Perceptual Display:
Towards Reducing Gaps
Between Real World and Displayed Scenes

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Modern Displays

Bigger & brighter

More resolution

Higher refresh rates

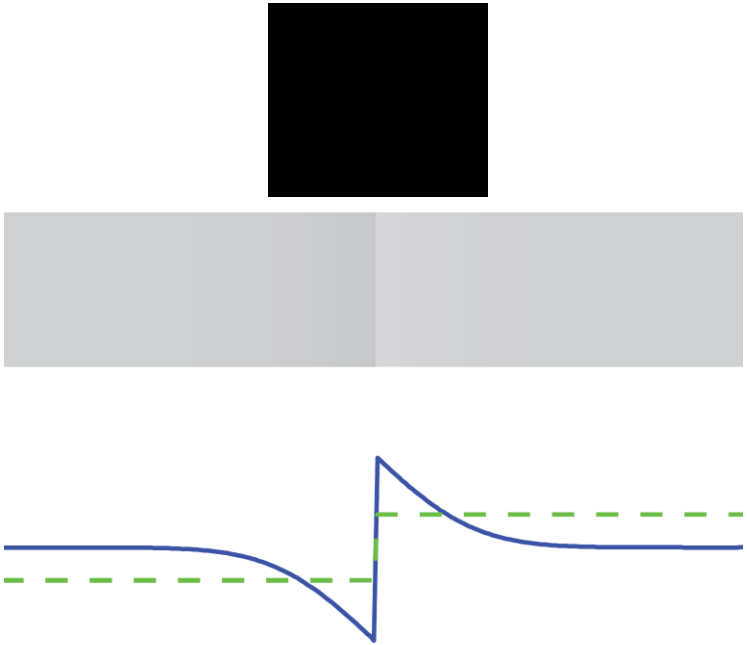
3D

Display Qualities and Human Perception

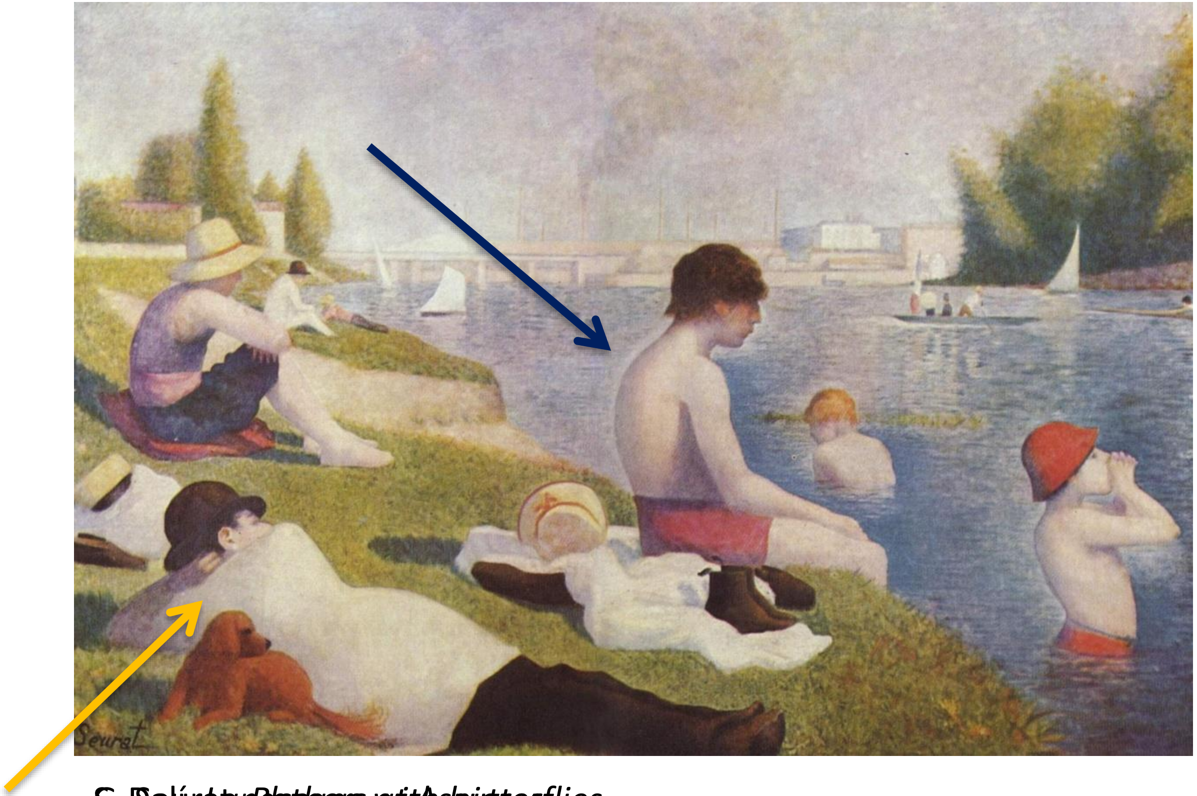
- **Capabilities of displays are limited:**
  - Contrast
  - Brightness
  - Temporal resolution
  - Spatial resolution
  - Depth processing in Stereo 3D

- **Idea:** take advantage of the visual system properties to improve apparent qualities

Cornsweet Illusion



Usage Examples From Art

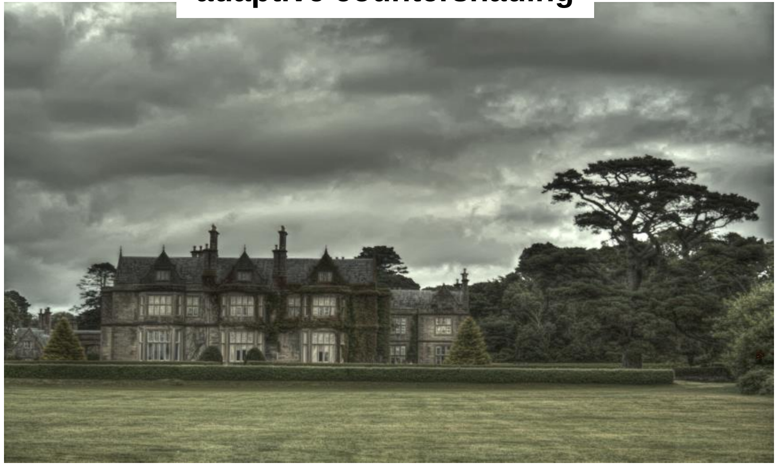


G. Seurat, *Bathers at Asnières*

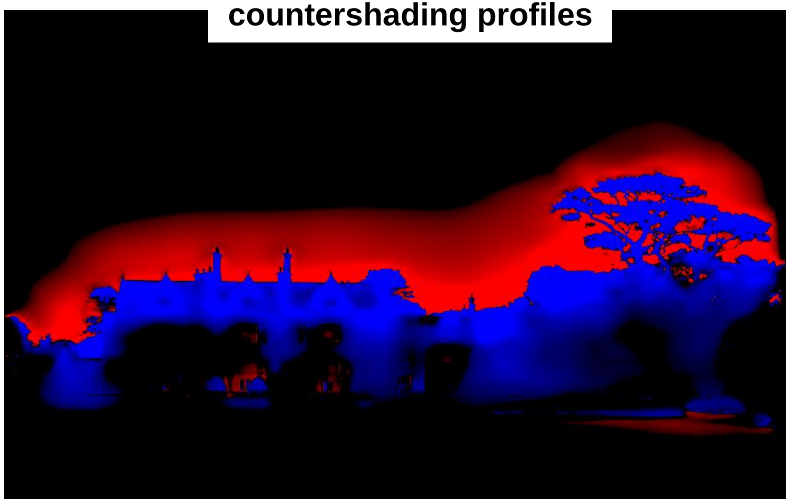
S. Dalí, *Landscape with Butterflies*

tone mapping

unsharp masking



adaptive countershading



countershading profiles

Cornsweet Profiles in Object Space

Unsharp Masking, Countershading and Haloes: Enhancements or Artifacts?

Matthew Trentacoste
Rafal Mantiuk
Wolfgang Heidrich
Florian Dufrot

University of British Columbia
Bangor University

- Same countershading operation is perceived differently, depending on parameter choice
- Some parameters increase sharpness or contrast
- But other choices can introduce haloes

Sharpeness

Contrast

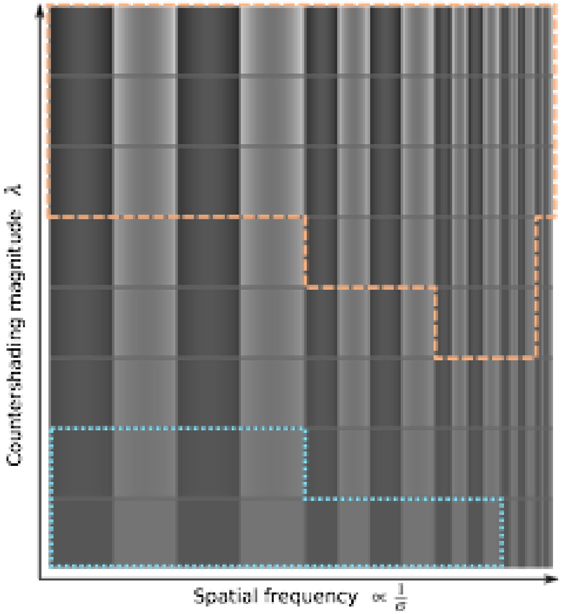
Haloes

Model of acceptable countershading

Matthew Trentacoste
Rafal Mantiuk
Wolfgang Heidrich
Florian Dufrot

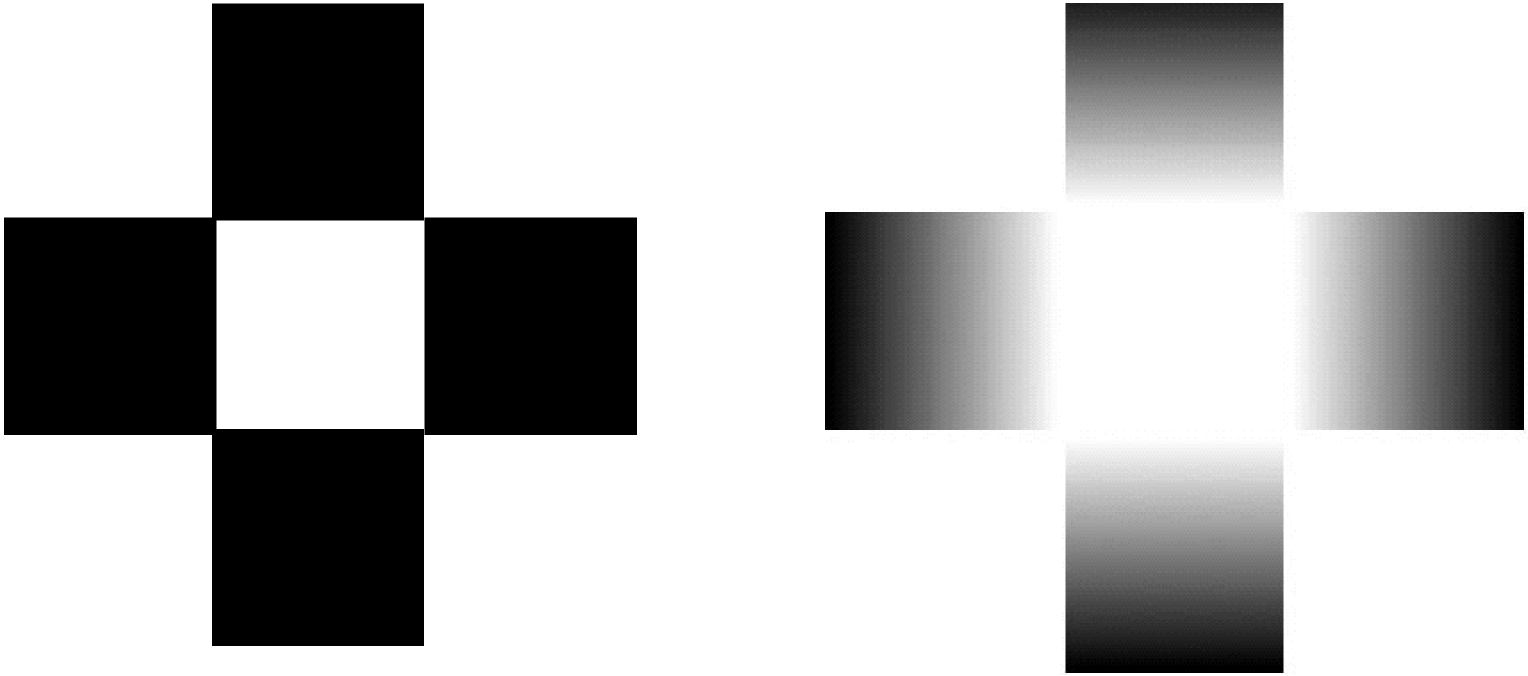
University of British Columbia
Bangor University

Objectionable
countershading (halos)



Indistinguishable
countershading

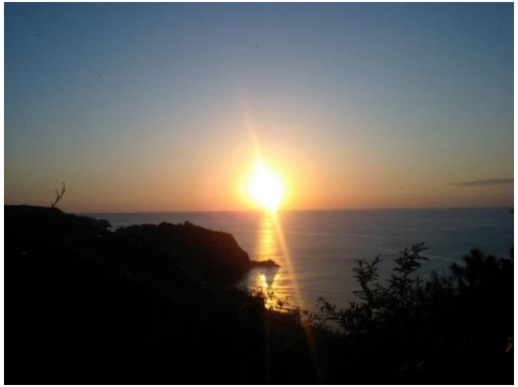
Glowing Effect



[Zavagno and Caputo 2001]

Glare Illusion in Different Media

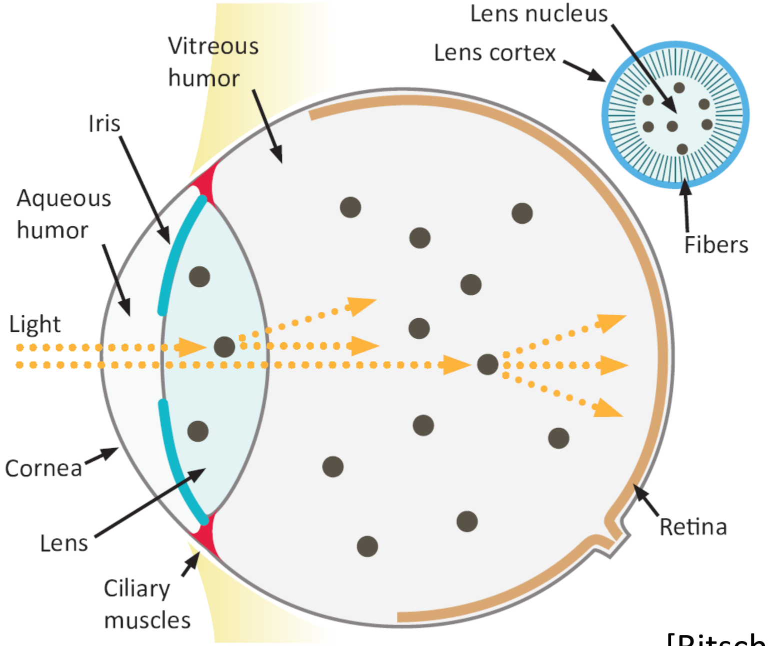
Arts



Photography

Computer Games

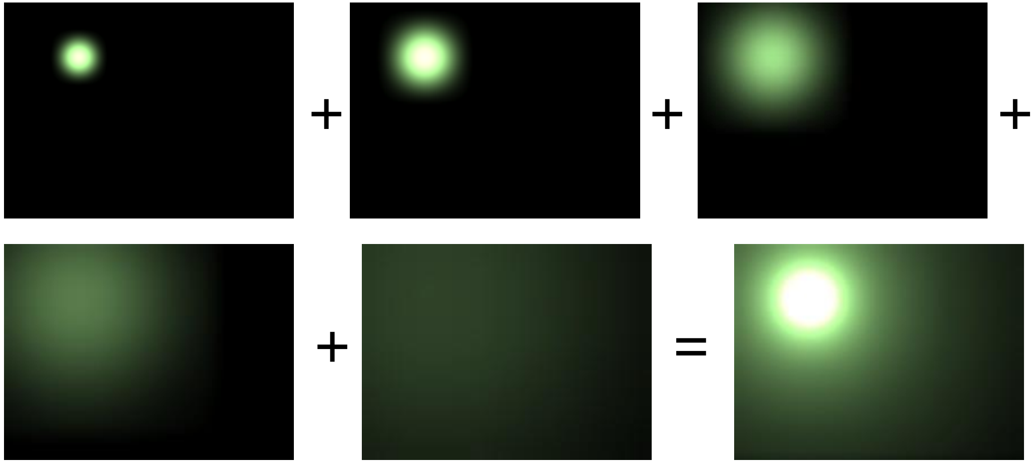
Glare Illusion: Brightness Boost



[Ritschel et al. 2008]

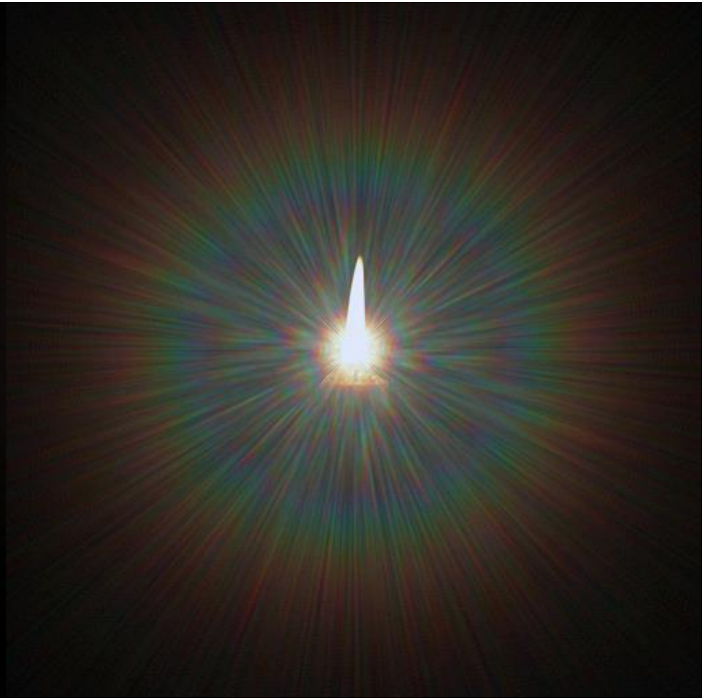
Glare Illusion in Games

- Kawase, Practical Implementation of High Dynamic Range Rendering, Game Developer's Conference 2004

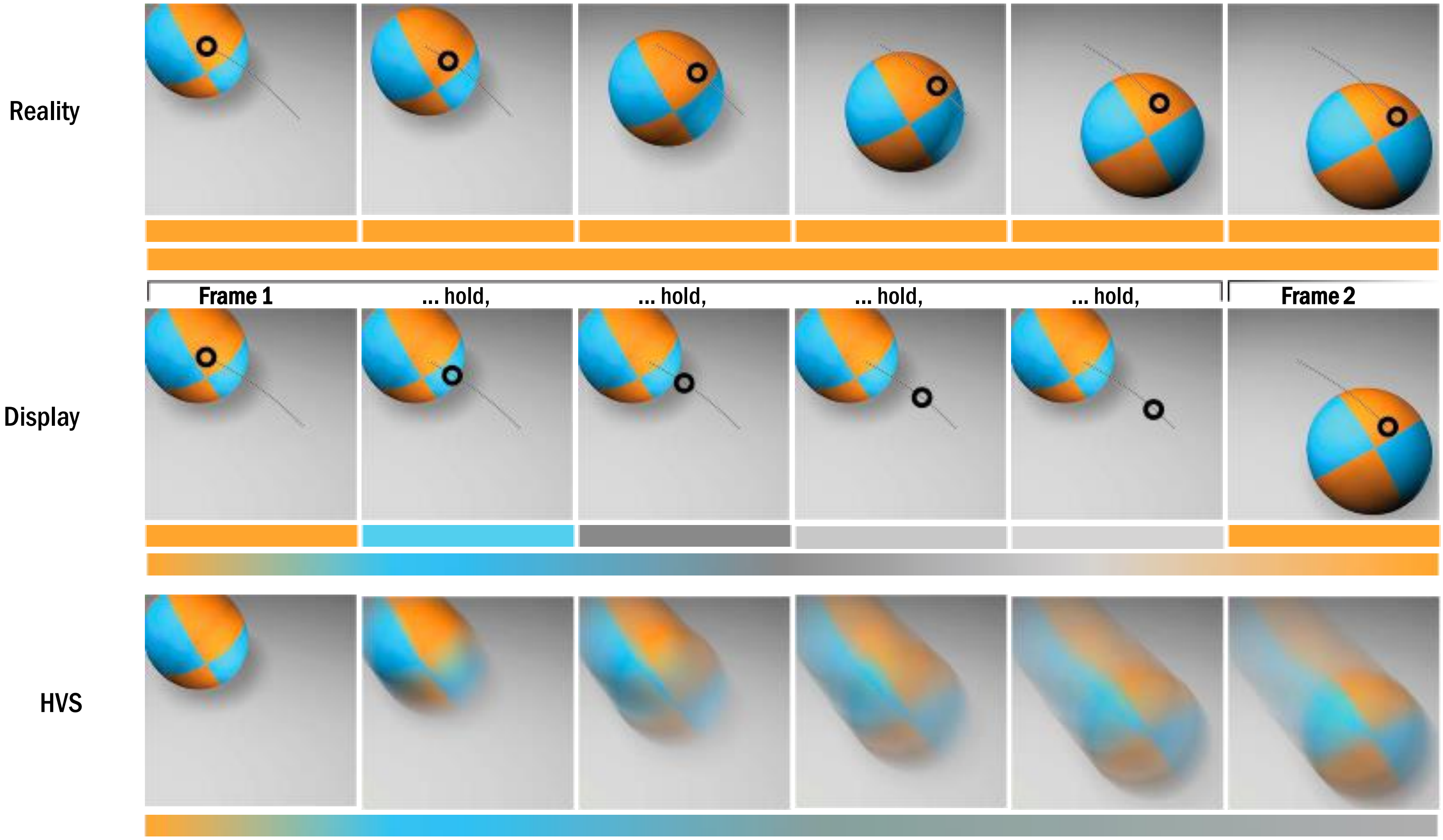


Light Scattering Modeling: Convolution vs. Billboard

Convolution



Billboard

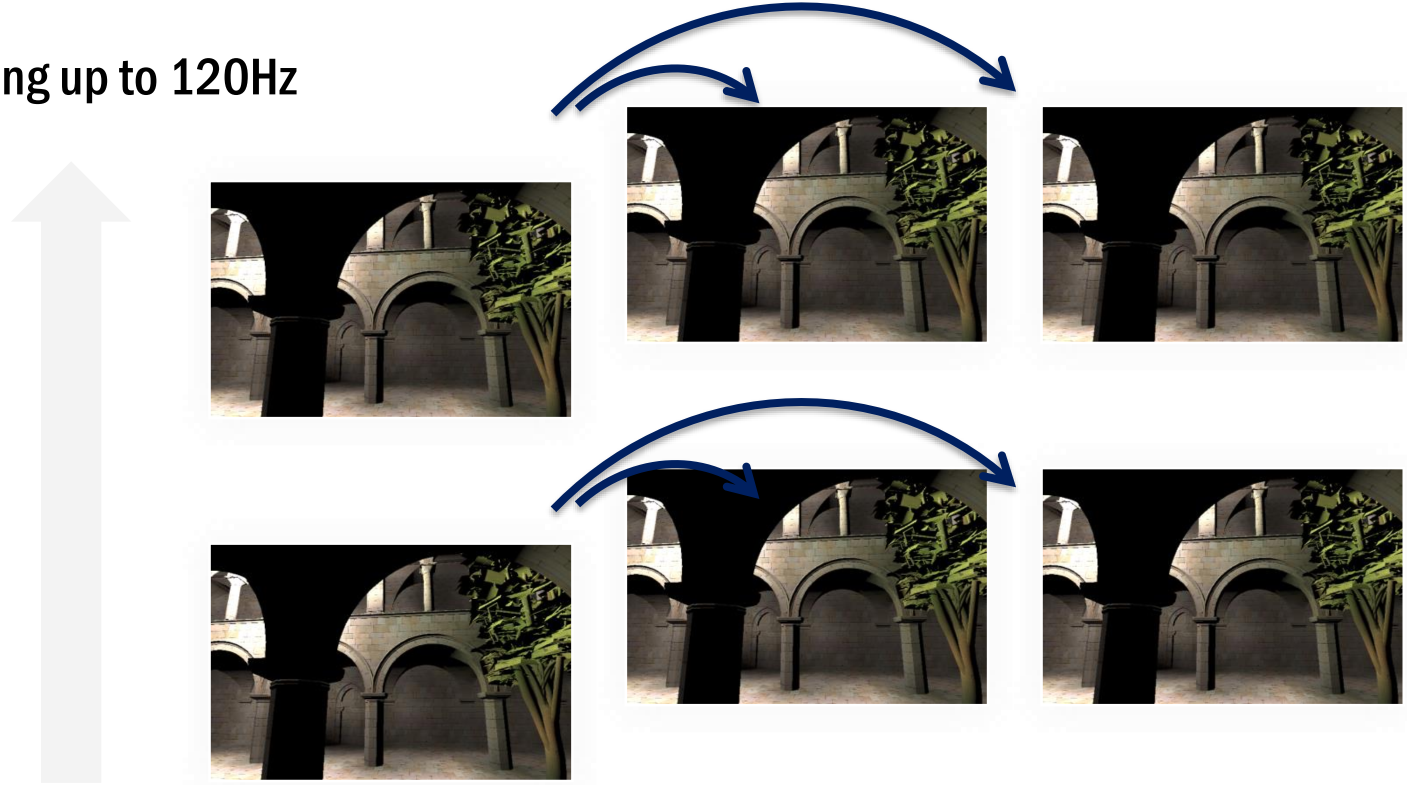

Reality
Frame 1
... hold,
... hold,
... hold,
... hold,
Frame 2
Display
HVS

Observations: Bigger & Higher Resolution

- More pixels to render
  - 8k and 4k UHD
- People move closer
  - Higher angular and pixel velocity
  - More perceived **blur** due to smooth pursuit eye motion

© C SEED / SWNS.com

Combating Hold-type Blur in Rendering



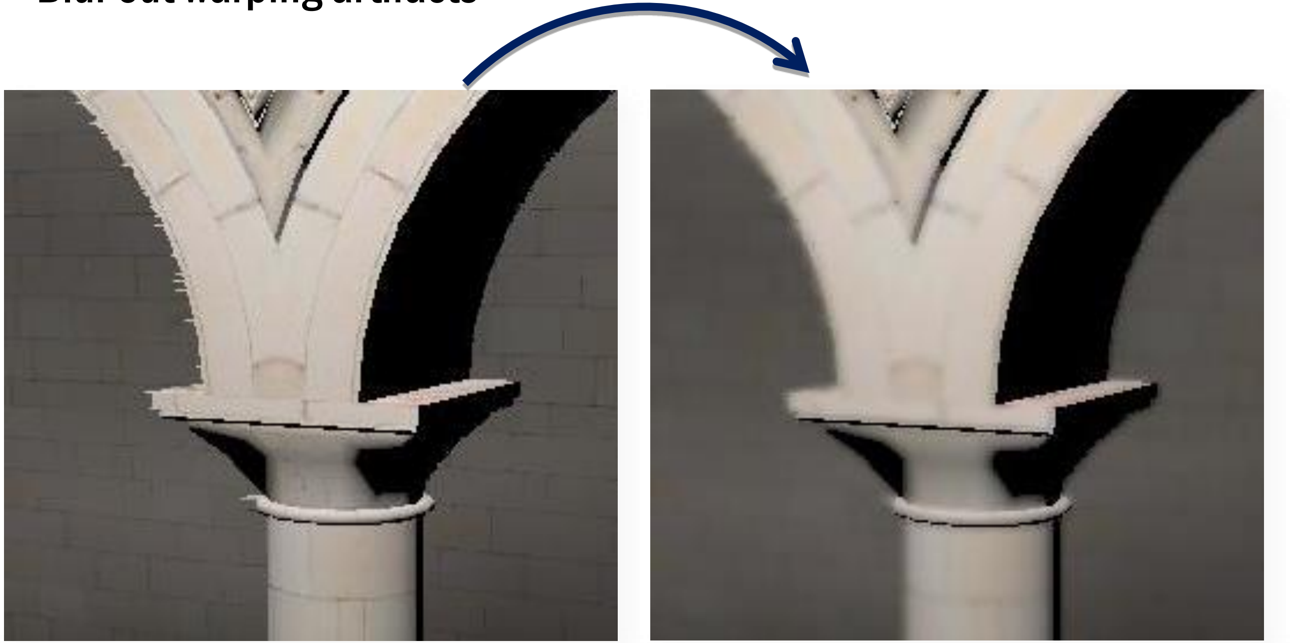
Frame warping up to 120Hz

40 Hz
rendering

[Didyk et al. 2010]

Combating Hold-type Blur in Rendering

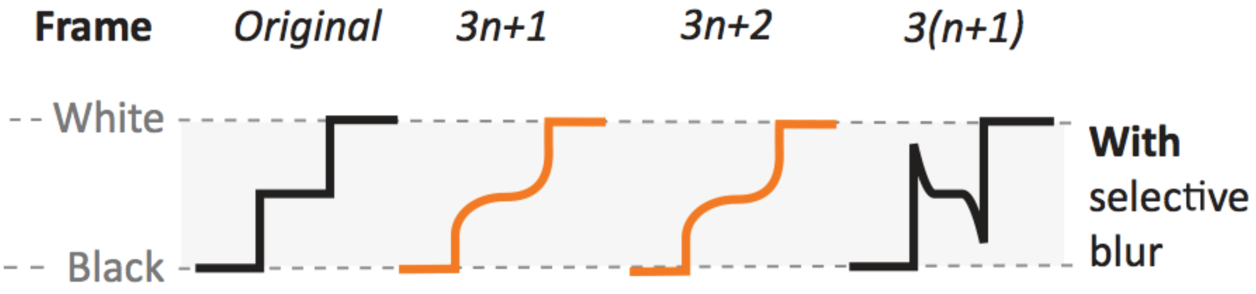
Blur out warping artifacts



[Didyk et al. 2010]

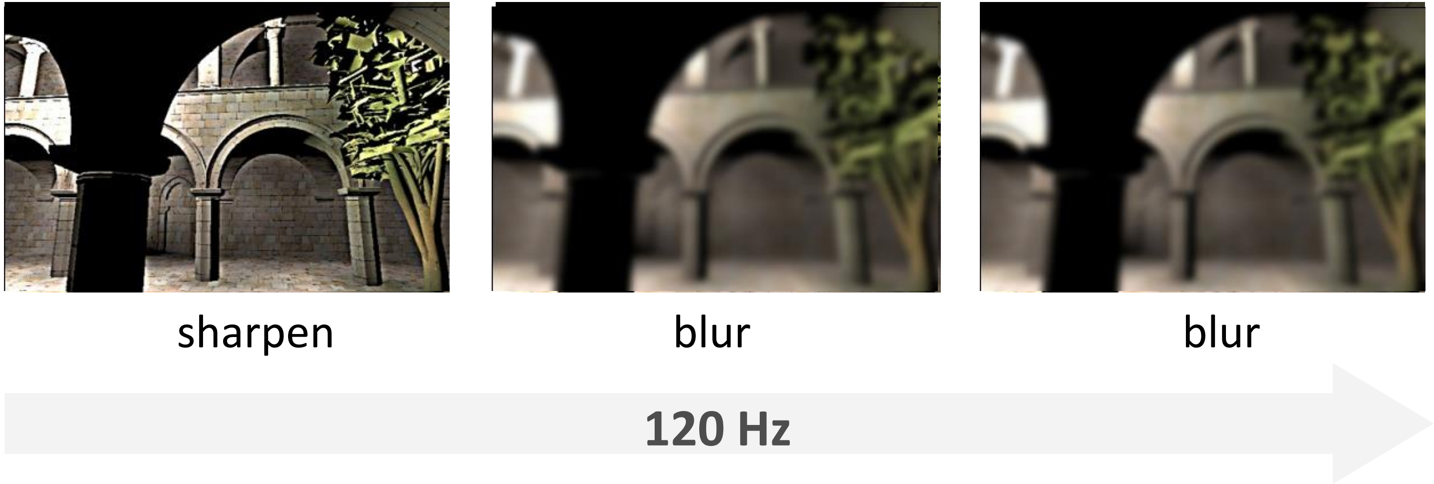
Combating Hold-type Blur in Rendering

- Compensation may lead to clipping problems
- Distorted regions must always be blurred



Combating Hold-type Blur in Rendering

- Interleave blurred and sharp (with doubled high-pass frequencies) frames
  - Hold effect reduced as high frequencies displayed shorter and low frequencies do not matter for blur



sharpen blur blur

120 Hz

[Didyk et al. 2010]

Frame Rates in Films

- Regular films: 24 fps
- Emerging trend: higher frame rates (48 fps or more)
- Completely different appearance

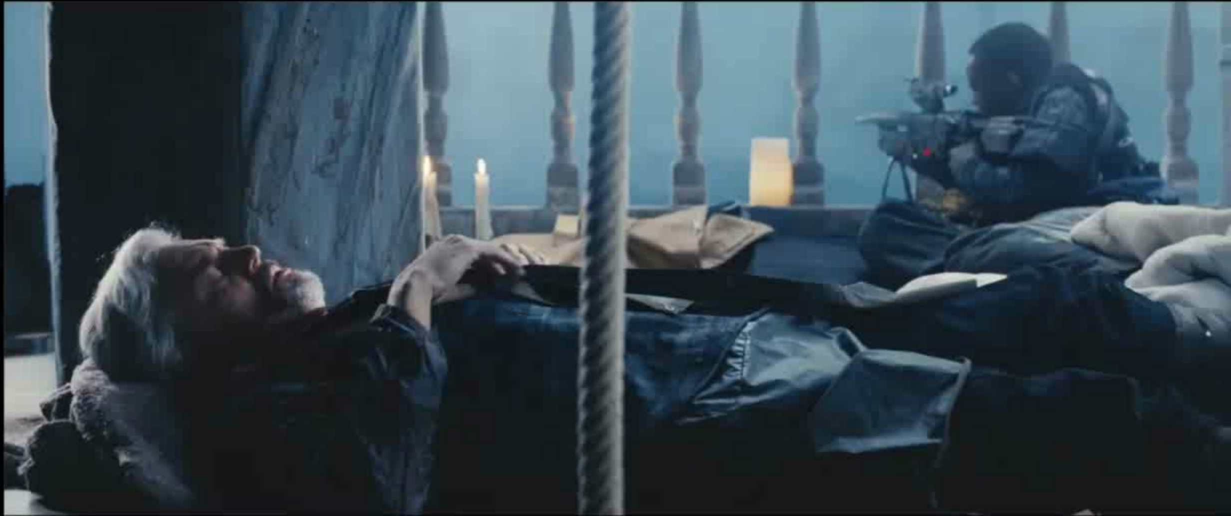
HFR Pros and Cons

- **Less artifacs, such as flicker and blur |** objectively better quality

- **So-called *soap-opera look* |** subjectively worse quality

24 FPS

48 FPS



Frame Rate Selection

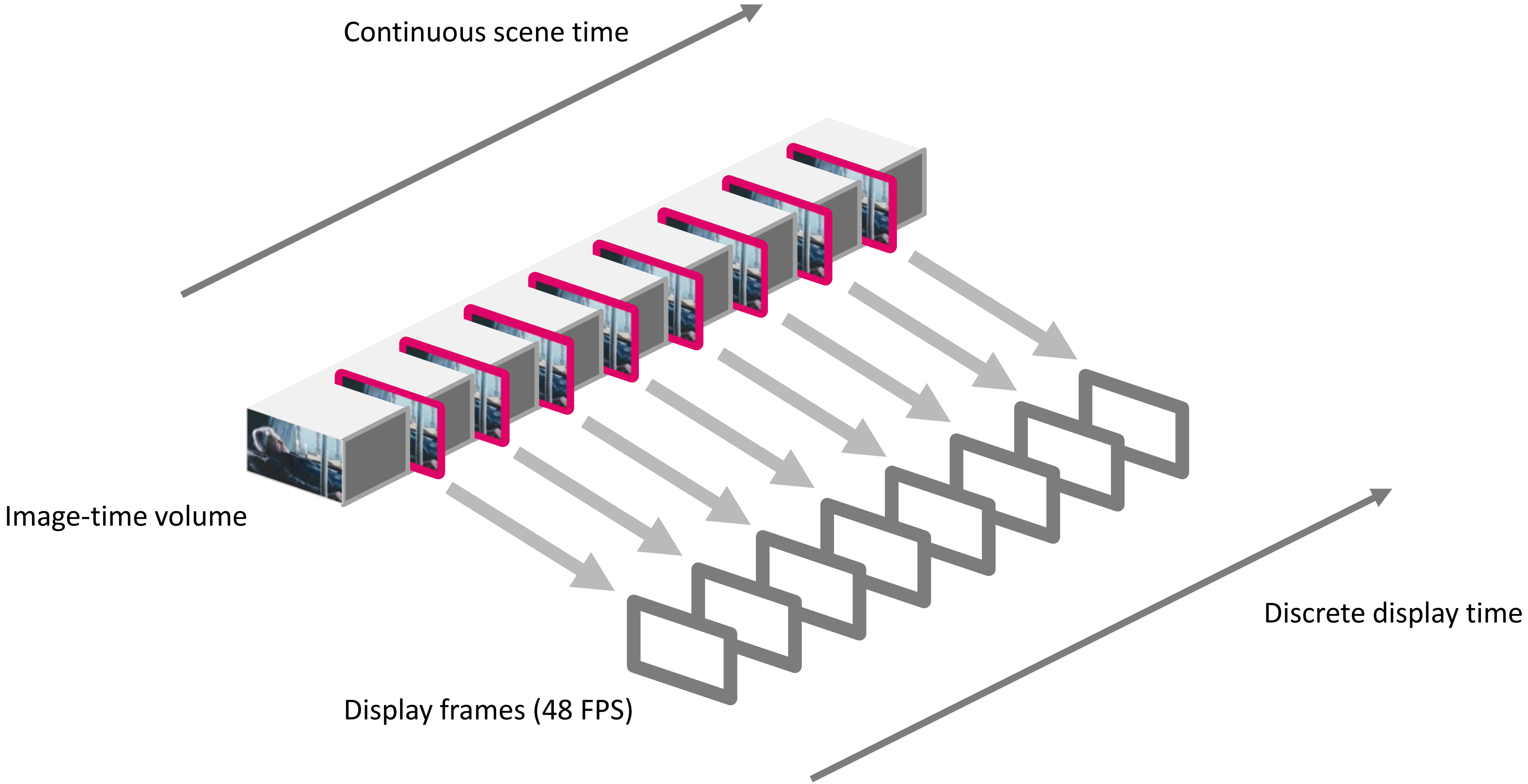
- Look-quality balance
- Story-telling purposes

Quesnel et al., 2013
An exploration into the creation of variable frame rate (VFR) stereoscopic 3D narrative productions

Disney Research, 2015
Lucid Dreams of Gabriel

Idea – More Artistic Freedom

- In-between frame rate (eg., 36 FPS)
- Frame rate that changes over time
- Different frame rates in different image regions



