Comparison between different approaches

	BDI	BF	FRD	MCIF
Requirement on LCD temporal response	**High**	**Medium**	**High**	**No**
Requirement on backlight temporal response	**No**	**High**	**No**	**No**
Other Requirement	**No**	**Sync between LCD and backlight**	**Accurate motion estimation**	**Motion estimation**
The ghosting artifact	**Likely**	**Likely**	**No**	**No**
The luminance reduction artifact	**Yes**	**Yes**	**No**	**No**
flickering artifact	**Yes**	**Possible**	**No**	**No**
Reduction of motion blur (smaller the number is, the better)	**50%** (limited by LCD temporal response)	**25% or less** (limited by backlight temporal response)	**50%** (limited by LCD temporal response)	**?**

Perceptual Motion Sharpening

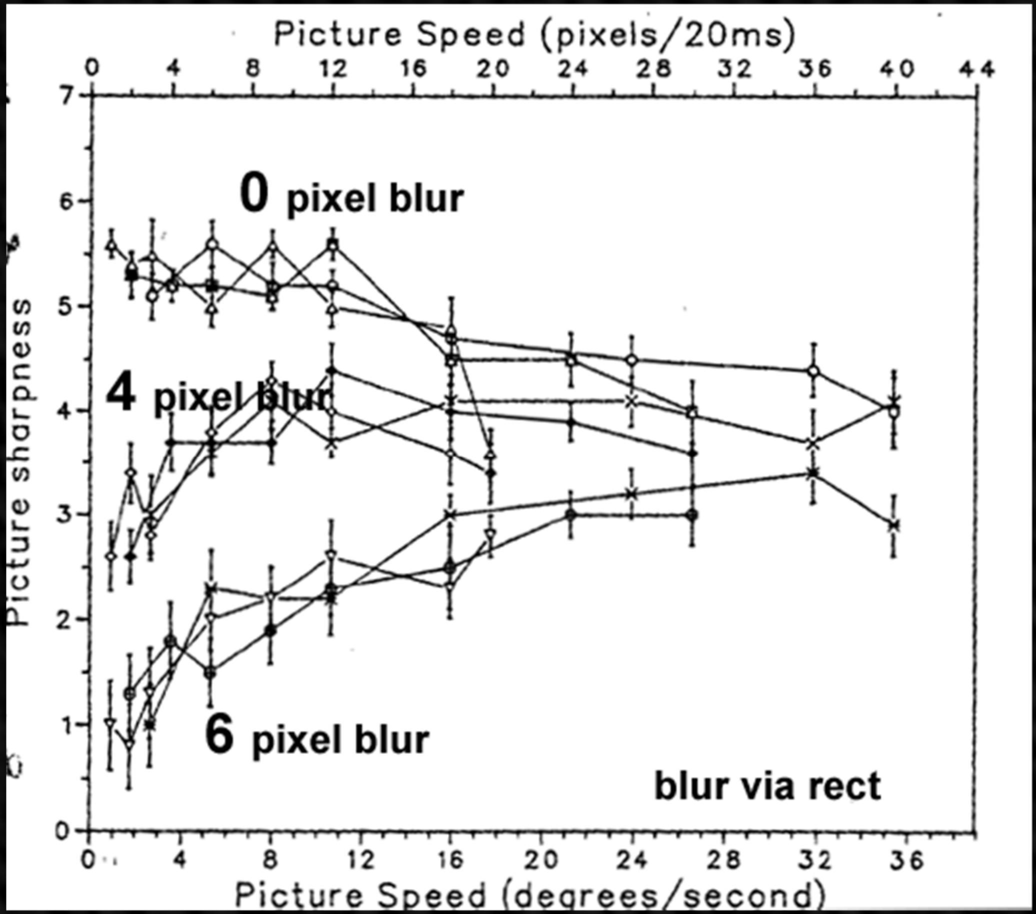
Motion Sharpening

- **Ramachandran '74 (observations on blurred movie frames)**
  - things tend to look blurred when they are moving fast-----but---
  - blurred edges look sharper when they are moving than when stationary
- **Poor tracking ➔ blurred retina image**
- **Motion sharpening effect ➔**
  perceived motion is sharper than the still images, which suggests that the perception of smooth pursuit is different from still image.
- **Less understood , higher order effect**
  - Sharpness constancy
  - Deblurring
- **If motion sharpening effect is involved, previous analysis based on retinal image blur is insufficient**



