Vision Science Meets Computer Graphics:

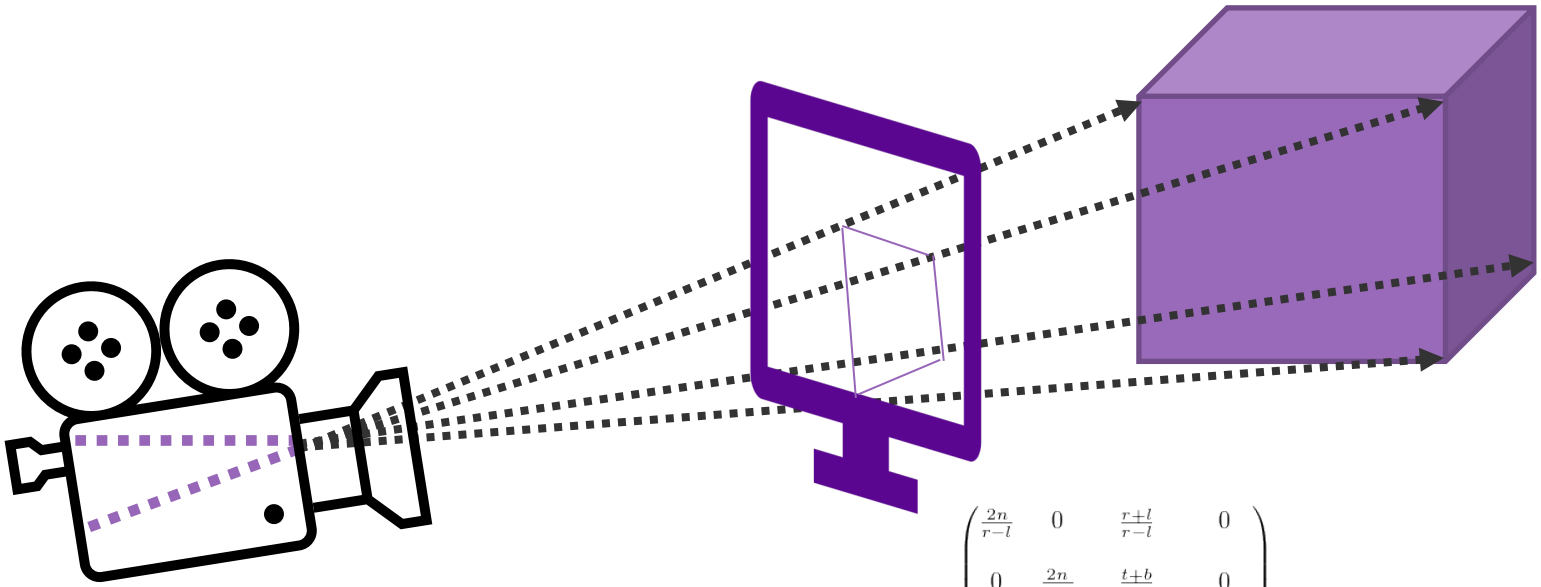
Facts, Models, and Applications

Qi Sun

08/19/2021

https://www.immersivecomputinglab.org/

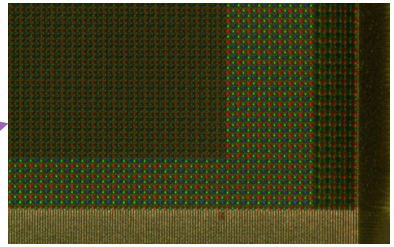
The “Eye Model” in Graphics

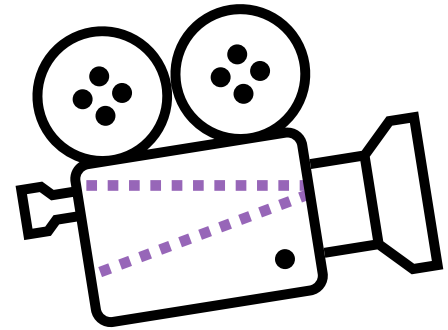


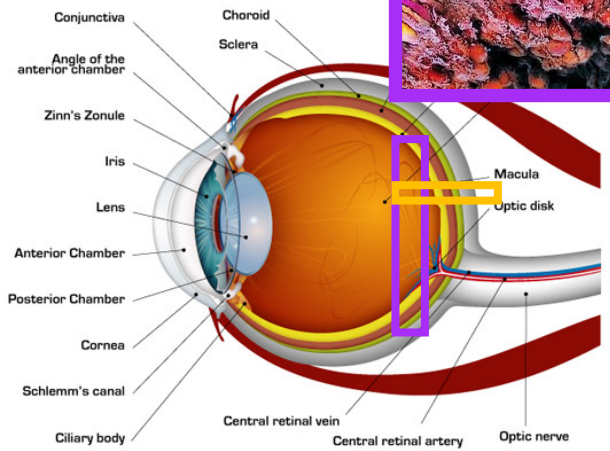
$$\begin{pmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & \frac{-(f+n)}{f-n} & \frac{-2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