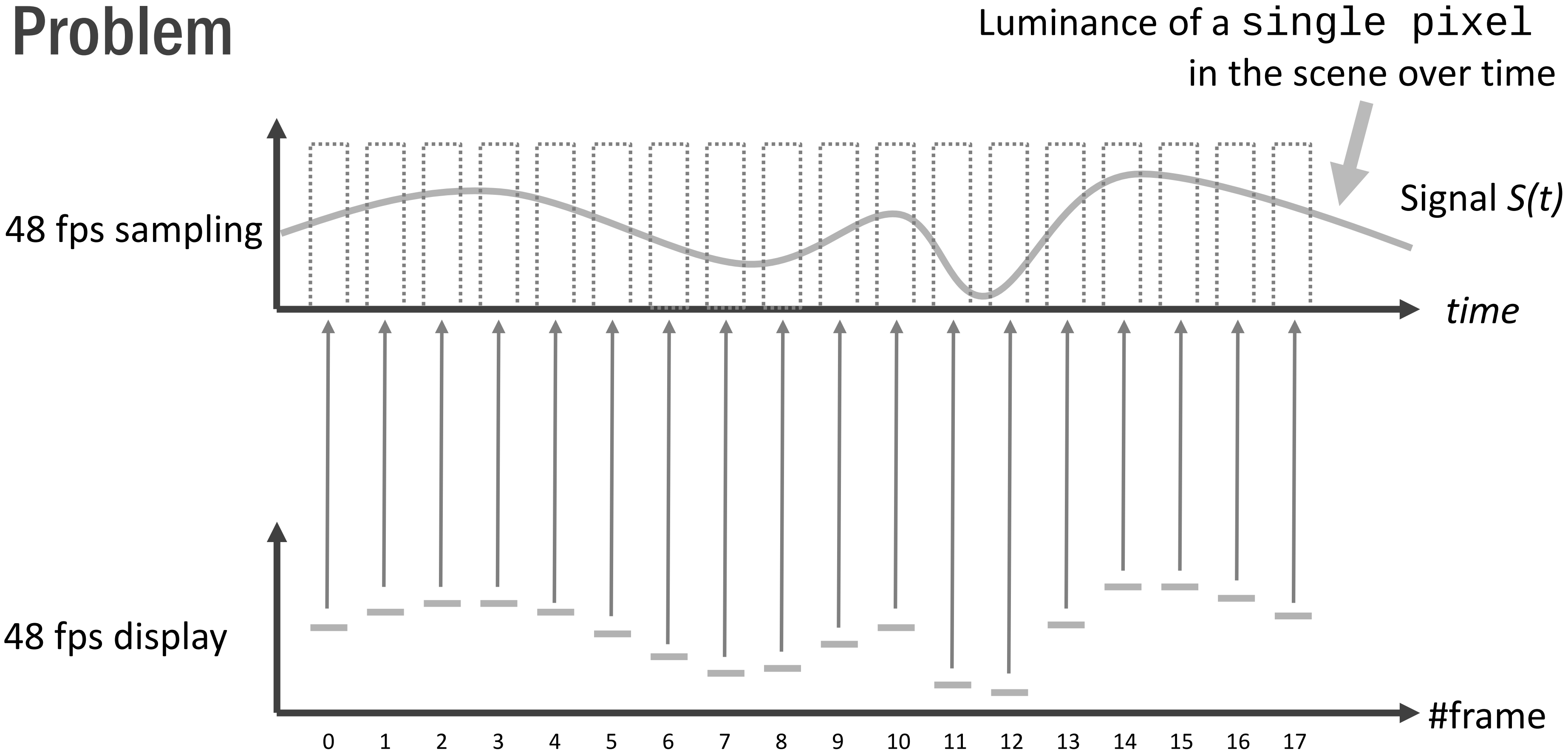
Continuous scene time

Image-time volume

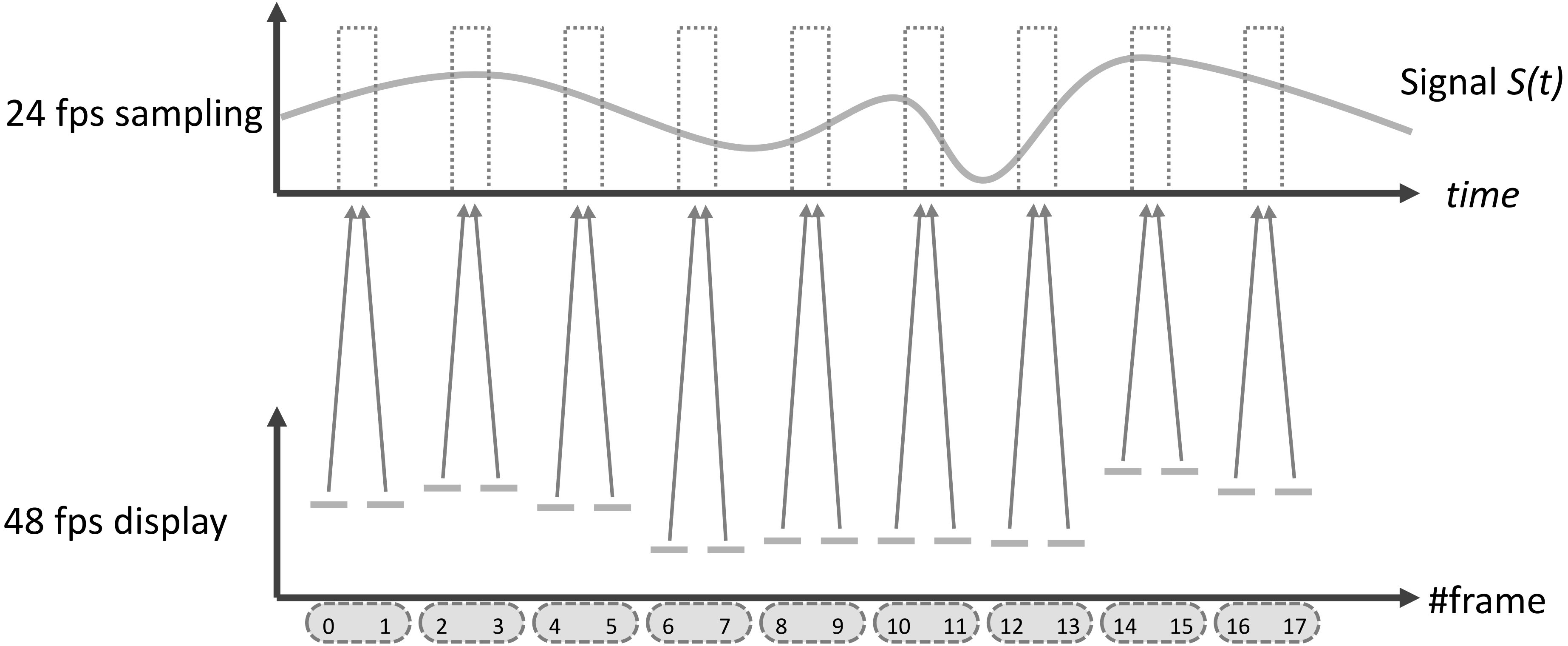
Display frames (48 FPS)

Discrete display time

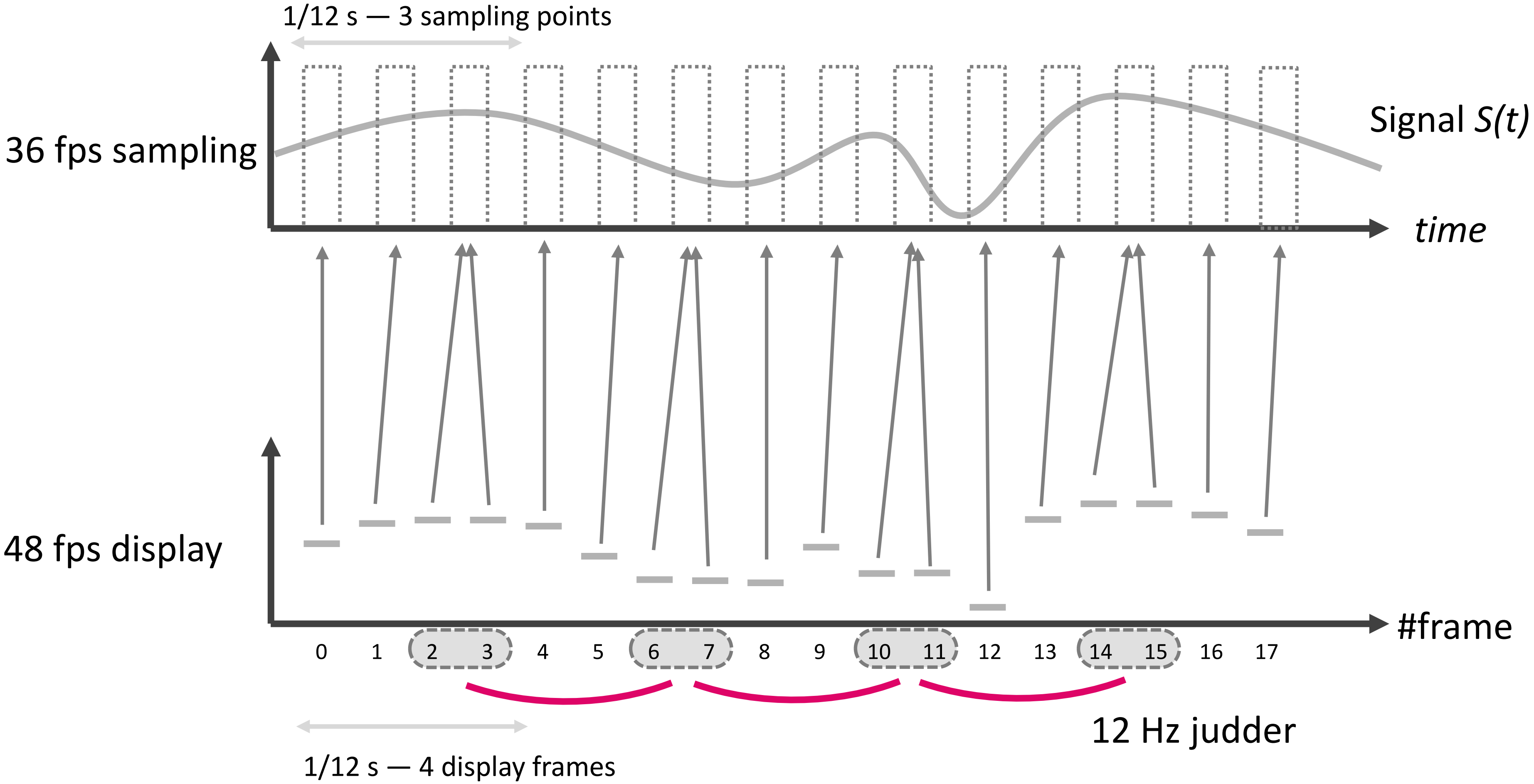
Problem


Luminance of a `single pixel`
in the scene over time
Signal *S(t)*
48 fps sampling
time
48 fps display
#frame
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Problem

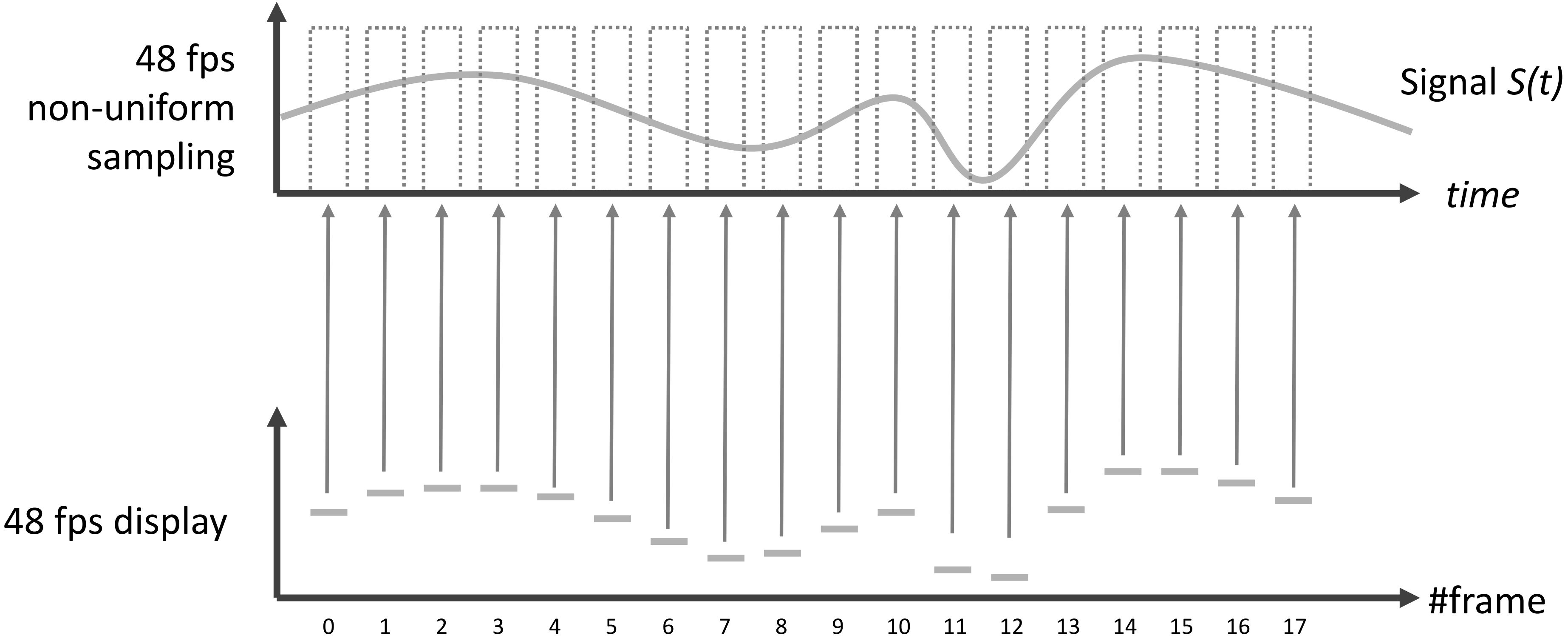

24 fps sampling
Signal S(t)
time
48 fps display
#frame
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Problem

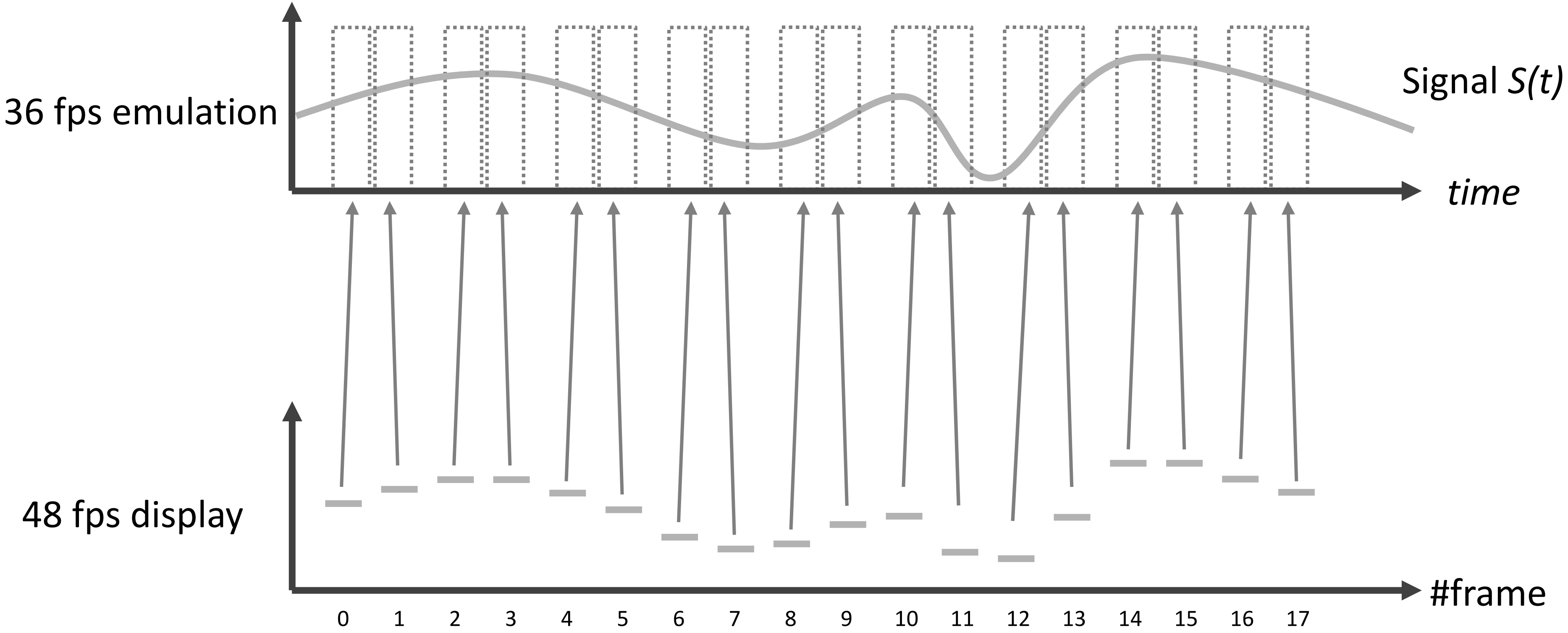


1/12 s — 3 sampling points
36 fps sampling
Signal *S(t)*
time
48 fps display
#frame
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
12 Hz judder
1/12 s — 4 display frames

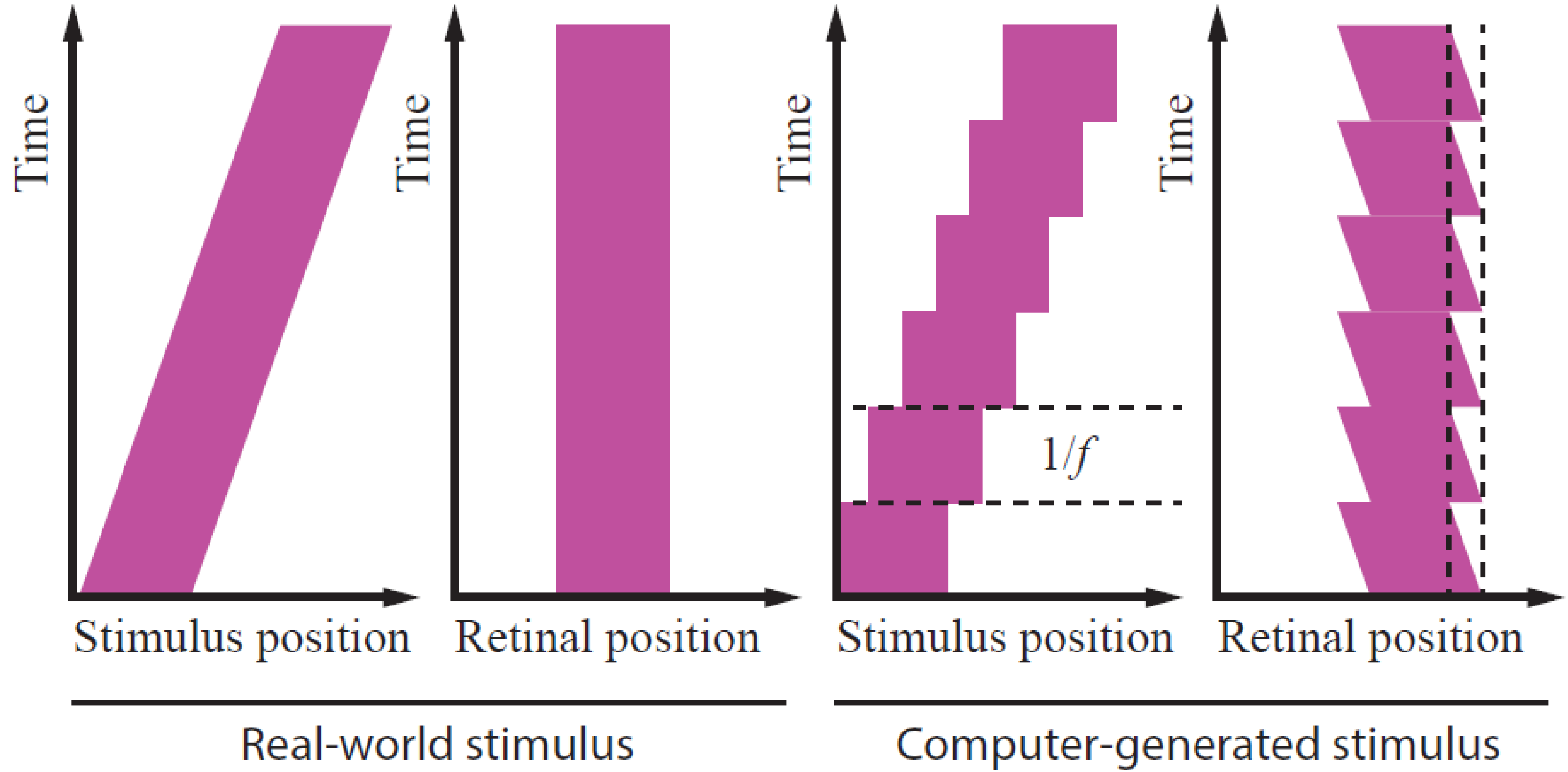
Problem


48 fps
non-uniform
sampling
Signal S(t)
time
48 fps display
#frame
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

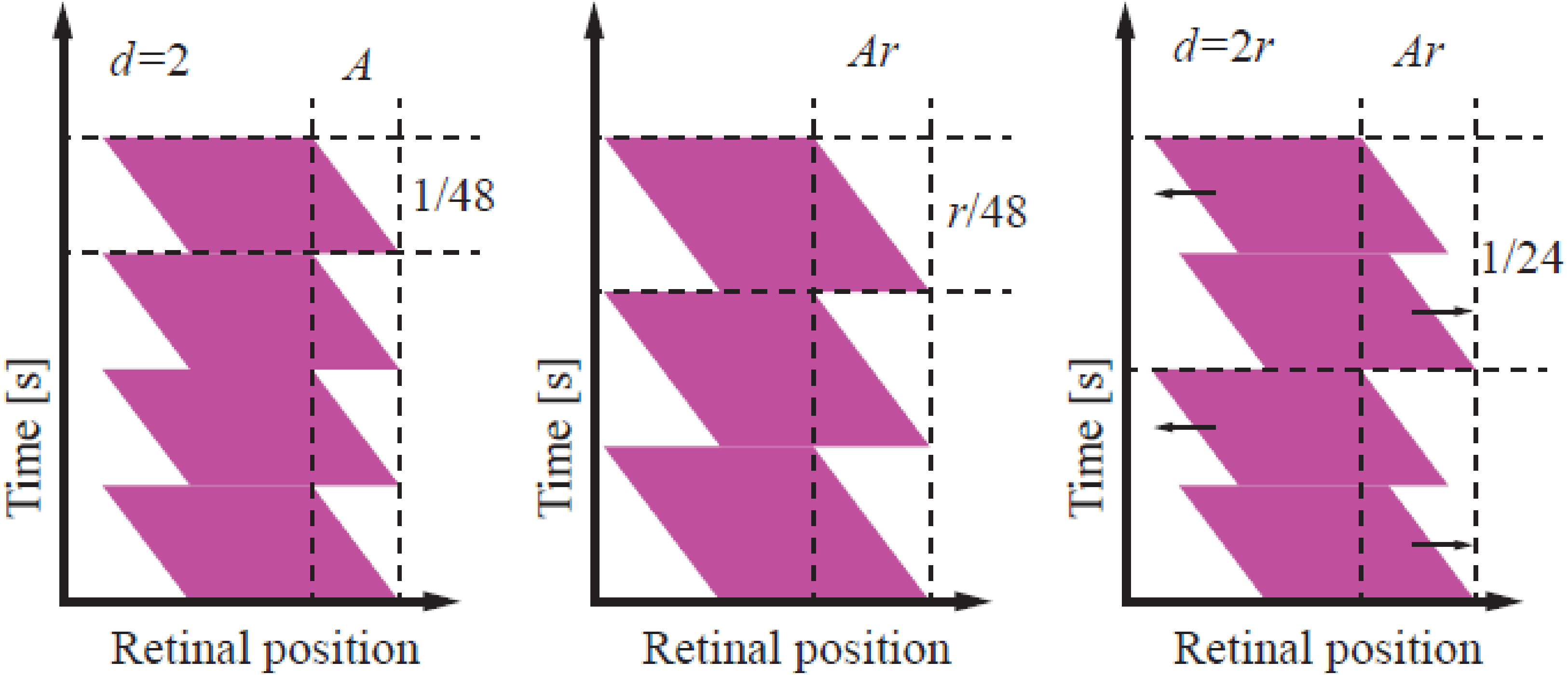
Problem


36 fps emulation
Signal *S(t)*
time
48 fps display
#frame
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

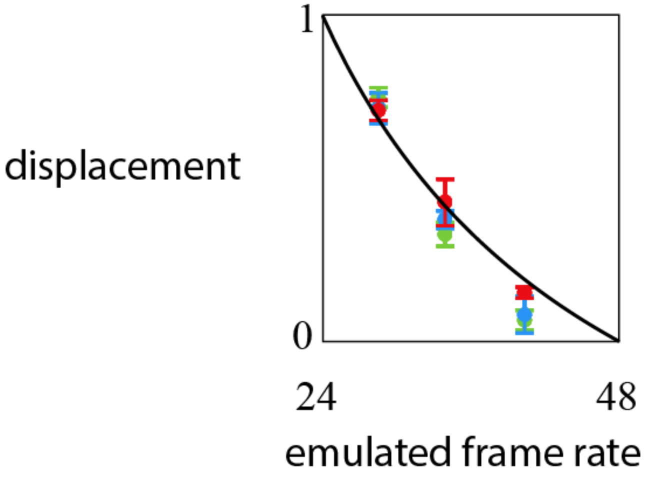
Real World vs. Displayed Stimuli



Flickering Region Control by Frame Shifting



Calibration Experiment



shutter 0.5

- ● 256 px/s
- ● 512 px/s
- ● 1024 px/s

Standard solution

48 fps

continuous

24 fps

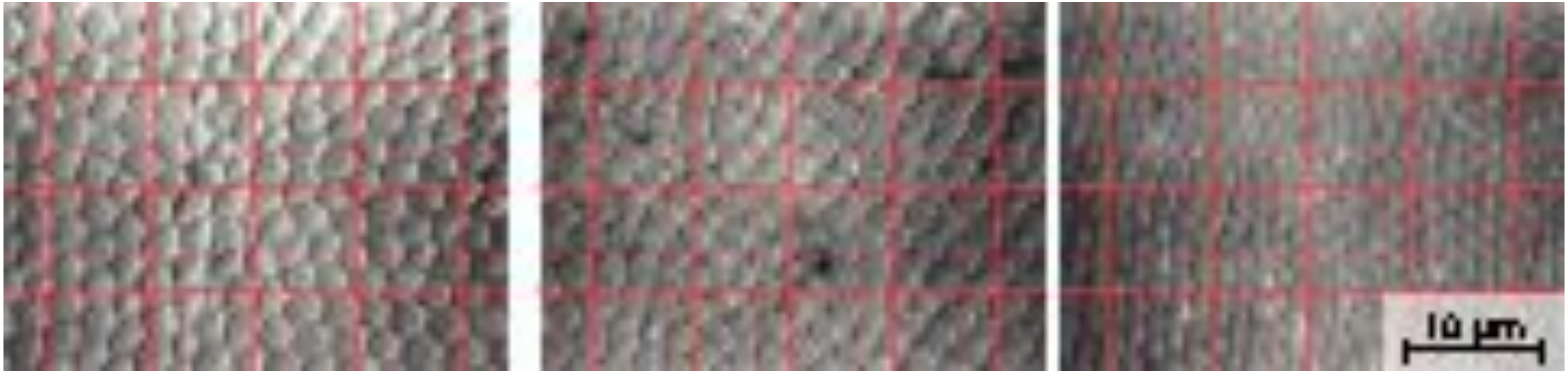
Variable

(Less smooth)

48 FPS

Spatial Resolution

- Density of cones in the fovea per pixel of 22-inch Full-HD display observed from the distance 50cm for three different persons



[Didyk et al. 2010]

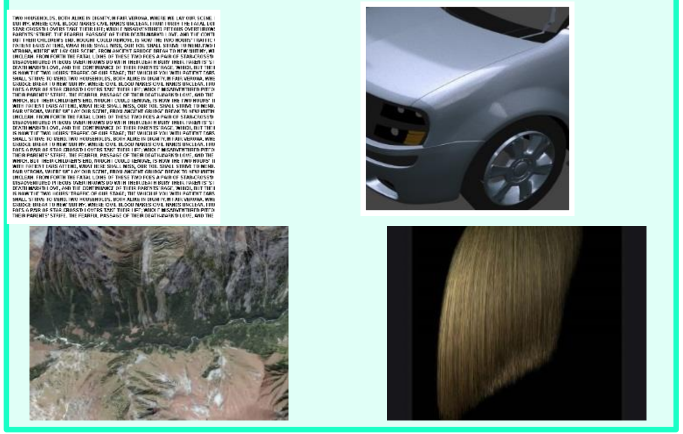
Many High-Resolution Sources

Photographs: > 10MPix

Panoramas: > 50MPix

Gigapixel Photography:

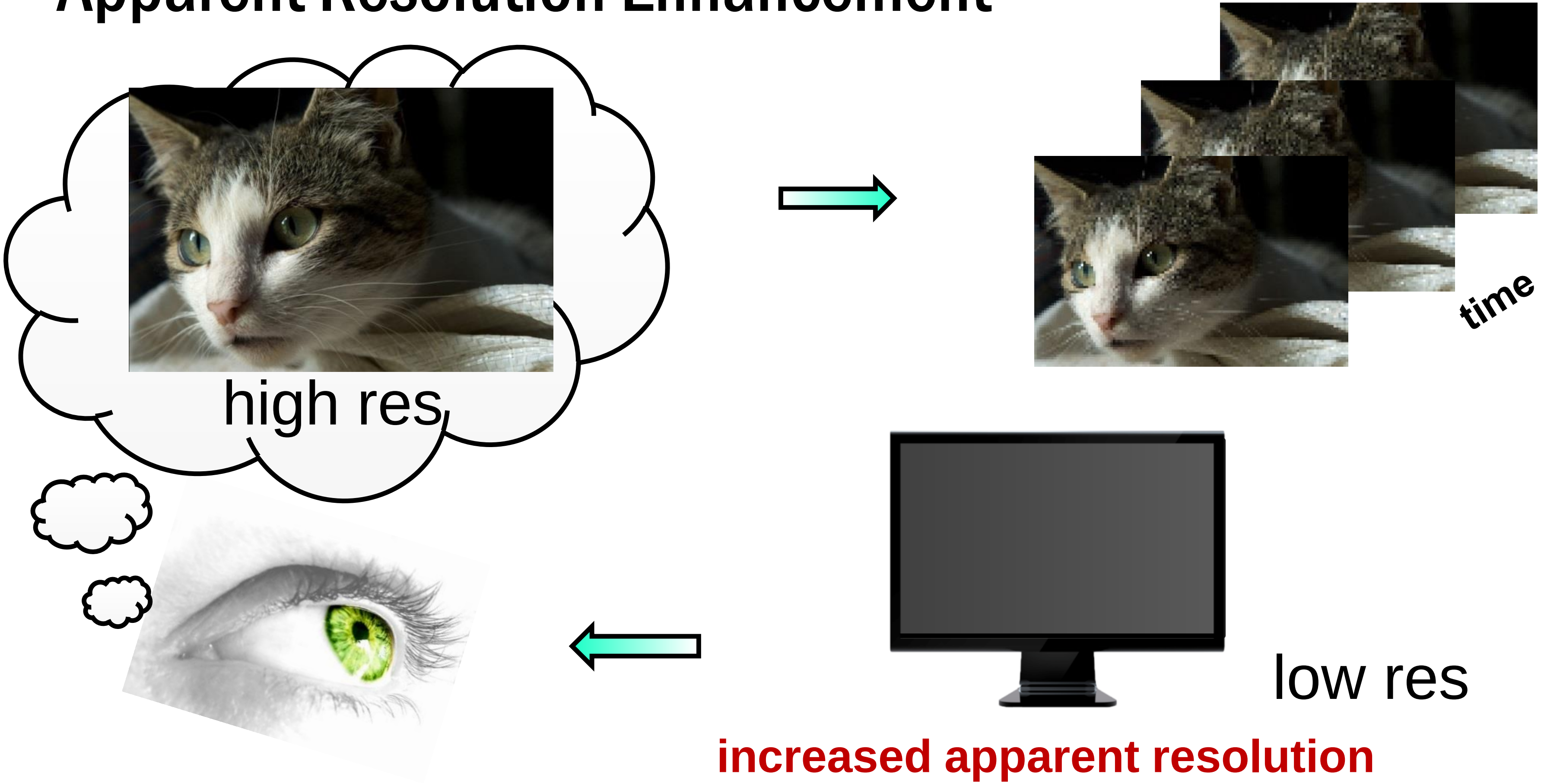
Computer generated: Unlimited



Display content?

Resolution mismatch!

Apparent Resolution Enhancement



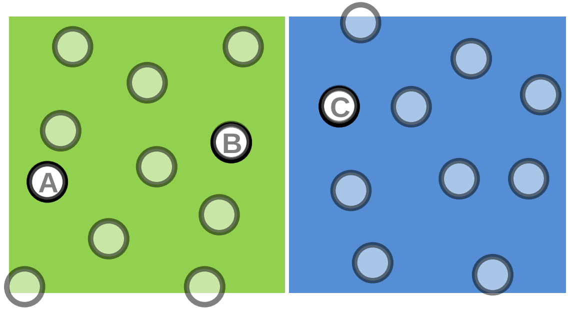
high res

time

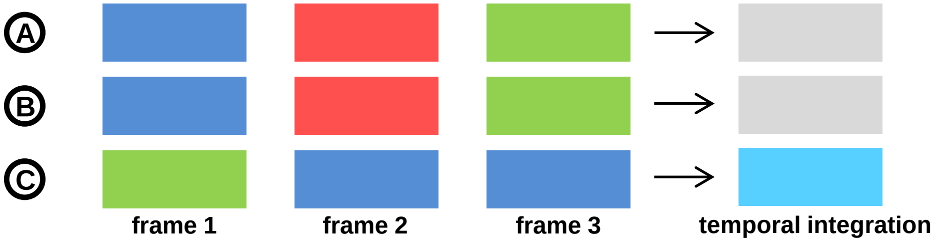
low res

increased apparent resolution

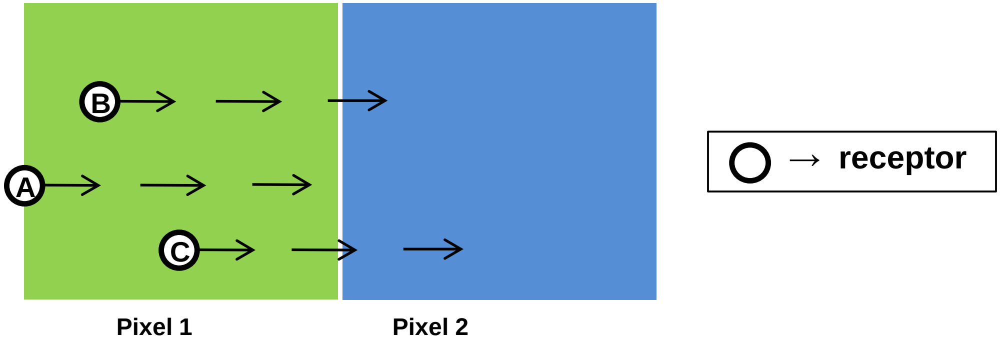
Temporal Domain – Static Case

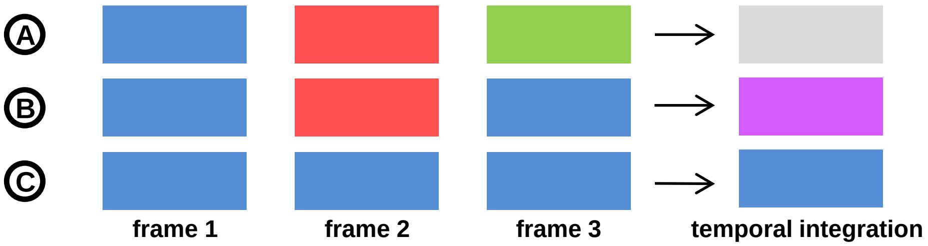


○ → receptor



Temporal Domain – Dynamic Case



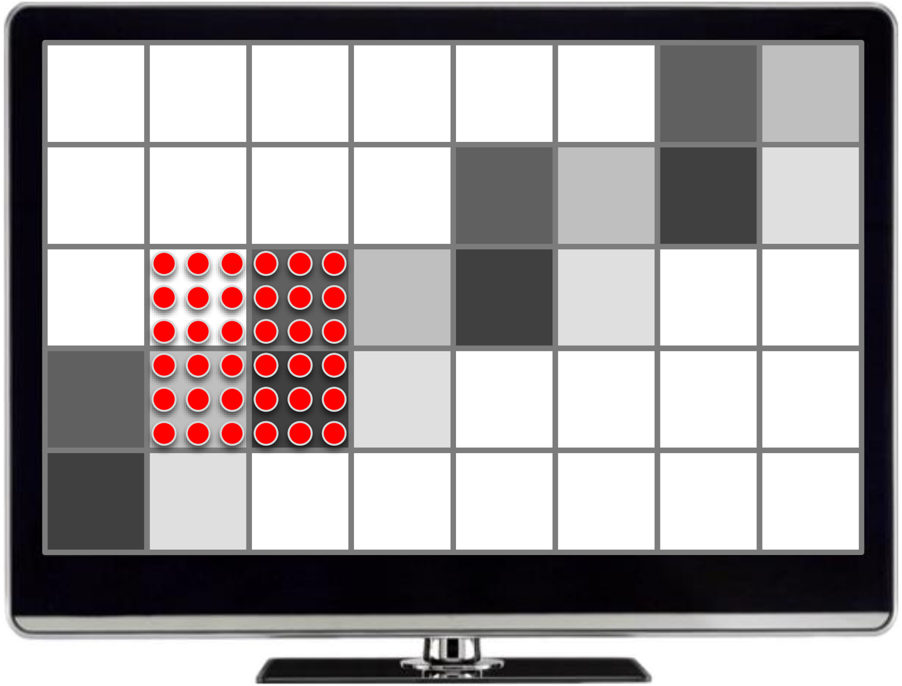


$$\sum_{i=0}^{N} w_i I(p(i), i)$$

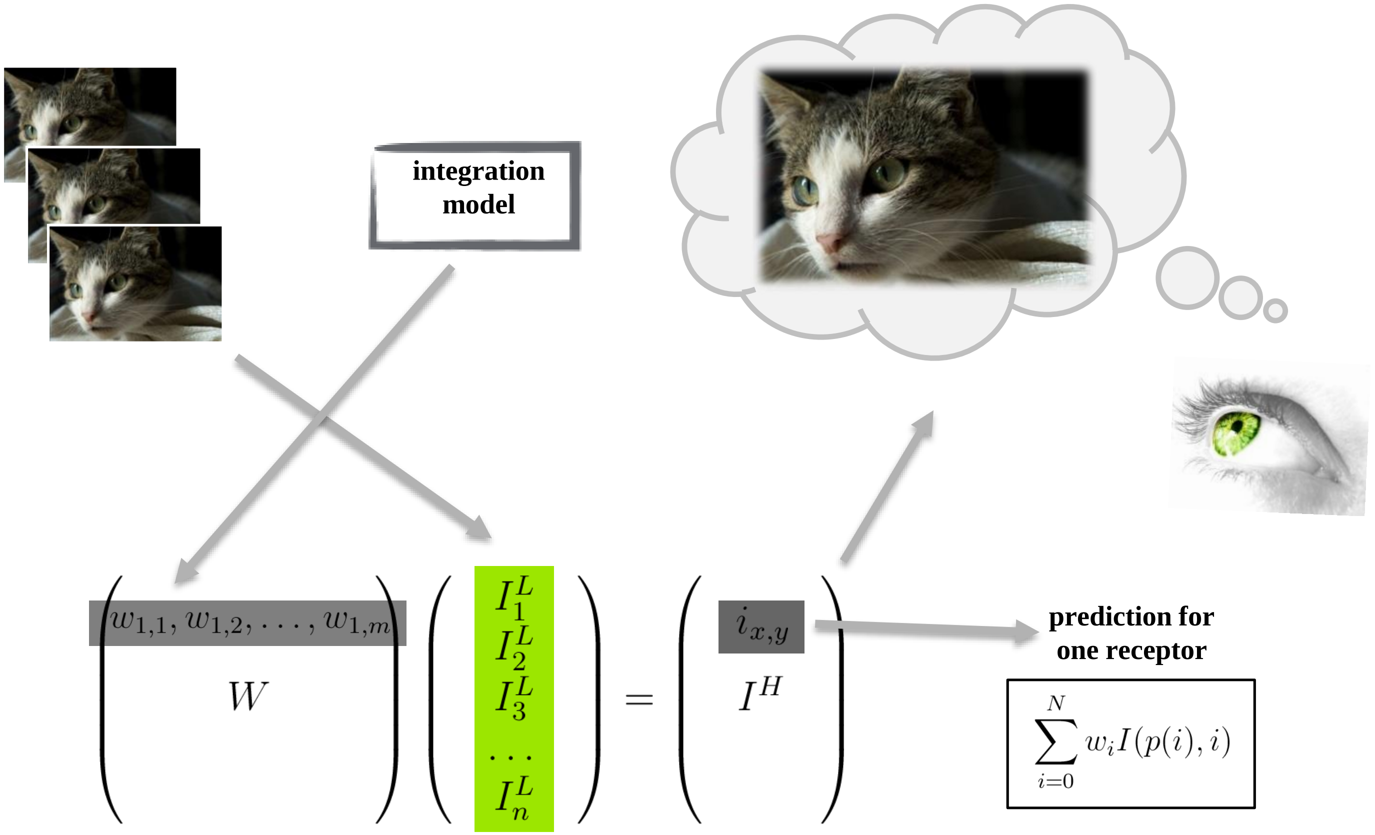
i	segment
$p(i)$	pixel in segment i
$I(x, i)$	intensity of pixel x in segment i

w_i weights proportional to the length of the segment

Receptor Layout



Prediction in Equations



integration model

$$\begin{pmatrix} w_{1,1}, w_{1,2}, \dots, w_{1,m} \\ W \\ \\ \\ \end{pmatrix} \begin{pmatrix} I_1^L \\ I_2^L \\ I_3^L \\ \dots \\ I_n^L \end{pmatrix} = \begin{pmatrix} i_{x,y} \\ I^H \\ \\ \\ \end{pmatrix}$$