Motion induced Blur and Sharpening

- **Westerinck 90**
- **Studied perceived sharpness of images**
  - with varying degrees of blur
  - As a function of translational motion speeds



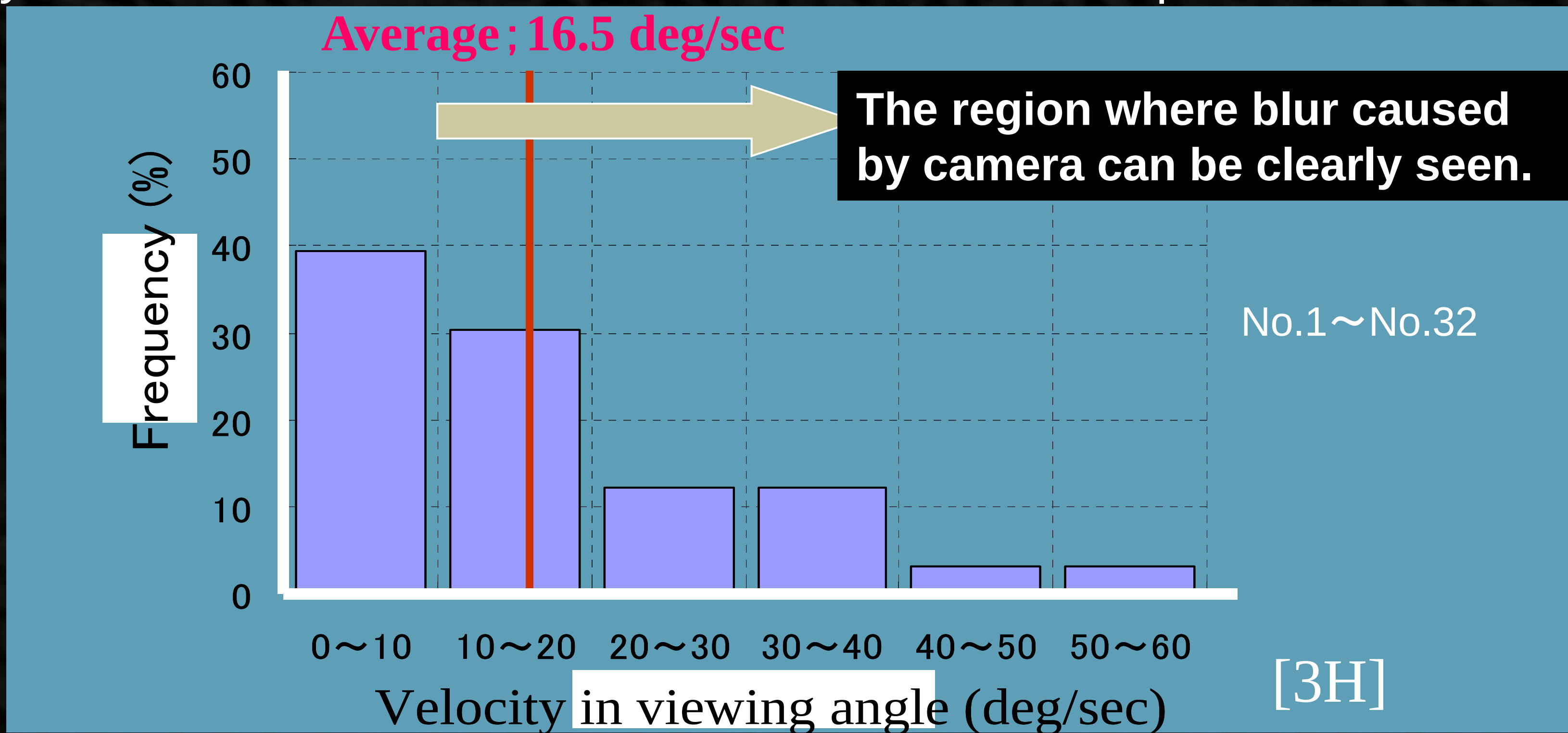
Conclusion: Evaluation of Motion Blur Reduction

- **Motion blur characterization**
  - Objective method: measured retina image using a simulated tracking camera – assuming perfect tracking
  - Subjective method: Compared the perceived blur with blurred edge of a still image
- **Motion blur perception**
  - The subjective method agrees with the objective derived motion blur ➔ Perception of motion blur is similar to perception of still image blur
  - Backlight flashing can significantly reduce the perception of motion blur.