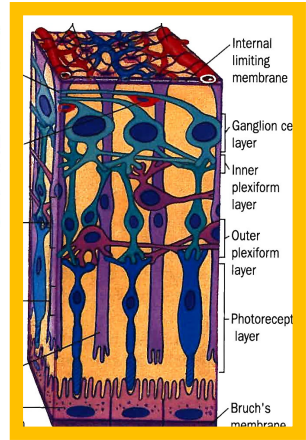
NYU

The Biological Eye in Reality



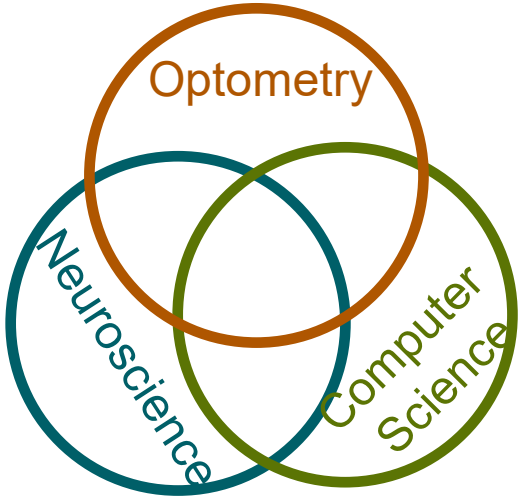






NYU

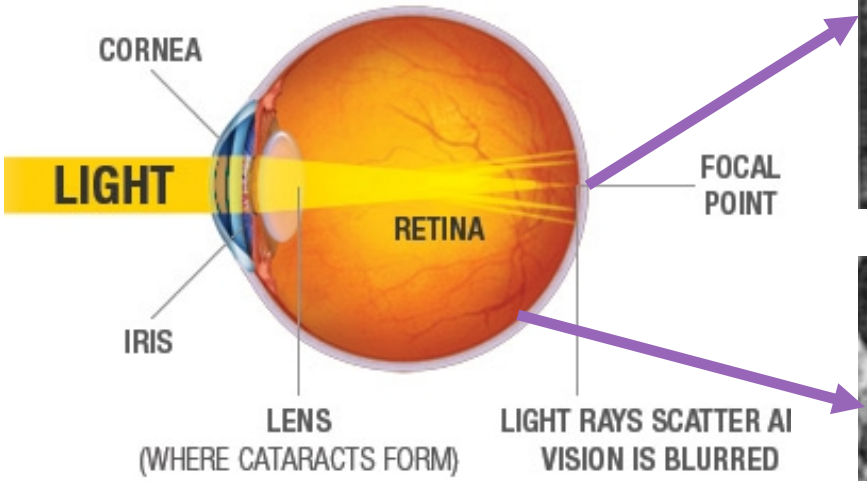
Vision Science

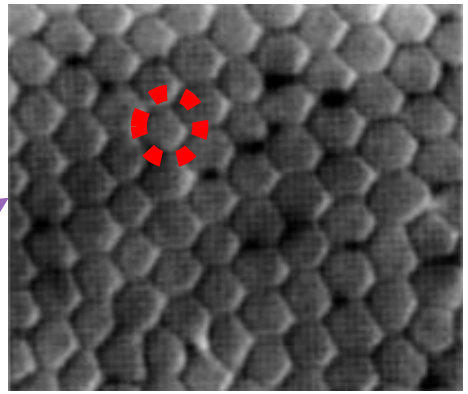


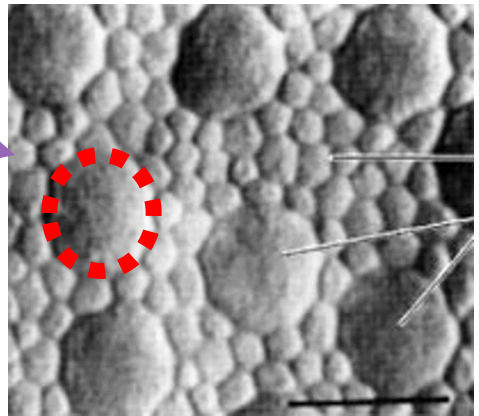
- Psychophysical studies on human visual system
- Understand visual perception mechanism s
- Derive computational models
- Advance human -inspired methods for computer vision, AI, etc.

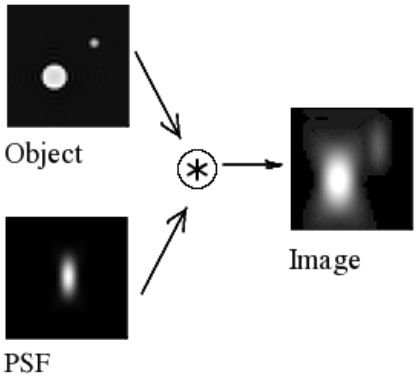
NYU

Optical Propagation







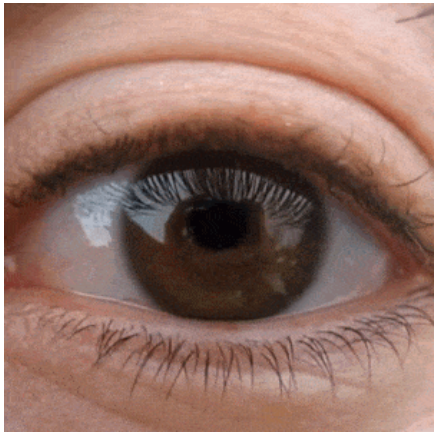


Source: Mango Optics

NYU

Dynamic Behaviors

vergence

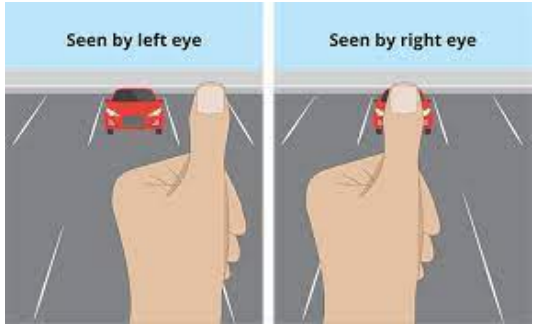


saccade

vestibulo–ocular reflex

NYU

Integration: Depth Perception



Motion

Motion Parallax

Binocular

left -right eye parallax

Monocular

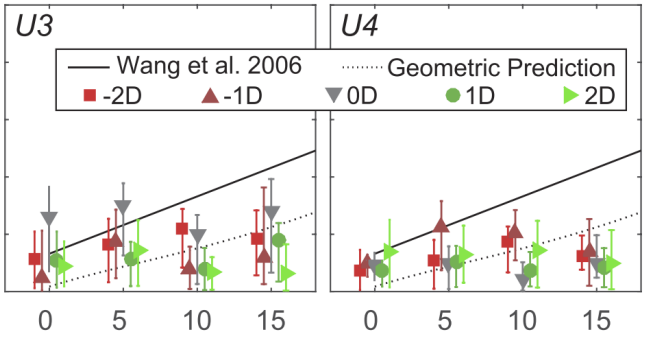
Accommodation

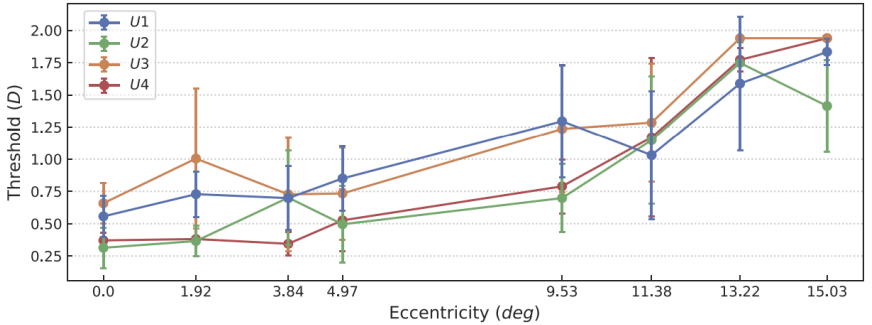
vergence

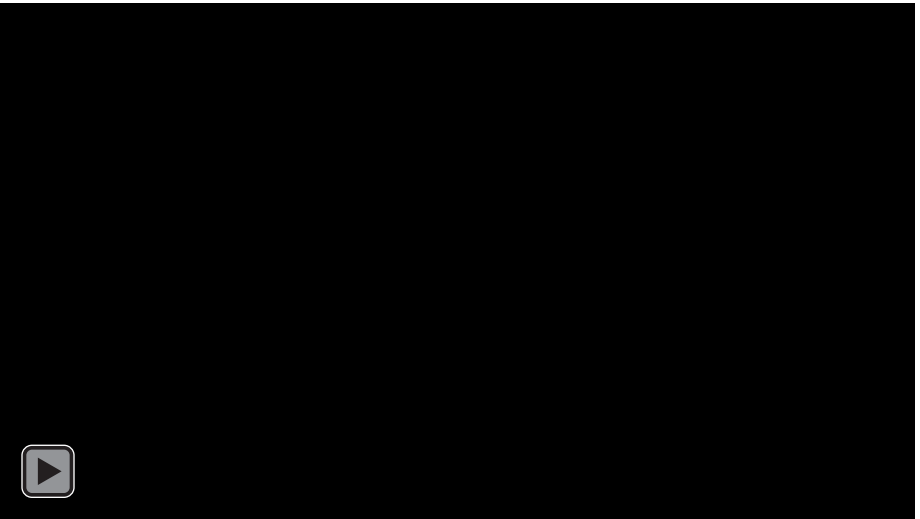

[Sun et al. SIGGRAPH Asia 2017]