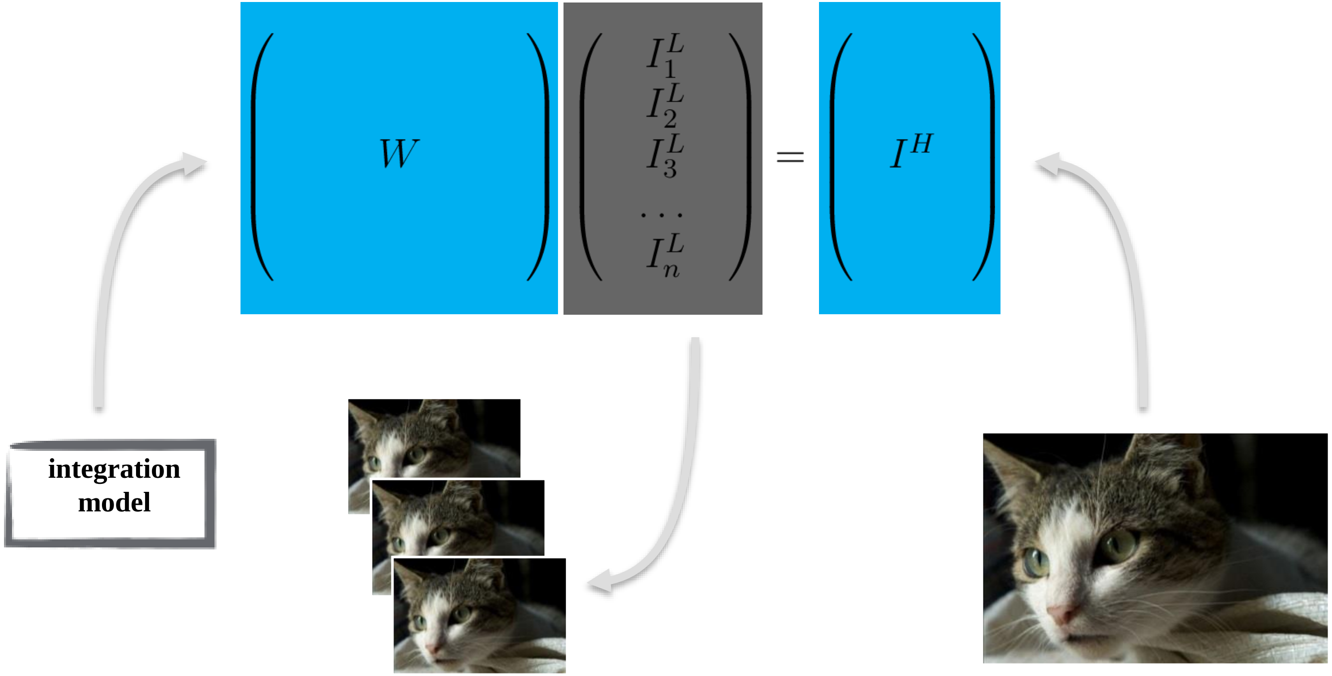
prediction for one receptor

$$\boxed{\sum_{i=0}^{N} w_i I(p(i), i)}$$

Prediction in Equations

$$\begin{pmatrix} \\ \\ & & W & & \\ \\ \\ \end{pmatrix} \begin{pmatrix} I_1^L \\ I_2^L \\ I_3^L \\ \dots \\ I_n^L \end{pmatrix} = \begin{pmatrix} \\ \\ I^H \\ \\ \\ \end{pmatrix}$$

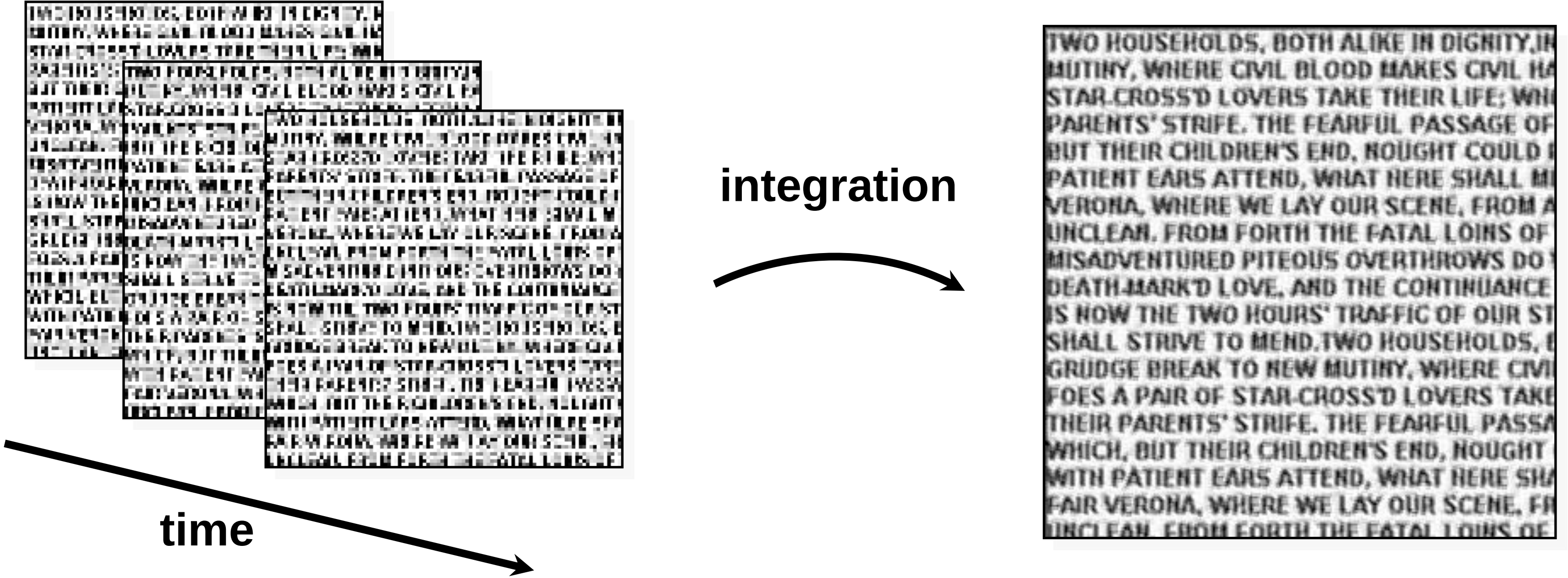
Optimization Problem



$$\begin{pmatrix} & & \\ & W & \\ & & \end{pmatrix}\begin{pmatrix} I_1^L \\ I_2^L \\ I_3^L \\ \dots \\ I_n^L \end{pmatrix} = \begin{pmatrix} \\ I^H \\ \\ \end{pmatrix}$$

integration model

Optimization Result



Display

Predicted image on the retina

integration

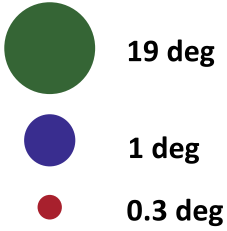
time

[Didyk et al. 2010]

Critical Flicker Frequency

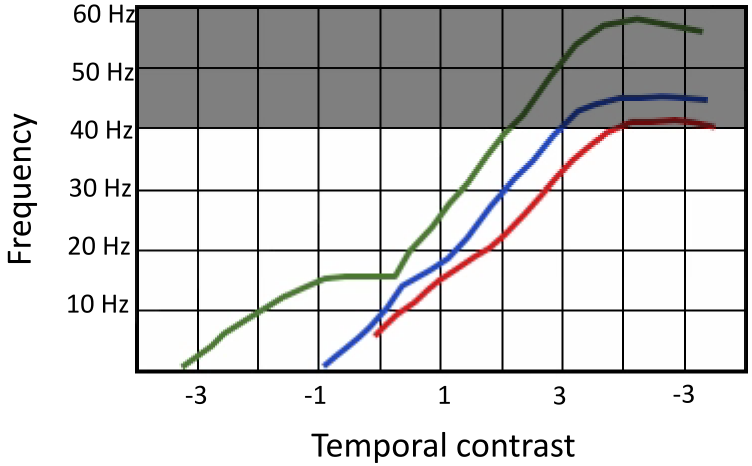
Fusion frequency depends on:

- Temporal contrast
- Spatial extent



Three-frame cycle
on 120 Hz display

40 Hz signal



Critical Flicker Frequency – Hecht and Smith's data from
Brown J.L. *Flicker and Intermittent Simulation*

Depth Perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence

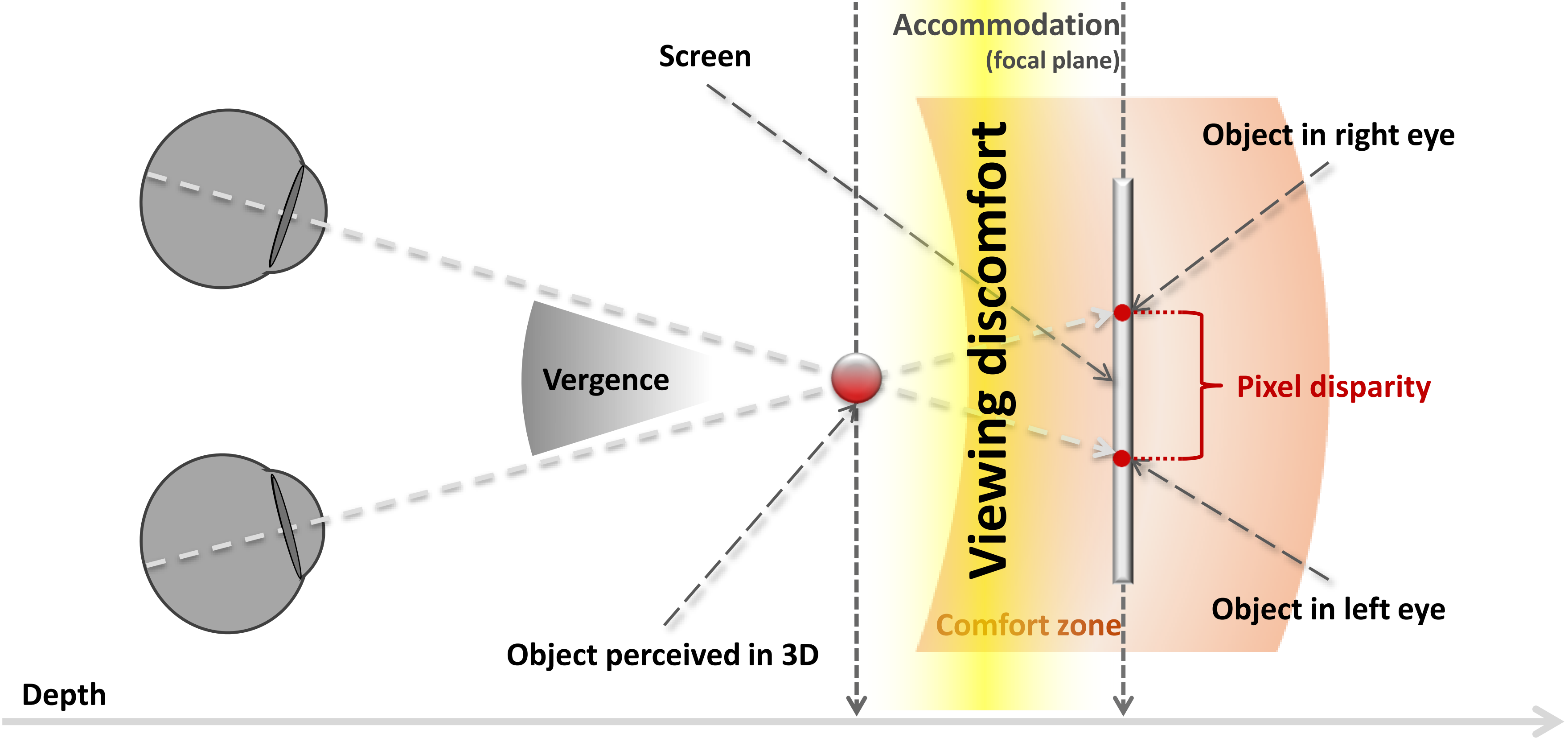
Require 3D space

We cheat our Human Visual System!

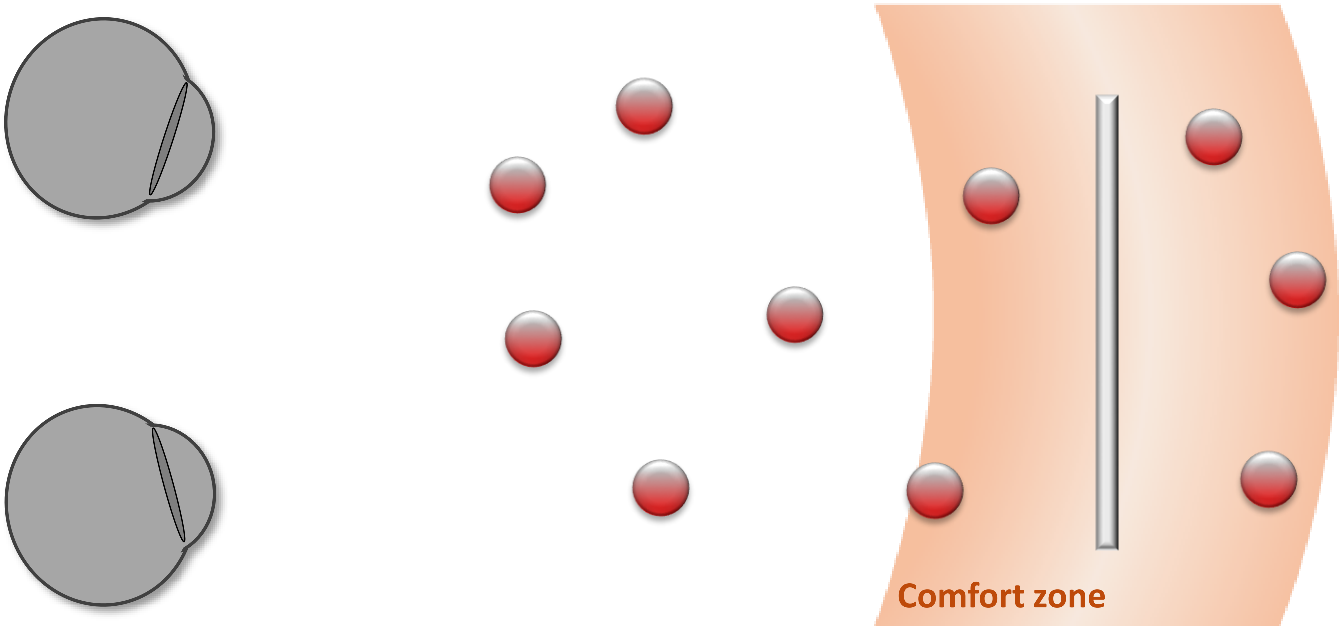
Pictorial depth cues:
occlusion, size, shadows…

Reproducible on a flat displays

Stereo 3D: Binocular Disparity



Depth Manipulation



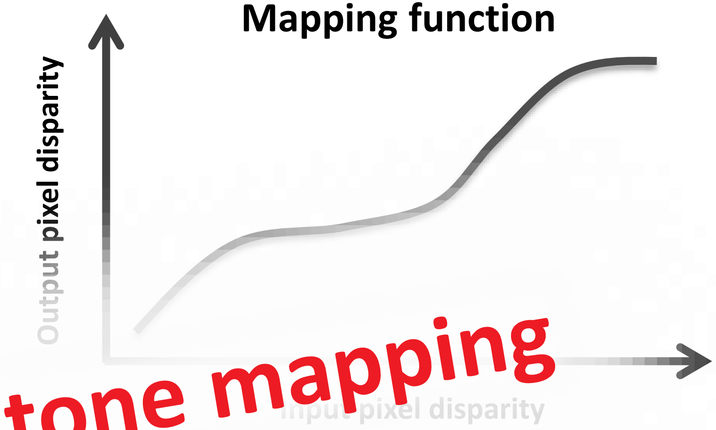
Scene manipulation

Viewing discomfort → Viewing comfort

Depth Manipulation

Pixel disparity map

Modified pixel disparity



Mapping function

Similar to tone mapping

Function:

- Linear
- Logarithmic
- Content dependent

Other possibilities:

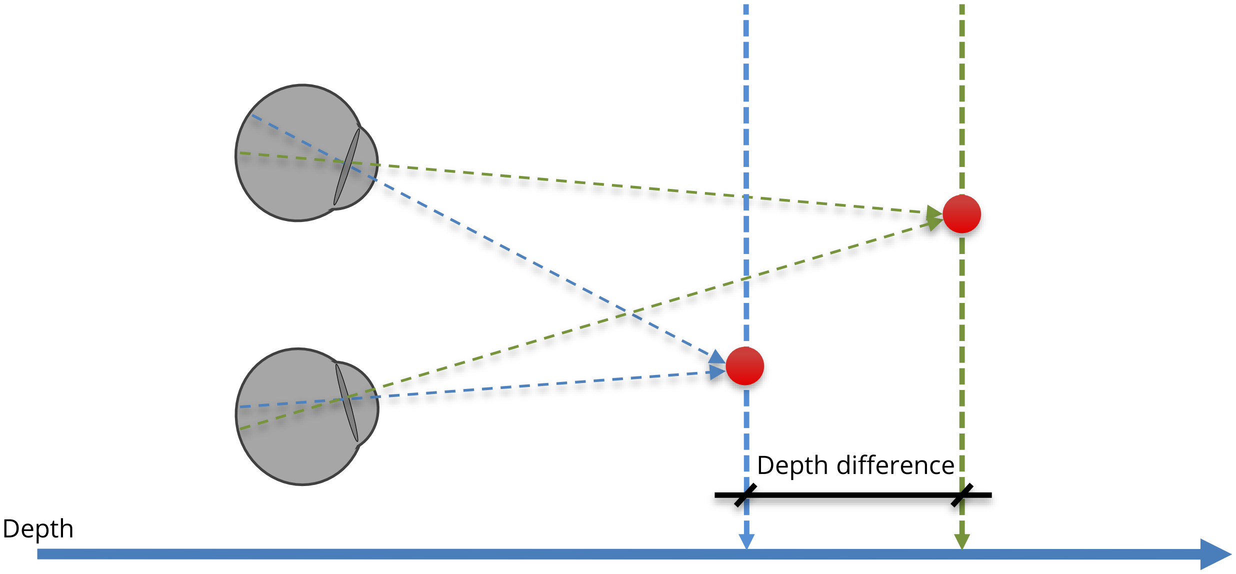
- Gradient domain
- Local operators

"Nonlinear Disparity Mapping for Stereoscopic 3D" [Lang et al. 2010]

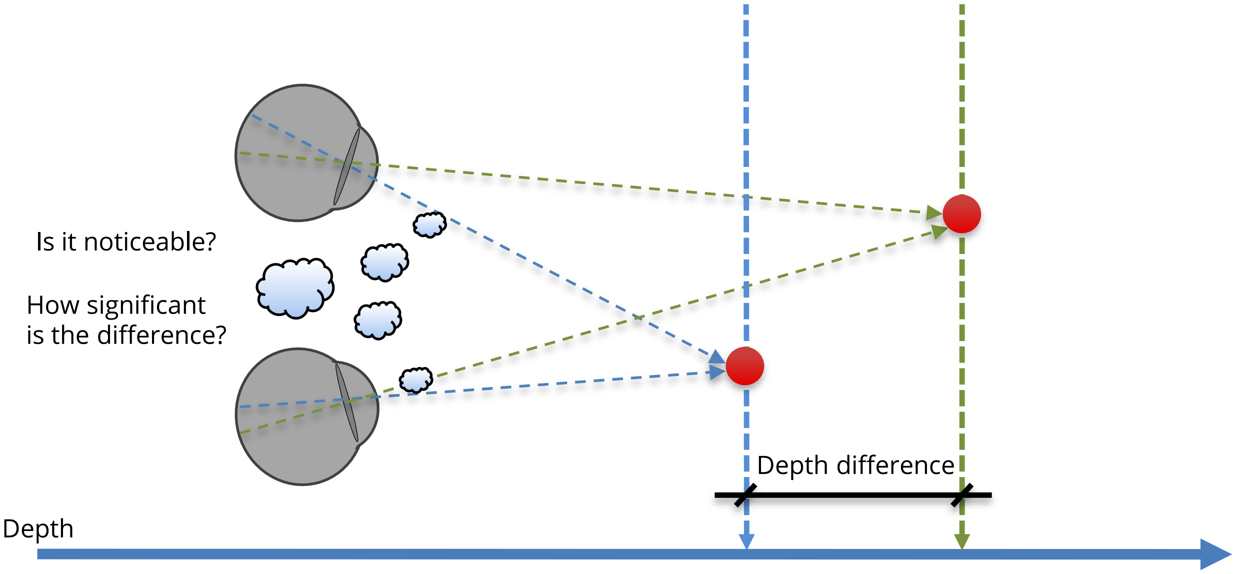
Depth Manipulation

Disparity distortion metric required

Disparity Perception



Disparity Perception



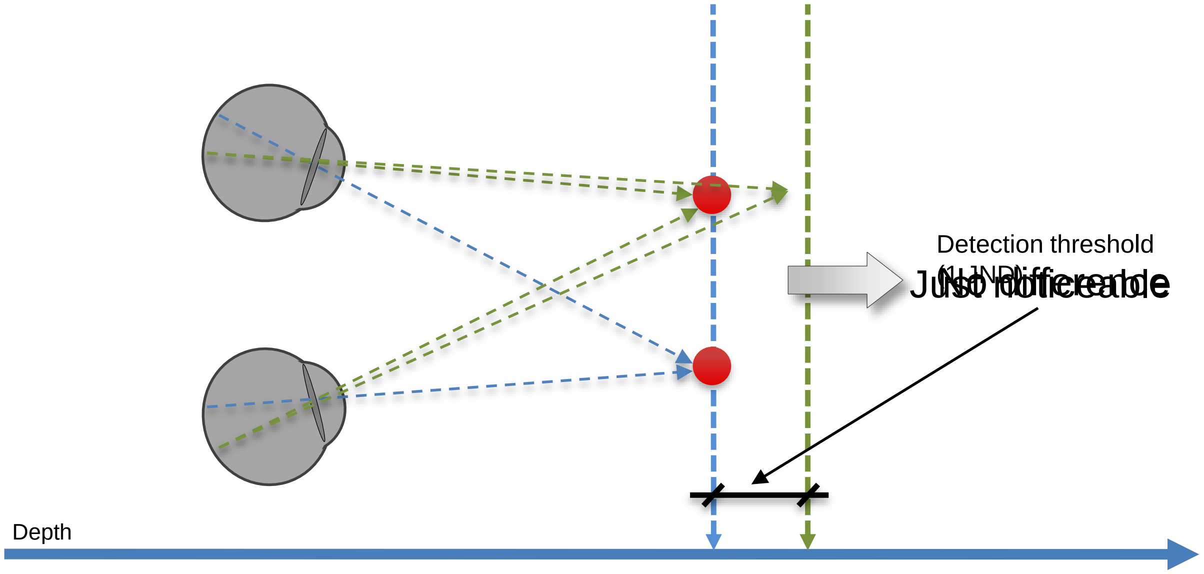
Is it noticeable?

How significant is the difference?

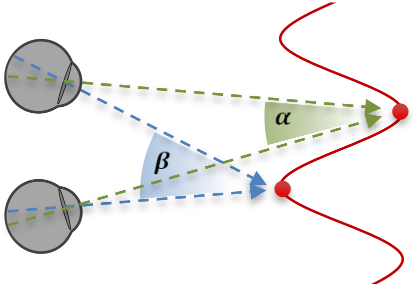
Depth difference

Depth

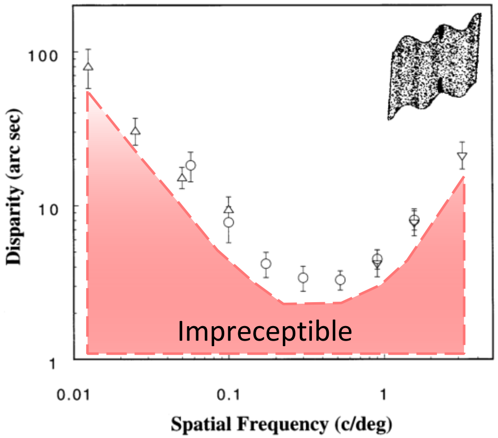
Detection Threshold



Detection Threshold



$$disparity = |\alpha - \beta|$$

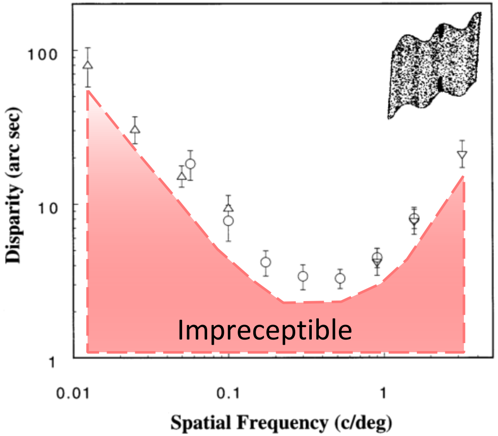

Disparity Sensitivity Function

For sinusoidal depth corrugation

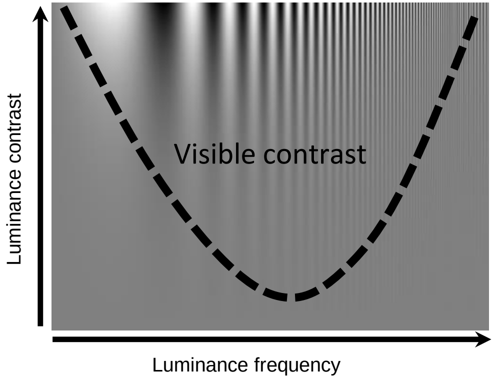
"Sensitivity to horizontal and vertical corrugations defined by binocular disparity" [Bradshaw et al. 1999]
"Spatial organization of binocular disparity sensitivity" [Tyler 1975]

Detection Threshold

Disparity Sensitivity Function



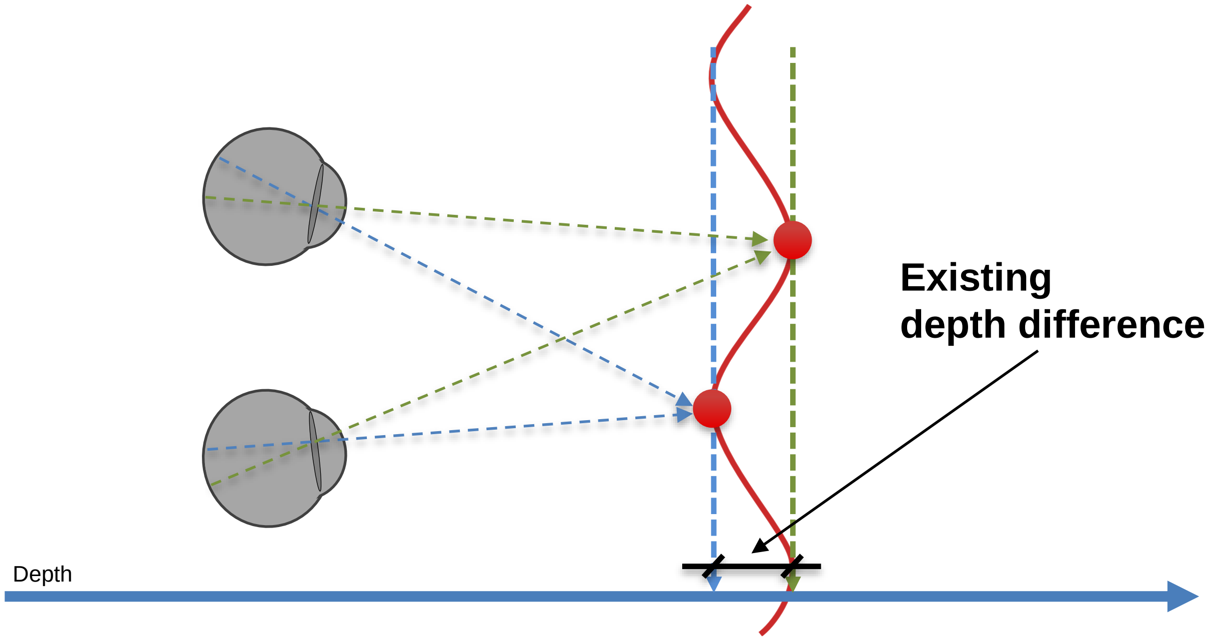
Contrast sensitivity function



Disparity and luminance perception follows similar mechanisms

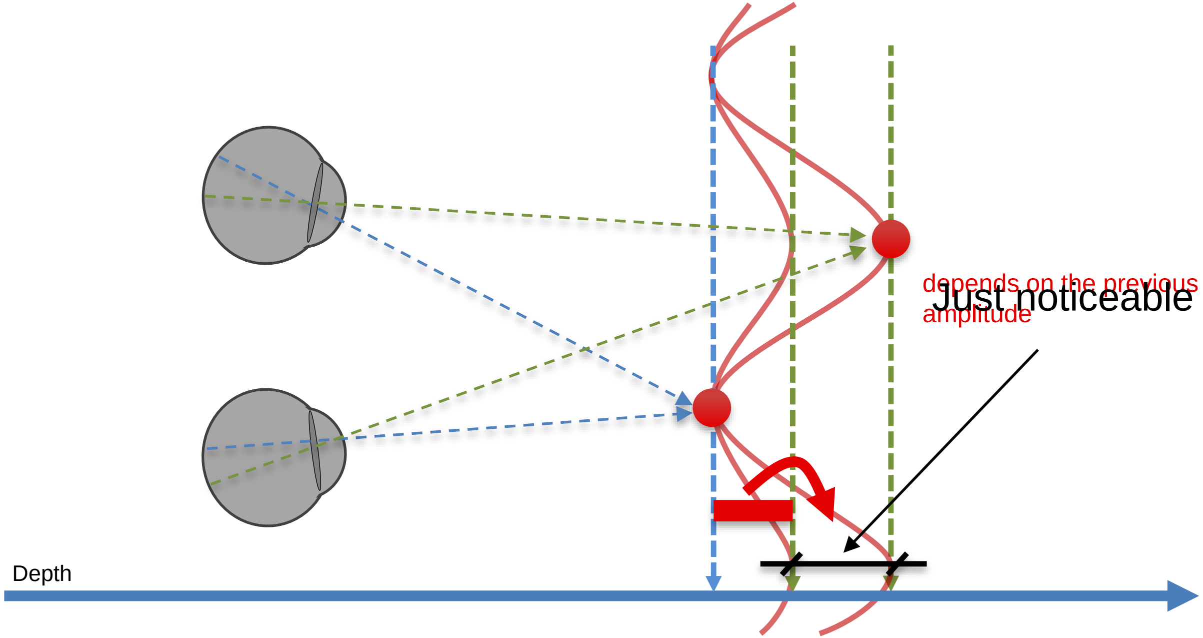
"Seeing in depth" by Howard and Rogers 2002

Discrimination Threshold



Existing depth difference

Discrimination Threshold



Disparity Perception

Sensitivity to depth changes depends on:

- Spatial frequency of disparity corrugation
- Existing disparity (sinusoid amplitude)

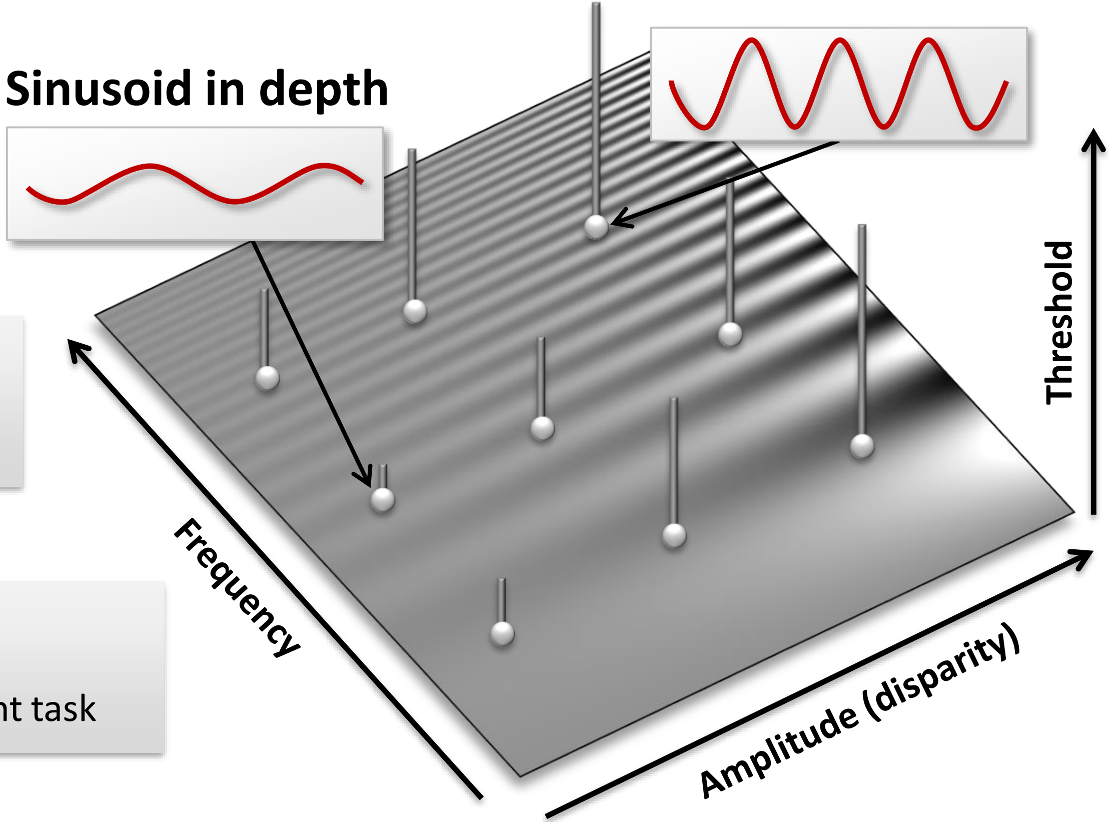
Measurements

Parameter space:

1. Sample the space

2. Measure thresholds

- ➢ Experiment with adjustment task

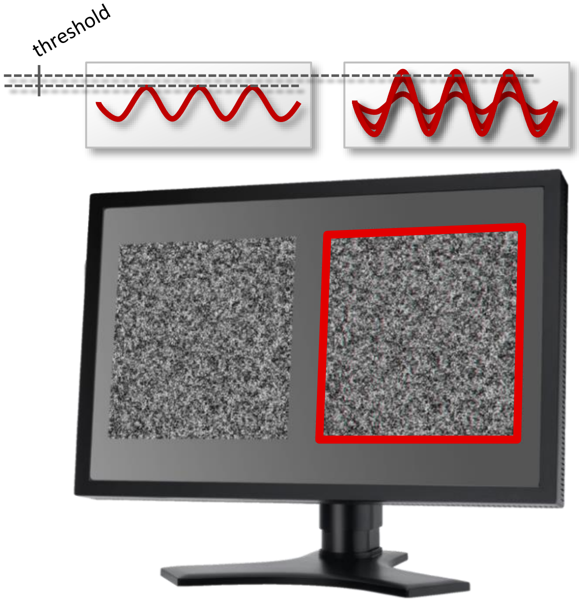


"A perceptual model for disparity" by Didyk et al. 2011

Measurements

Thresholds measurement:

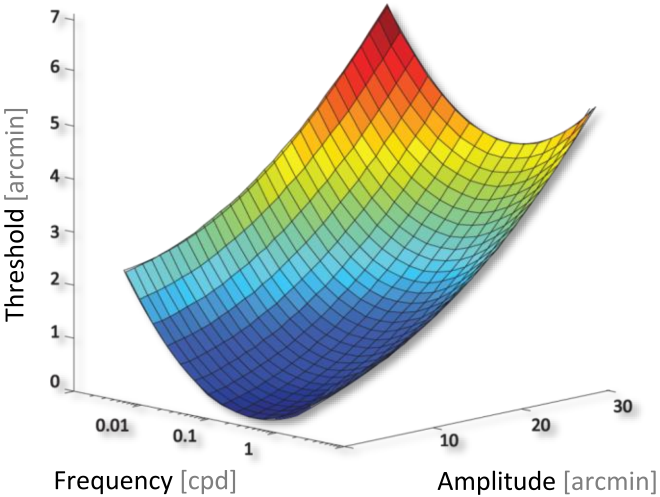
- Two sinusoidal corrugations
- Which has more depth? (left/right)
- Amplitude adjustment (PEST with 2AFC)
- 12 participants → 300+ samples



"A perceptual model for disparity" by Didyk et al. 2011

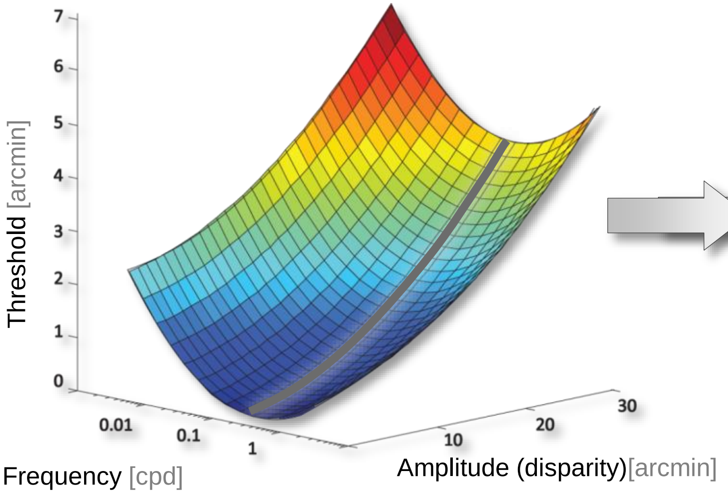
Model

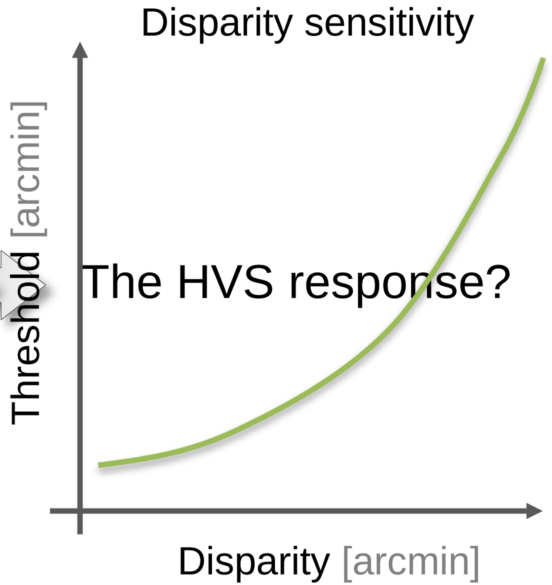
3. Fit analytic function



“A perceptual model for disparity” by Didyk et al. 2011

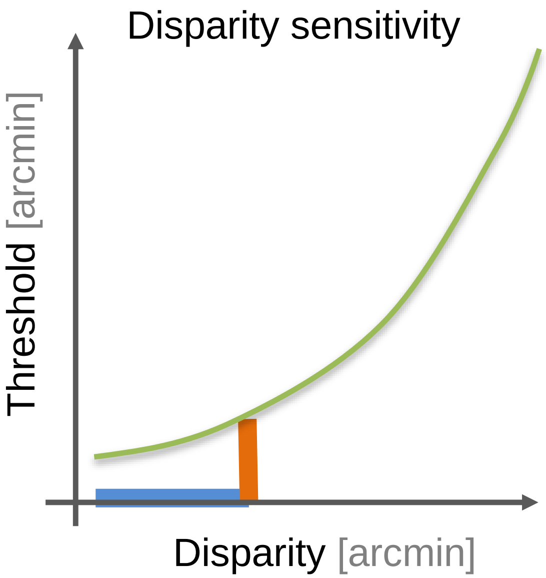
The HVS Response

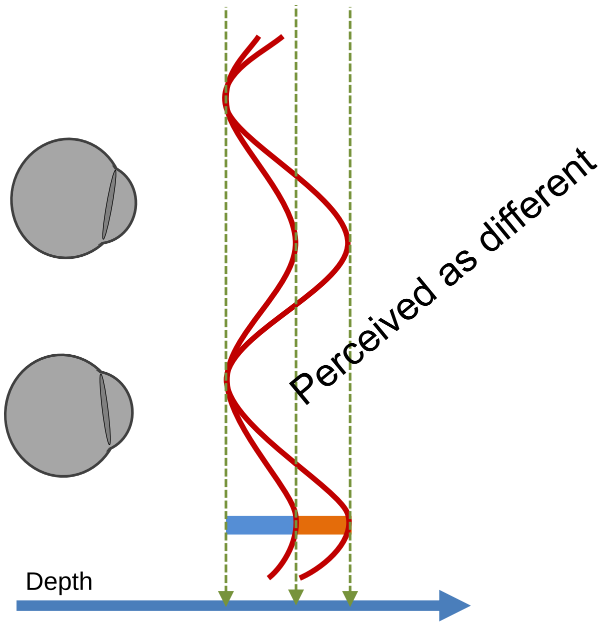




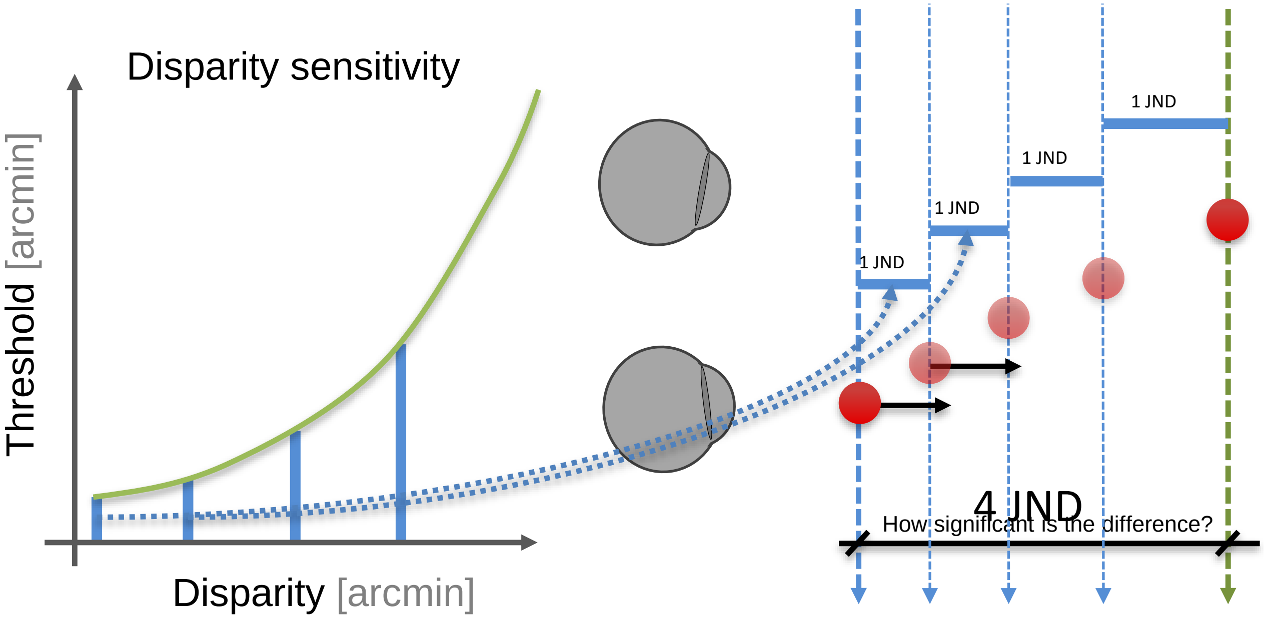
The HVS response?