Other Key Studies

Distribution of Moving Object Velocity

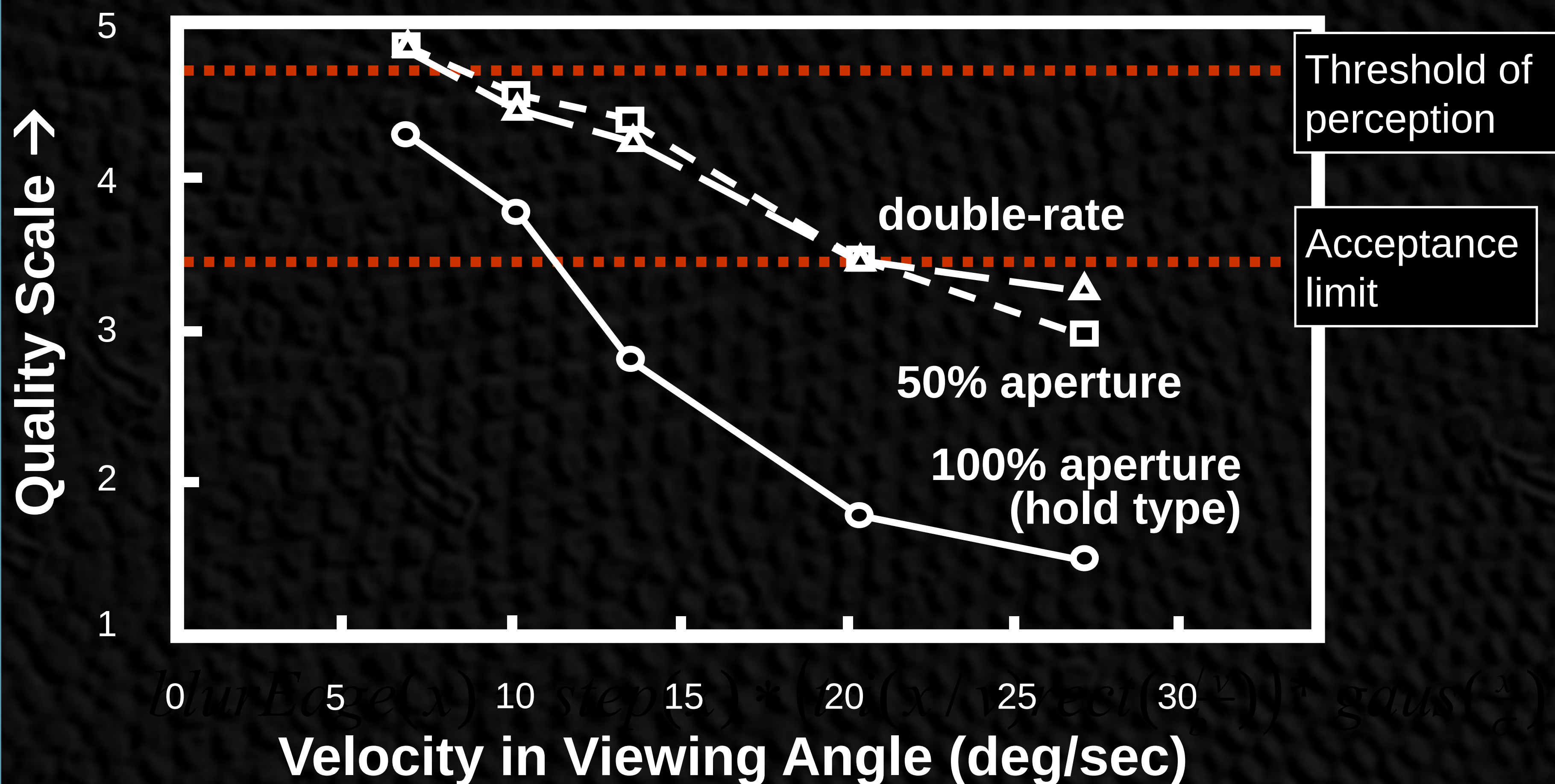
Analysis of ITU-R BT-1210-3 test material for HDTV sequence