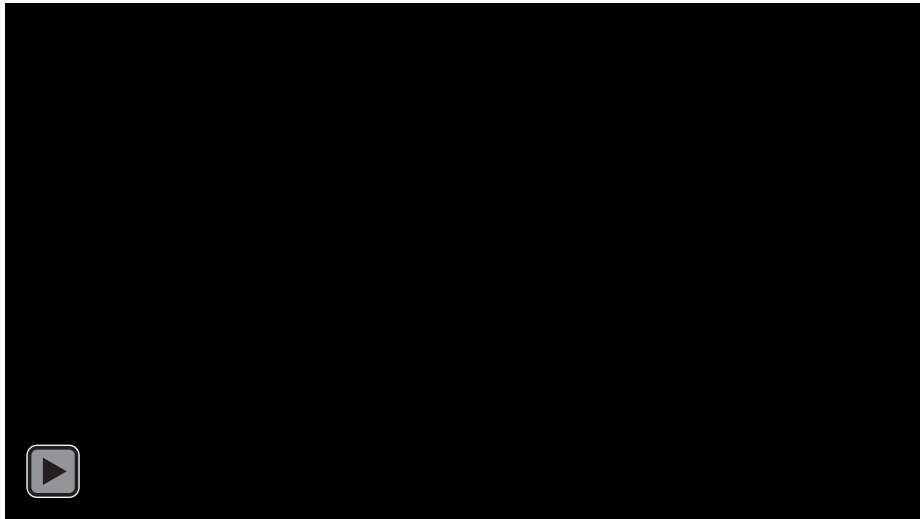

[Sun et al. SIGGRAPH Asia 2017]

Accommodation – Visuial or Muscular?

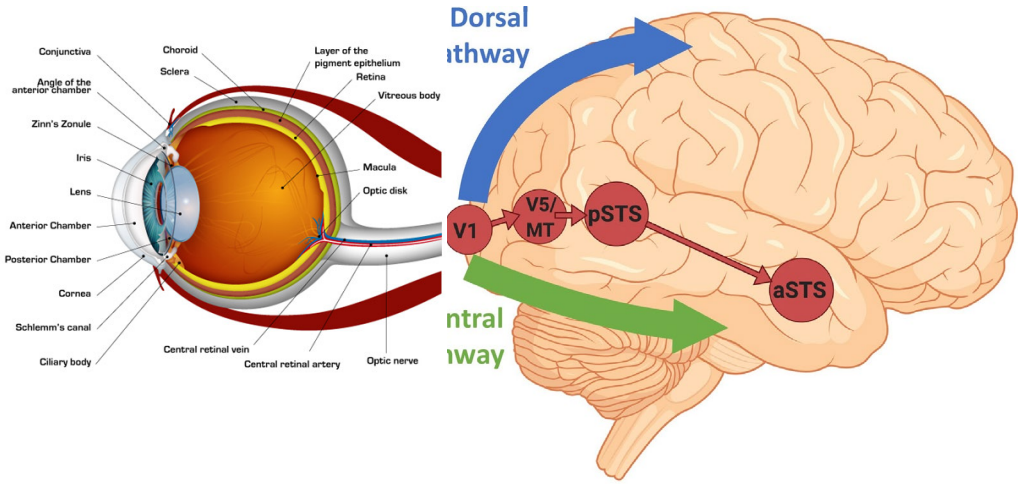


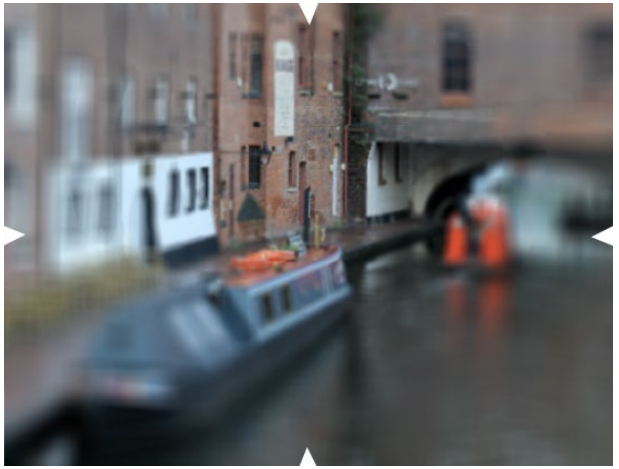






Visual Cortex



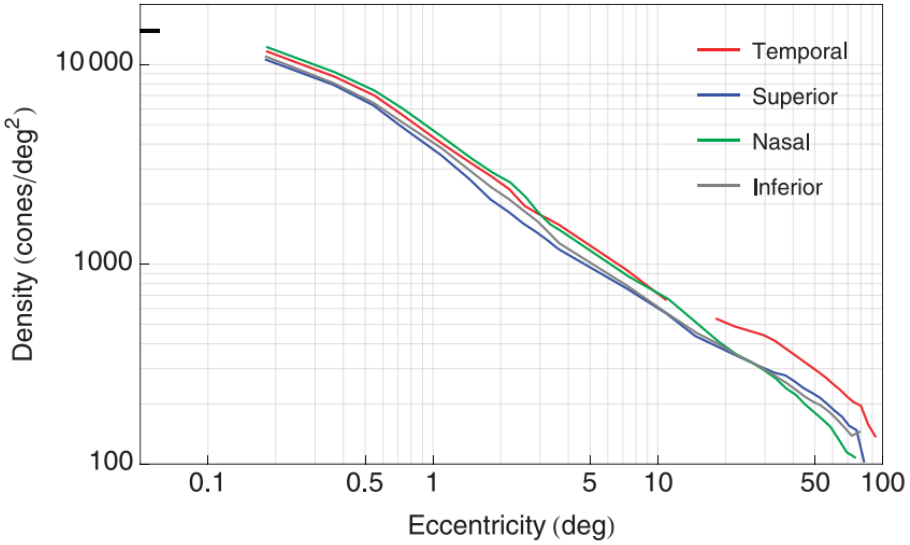


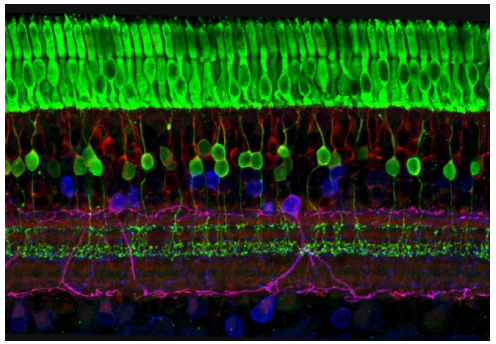
[Walton et al. 2021]