The HVS Response

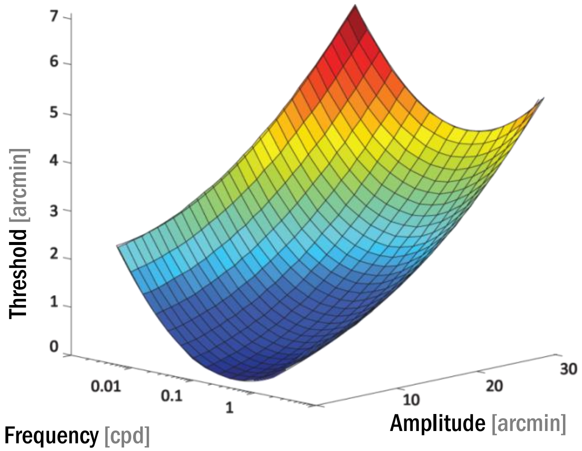


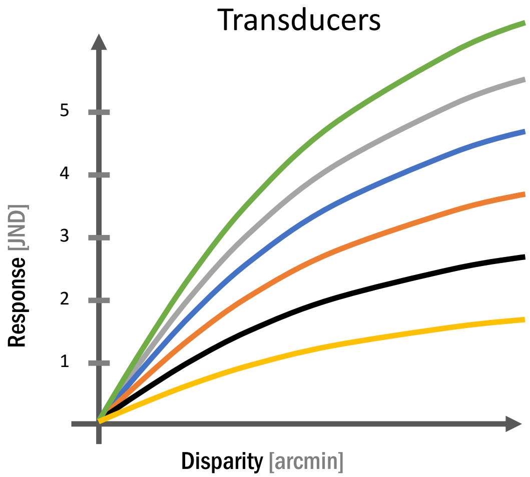


The HVS Response



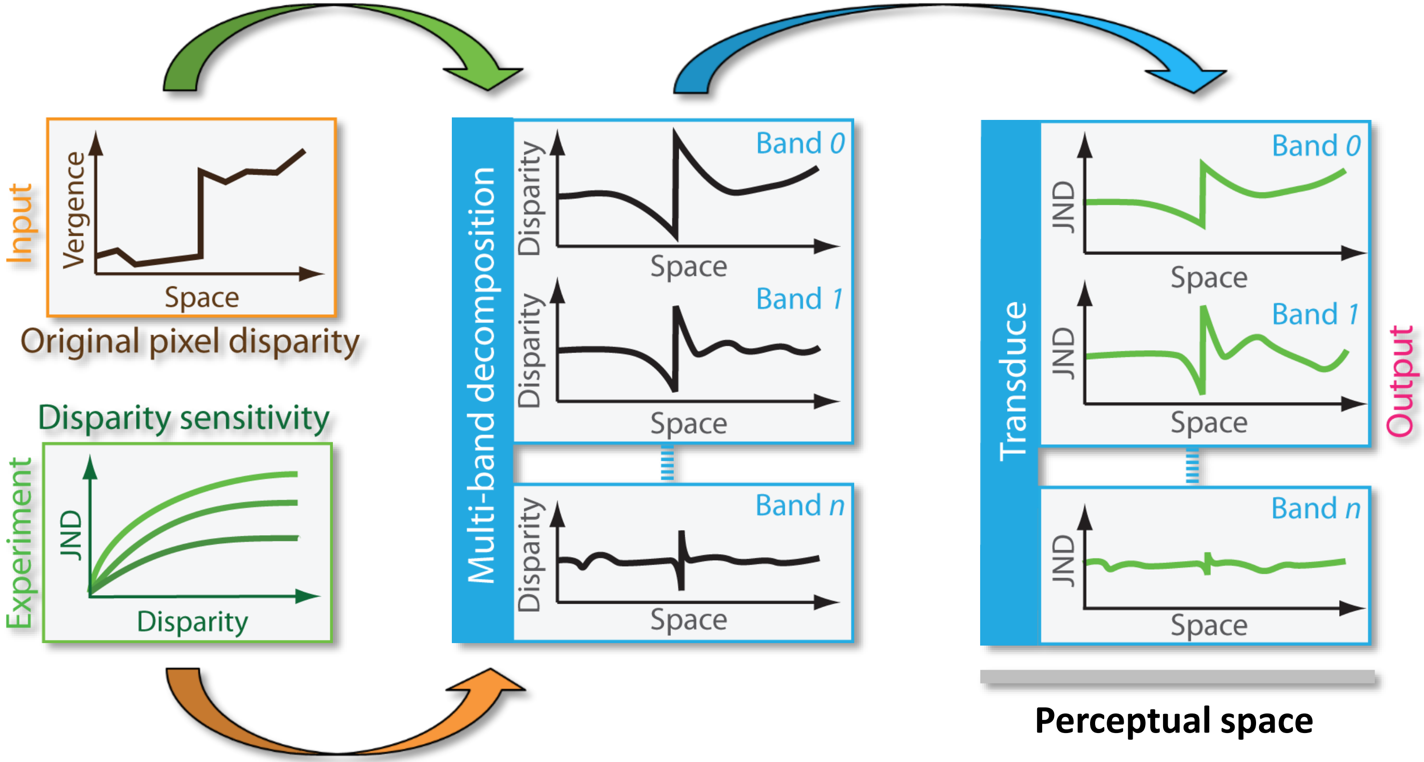
The HVS Response





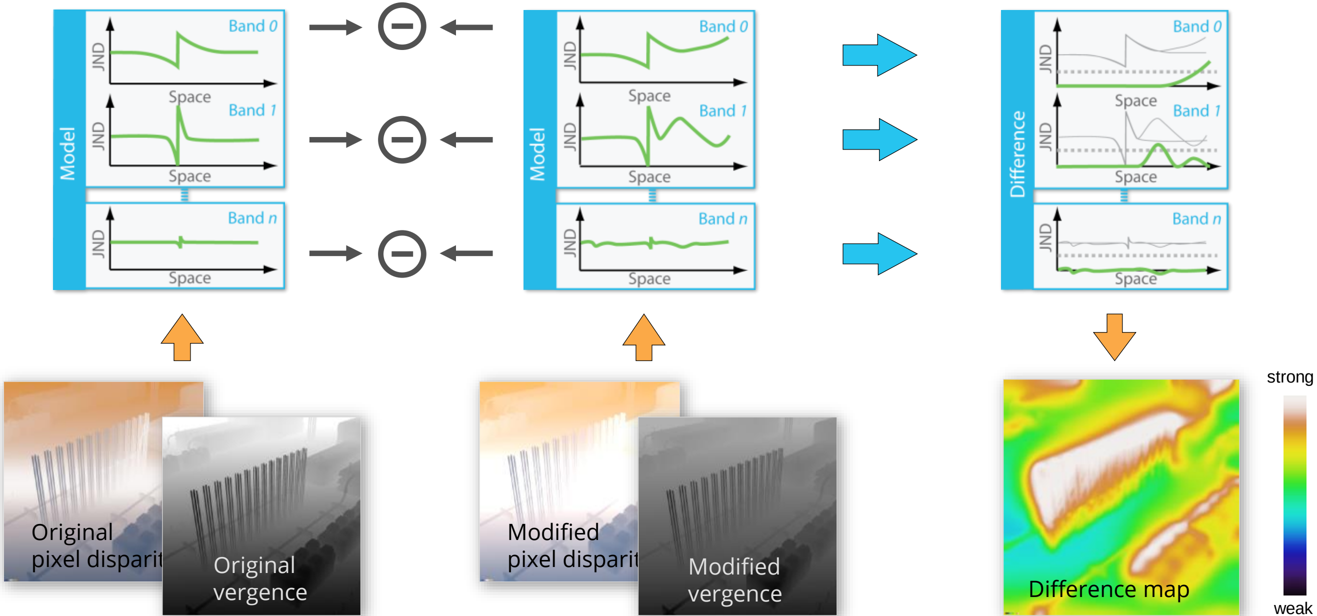
* one transducer per frequency

Perceptual Model



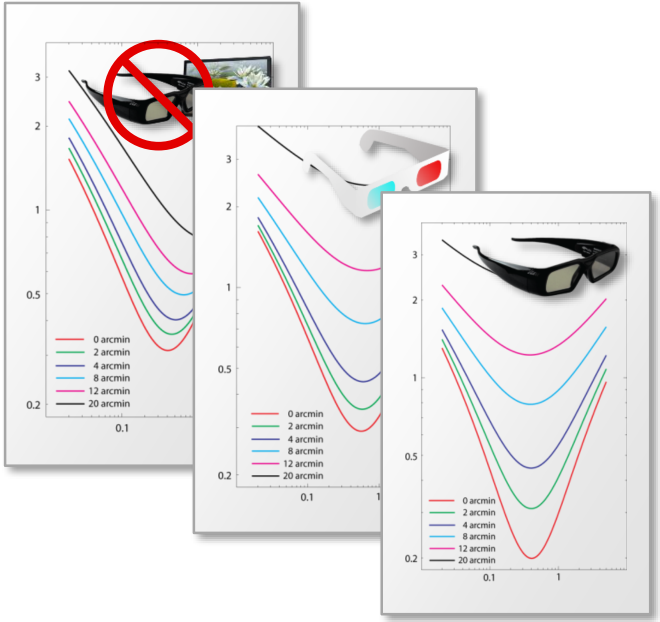
"A perceptual model for disparity" by Didyk et al. 2011

Disparity Metric



Personalization

Disparity perception depends on:

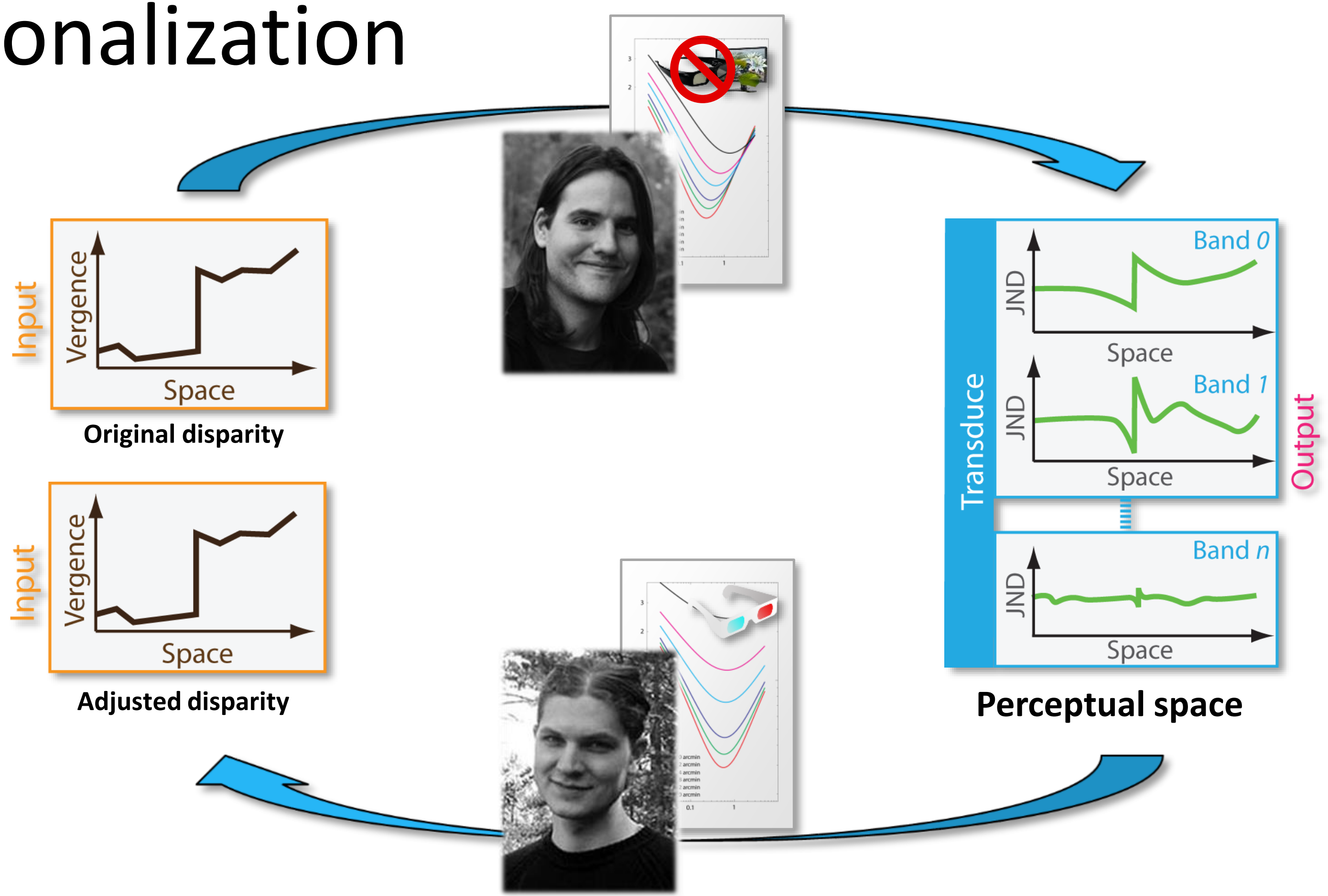


Equipment

User

"A perceptual model for disparity" by Didyk et al. 2011

Personalization



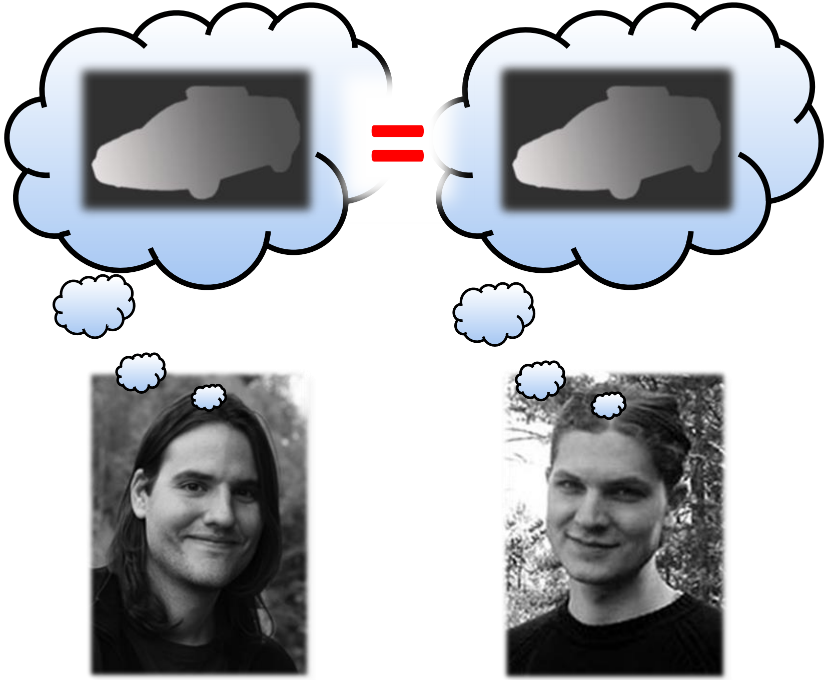
Original disparity

Adjusted disparity

Perceptual space

“A perceptual model for disparity” by Didyk et al. 2011

Personalization



All users perceive the same regardless:

- Equipment
- Disparity sensitivity

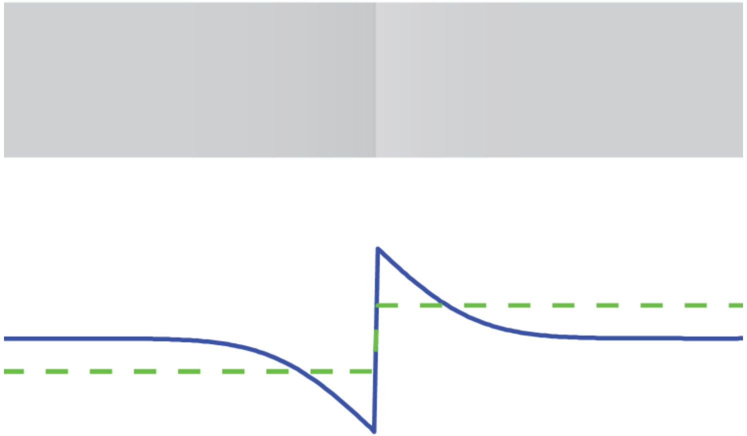
Backward-compatible Stereo

Backward-compatible stereo

Standard 2D image

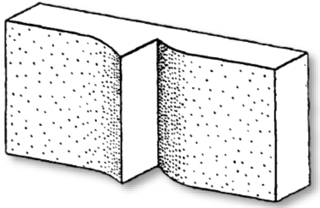
Standard stereo

Cornsweet Illusion



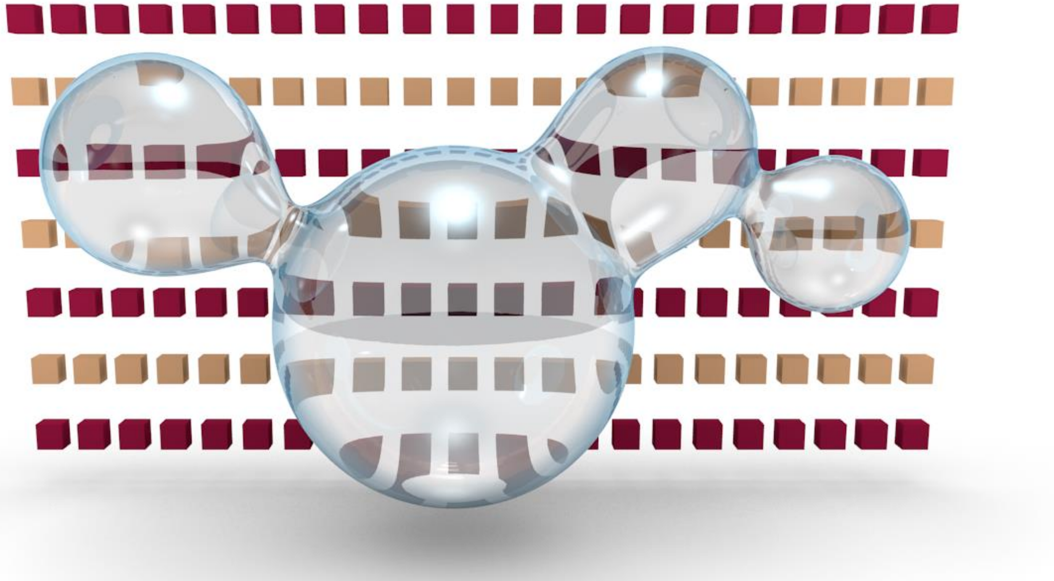
- Similar perceived contrast
- Luminance range reduced

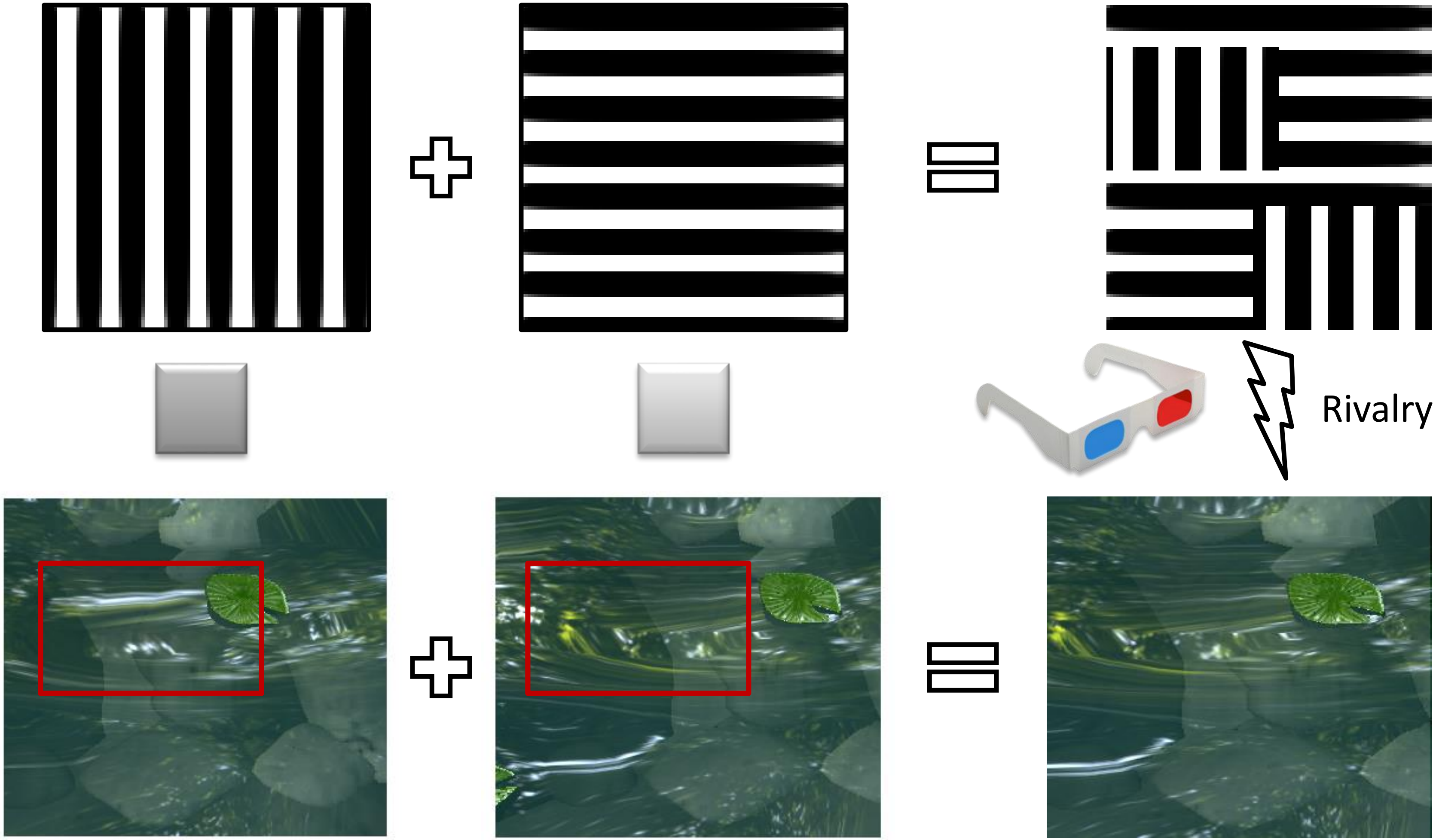
Cornsweet illusion works for depth:

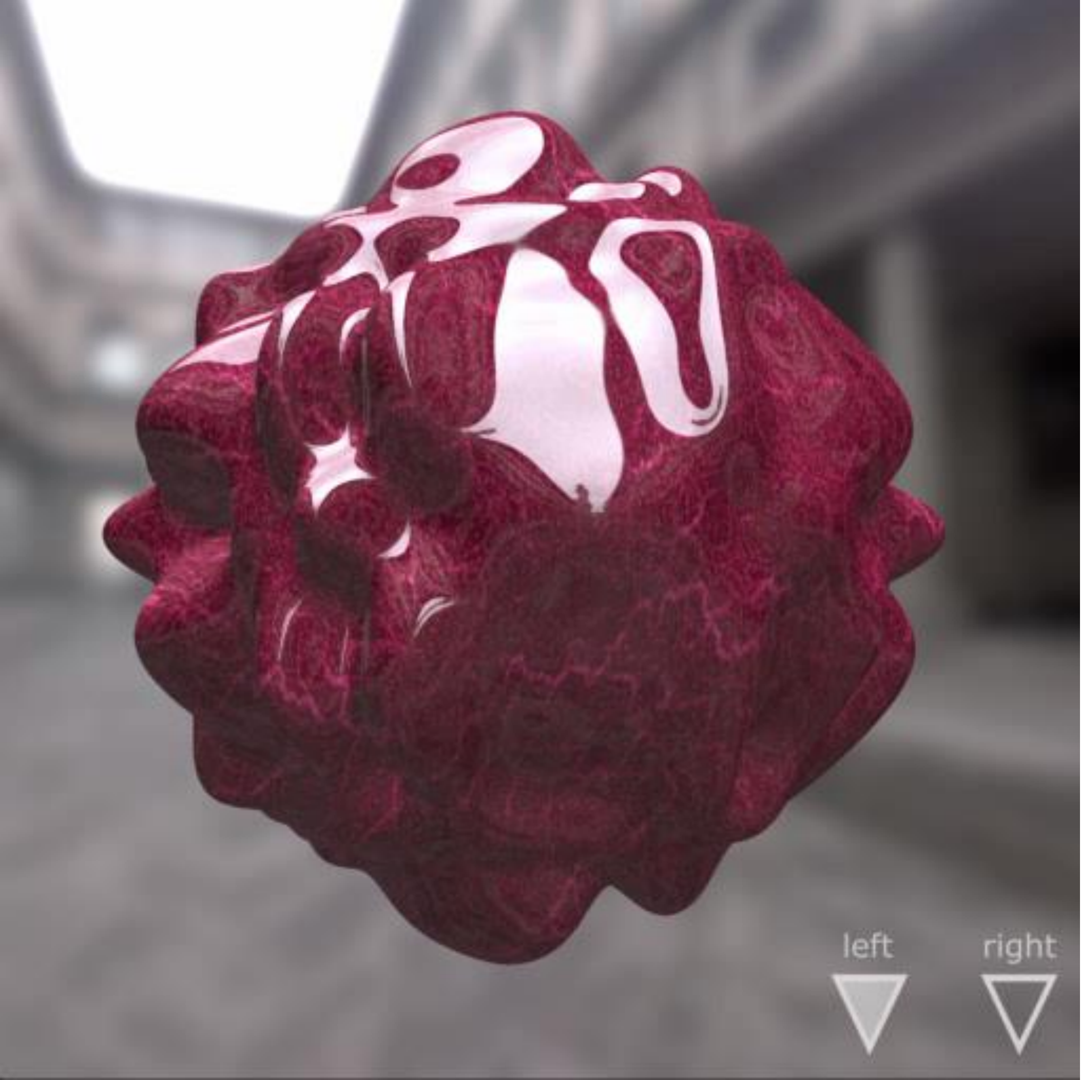


“A Craik-O'Brien-Cornsweet illusion for visual depth ” by Anstis et al. 1997

Reflections and Refractions in S3D

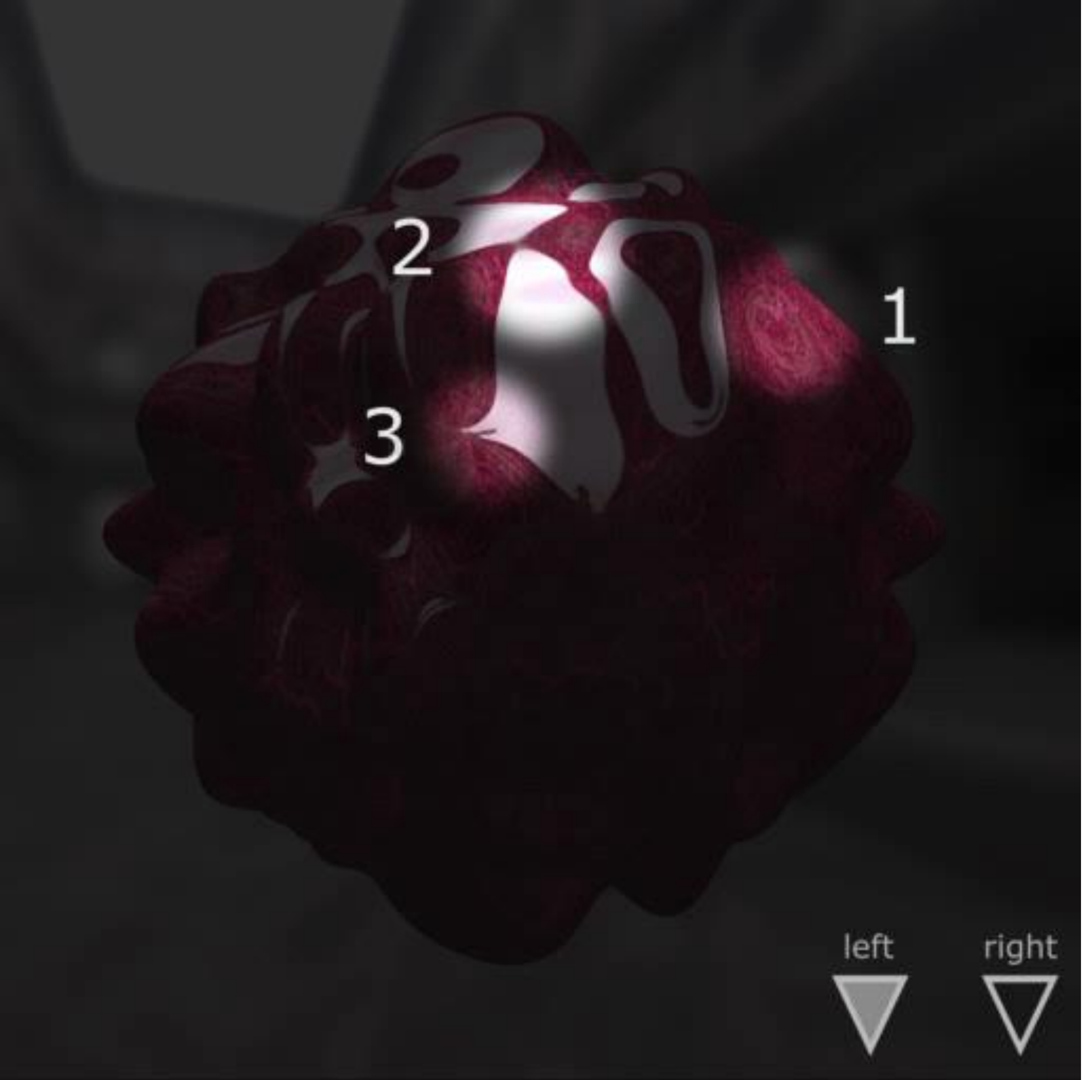



Rivalry



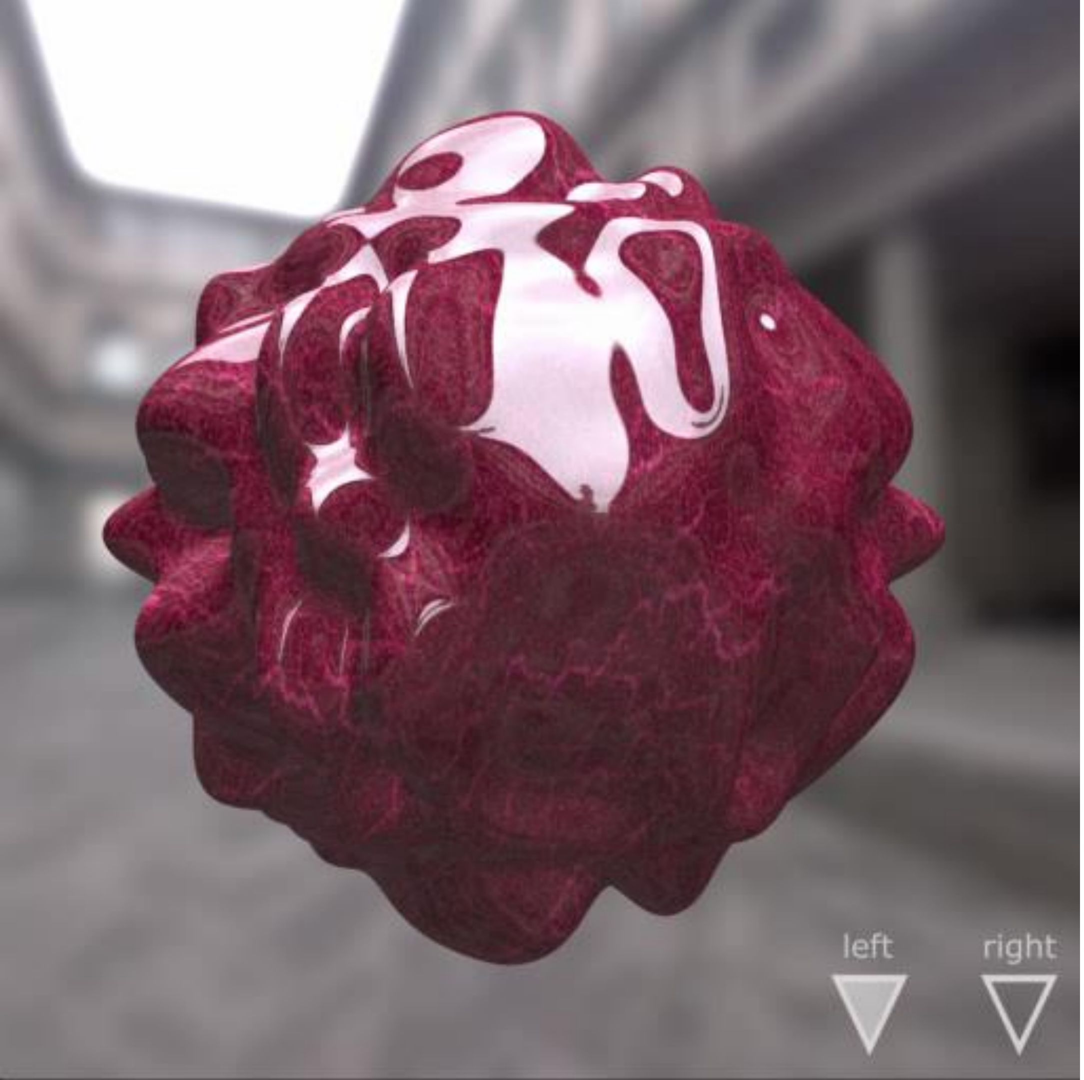
correct highlights

binocular conflicts

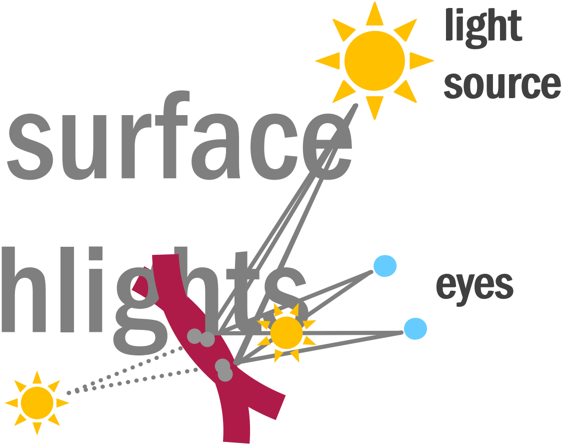


correct highlights

binocular conflicts

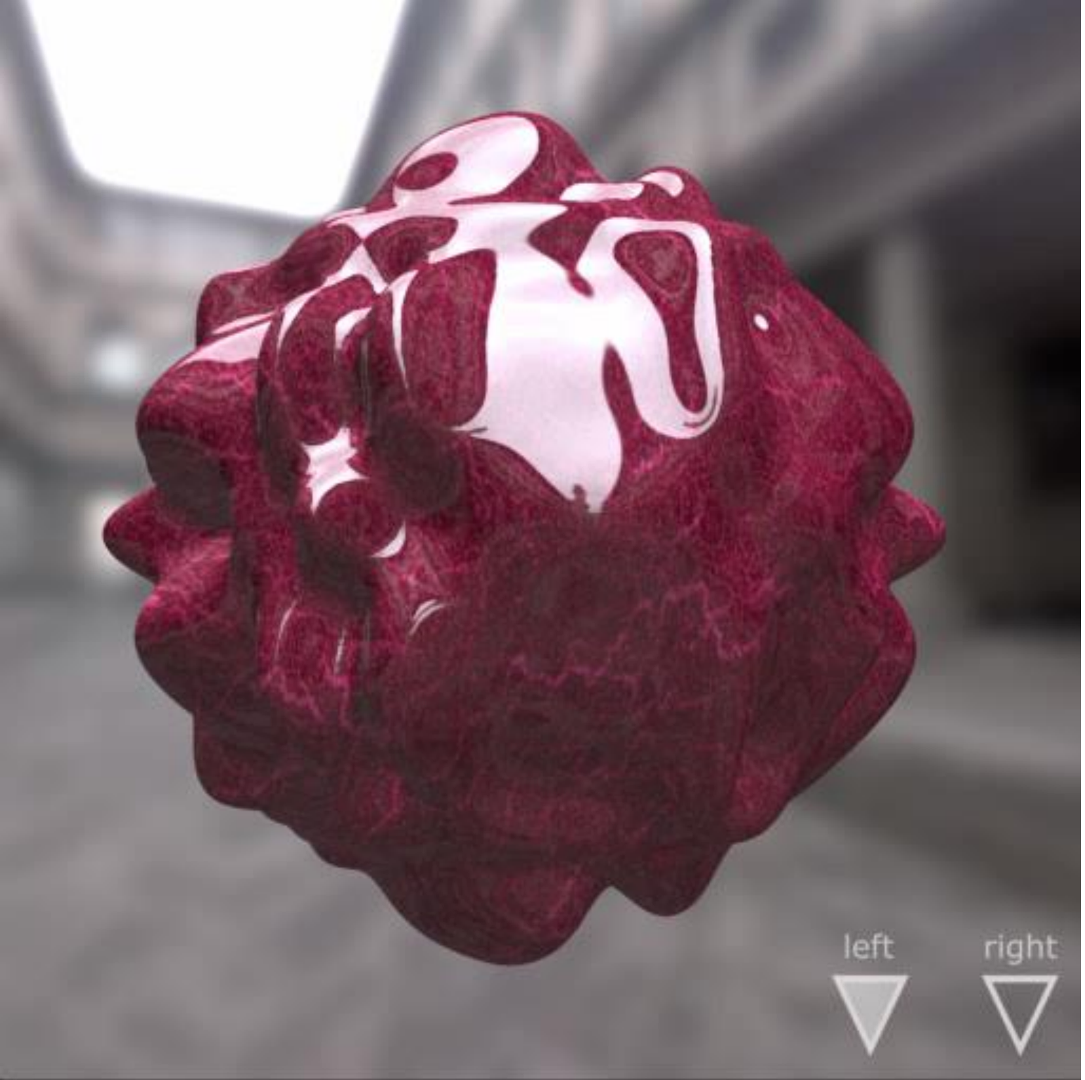


on-surface highlights



matte look

see: G. Wendt et al., 2008
Highlight disparity contributes to the authenticity and strength of perceived glossiness



our goal

no conflicts + glossy look

see: **E. A. Khan et al., 2006**

Image-based Material Editing

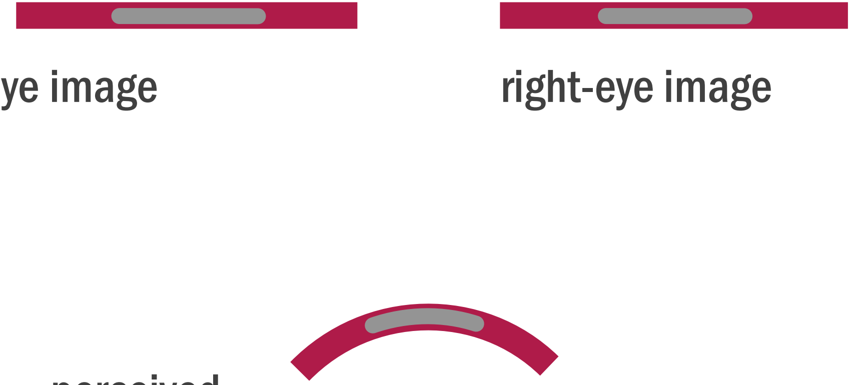
see: T. Ritschel et al., 2009

Interactive Reflection Editing

top view

🟥 surface

◼ highlight



left-eye image

right-eye image

perceived
3D image

see: A. Blake and H. Bülthoff, 1990
Does the brain know the physics of specular reflection?