In terms of the fastest motion within every sequence, 70% of the sequence distributed below 20[deg/sec]

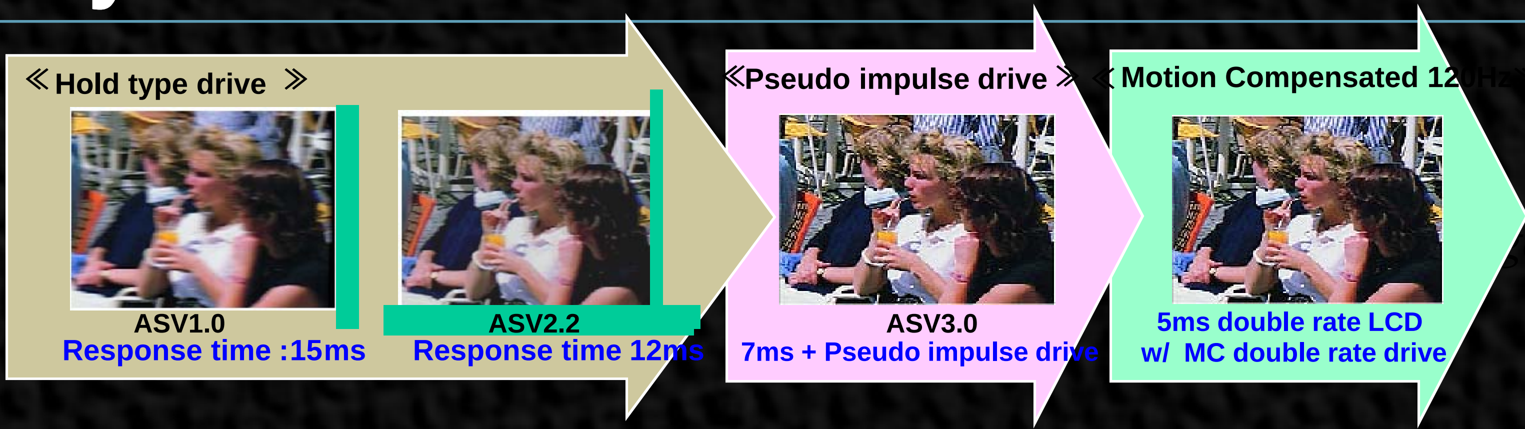
T.Fujine et.al.;"Real-Life In-Home Viewing Conditions for FPDs and Statistical Characteristics of Broadcast Video Signal," Digest AM-FPD'06

Observer Study of Picture Quality Improvement



T.Kurita; "Moving Picture Quality Improvement for Hold-type AM-LCDs," SID'01, 35.1, pp.986-989 (2001)

Analysis of Methods to Overcome Hold-Blur

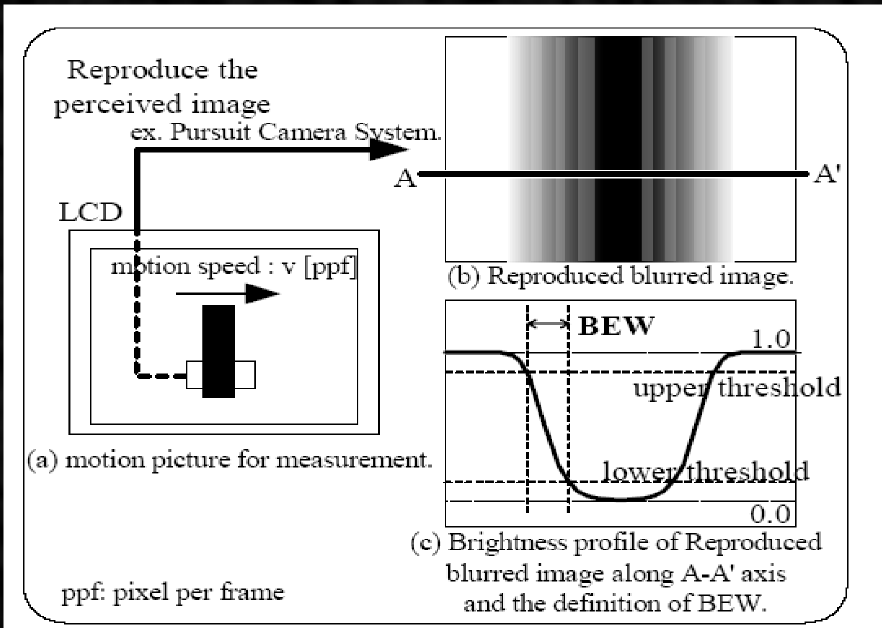


Pan, Feng, & Daly: "Quantitative Analysis of LCD Motion Blur and Performance of Existing Approaches" ICIP 2005