Computational Models

Adaptive Spatial Acuity

Anatomical Statistics



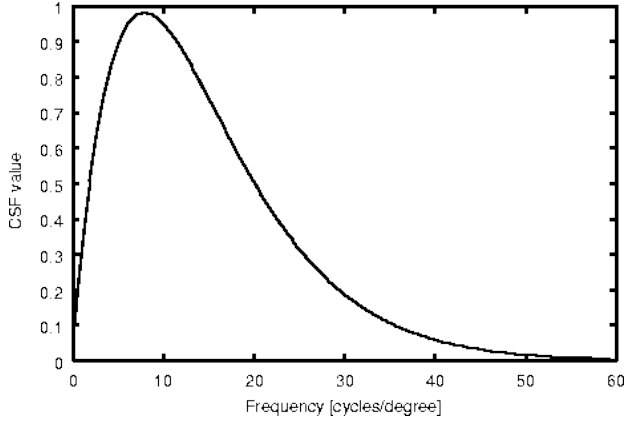


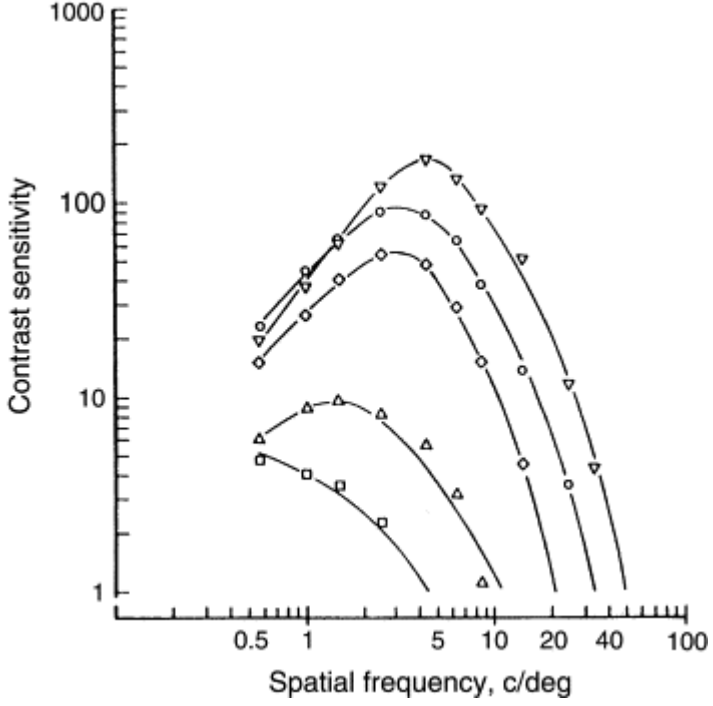
$$d_{gf}(r,k) = d_{gf}(0) \times \left[a_k \left(1 + \frac{r}{r_{2,k}} \right)^{-2} + (1 - a_k) \exp\left(-\frac{r}{r_{e,k}} \right) \right]$$

[Watson J Vis. 2014]