specular part

detached highlights

surface highlights

specular part

glossy appearance

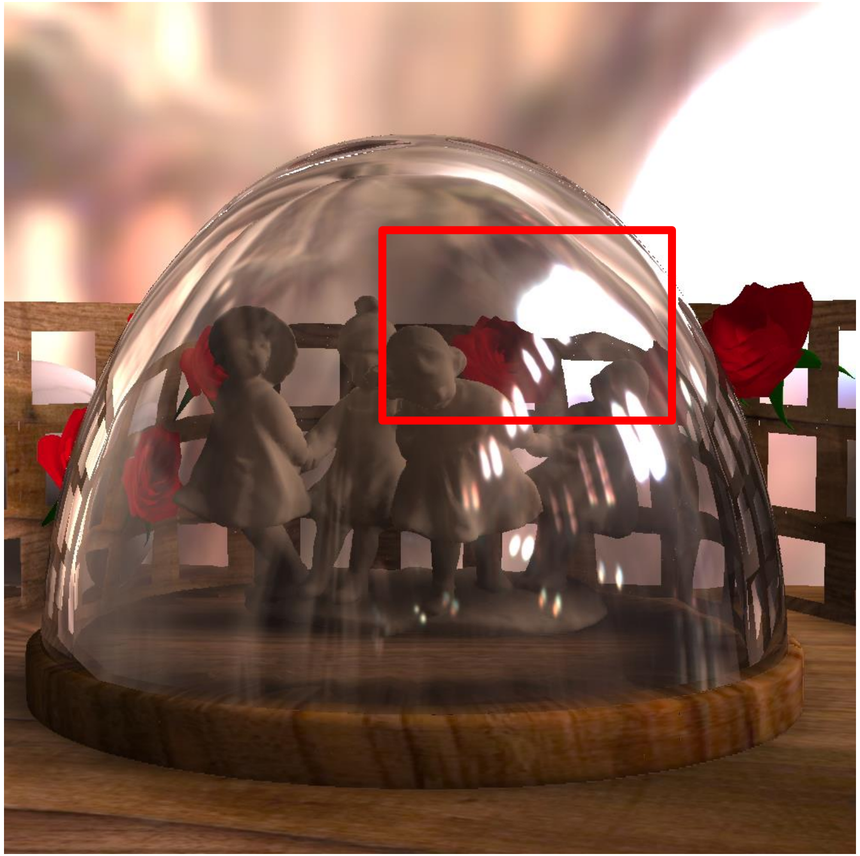
matte appearance

diffuse part

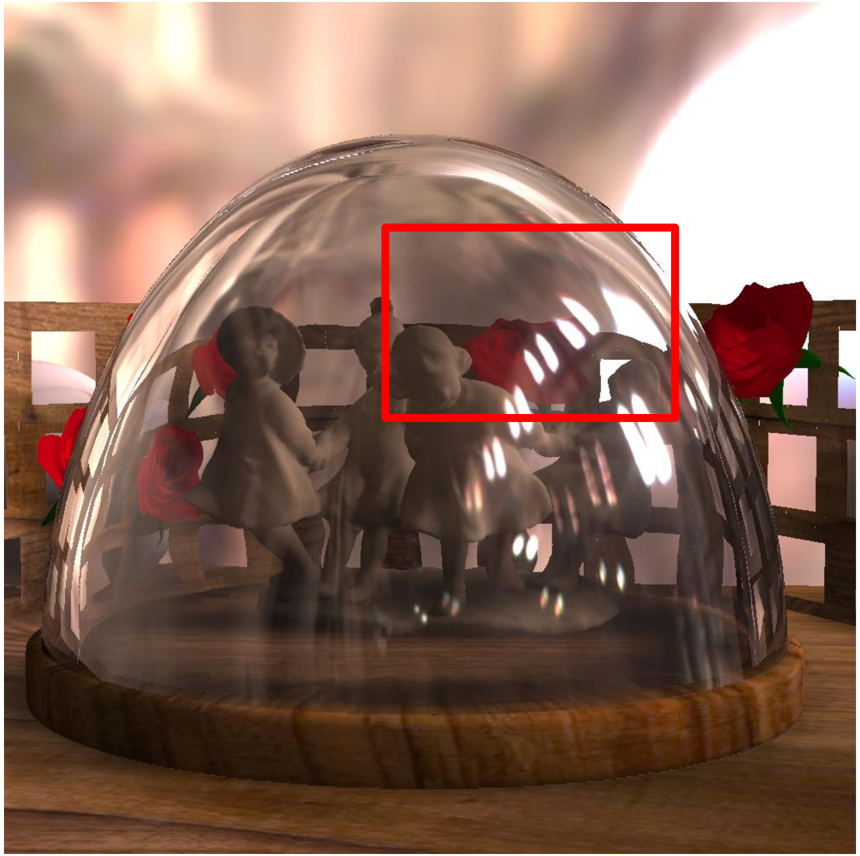
diffuse part

left-eye image

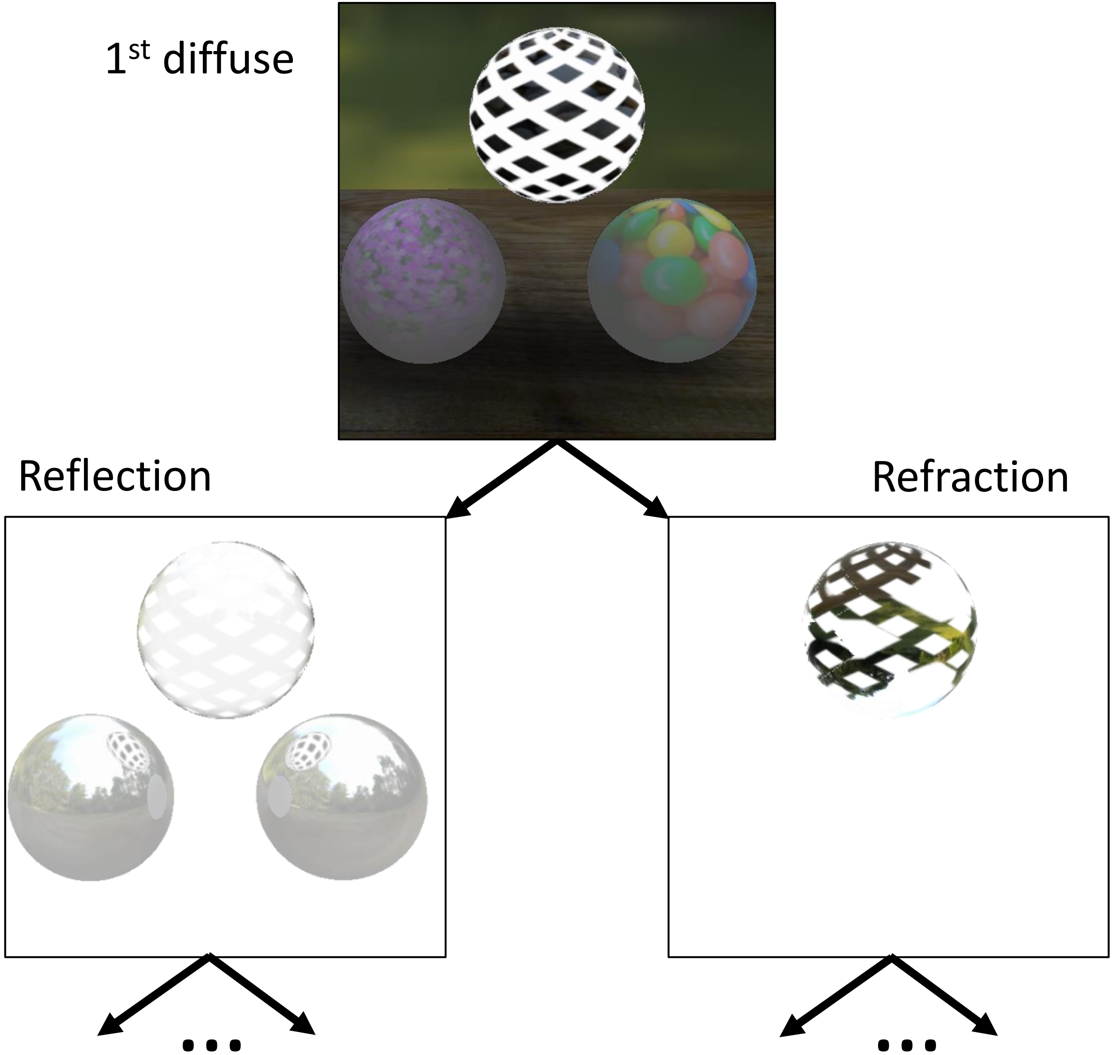
right-eye image



Physical



Ours



1st diffuse

Reflection

Refraction

...

...

Optimizing Eye Vergence – Film C

Cut in a Regular Film

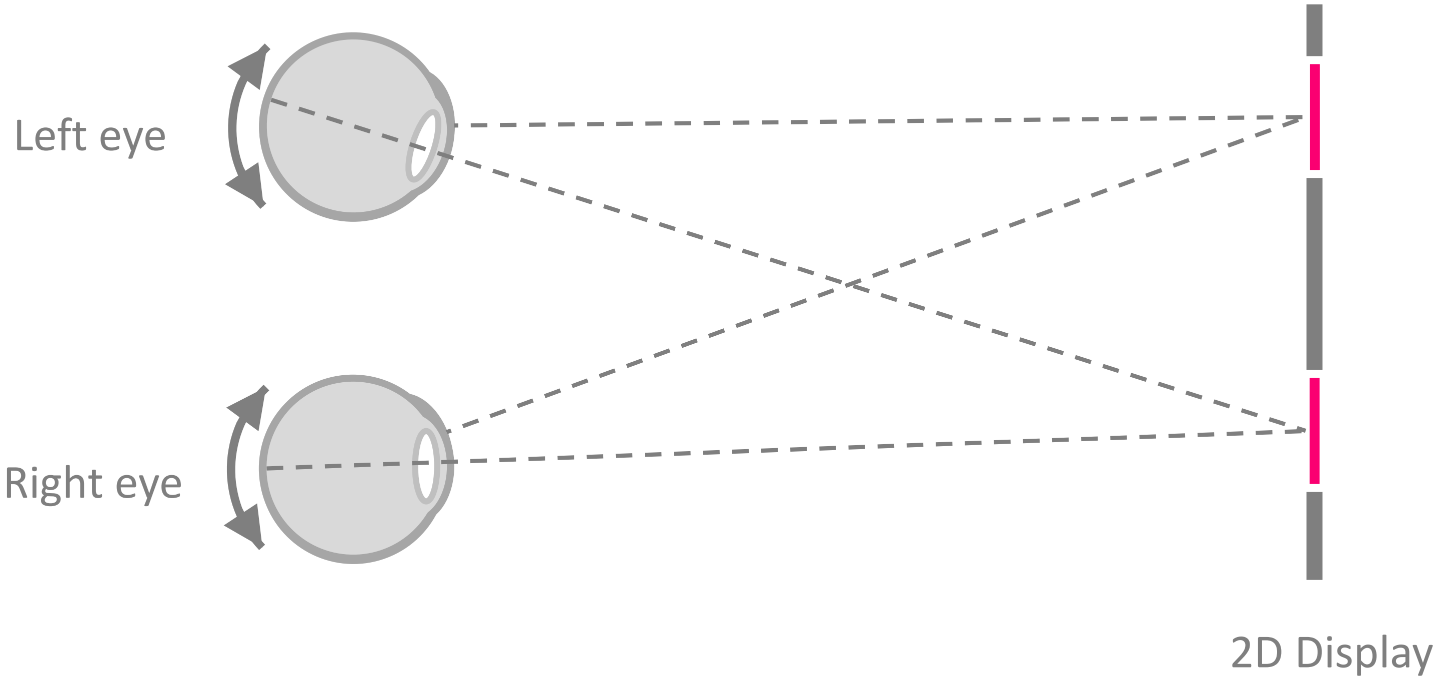
Shot 1

Shot 2

Cut

Source: *Big Buck Bunny* CC-BY Blender Foundation, Janus B. Kristensen

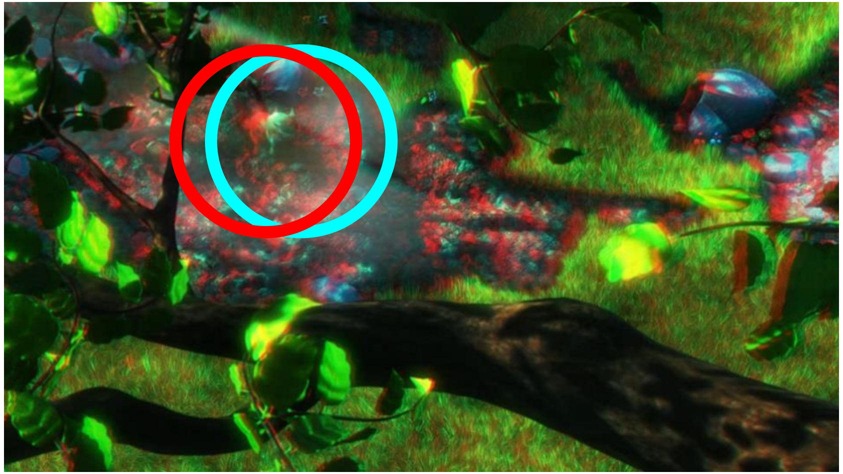
Saccades



Cut in a Stereoscopic 3D Film

● Left eye ● Right eye

Shot 1

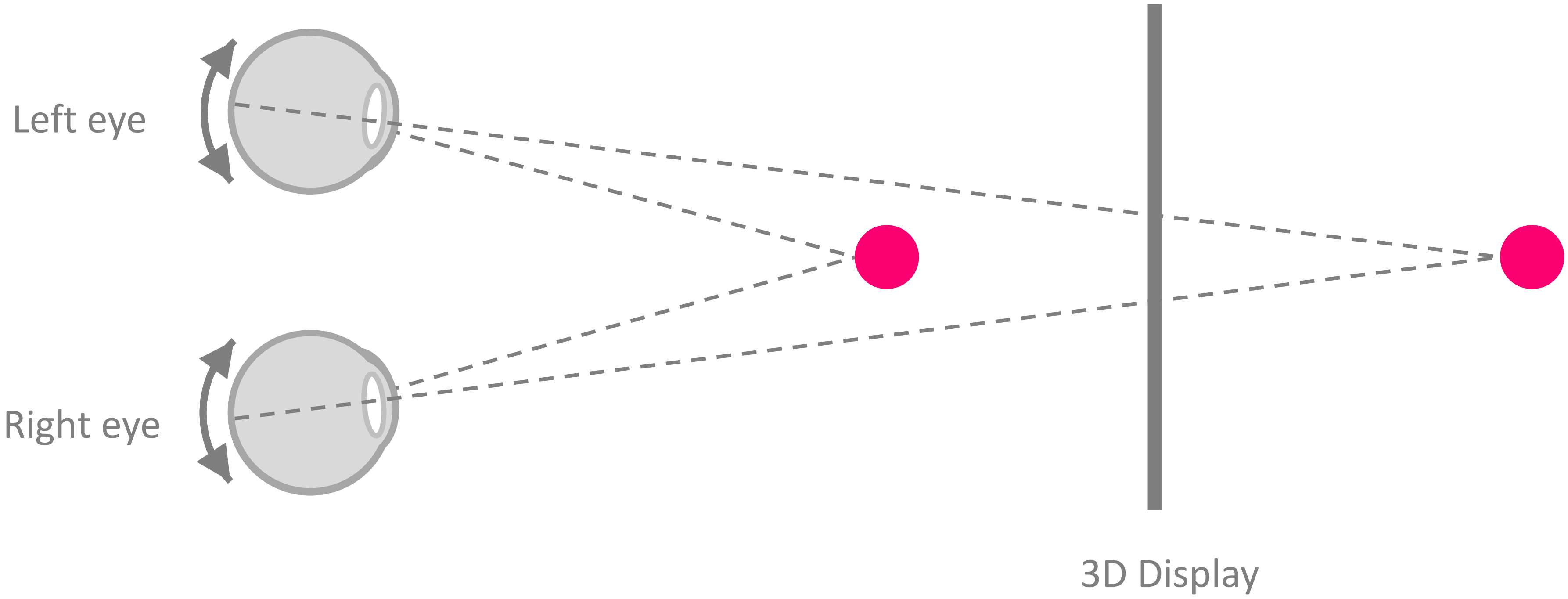


Shot 2

Cut

Source: *Big Buck Bunny* CC-BY Blender Foundation, Janus B. Kristensen

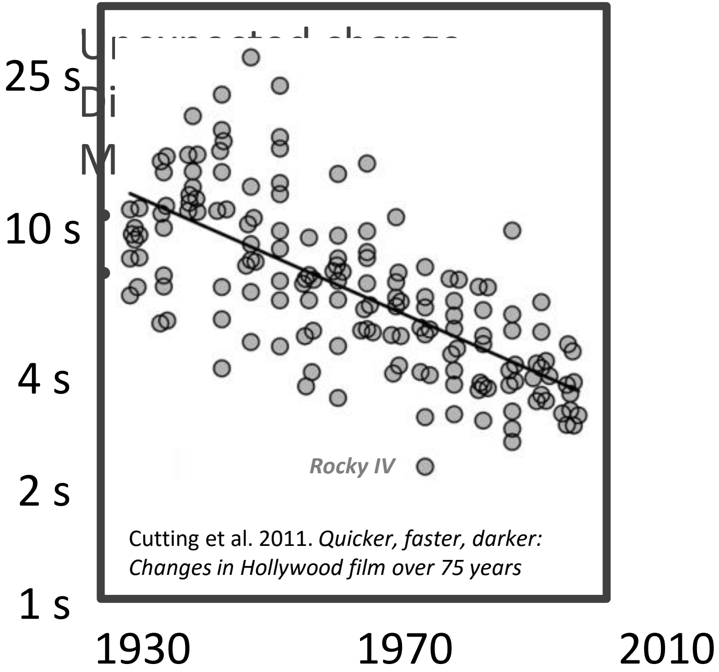
Vergence



Vergence vs. Film Editing

3D cuts are challenging

Average shot length

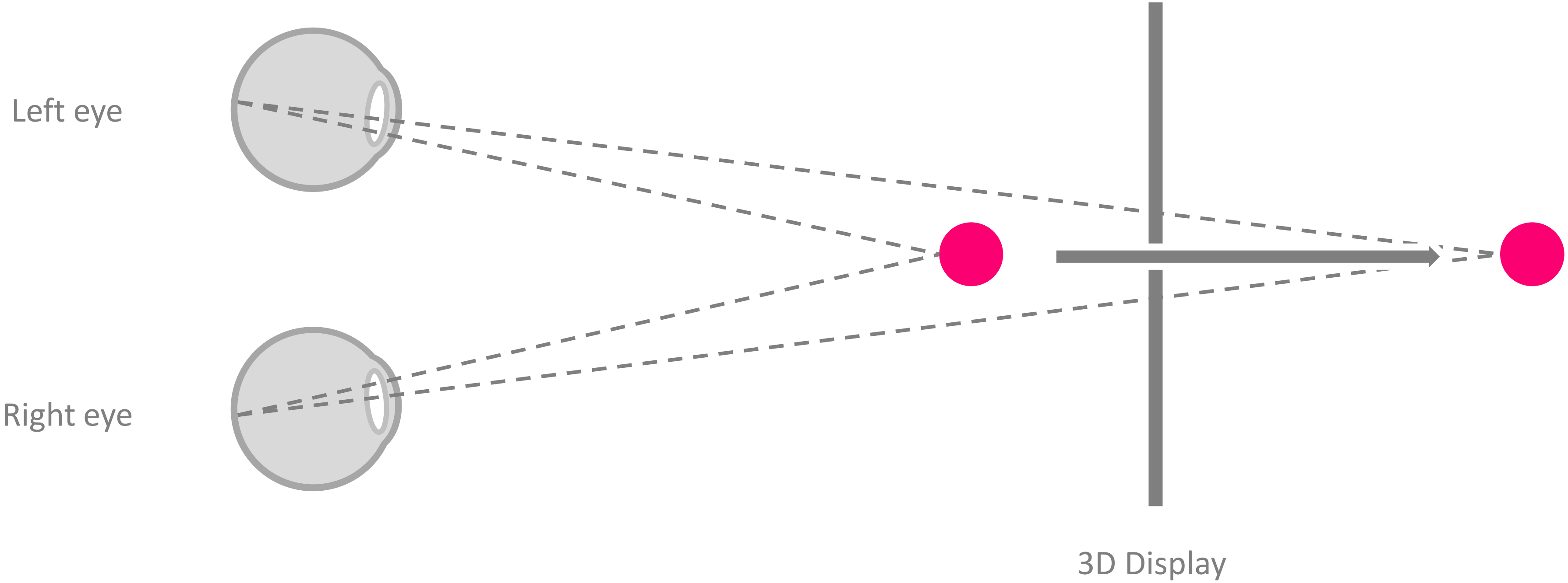


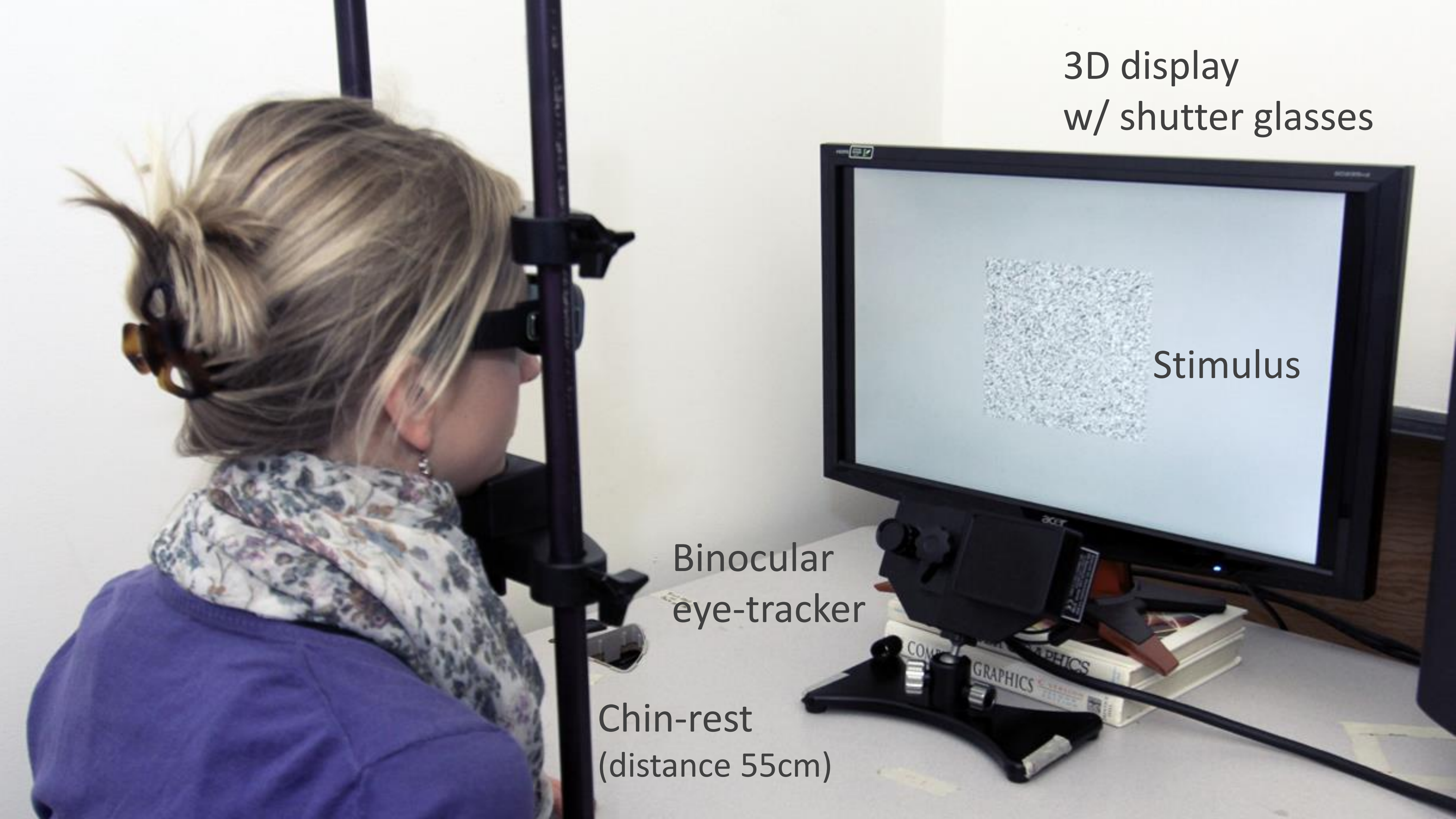
Cutting et al. 2011. *Quicker, faster, darker: Changes in Hollywood film over 75 years*

We want fast-paced editing

Vergence is slow

Eye-tracking Experiment



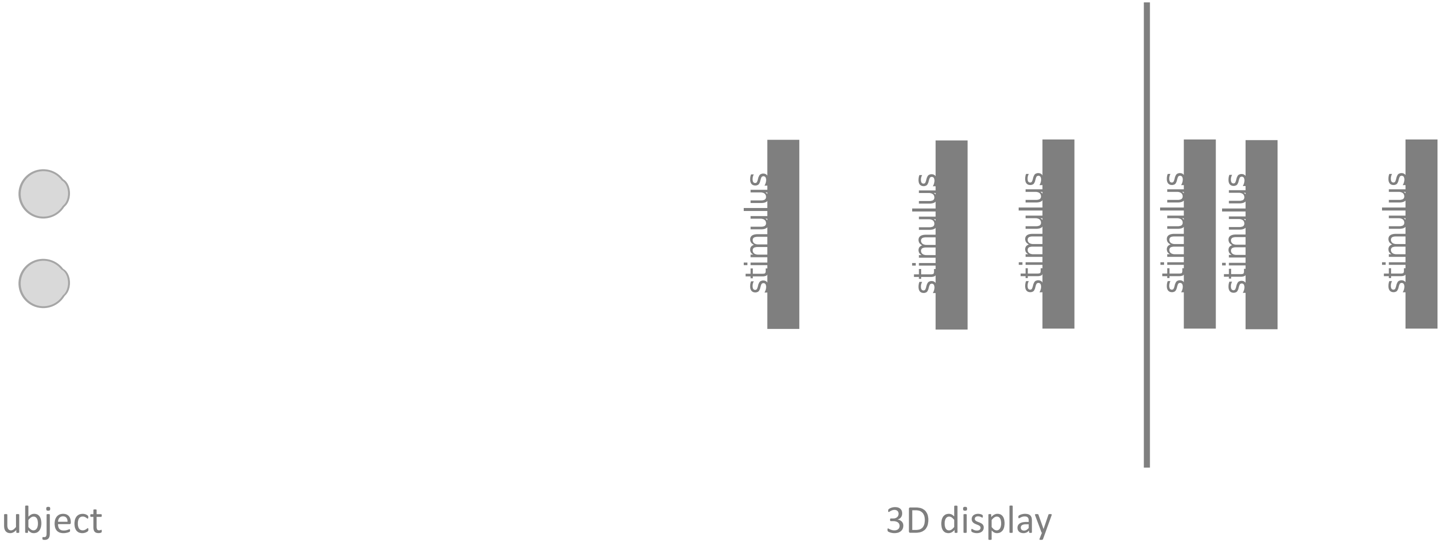

3D display
w/ shutter glasses

Stimulus

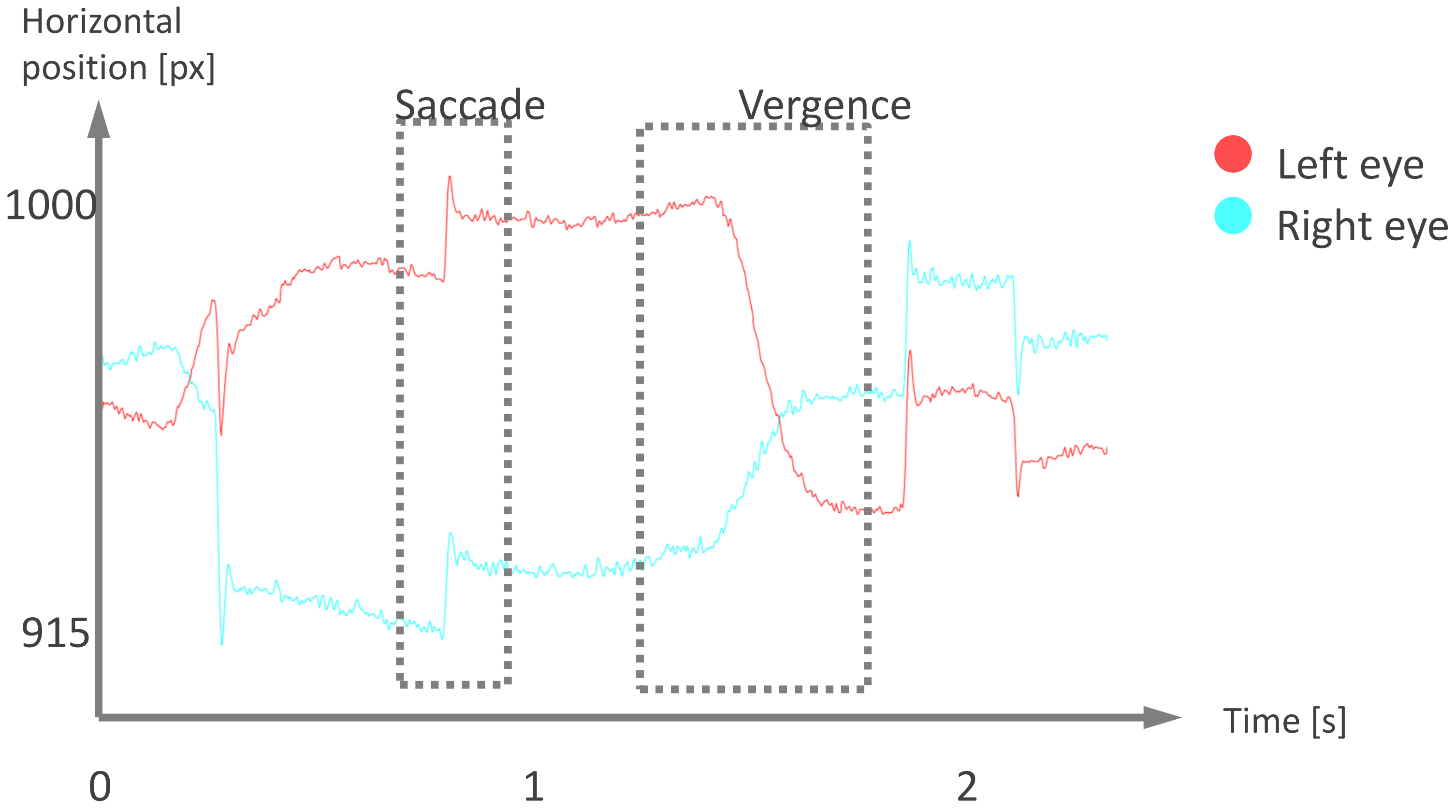
Binocular
eye-tracker

Chin-rest
(distance 55cm)