	BDI (black data insertion)	BF (backlight flashing)	FRD (frame doubling)
Requirement on LCD temporal response	**High**	**Median**	**High**
Requirement on backlight temporal response	**No**	**High**	**No**
Other Requirement	**No**	**Sync between LCD and backlight**	**Accurate motion estimation**
The ghosting artifact	**Likely**	**Likely**	**No**
The luminance reduction artifact	**Yes**	**Yes**	**No**
flickering artifact	**Yes**	**Yes**	**No**
Reduction of motion blur (smaller the number is, the better)	**50% (limited by LCD temporal response)**	**25% or less (limited by backlight temporal response)**	**50% (limited by LCD temporal response)**

Standardized Metrics

Motion Picture Response Time (MPRT)



Steps to Measure MPRT

1. Move an edge cross screen. The edge is made of a transition from one gray level to another level. Total of 30 transitions (6 levels in digital counts or L* space)
2. Using the pursuit camera to measure the blur width
3. MPRT is average blur edge width (BEW) normalized by the moving speed

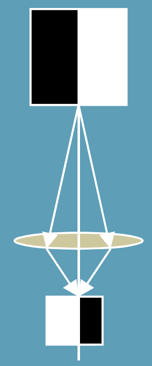
   - also referred to as E-BET (extended blurred edge time)

MPRT basics and issues

- **Motion blur can be characterized by motion picture response time (MPRT) metric, which is measured with a tracking camera that simulates the eye tracking of a moving edge**
- **The system is expensive and time consuming**
- **Theoretically, motion blur is a pure temporal issue that can be uniquely determined by the temporal response function (via LTI: linear systems theory)**
  - Nonlinearities (of both LCD and HVS) are only reasons for failure of LTI
  - Small amplitude signals may be within linear region approximation of both
  - Still, MPRT does not consider HVS effects (too much normalization)
- **In Q&A with Someya (Mitsubishi) at IDW05, he thought that MPRT from temporal measurement is only accurate for hold displays, but not for impulse displays such as displays using backlight flashing and black data insertion**
- **At SID 06, Klompenhouwer described advanced motion blur measurement schemes as "inventing a complex system to measure a simple temporal response"**

Motion Blur Measurement with Simulated Tracking Camera

The simulated retina image is the integration of a sequence of temporal captured frames in the motion tracking trajectory