Adaptive Spatial Acuity

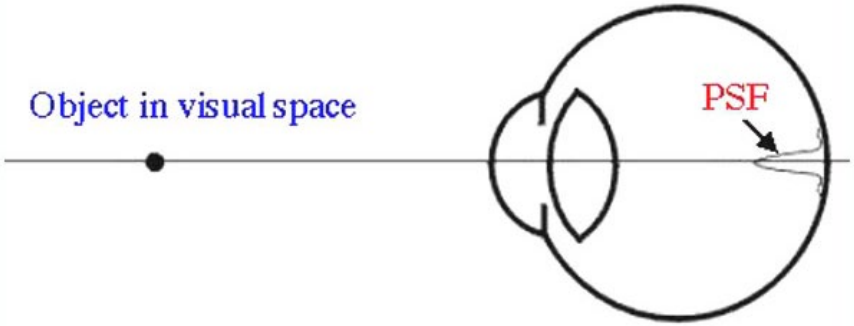
Contrast Sensitivity Function

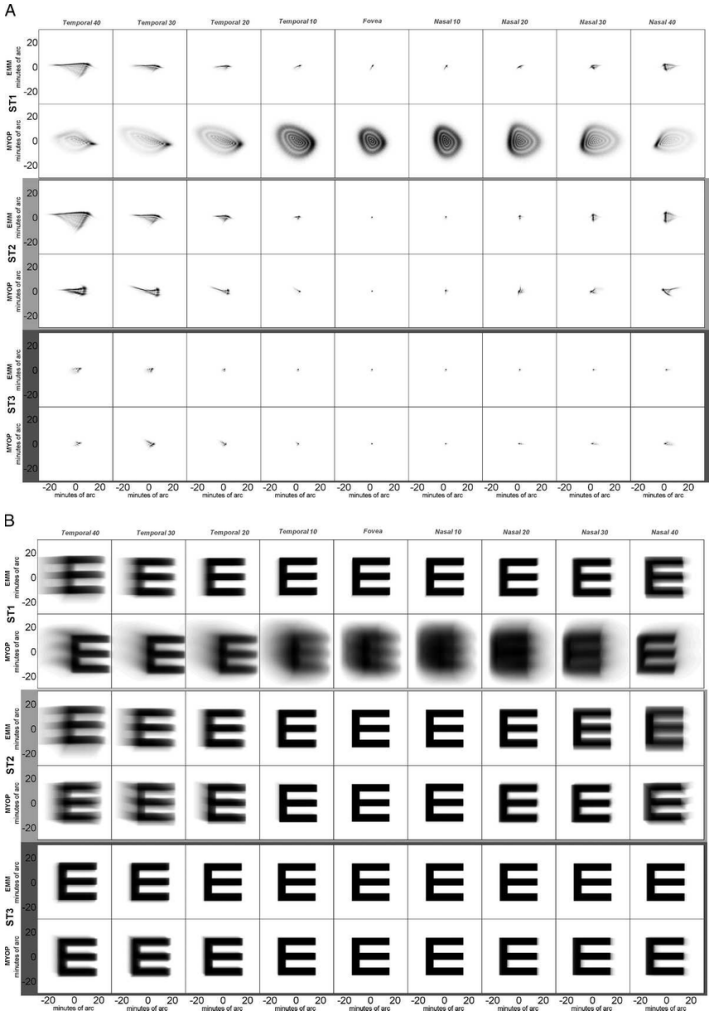




Adaptive Spatial Acuity

Point Spread Function

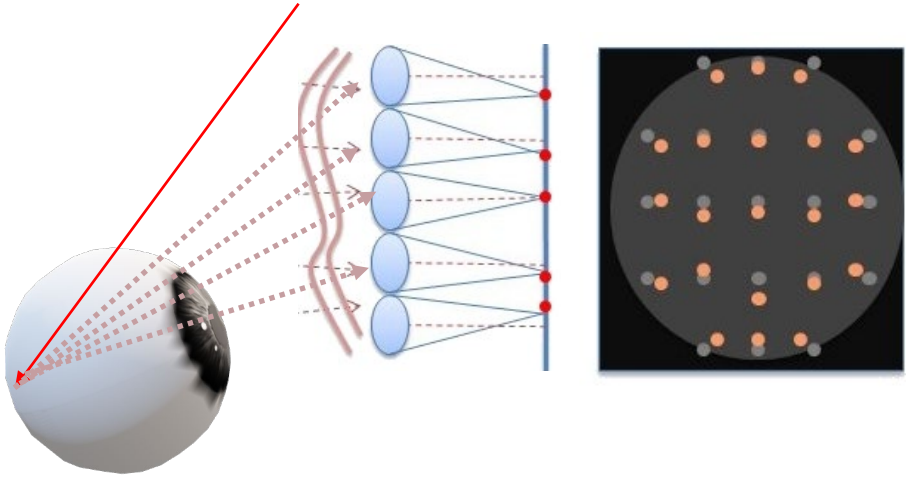




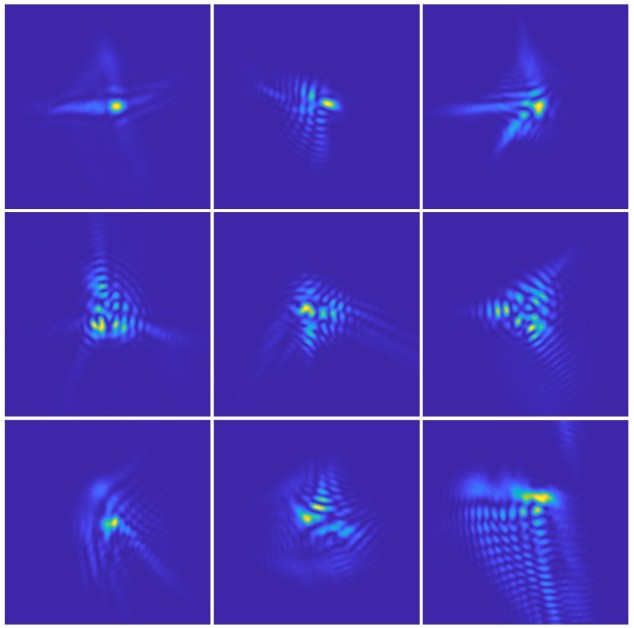
NYU

Adaptive Spatial Acuity

Point Spread Function

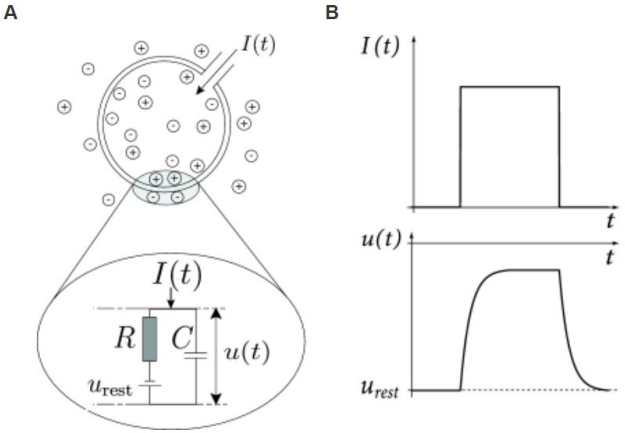


Shack–Hartmann wavefront sensor



[Chakravarthula et al. 2021]

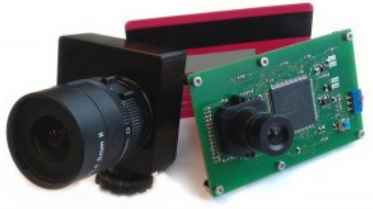
Integrate-and-Fire

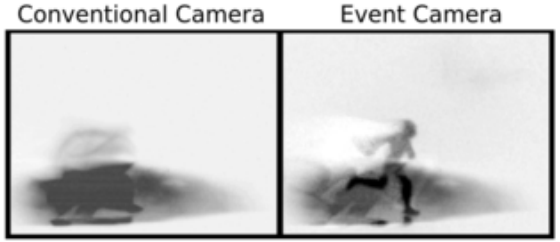


$$I(t) = I_R + I_C$$

$$= \frac{u(t) - u_{\text{rest}}}{R} + C\frac{\mathrm{d}u}{\mathrm{d}t}$$

$$\tau_m \frac{\mathrm{d}u}{\mathrm{d}t} = -\left[u(t) - u_{\text{rest}}\right] + R\,I(t)$$



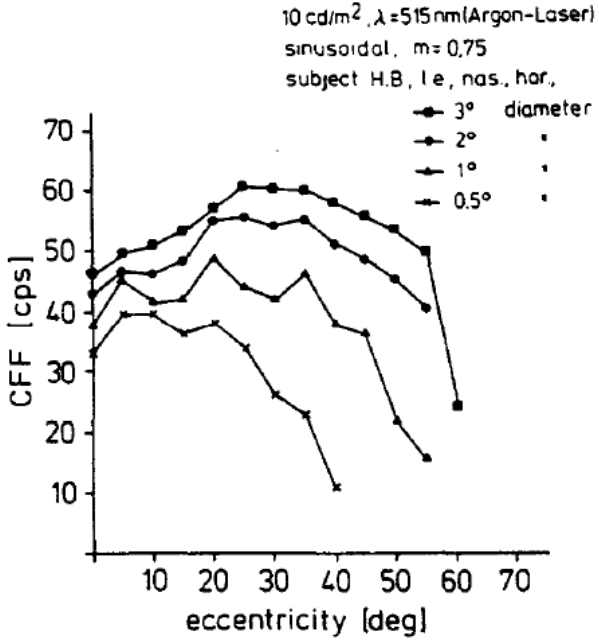


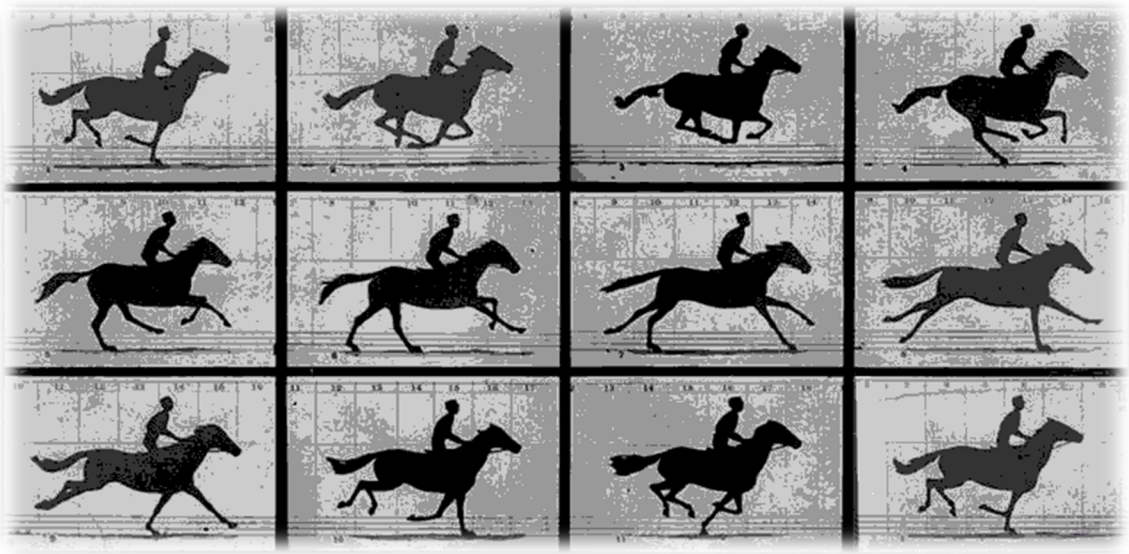
NYU

Temporal Model: Our Eyes Sample@ 30FPS

Persistence of vision/Flicker Fusion

$$FoV(\text{deg}\quad) = n1\log(l) + n2\log(a) + n3\log(r) + n4$$

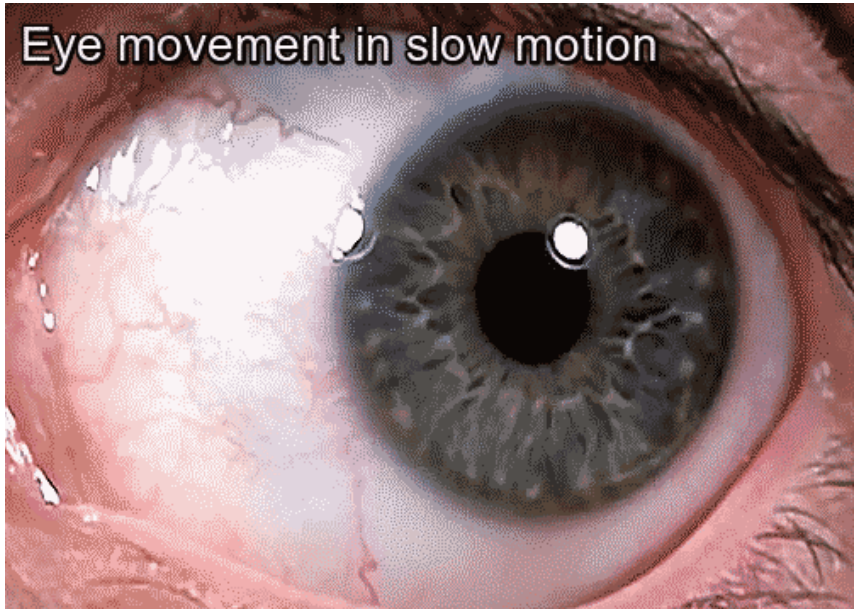




[Hartman et al.. 1978]