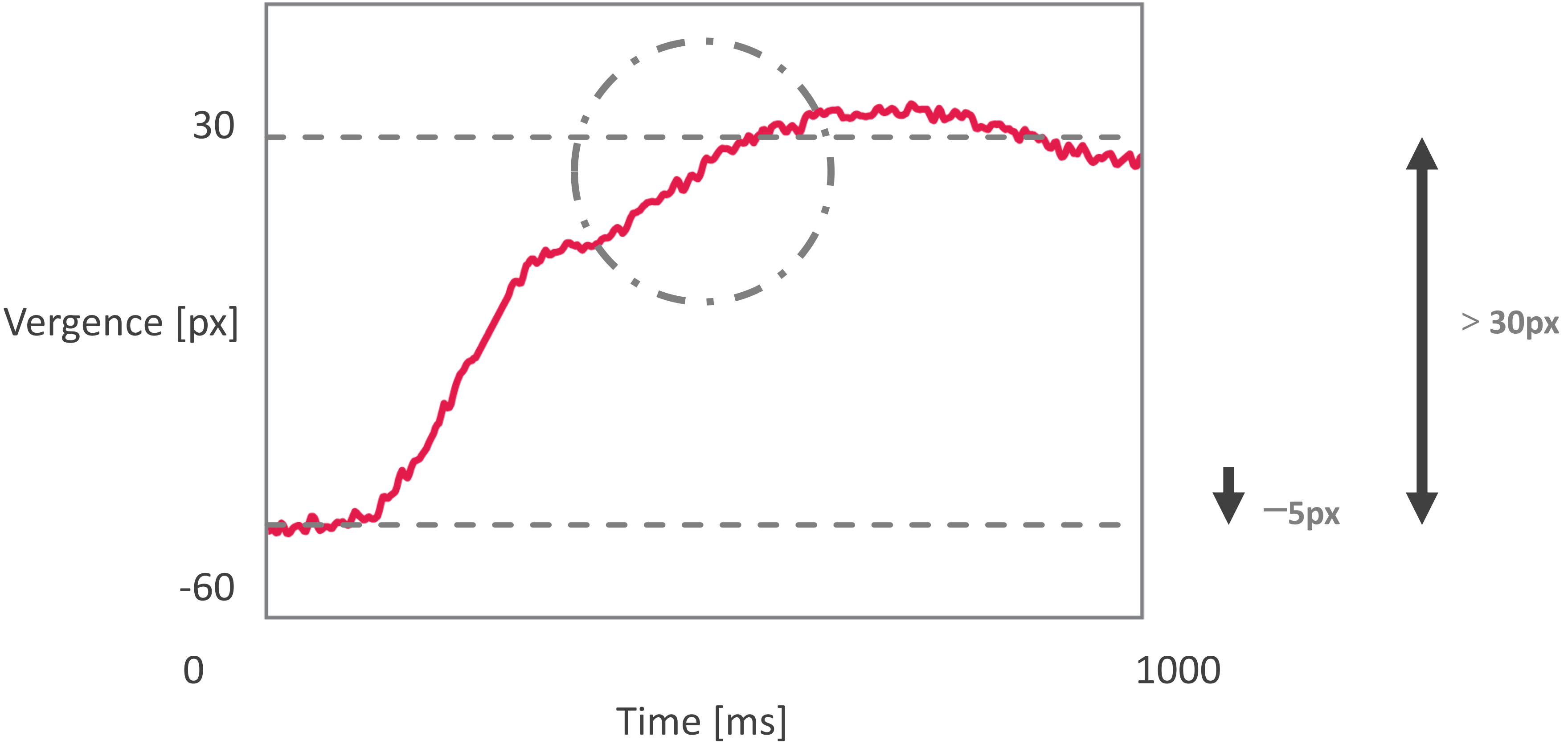
Eye-tracking Experiment



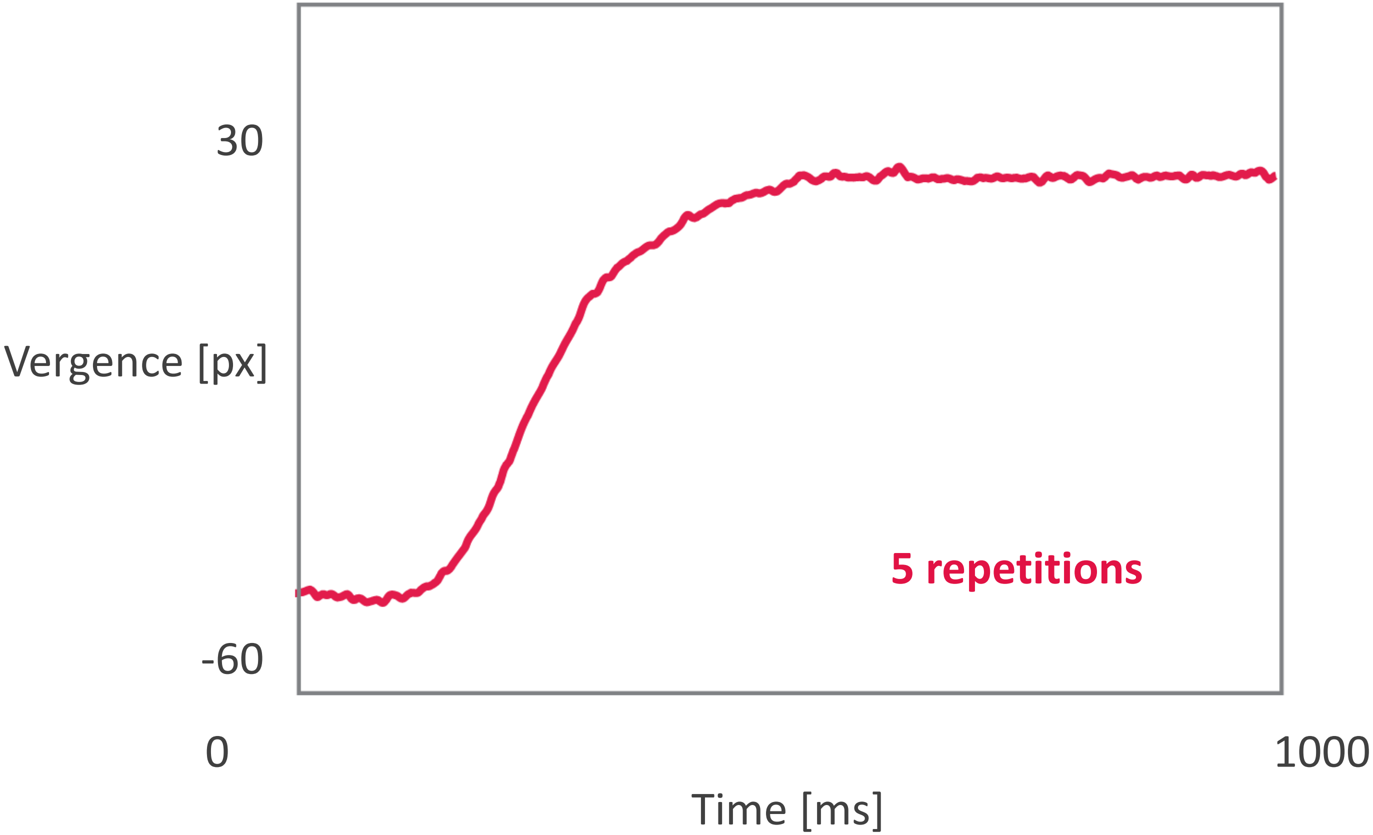
Vergence Response



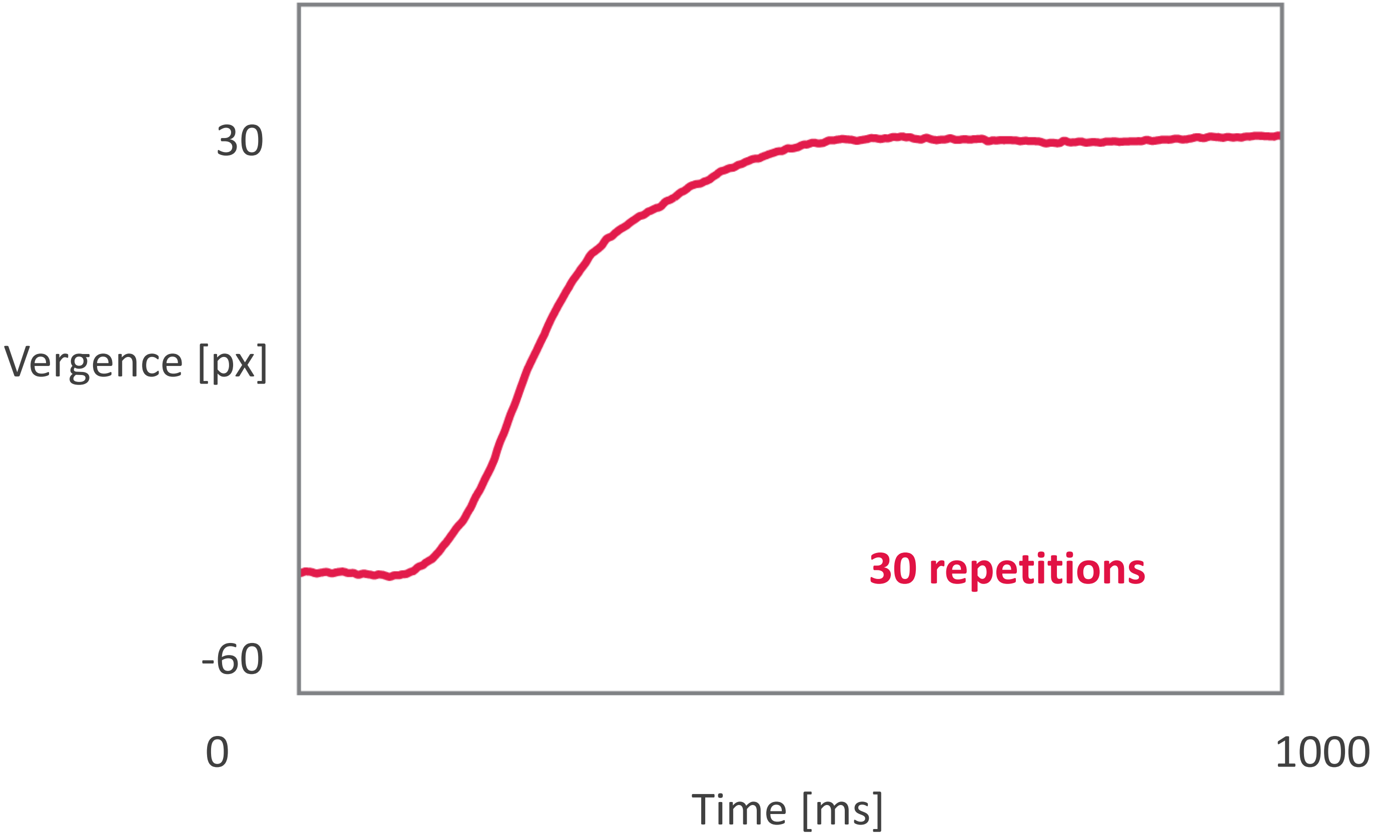
Vergence Curve



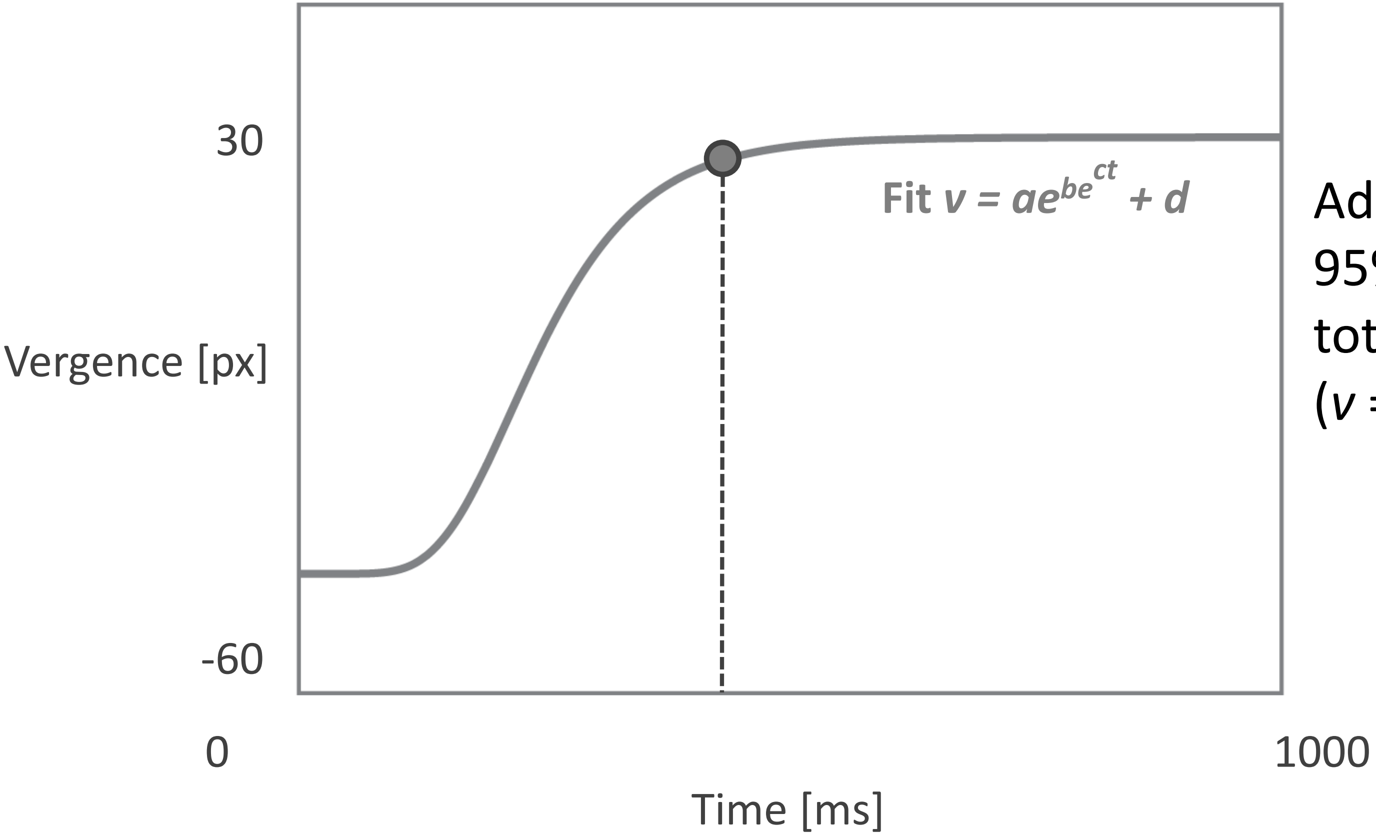
Response Averaging



Response Averaging

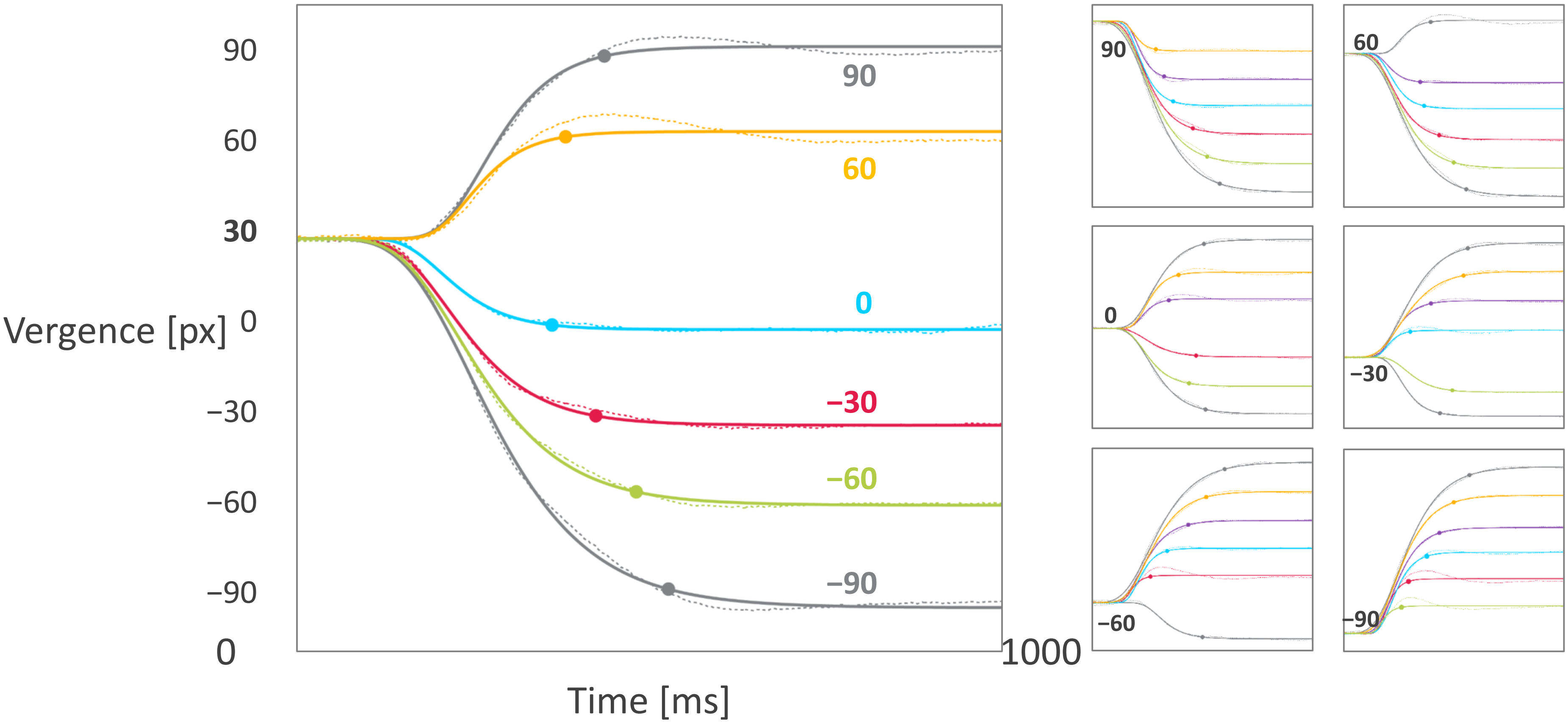


Adaptation Time Extraction



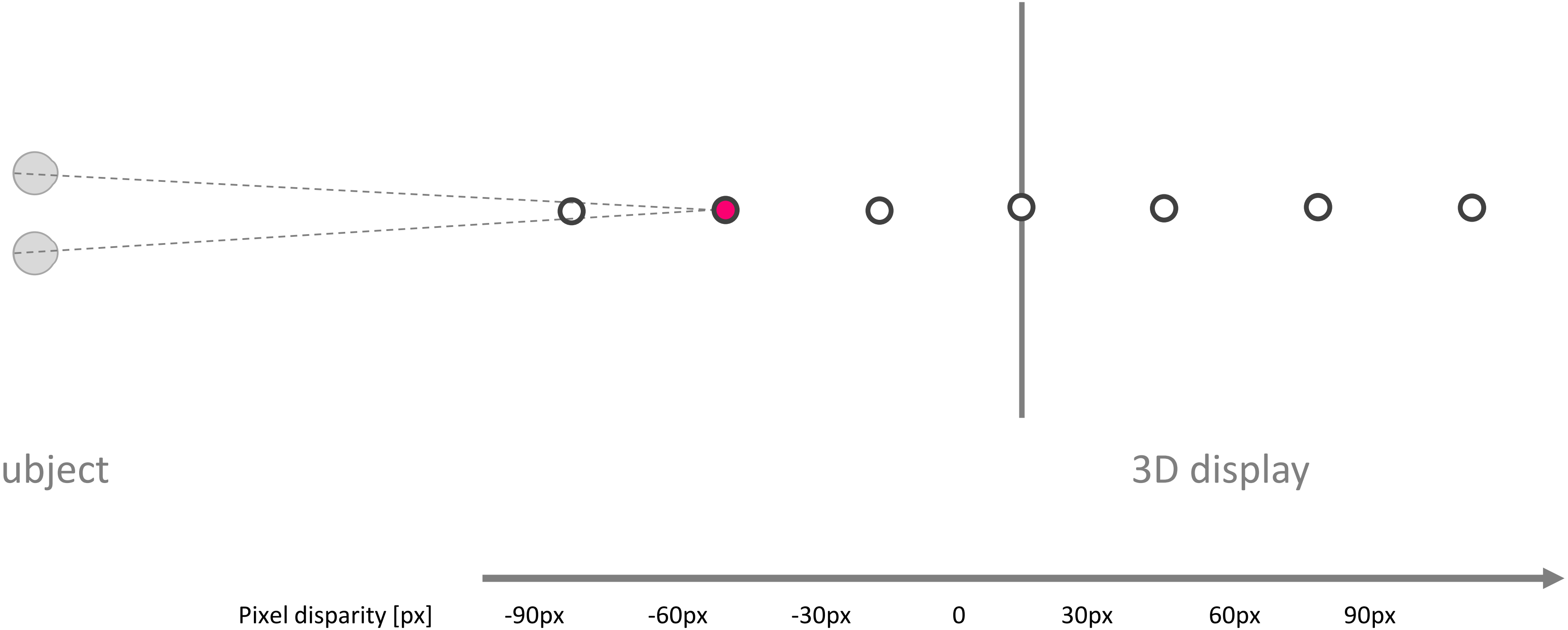
Adaptation time: 95% of the total change ($v = d + .95a$)

Experiment

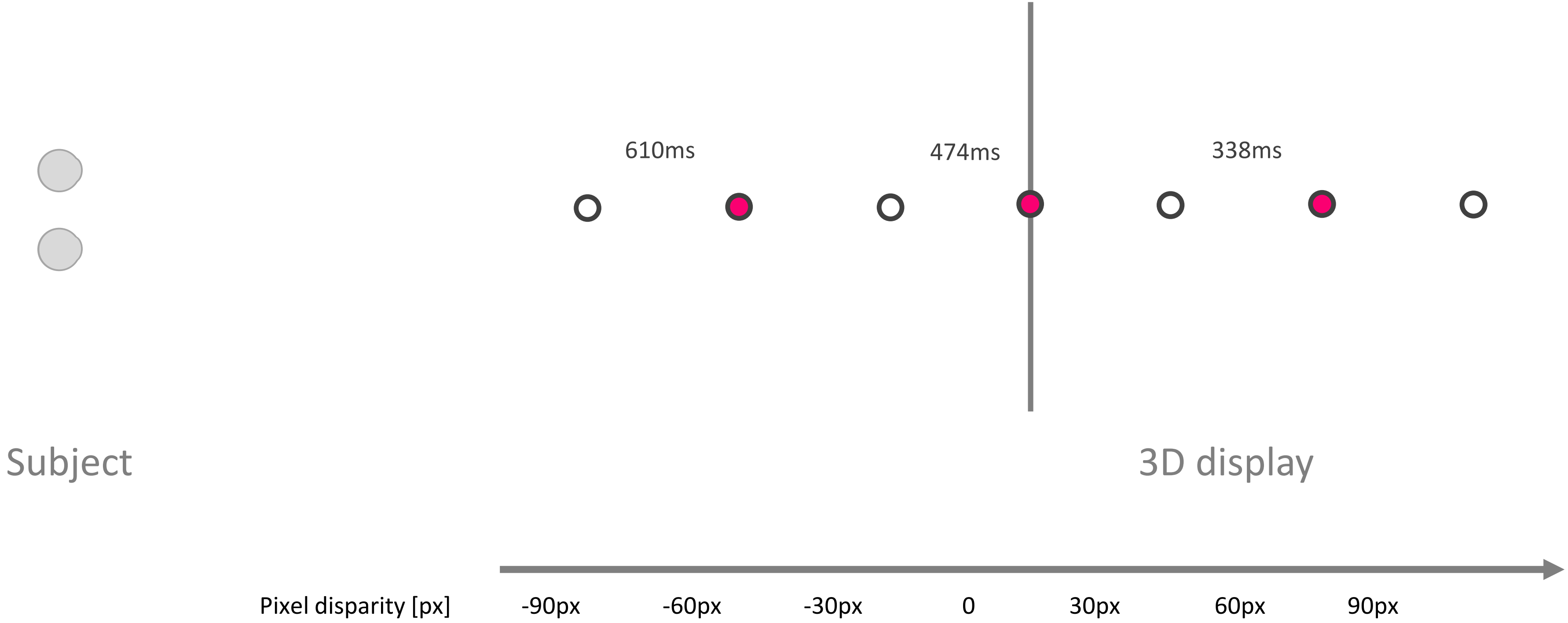


Vergence [px]
90
60
30
0
−30
−60
−90
0
1000
Time [ms]
90
60
0
−30
−60
−90
90
60
0
−30
−60
−90

Properties of the Model



Properties of the Model



610ms

474ms

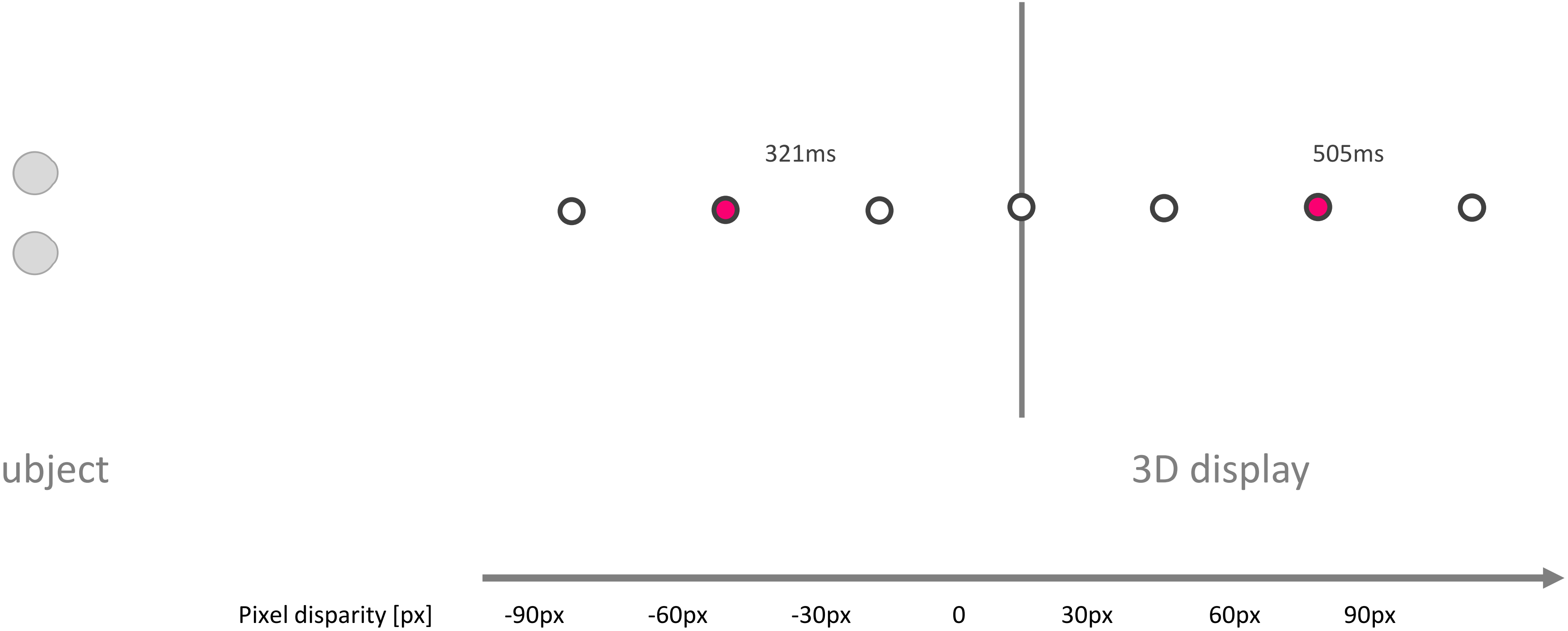
338ms

Subject

3D display

Pixel disparity [px] -90px -60px -30px 0 30px 60px 90px

Properties of the Model



321ms

505ms

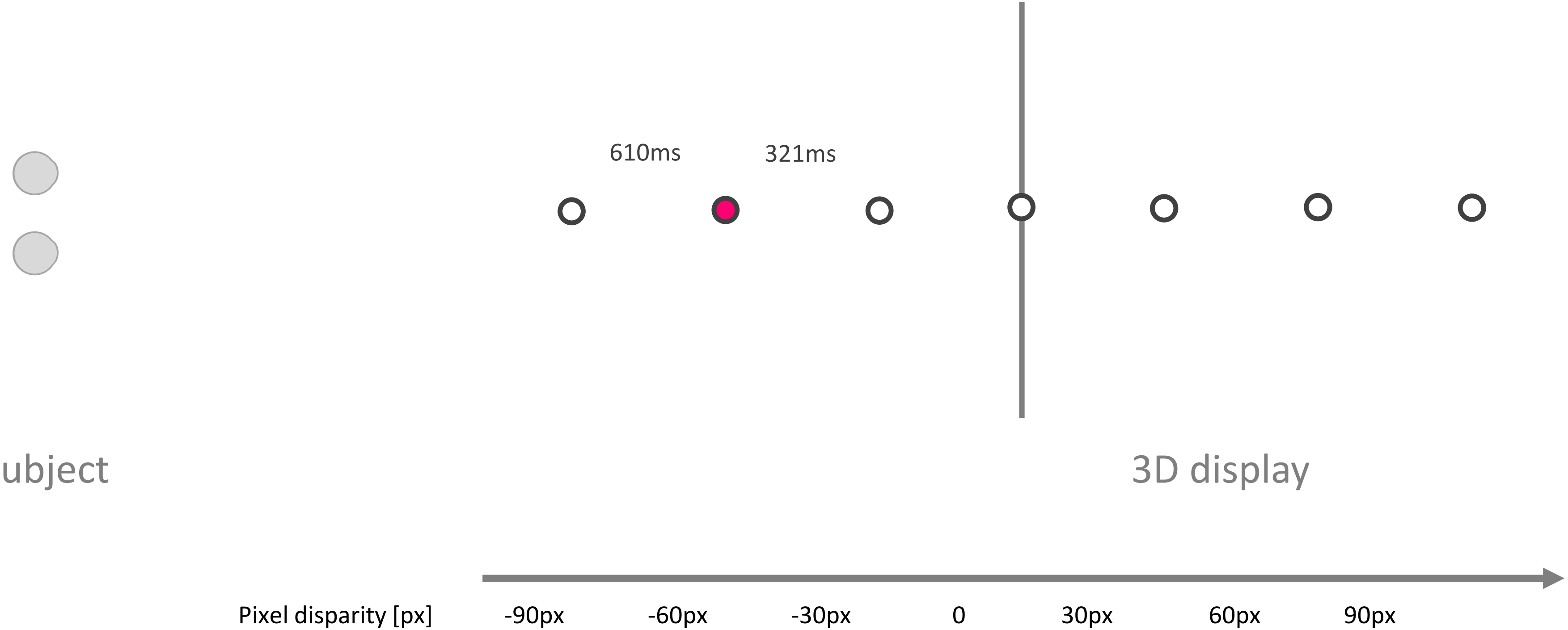
Subject

3D display

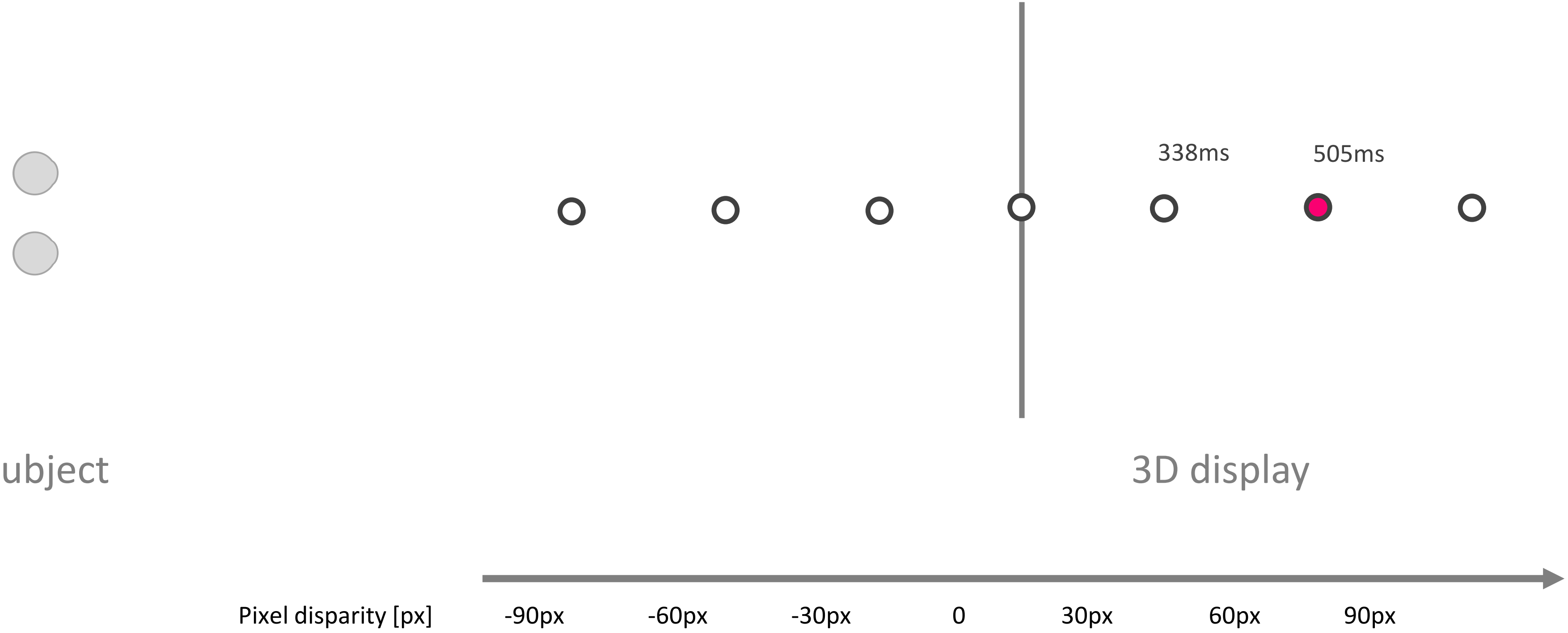
Pixel disparity [px]

-90px -60px -30px 0 30px 60px 90px

Properties of the Model



Properties of the Model



338ms

505ms

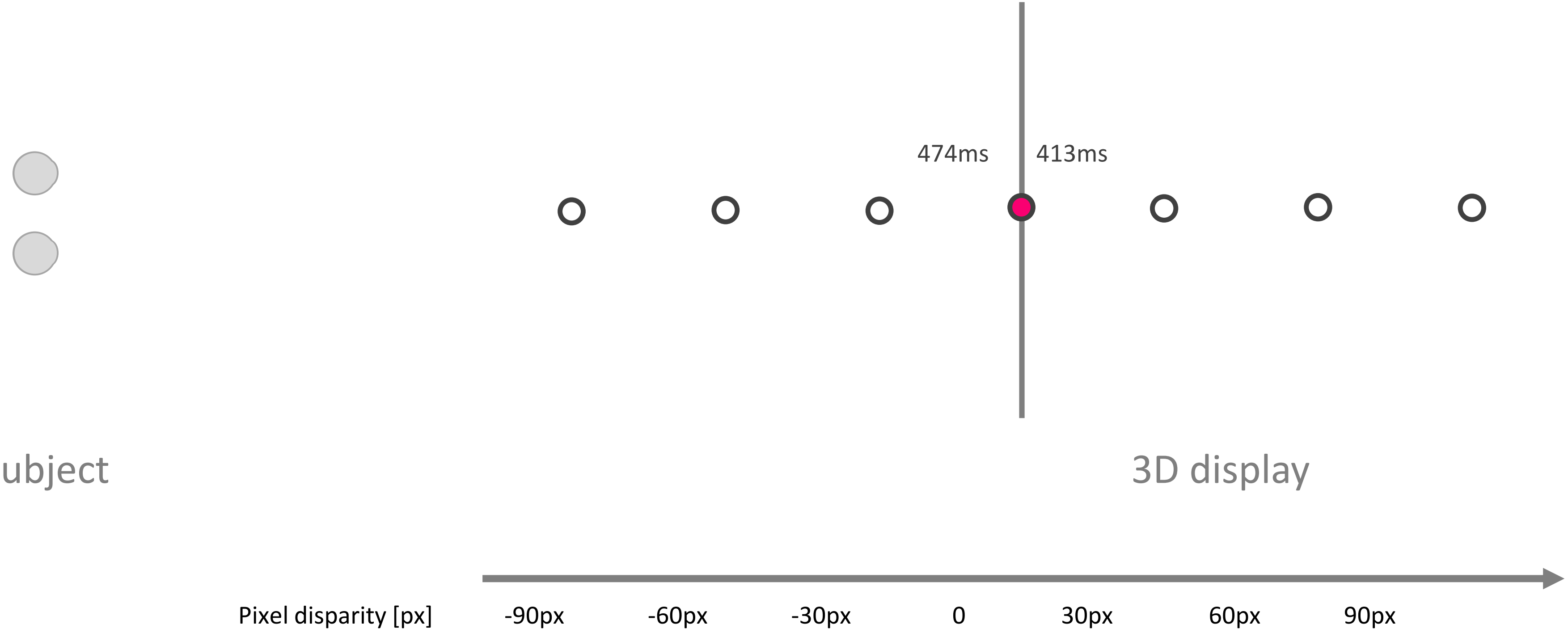
Subject

3D display

Pixel disparity [px]

-90px -60px -30px 0 30px 60px 90px

Properties of the Model



474ms

413ms

Subject

3D display

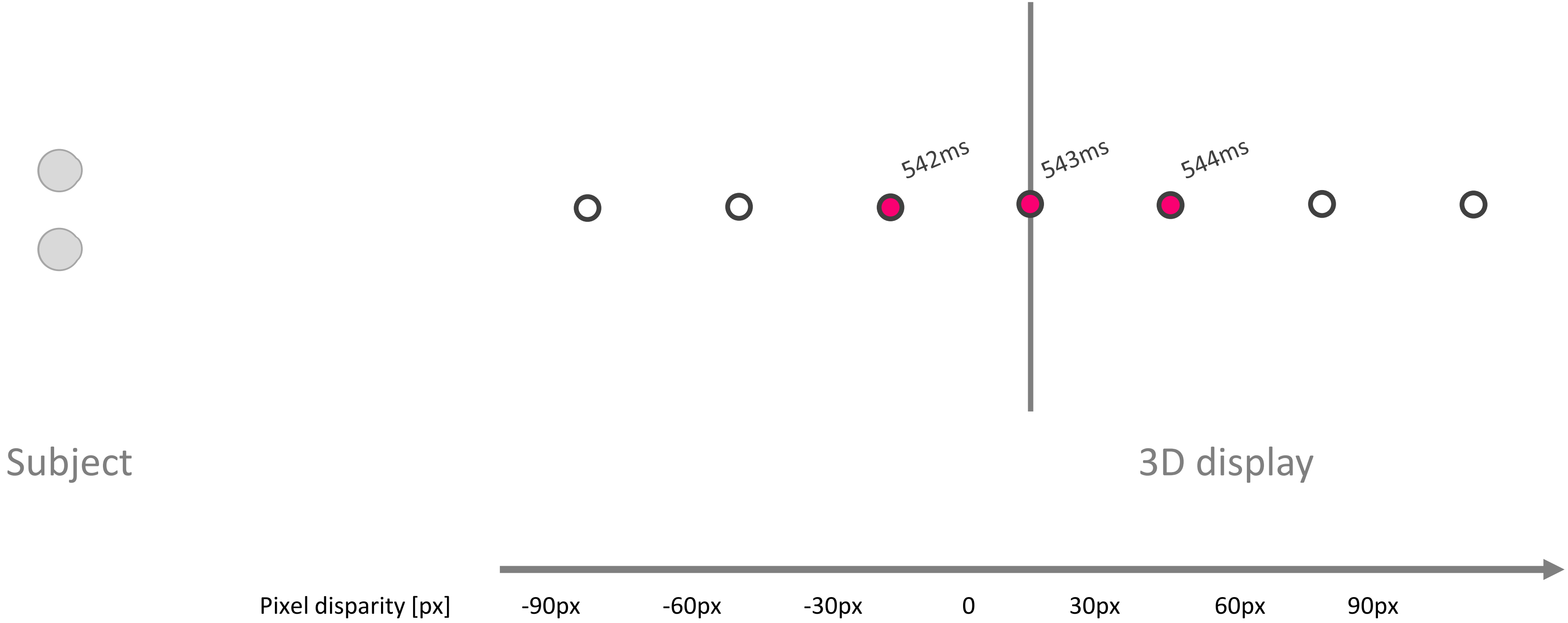
Pixel disparity [px]