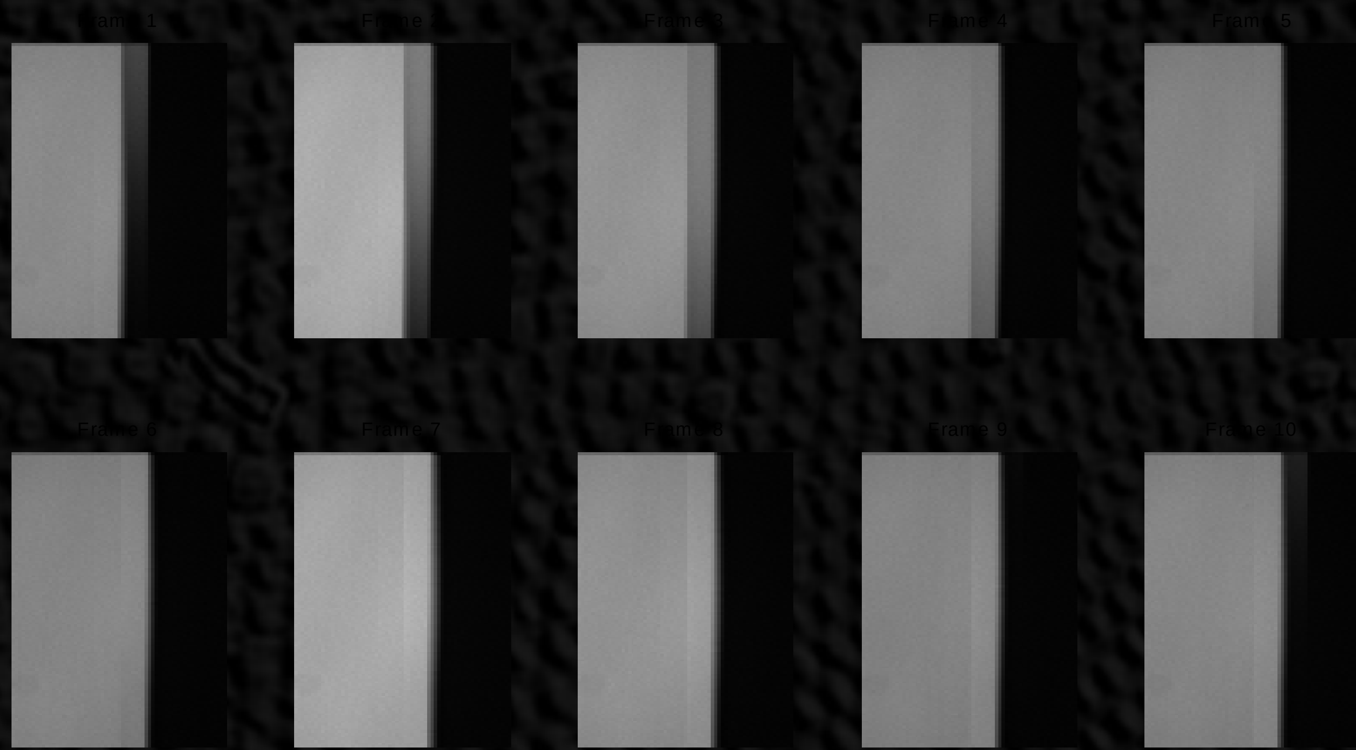


$$E_e(x) = \int E_{LCD}(x - vt)\,dt$$

$$E_e(x) = \sum_{i=1}^{N} E_{CCD}(x - iv\Delta t, i)\Delta t$$

Captured Frames in one Display Frame Period

Via high speed digital camera (900 fps)



Summary

Summary

- **Basic Spatiotemporal Vision**
- **Spatiotemporal Vision with Eye Movements**
- **LCD Motion Issues**
  - Temporal Response
  - Overdrive
  - Temporal Rendering Function
- **Observer study of LCTV motion sharpness matching**

$$blurEdge(x) = step(x) * \left(tri(x/v)\,rect(\tfrac{x/v}{t})\right) * gaus(\tfrac{x}{\sigma})$$

What's next :
Other Temporal Artifacts

Other Temporal Artifacts

- **Motion Blur and Sharpness … as discussed**
- **Flicker … mentioned**
  - Asymmetrical temporal response
  - Periphery & Brightness issues
- **Judder**
  - Stepper-motion, from slow steady motions (Larimer et al ‘01,03)
  - CRT’s fast temporal response is not desired
- **Multiple Edges**
  - Examples from Backlight Flashing + mismatched Overdrive
  - Hollywood is happy with 24 fps ? (looks cinematic)
    - DCI
    - Aliasing control via cameraman & editors

Understanding Motion Blur & LCD TV

References:

Spatiotemporal analysis of displaying perceived object motion:

- Frequency domain analysis, (Watson 85, Girod 93, Klompenhouwer 04)
- Spatiovelocity analysis (Watanabe 68 Kelly 79, Adelson & Bergen 85, Daly 98, Laird 06)
- Time domain analysis (Adelson & Bergen 85, Pan 05)
- Motion blur perception (Ramachandran 74, Parker '81, Westerink 90, Bex 95, Takeuchi 05, Laird 06)

Motion blur in LCD:

- Caused by the hold-type temporal rendering method of LCDs combined with the smooth pursuit eye movement of human visual system (HVS) – (Lindholm 96, Parker 97, Kurita 98, 01, Klompenhouwer 05, Pan 05)

Motion blur reduction approaches:

- Temporal overdrive (Okumura 01, Sekiya, 02)
- Temporal aperture reduction: black data insertion - BDI (Hong 04, Kimura 05), backlight flashing (Fisekovic 01, Sluyterman 05)
- Frame rate doubling – FRD (Sekiya 02, Kurita 05)
- Motion compensated inverse filtering –MCIF (Klompenhouwer 01)

Thank you for your interest and patience

Reference Capability of Conference Projector

8 bit ramp