Fun Biophysical Models

$$F(t) = A\,t\,\exp\left[-\frac{t^{\mu}}{\tau^{\mu}}\right]$$

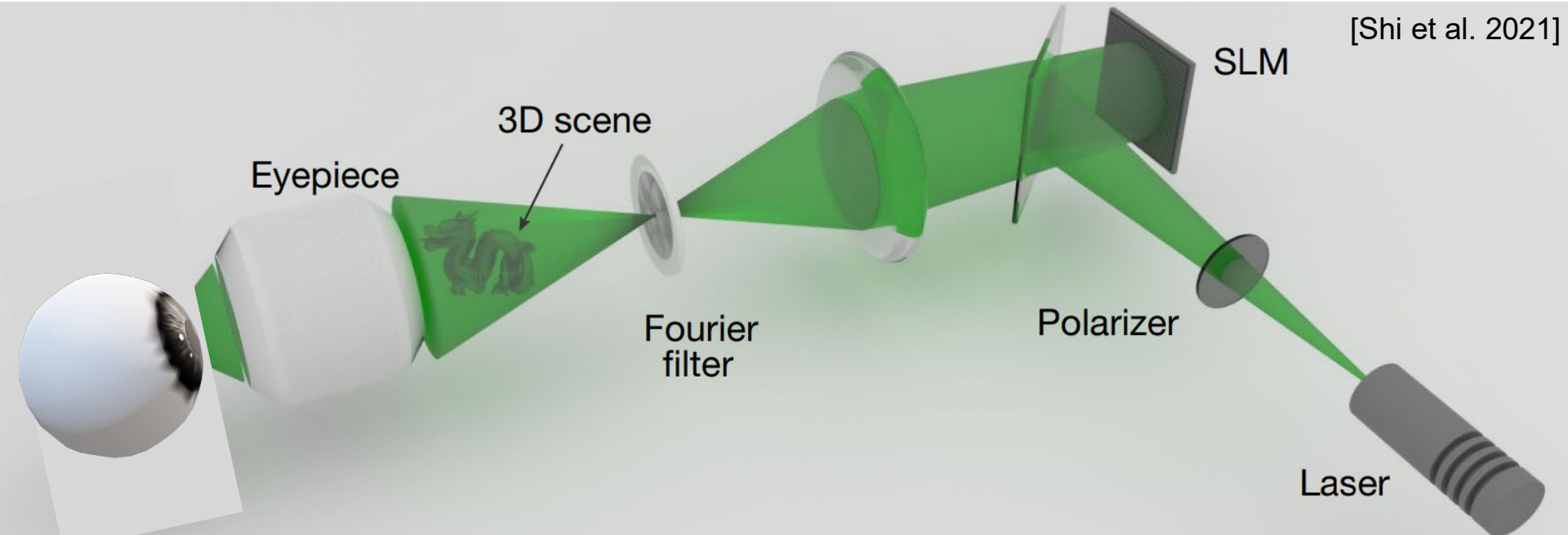


[Bouzat et al. 2018]

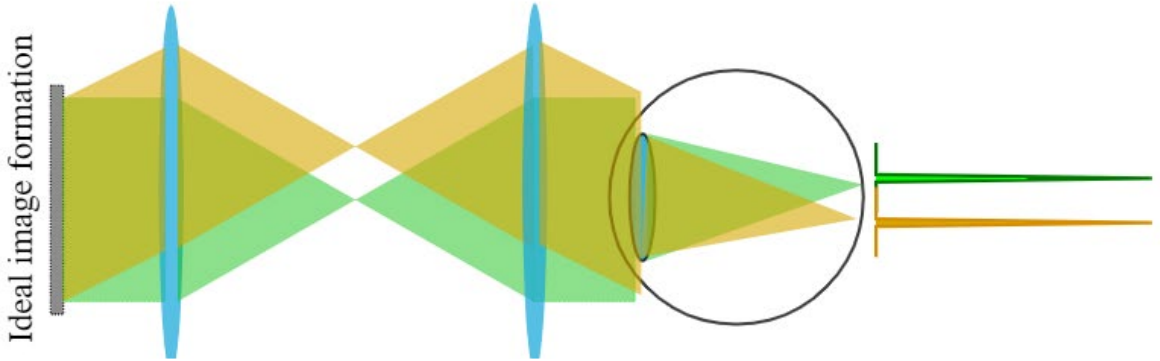
Example Applications

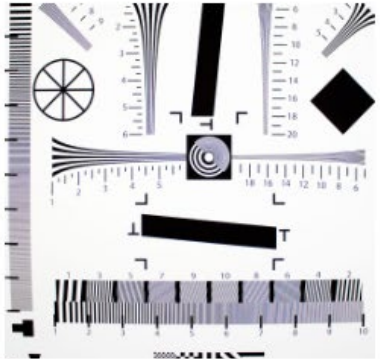
Computational Display and Rendering

Application I – Holographic Display



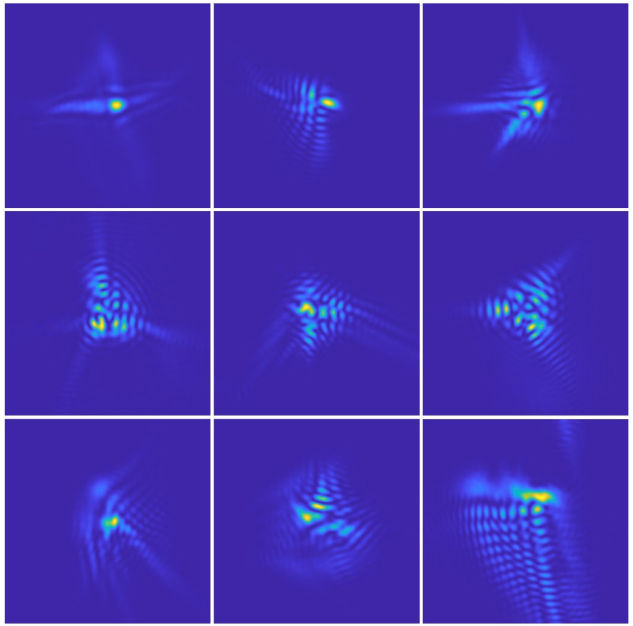
Applications – Holographic Display





Retina-in-the-Loop Holographic Display

$$G_{psf} \approx$$



NYU

[Chakravarthula et al. 2021]