-90px -60px -30px 0 30px 60px 90px

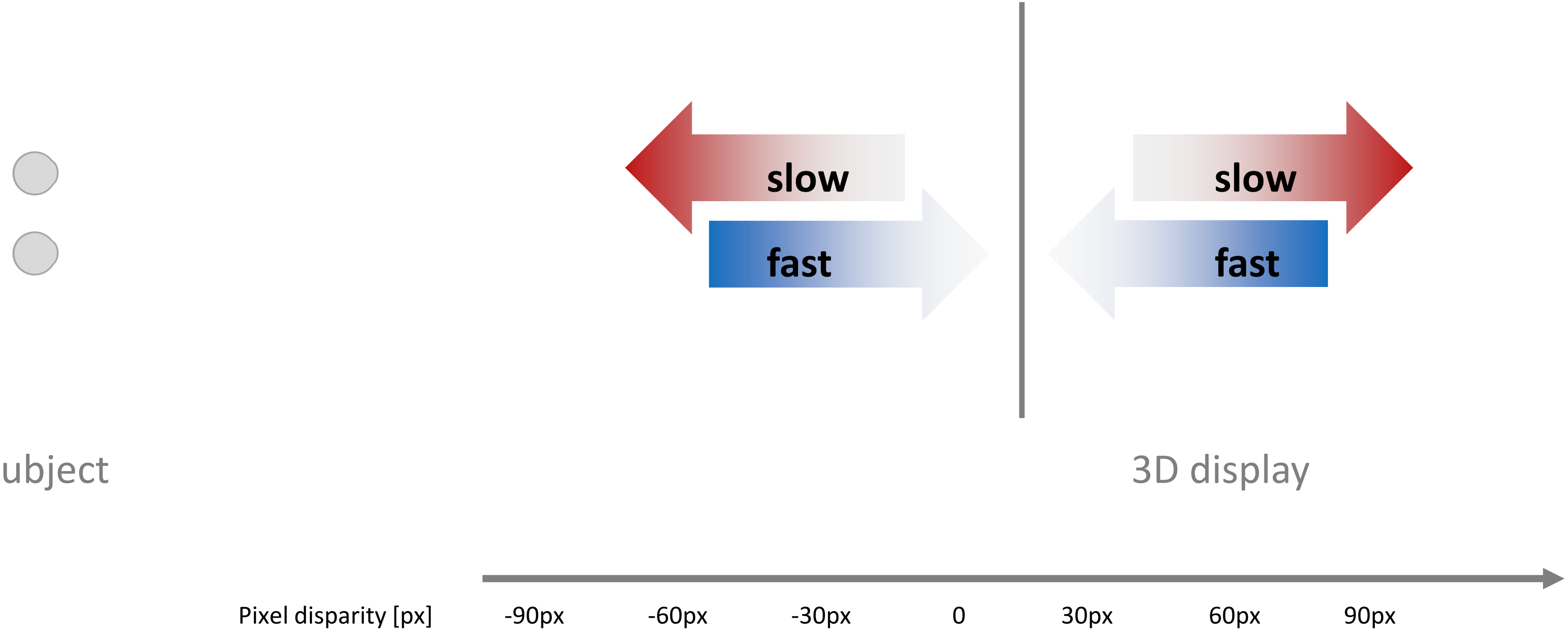
Properties of the Model

$$t = \boxed{0.04}\, d_i - 2.3\, d_t + 405.02$$

$$t = -1.96\, d_i + 3.49\, d_t + 308.72$$



Properties of the Model



slow

fast

slow

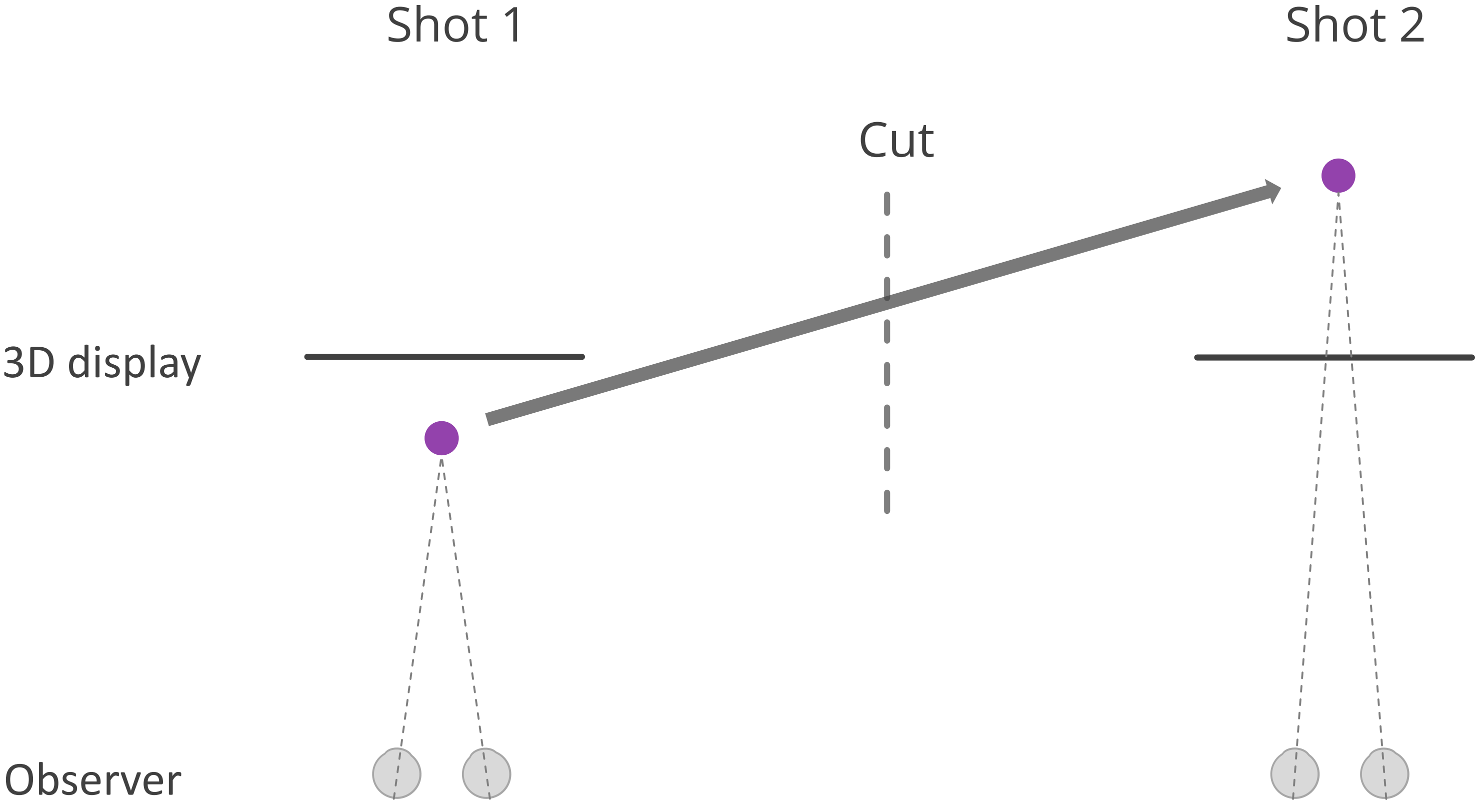
fast

Subject

3D display

Pixel disparity [px] -90px -60px -30px 0 30px 60px 90px

Cut Optimization



Shot 1

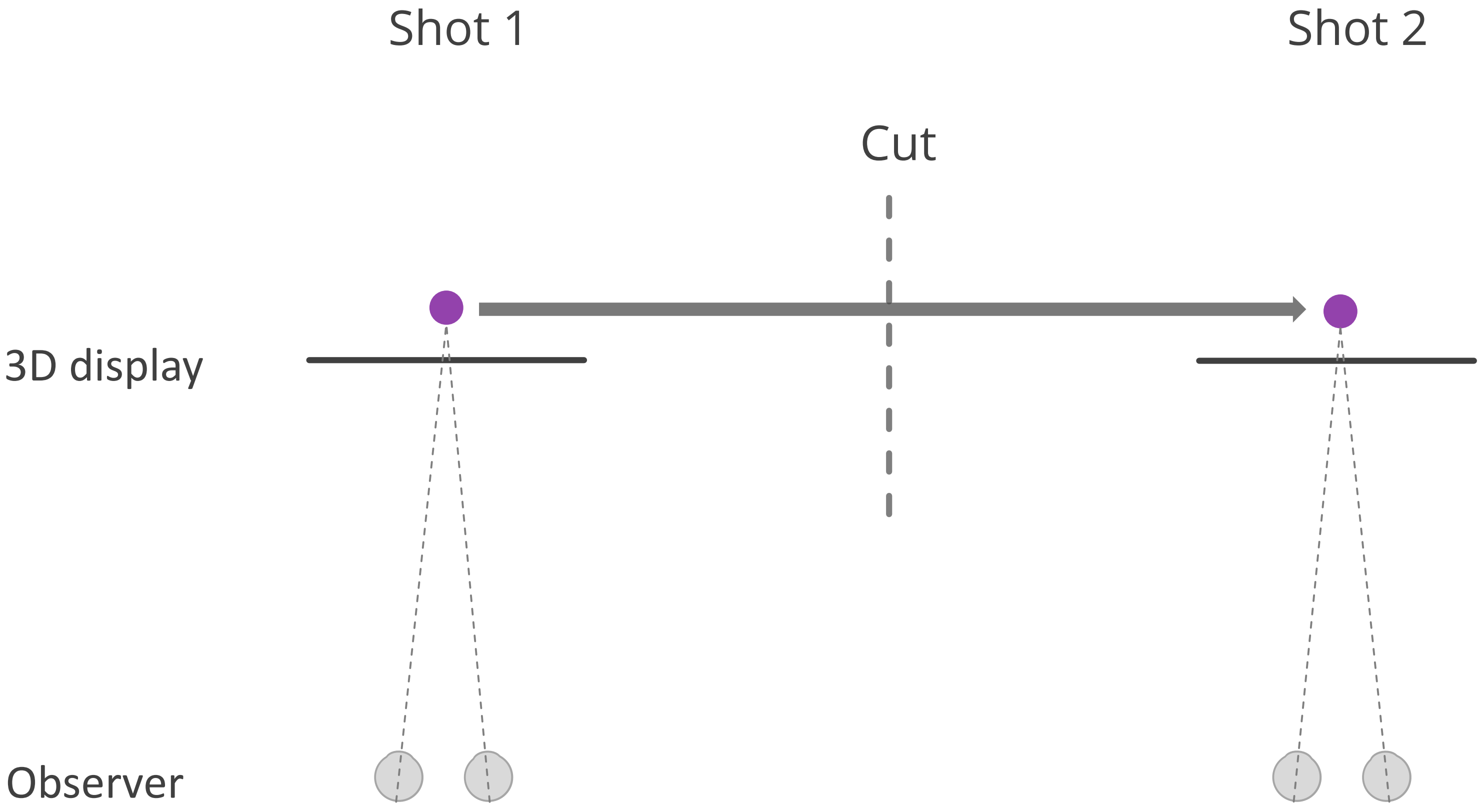
Shot 2

Cut

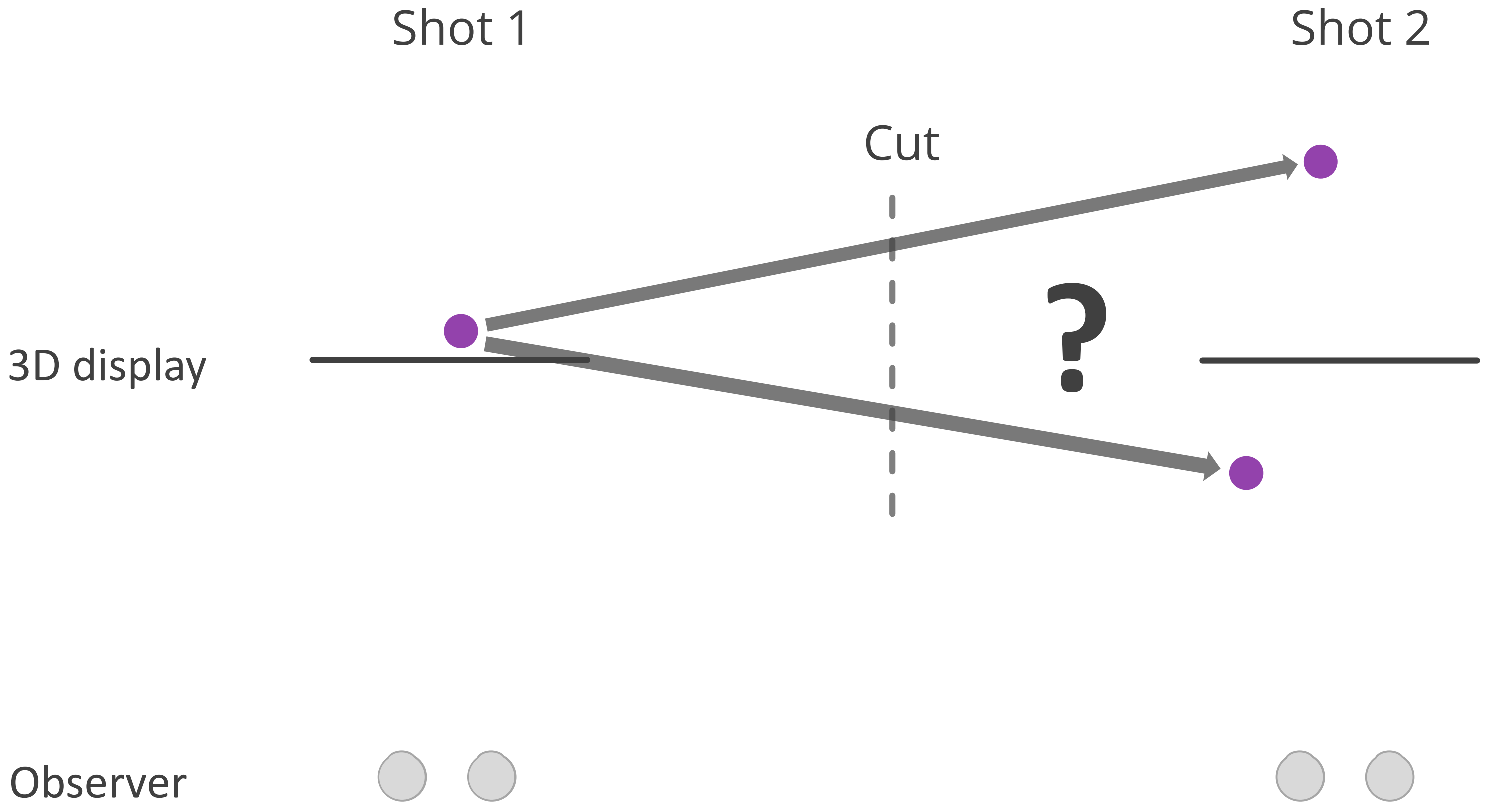
3D display

Observer

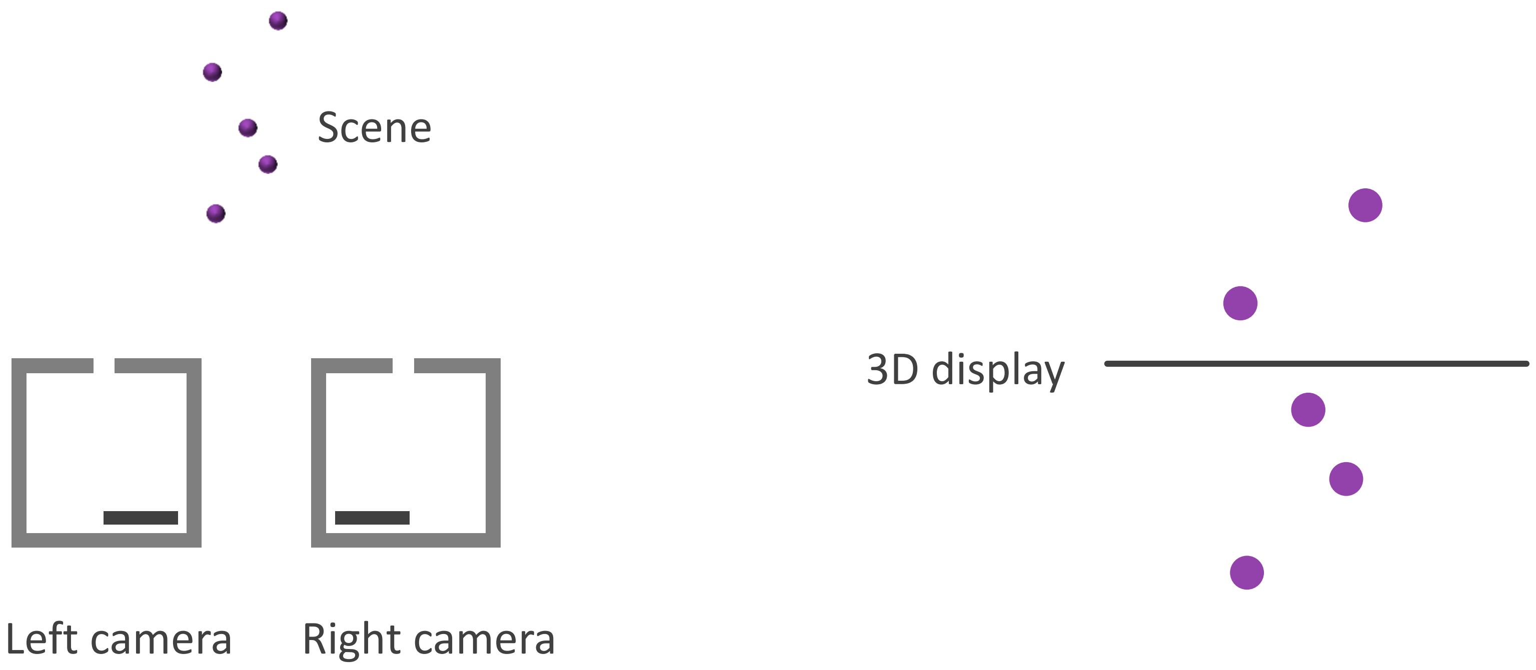
Cut Optimization



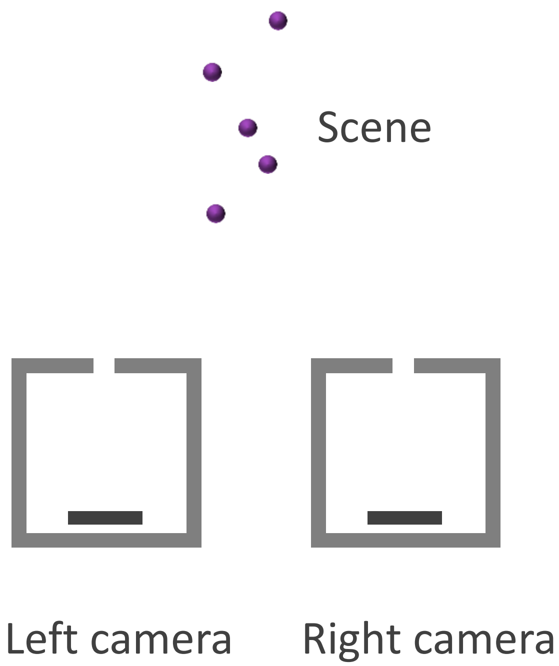
Cut Optimization

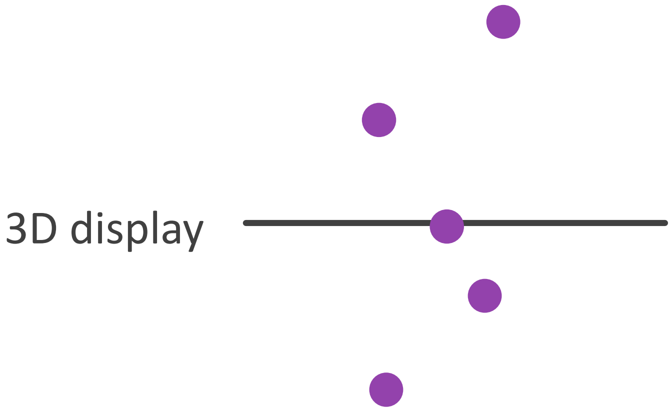


How To Adjust a Cut?

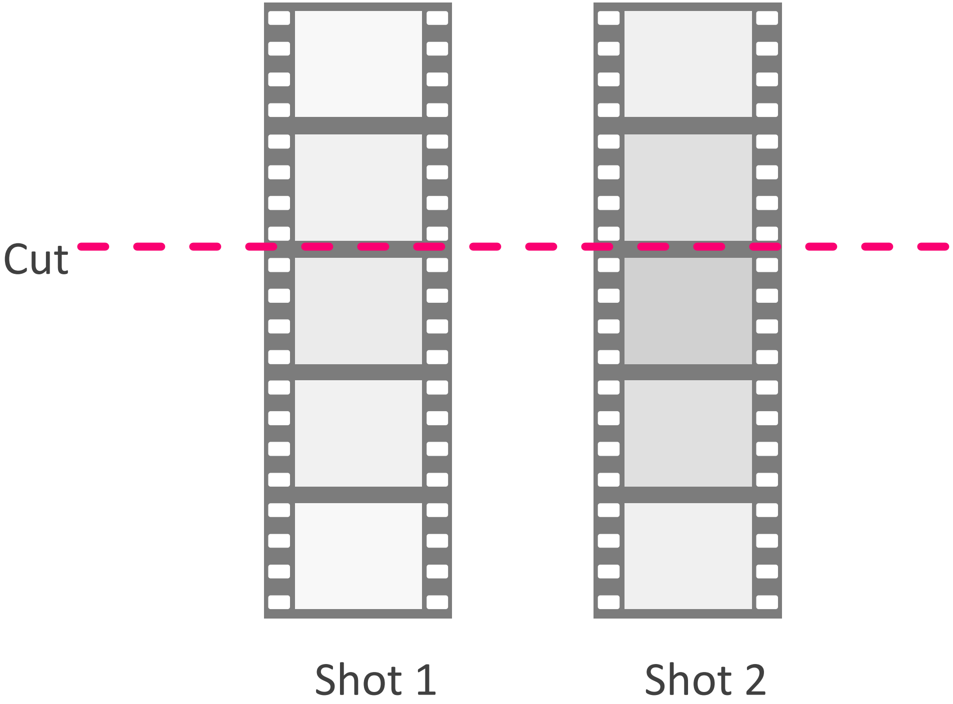


How To Adjust a Cut?

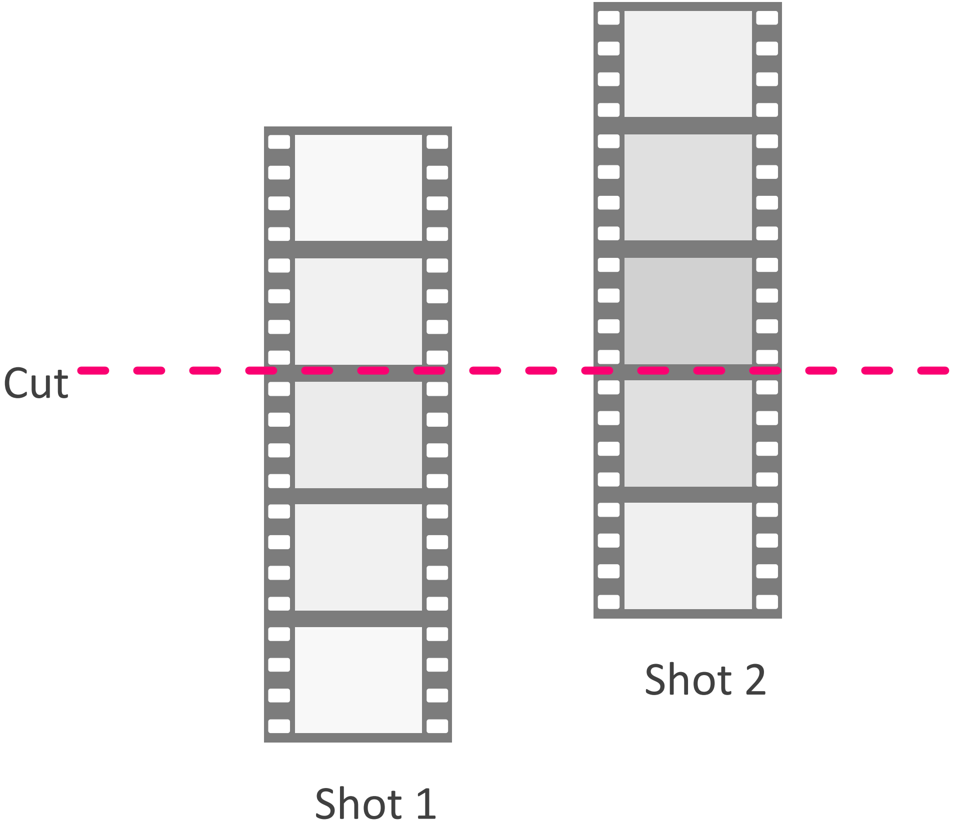




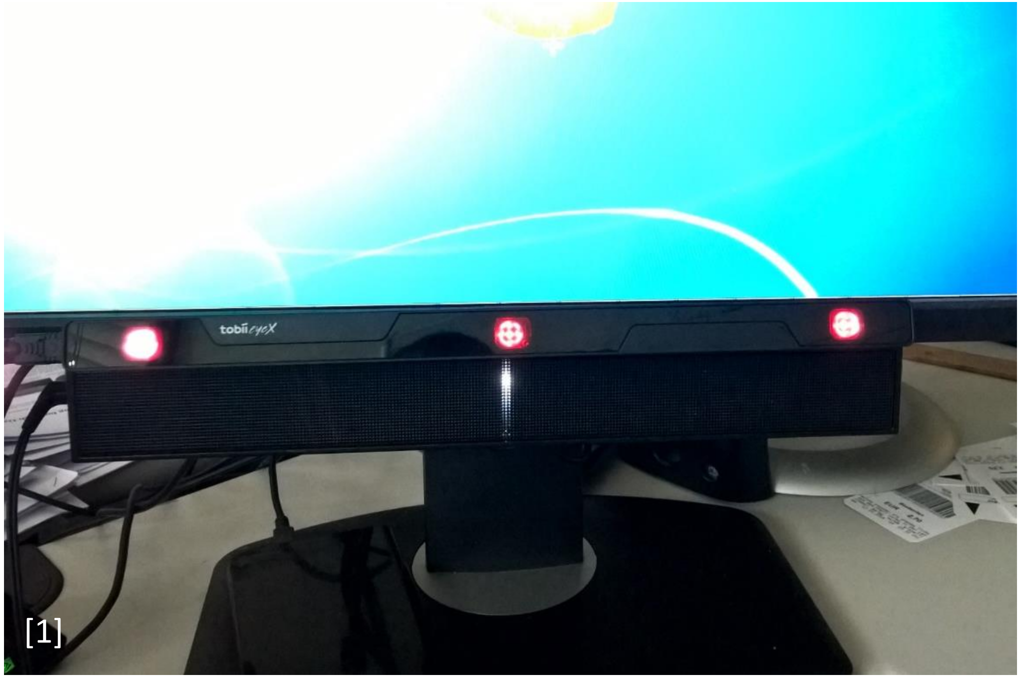
How To Adjust a Cut?



How To Adjust a Cut?

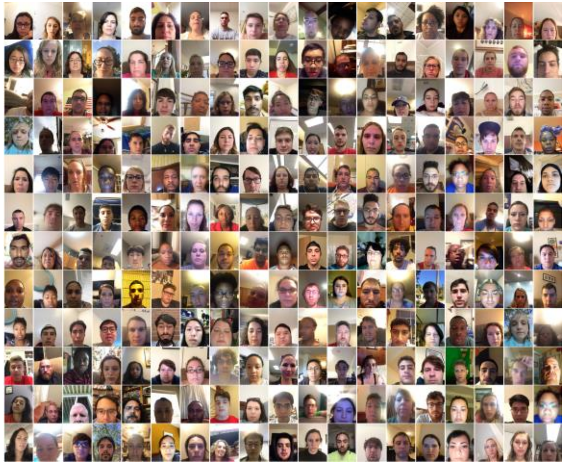


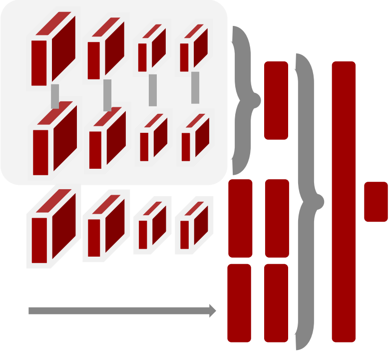
Gaze-driven Disparity Remapping



Dedicated HW

[2]





Computer vision

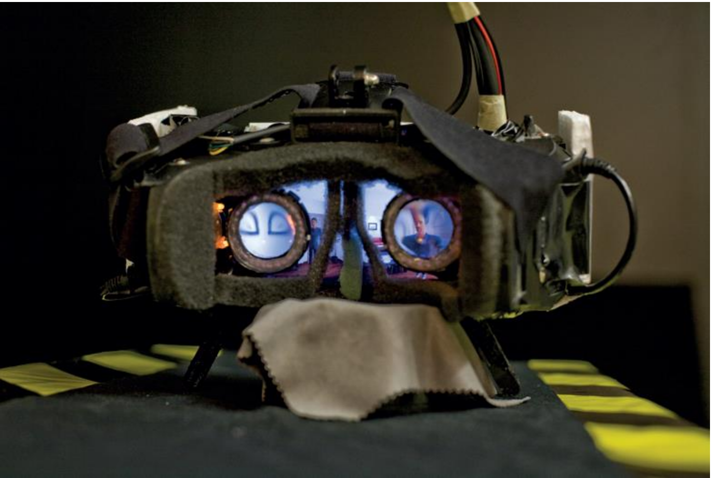
[1] custom [2] Krafka K., Khosla A. etal., 2016, *Eye Tracking for Everyone, CVPR*

FOVE

https://flic.kr/p/oSBK9D

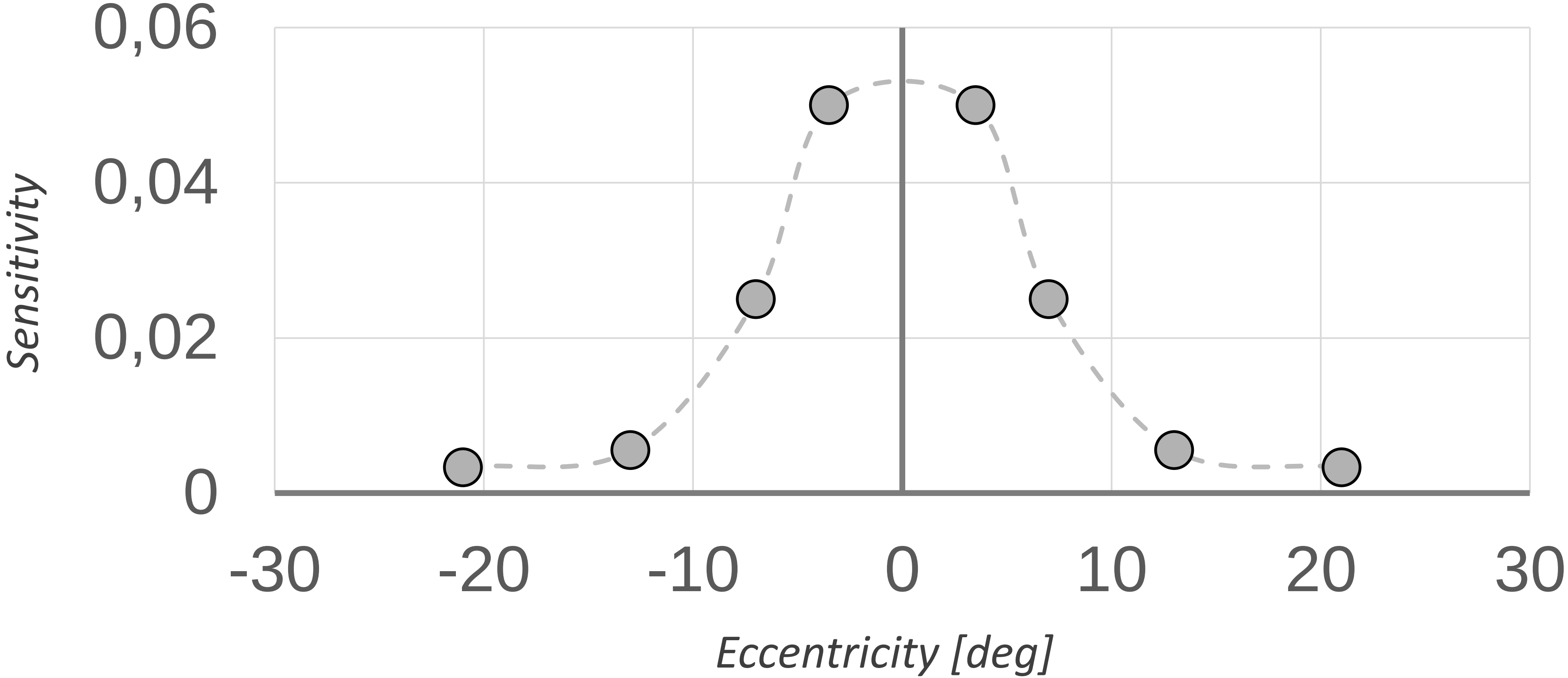
SMI (SensoMotoric Instruments)

https://flic.kr/p/pNPYrc

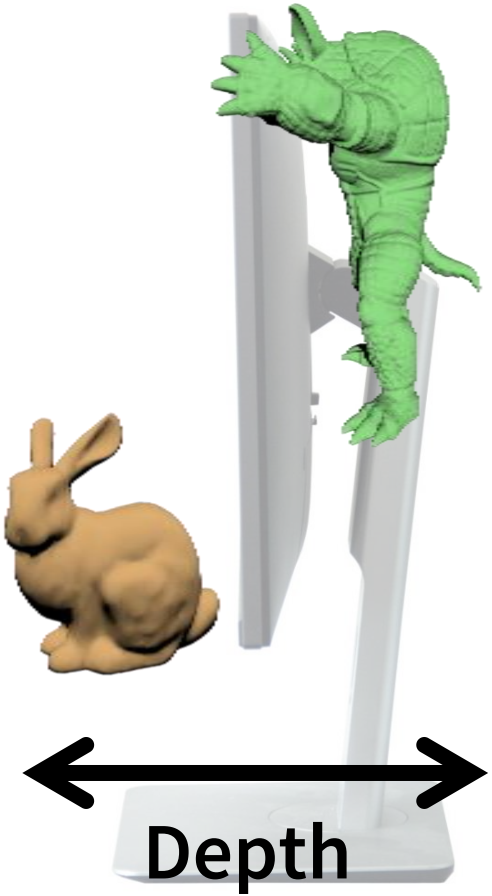


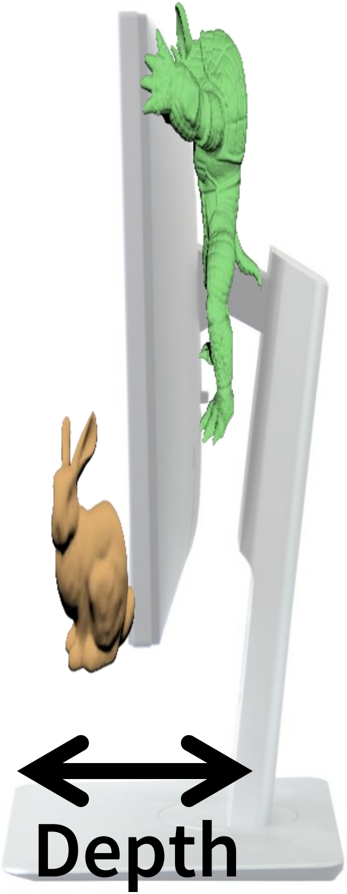
M. Stengel, S. Grogorick, M. Eisemann,
E. Eisemann and M. Magnor
Non-obscuring binocular eye tracking
for wide field-of-view head-mounted-displays
2015 IEEE Virtual Reality (VR), Arles, 2015, pp. 357-358.

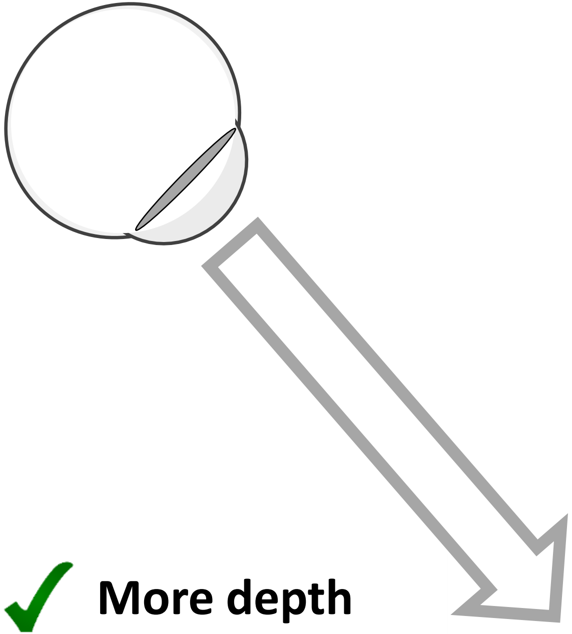
Disparity perception



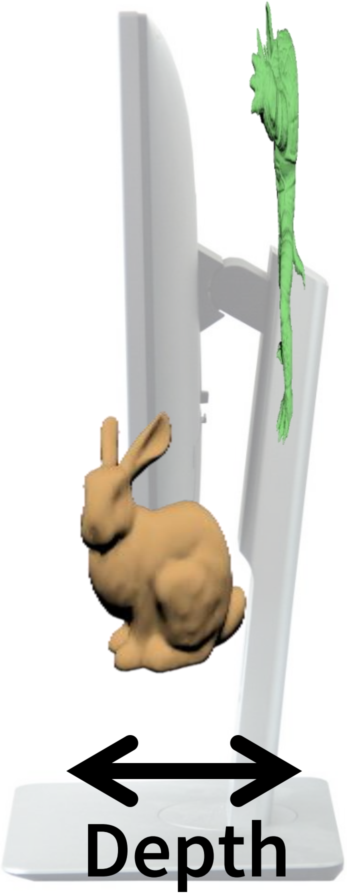
Replotted from Figure 3 of Simon J.D Prince, Brian J Rogers
Sensitivity to disparity corrugations in peripheral vision, Vision Research, Volume 38, Issue 17, September 1998

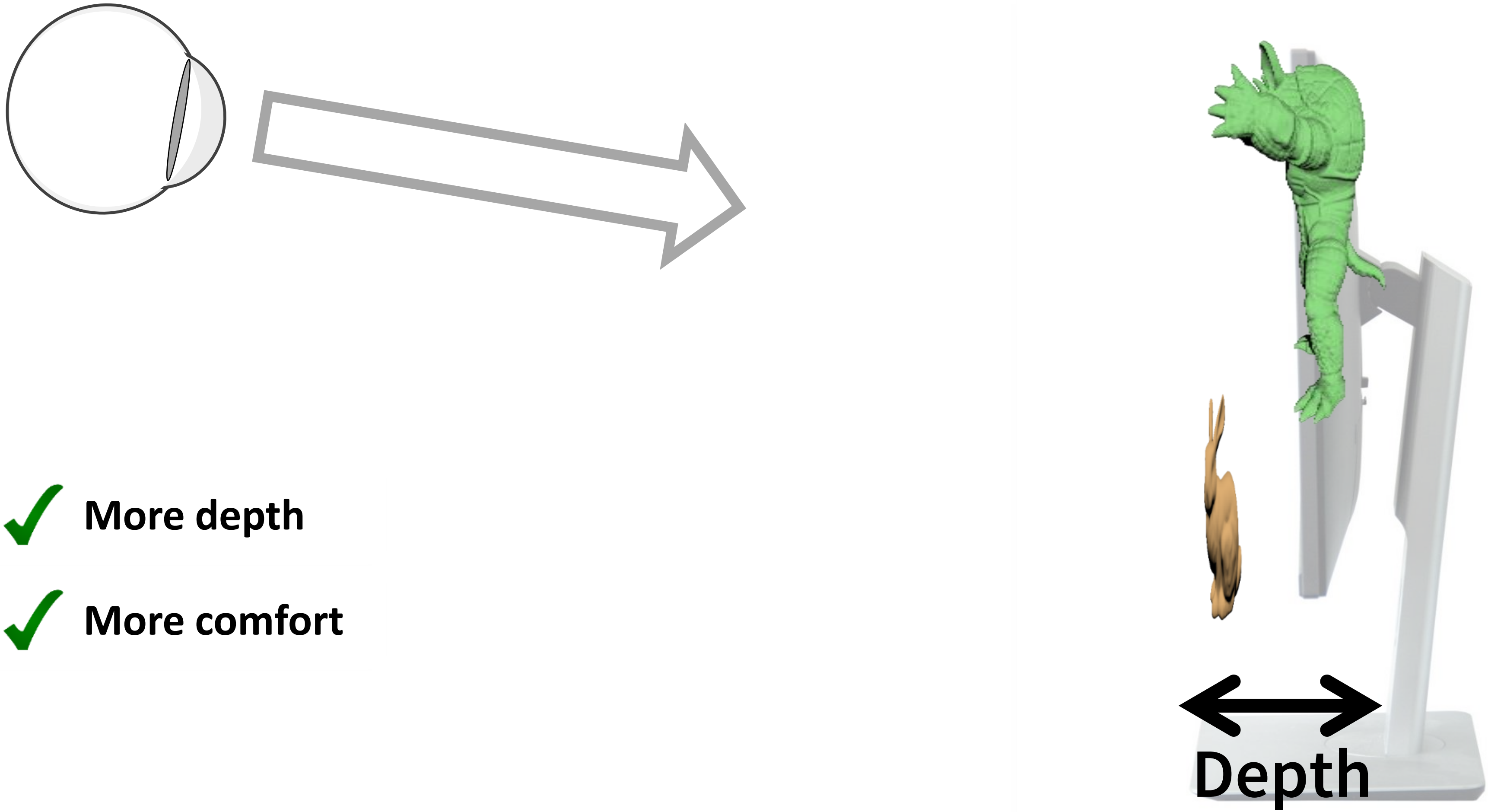

Depth


Depth

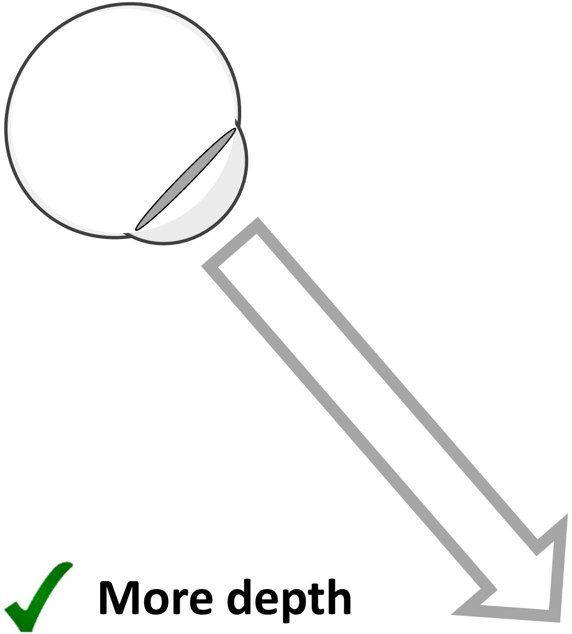


✓ **More depth**

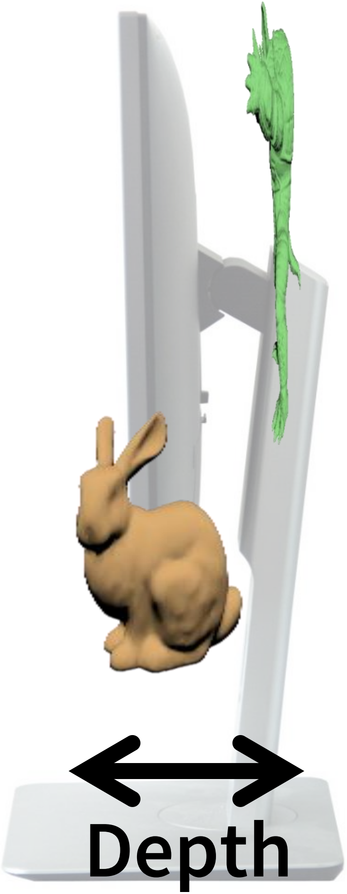


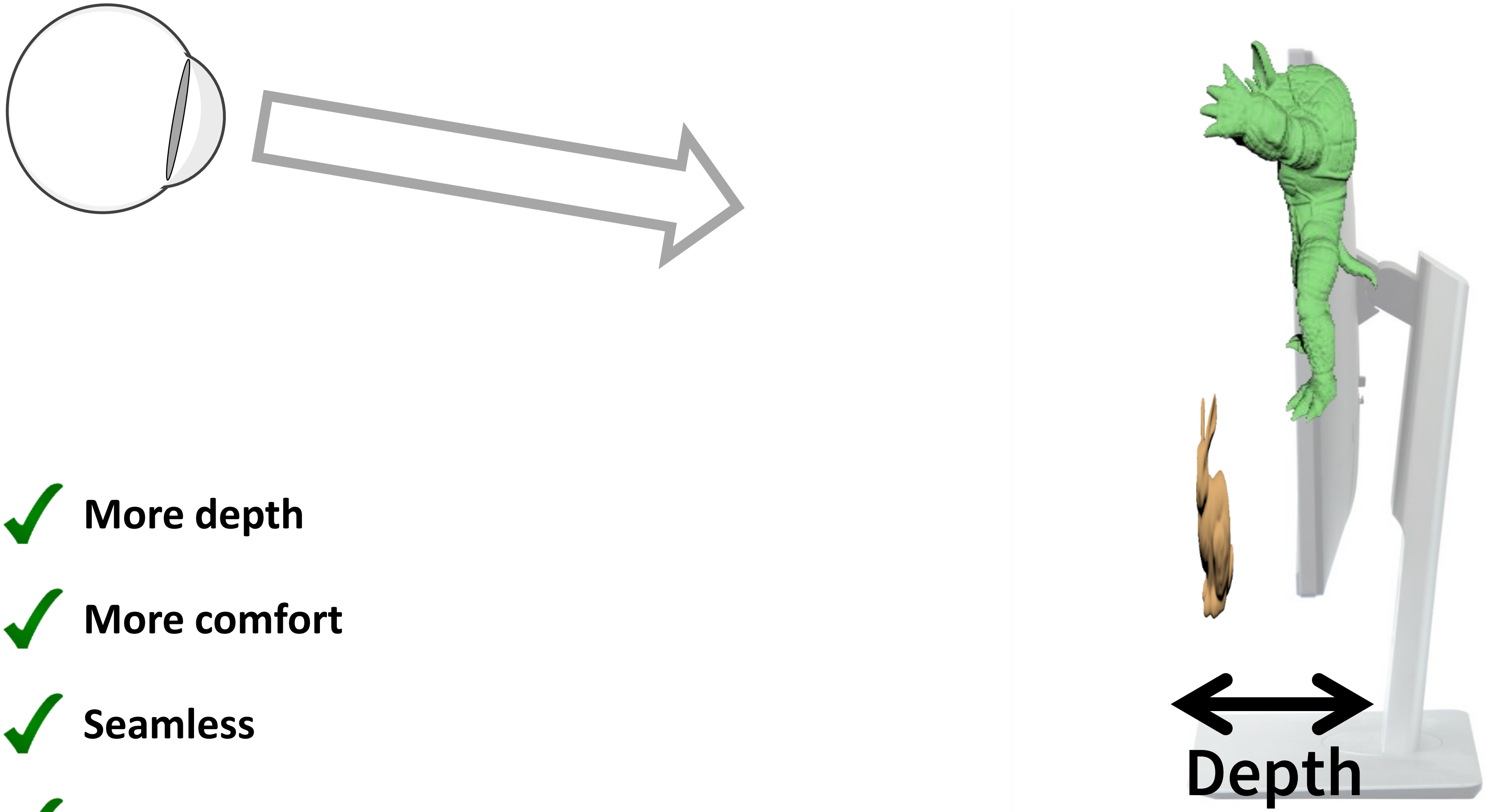


- ✓ **More depth**
- ✓ **More comfort**

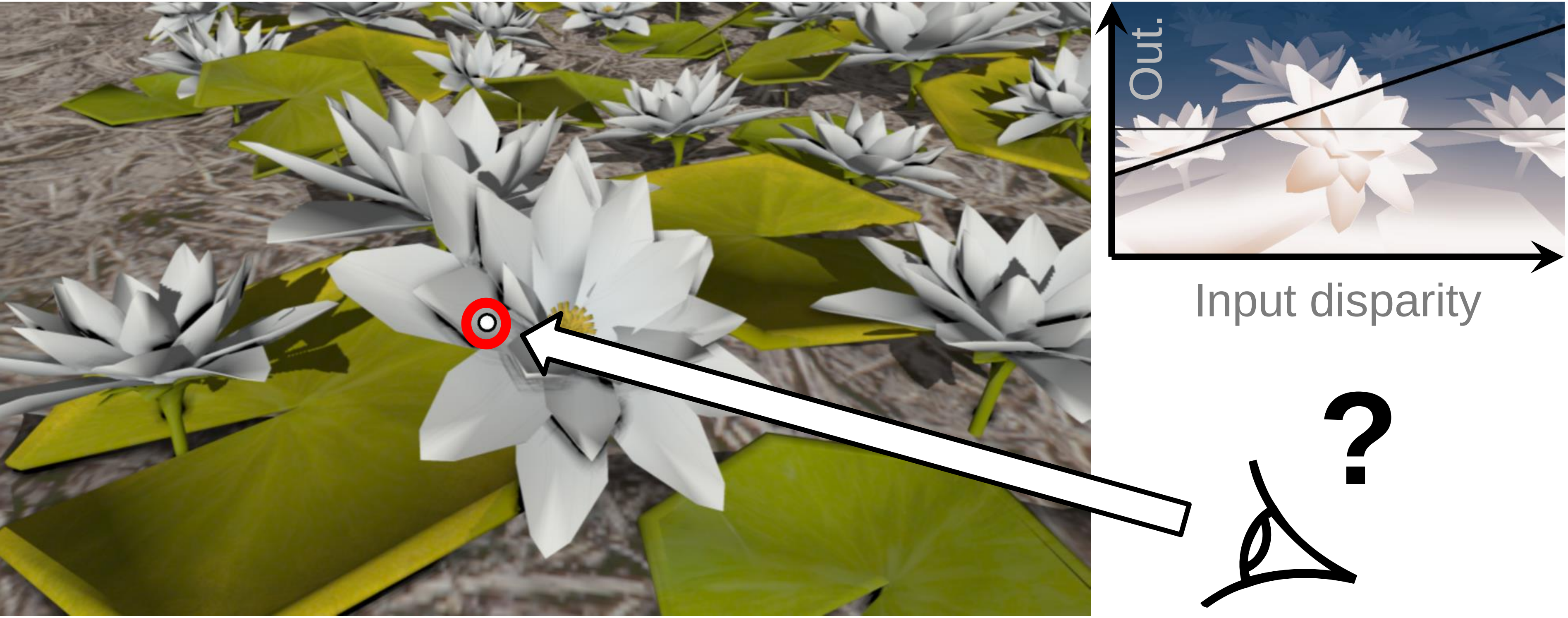


- ✓ More depth
- ✓ More comfort
- ✓ Seamless

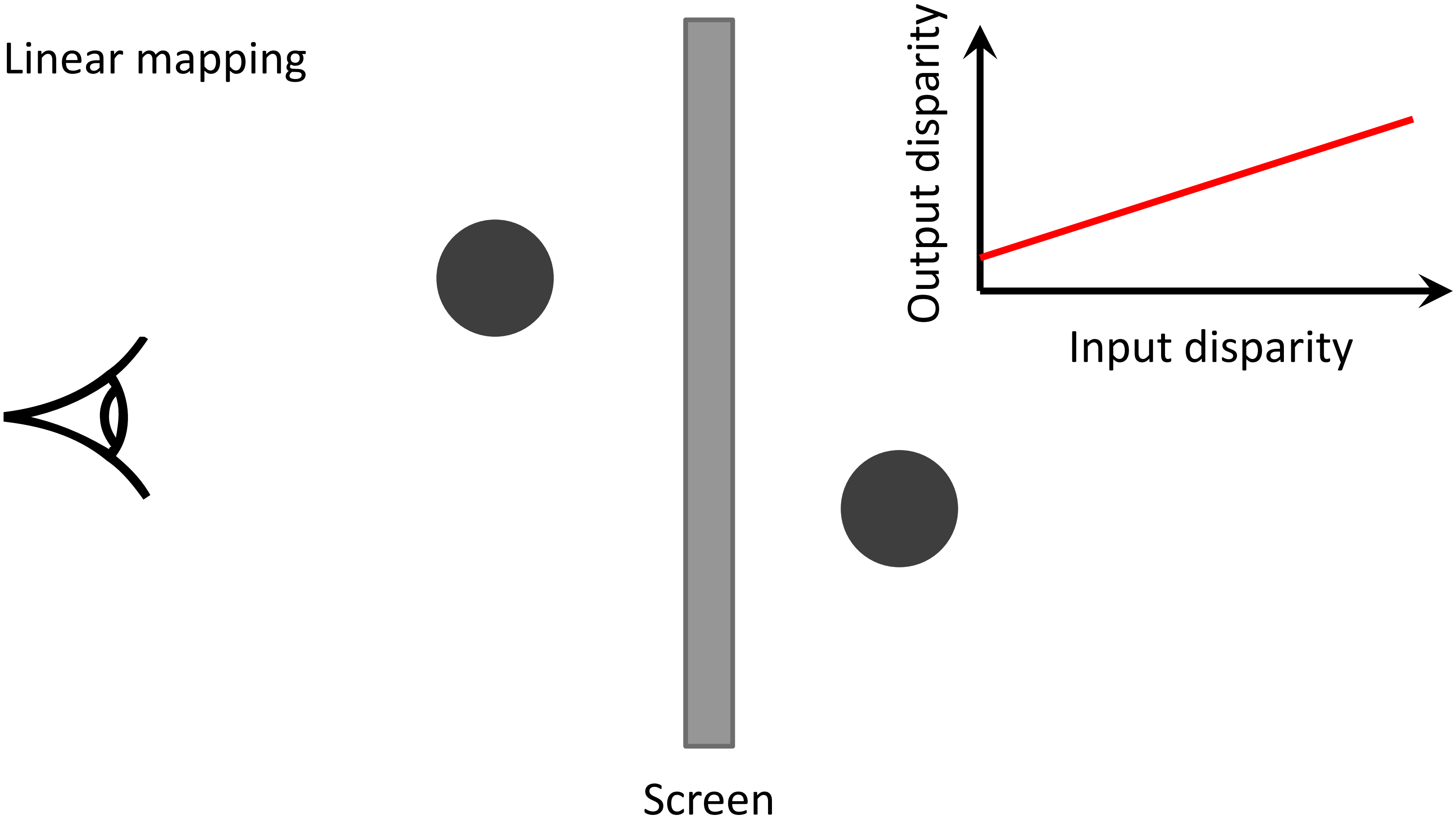




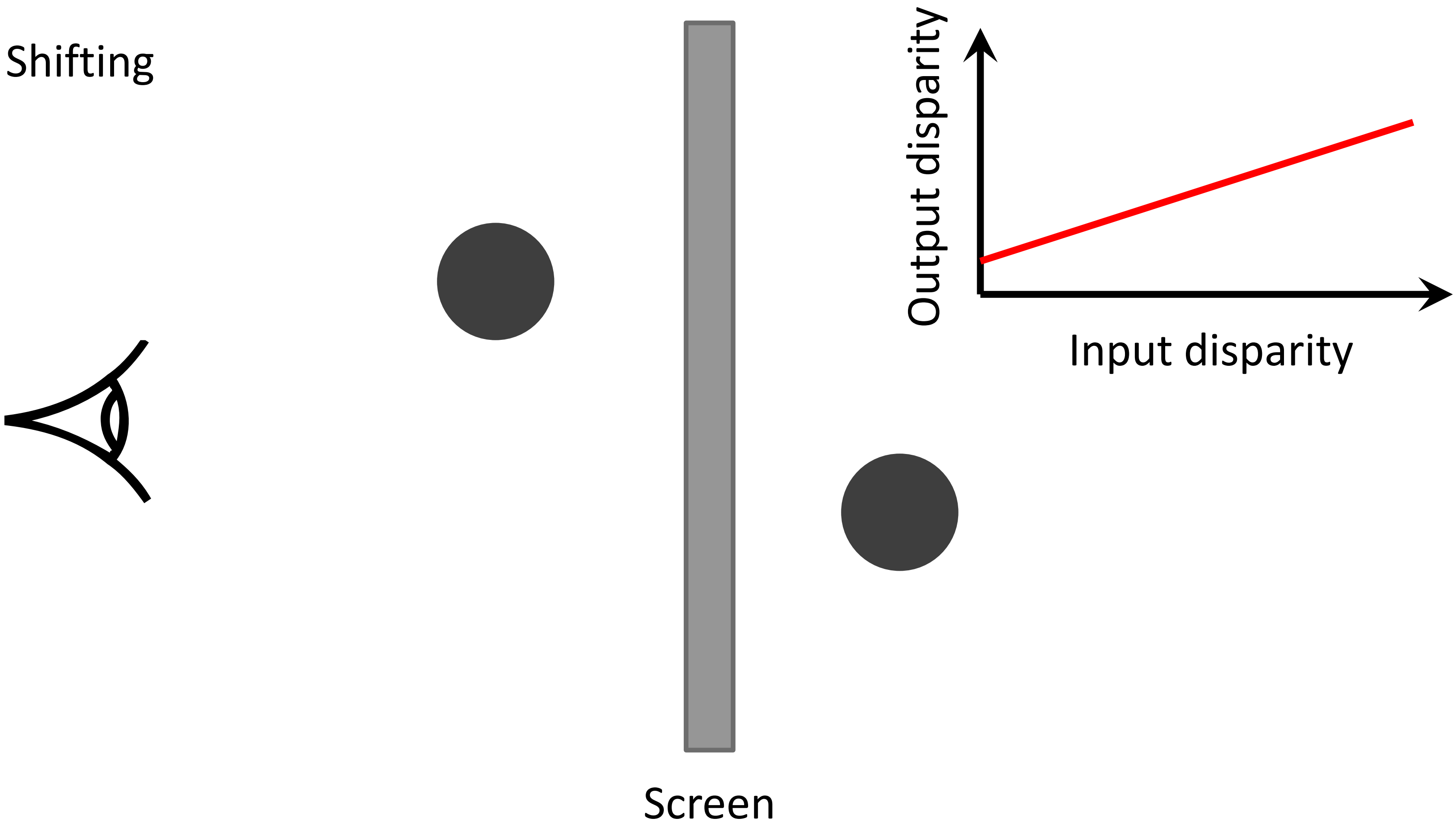
- ✓ **More depth**
- ✓ **More comfort**
- ✓ **Seamless**
- ✓ **Low cost**


Out.
Input disparity
?