Gaze-Aware Holographic Optimization

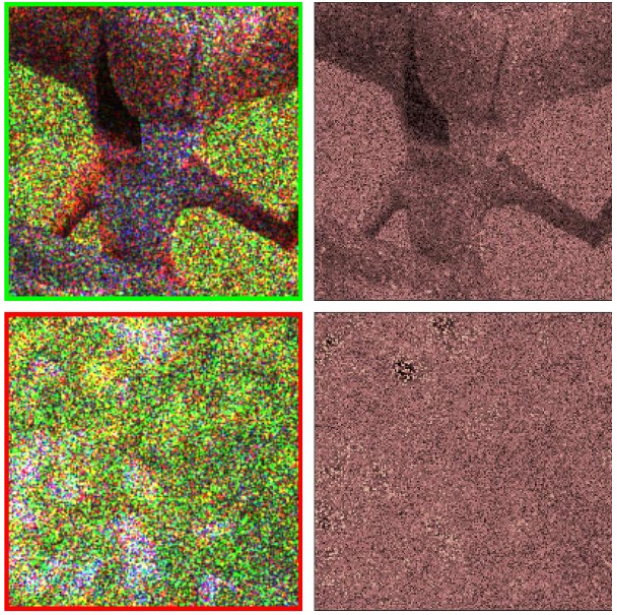
$$PSF(z) \triangleq z * G_{psf}$$

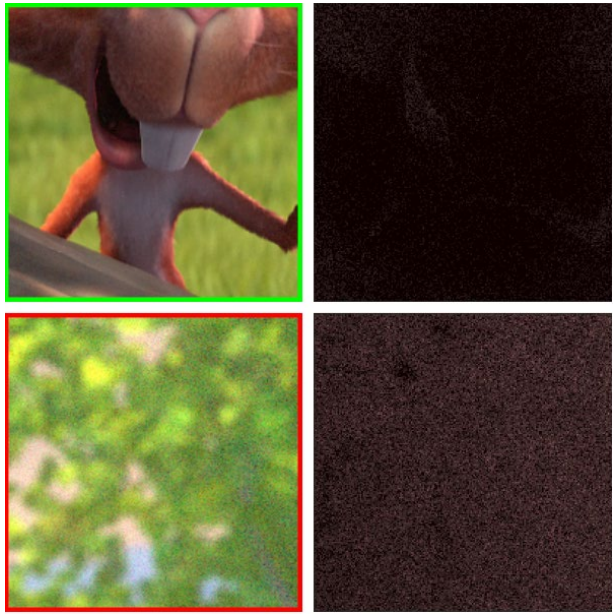
$$\mathcal{L}_{ours} = \sum_x \sum_y mask_{foveation}(x,y) ||PSF(z)_{x,y} - I_{x,y}||^2$$

NYU

Original

Optimized

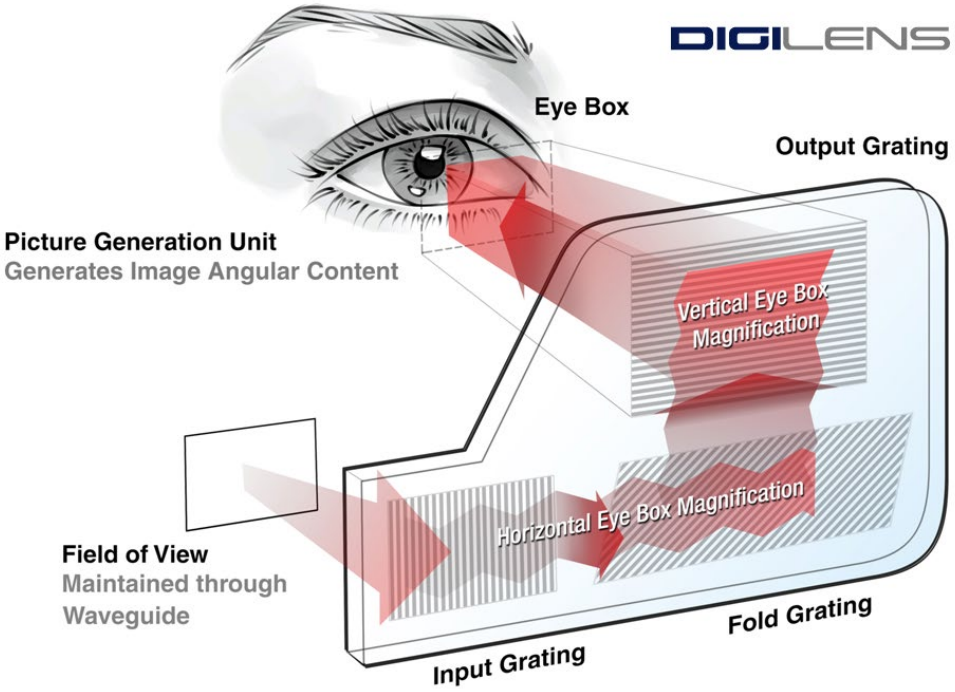




Application II – Transparency Control

A Transparent Display With Per-Pixel Color and Opacity Control
Rhodes et al. SIGGRAPH 2019 Emerging Technologies

Why Transparency Matters?

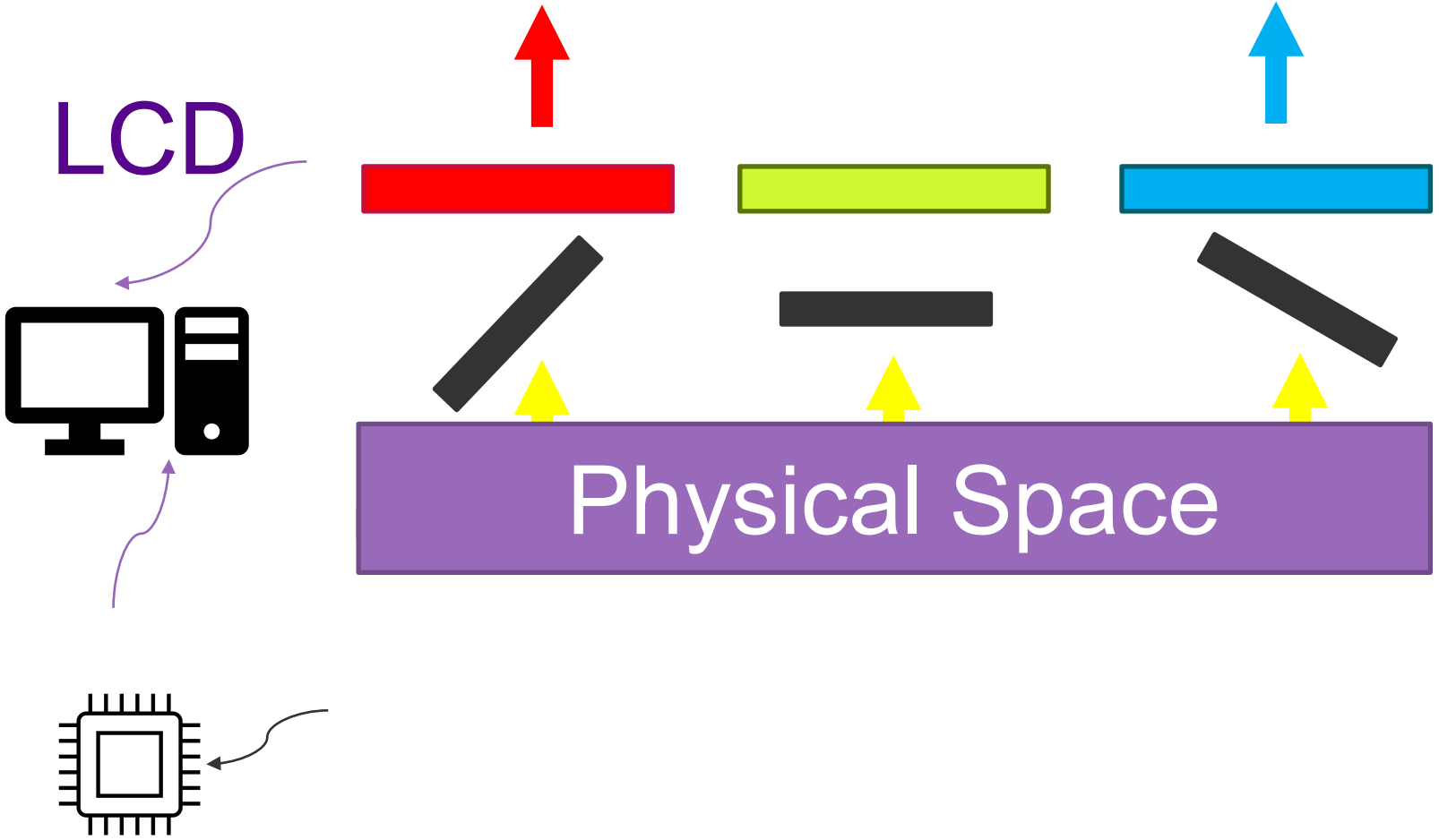


Source: road2VR

Why Transparency Matters?

Why Transparency Matters?

Why Transparency Matters?



[Rhodes et al. 2019]

retinal signal amplitude from display

visible threshold

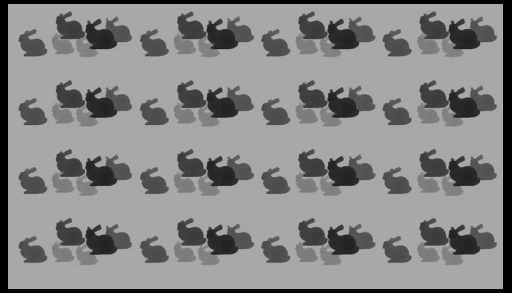
time

[Rhodes et al. 2019]

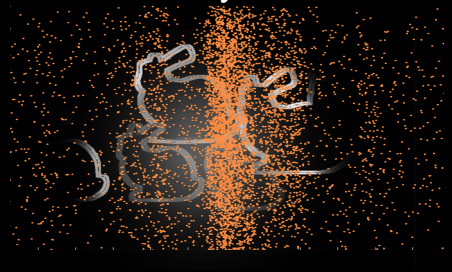
[Rhodes et al. 2019]

Application III – Optimizing Rendering

Low-Res 4D Rendering



Perceptual-Content Analysis



$$w'_d(\hat{k}) \approx \int_0^{B_x} \sum_{i=1}^{2} -1^{i-1} a\omega'_x \left(3a_3(a\omega'_x(\hat{k}-\hat{k}_i))^2 + 2a_2(a\omega'_x(\hat{k}-\hat{k}_i)) + a_1\right) \mathrm{d}\omega'_x$$

$$\propto \int_0^{B_x} \omega'_x \left(3a_3 a\omega'^2_x(2\hat{k}-\hat{k}_1-\hat{k}_2) + 2a_2\omega'_x\right) \mathrm{d}\omega'_x$$

$$\propto 9a_3 a(2\hat{k}-\hat{k}_1-\hat{k}_2)B_x + 8a_2.$$

Using the estimation of w_d above, we obtain

$$W(\hat{k}_1,\hat{k}_2) \propto \iint \left(9a_3 a\left(2\frac{\omega'_u}{\omega'_x}-\hat{k}_1-\hat{k}_2\right)B_x + 8a_2\right)\left(t\left(\frac{\omega'_u}{\omega'_x},\hat{k}_1,\omega'_x\right) - t\left(\frac{\omega'_u}{\omega'_x},\hat{k}_2,\omega'_x\right)\right)\mathrm{d}\omega'_x\mathrm{d}\omega'_u$$

$$= \iint \frac{18a_3 a\omega'_u}{\omega'_x}B_x\left(\sum_{i=1}^{2} -1^{i-1}\,\mathrm{sinc}(a\omega'_u - a\hat{k}_i\omega'_x)\right)\mathrm{d}\omega'_x\mathrm{d}\omega'_u$$

$$+ \iint \left(8a_2 - 9(\hat{k}_1+\hat{k}_2)a_3 aB_x\right)\left(\sum_{i=1}^{2} -1^{i-1}\,\mathrm{sinc}(a\omega'_u - a\hat{k}_i\omega'_x)\right)\mathrm{d}\omega'_x\mathrm{d}\omega'_u$$

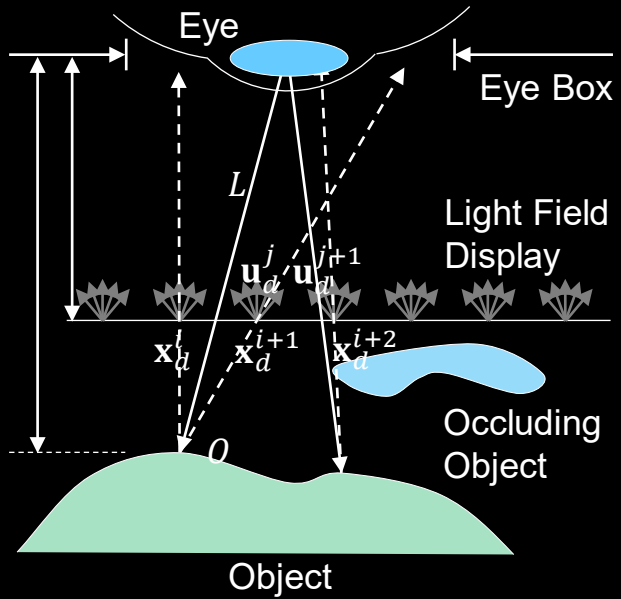
$$= 18a_3 B_x \int \left(\sum_{i=1}^{2} -1^{i-1}\left(\sin(a\omega'_u)(-\mathrm{Ci}(a\hat{k}_i\omega'_x)) + \mathrm{Si}(a\omega'_u - a\hat{k}_i\omega'_x) + \cos(a\omega'_u)\,\mathrm{Si}(a\hat{k}_i\omega'_x)\right)\right)\mathrm{d}\omega'_u$$

$$- \left(8a_2 - 9(\hat{k}_1+\hat{k}_2)a_3 aB_x\right)\int \left(\sum_{i=1}^{2} -1^{i-1}\frac{\mathrm{Si}(a\omega'_u - a\hat{k}_i\omega'_x)}{a\hat{k}_i}\right)\mathrm{d}\omega'_u \qquad (35)$$

Sampling

$$N\int I_x \;\rightarrow\; I_x$$

Post-Filtering: Separable 4D RBF Occlusion-aware Reconstruction



[Sun et al. 2017]

Future Directions

Future

- Individualized model
- Predictive and temporal effects
- Visual metrics for realism
- Differentiable->optimize
- Multi-modality

NYU

"It has become appallingly obvious that our ***technology*** has exceeded our ***humanity***." --Albert Einstein

NYU Immersive Computing Lab

Contact me: *qisun@nyu.edu*

https://www.immersivecomputinglab.org/

NYU

Adobe

MAX-PLANCK-GESELLSCHAFT

NVIDIA