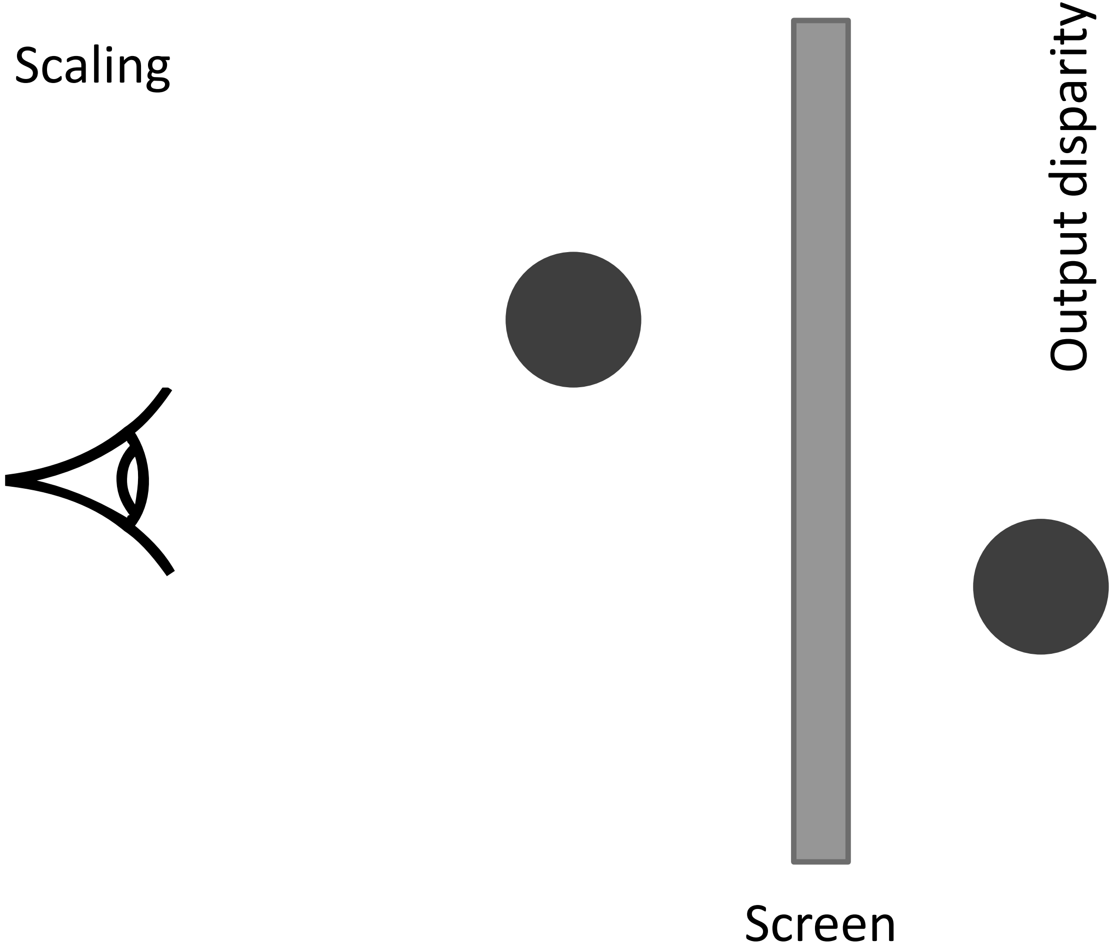
Linear mapping

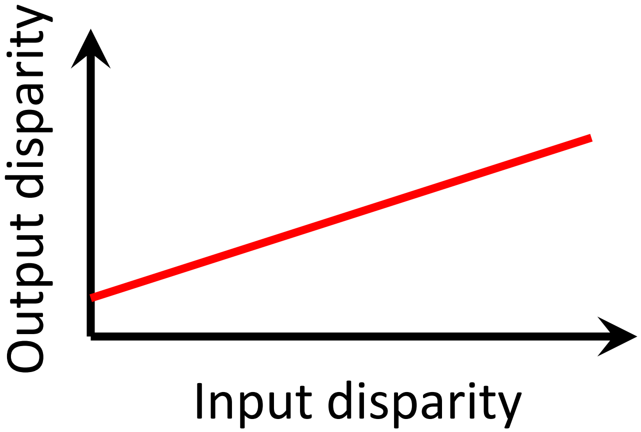


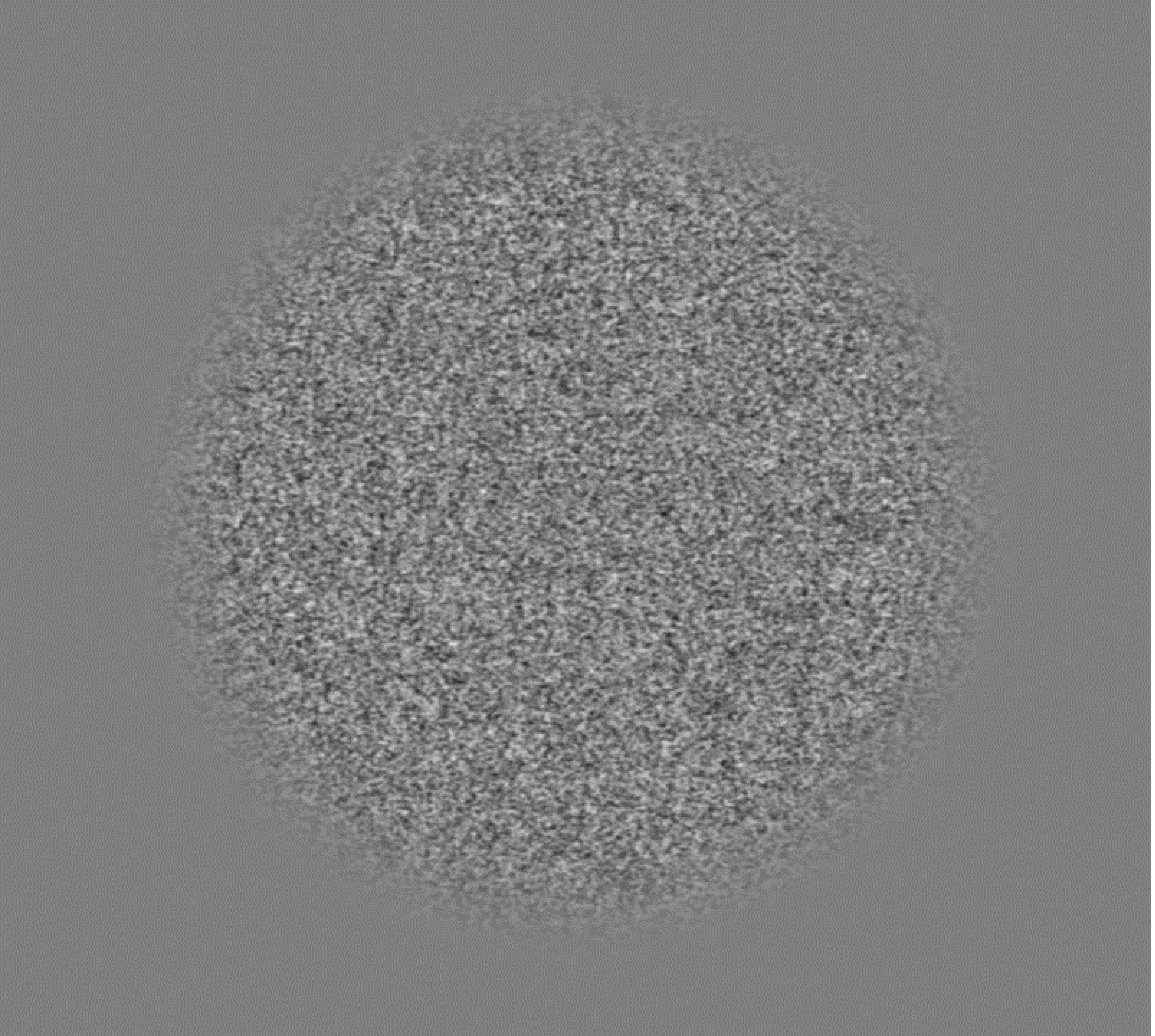
Shifting

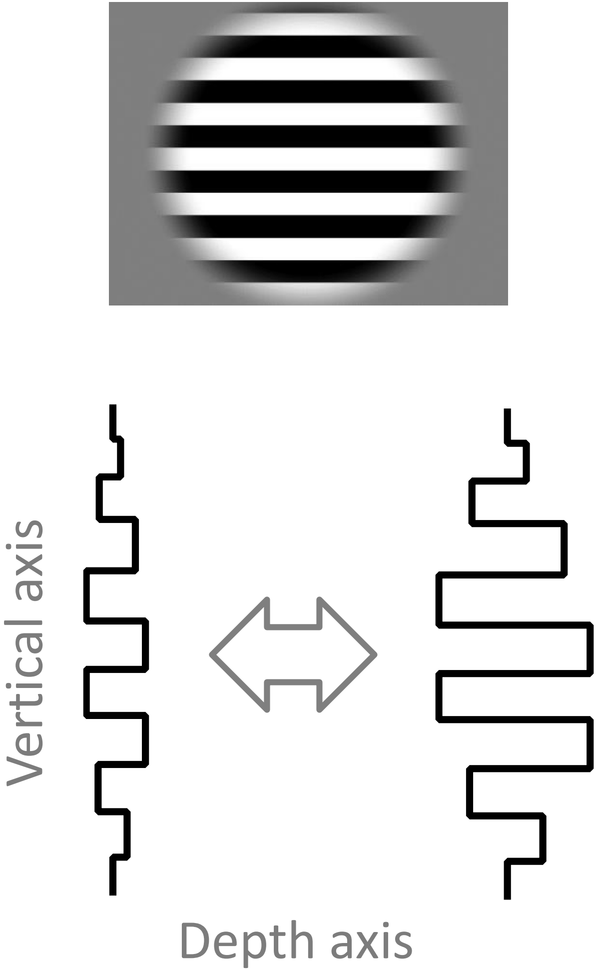


Scaling



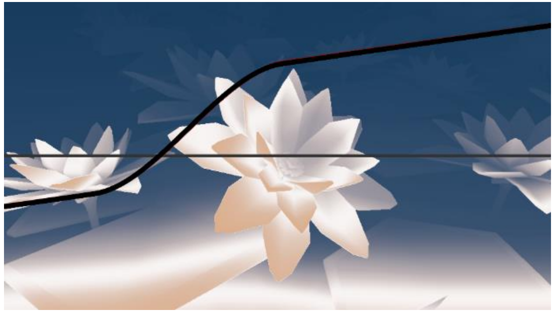





Vertical axis
Depth axis

Original

Ours



Original

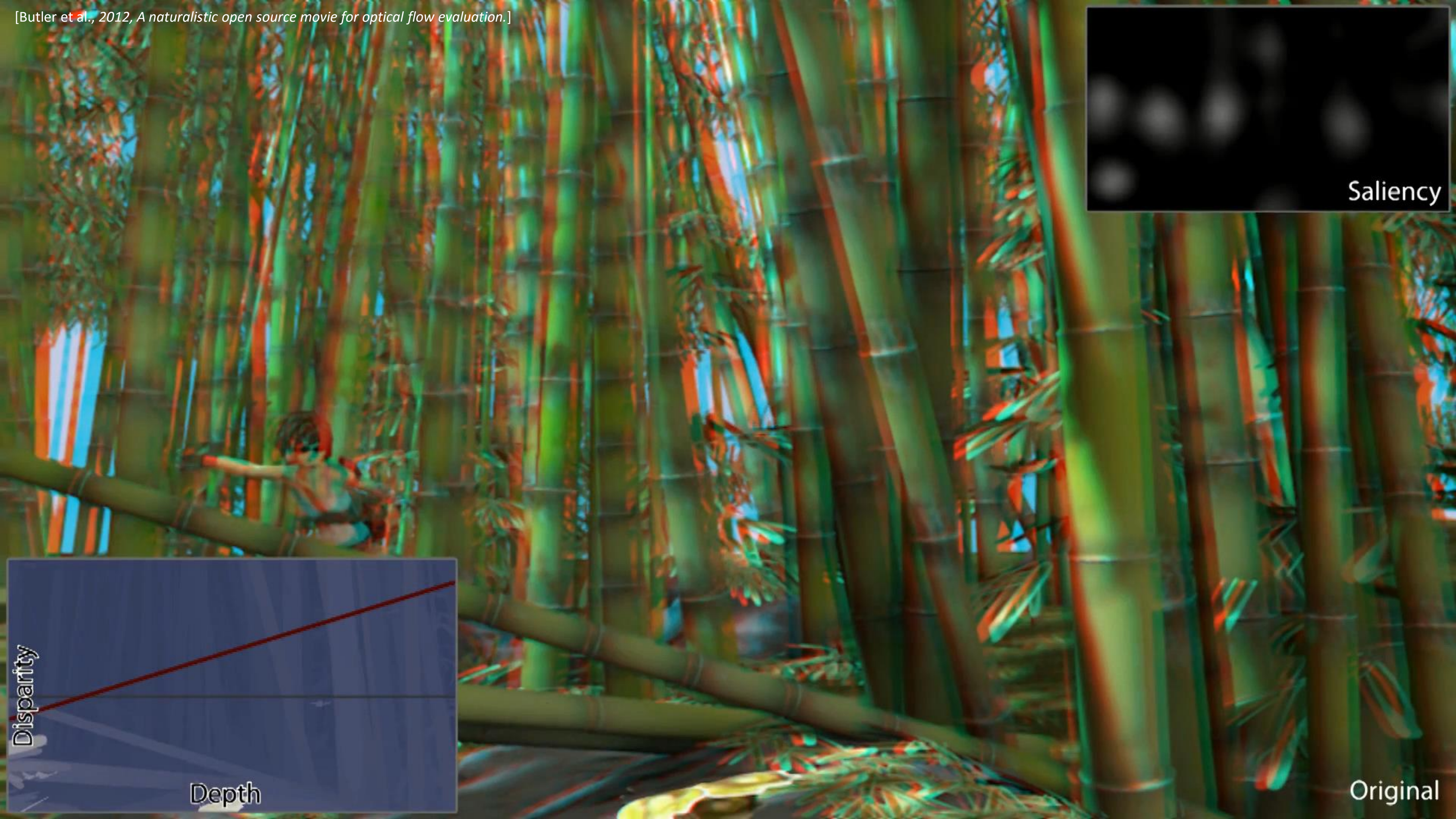
Ours

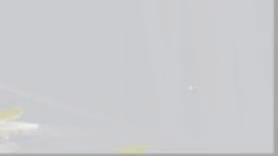
[Scharstein et al., 2014, *High-resolution stereo datasets with subpixel-accurate ground truth*.]

Ours

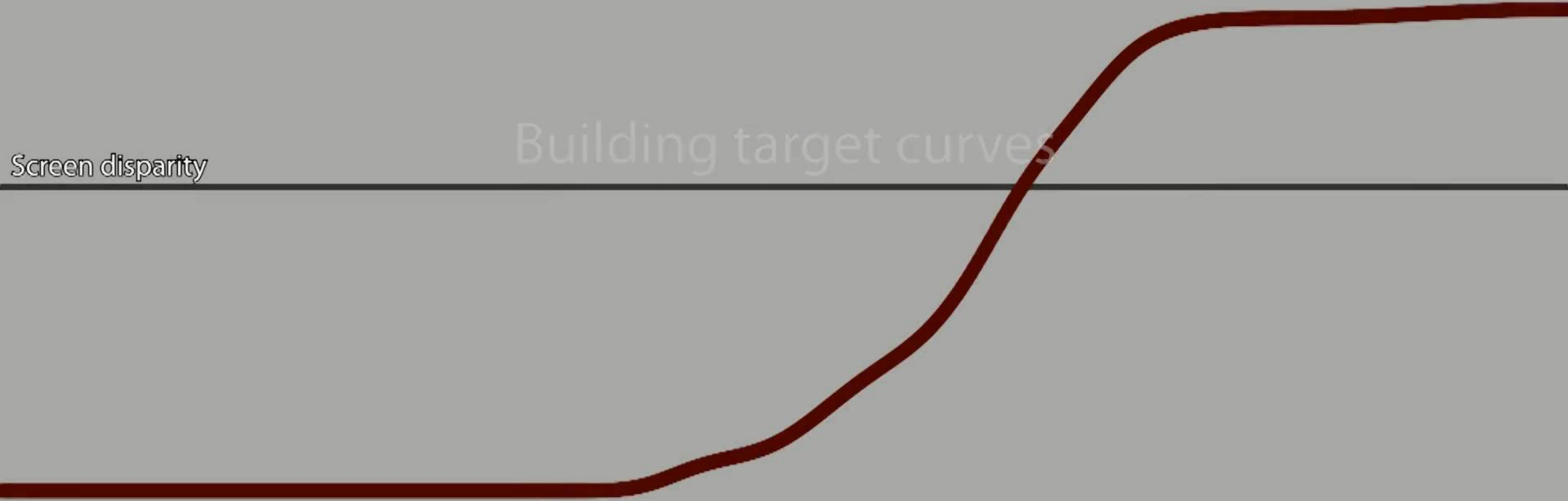
[Scharstein et al., *2014, High-resolution stereo datasets with subpixel-accurate ground truth.*]

[Butler et al., *2012, A naturalistic open source movie for optical flow evaluation.*]





Building target curves



Per-frame mapping curve construction

Actual speed

Temporal optimization

Temporal optimization

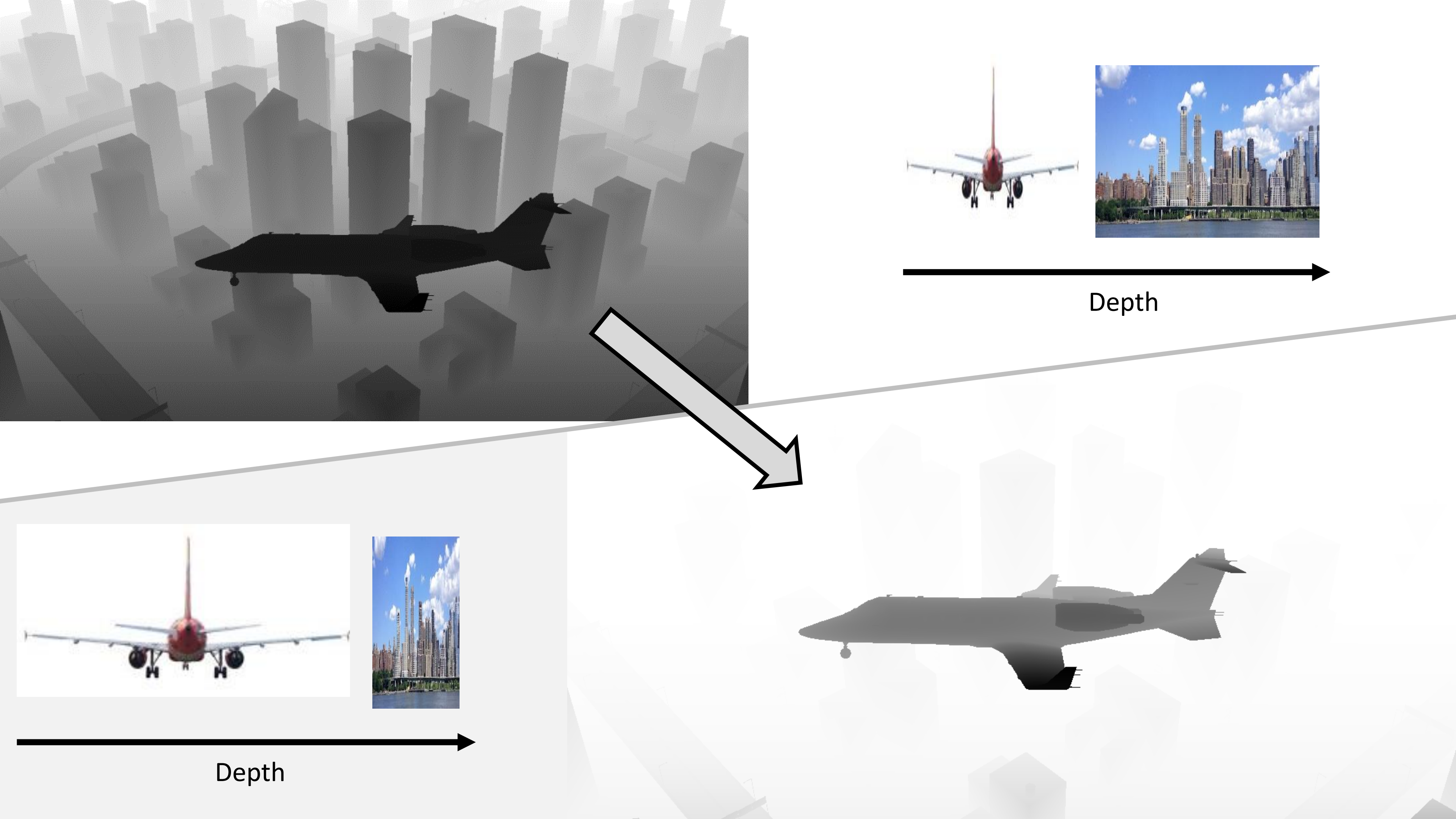
[Butler et al., *2012, A naturalistic open source movie for optical flow evaluation.*]

Per-frame remapping

Our optimized mapping

Just motion

Motion parallax


Depth
Depth

City flight

Linear remapping

Compression for autostereoscopic displays

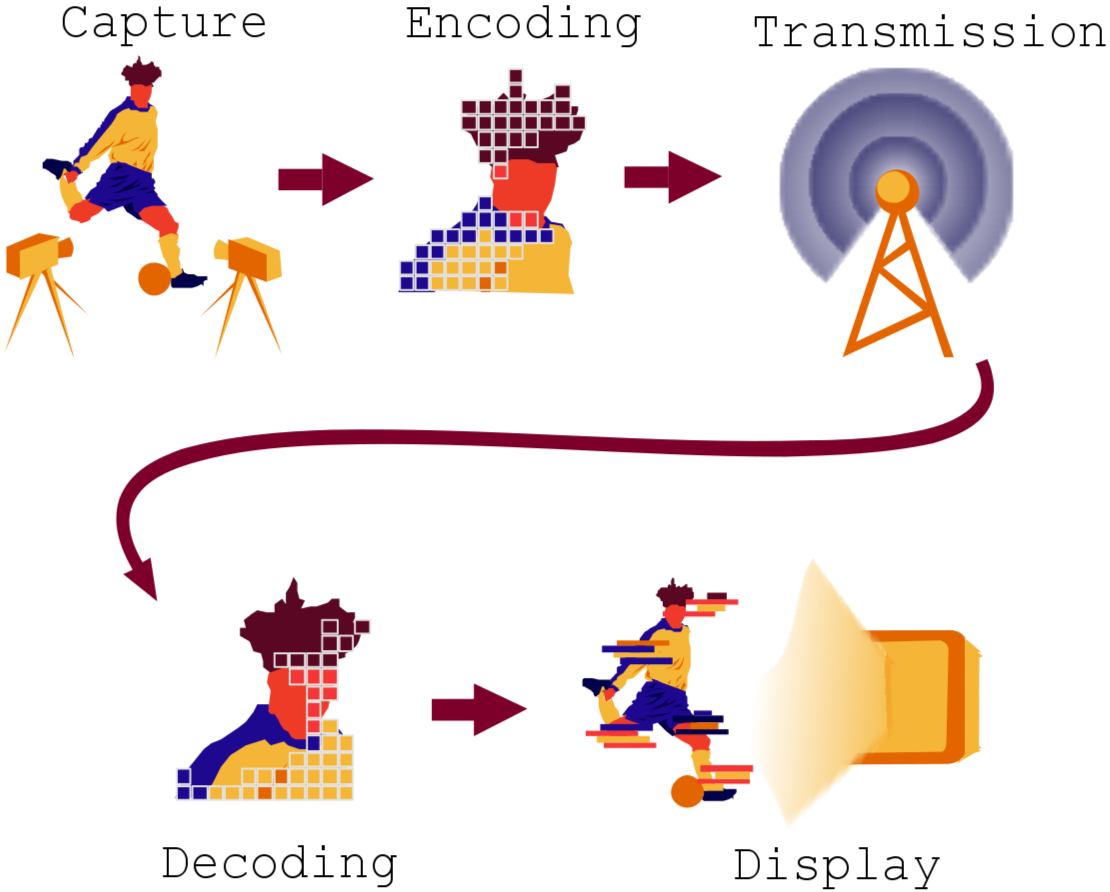
Conclusions

- Modeling perception can help in improving apparent image quality
  - Spatial and temporal resolution
  - Perceived depth
- Typically we aim for the impression of realism
  - Physical simulation is not always the best – specular effects
- Certain cinematographic effects might require different treatment
  - Scene cuts – eye vergence slower than saccades
  - High refresh rate – smoother motion, but “soap opera” look
- Eye tracking a powerful tool in exploring human perception
  - Better disparity budget reallocation that improves both visual comfort and enhances perceived depth
- There are many interactions of disparity with image content and other depth cues
  - Motion parallax - enables disparity budget reallocation

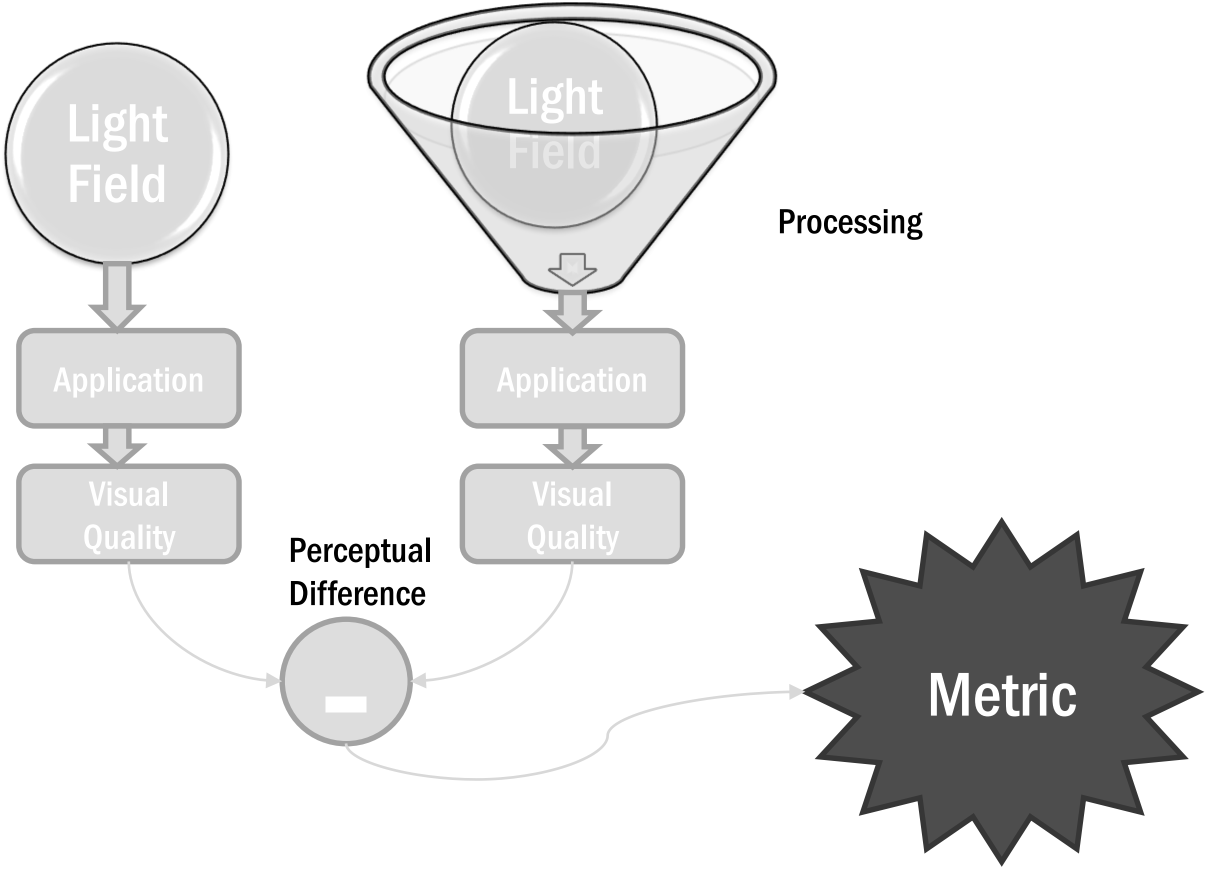
TOWARDS A NEW QUALITY METRIC FOR DENSE LIGHT FIELDS

V.K.Adhikarla, M.Vinkler, D.Sumin, R.Mantiuk, K.Myszkowski, P.Didyk and H.-P. Seidel

IEEE *Conf. on Computer Vision and Pattern Recognition* (CVPR)
21-26 July 2017.

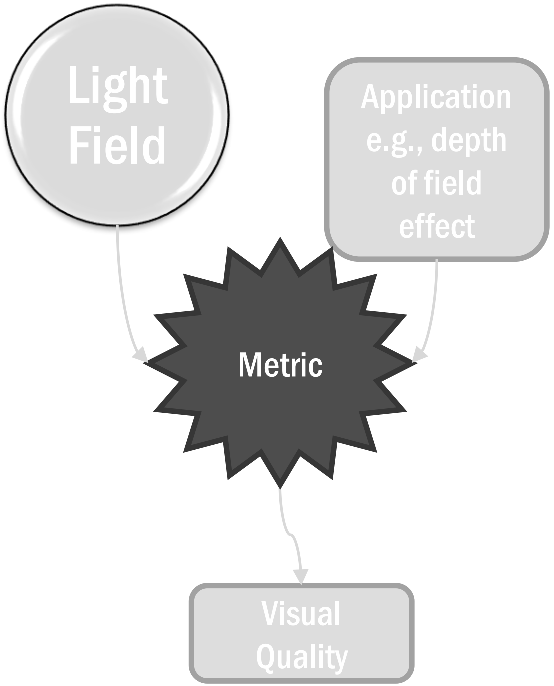

Capture
Encoding
Transmission
Decoding
Display

Goal



Light Field
Light Field
Processing
Application
Application
Visual Quality
Visual Quality
Perceptual Difference
–
Metric

Application Scenarios

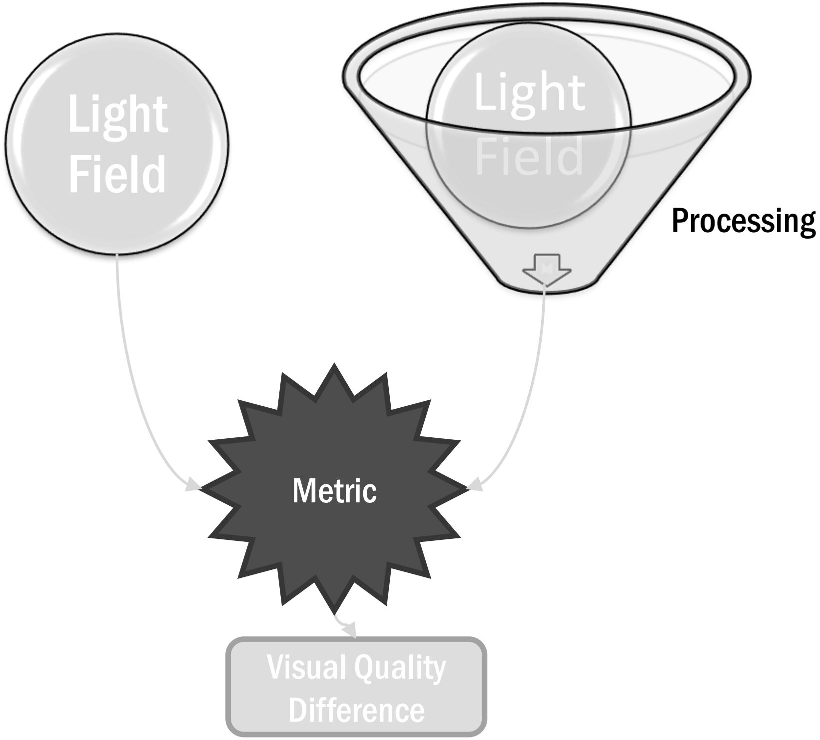


Light Field

Application e.g., depth of field effect

Metric

Visual Quality



Light Field

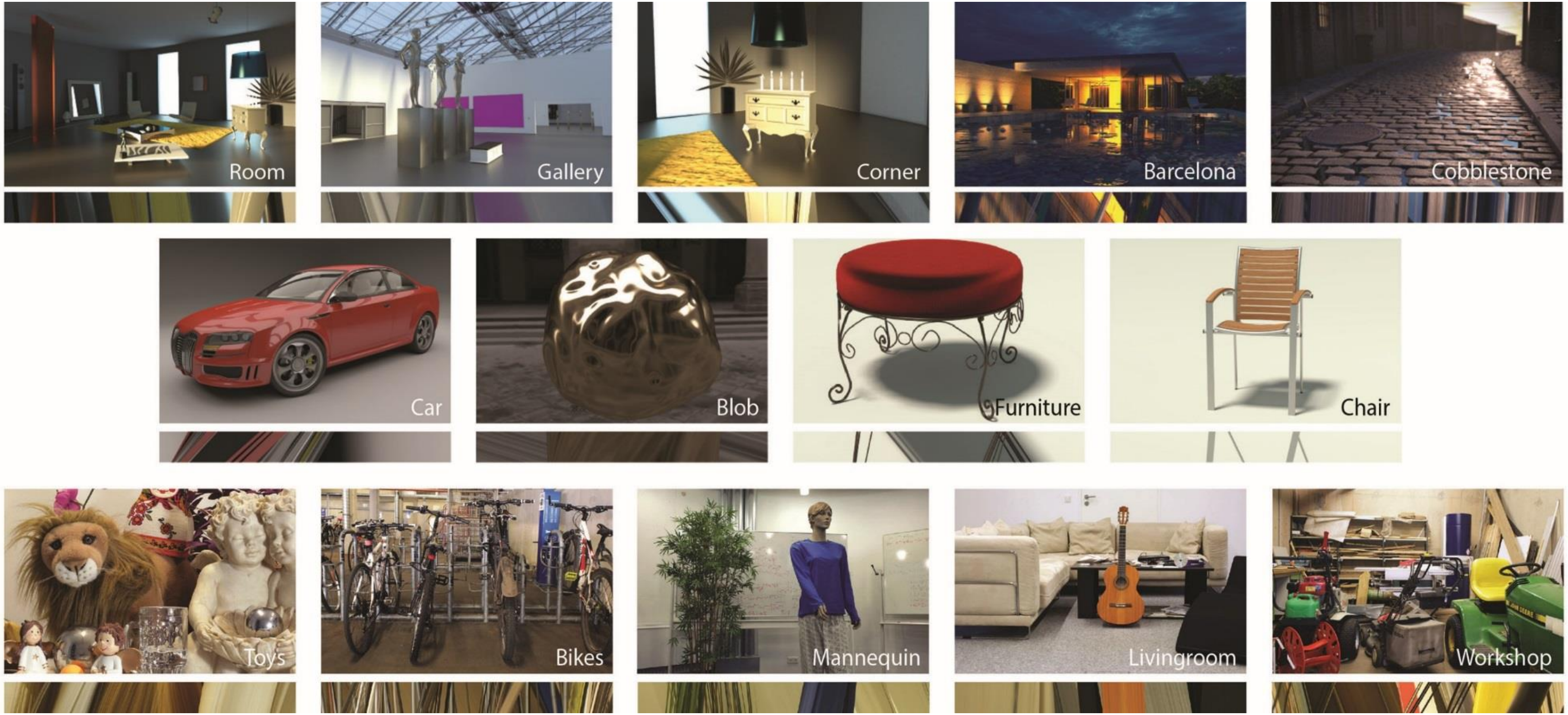
Light Field

Processing

Metric

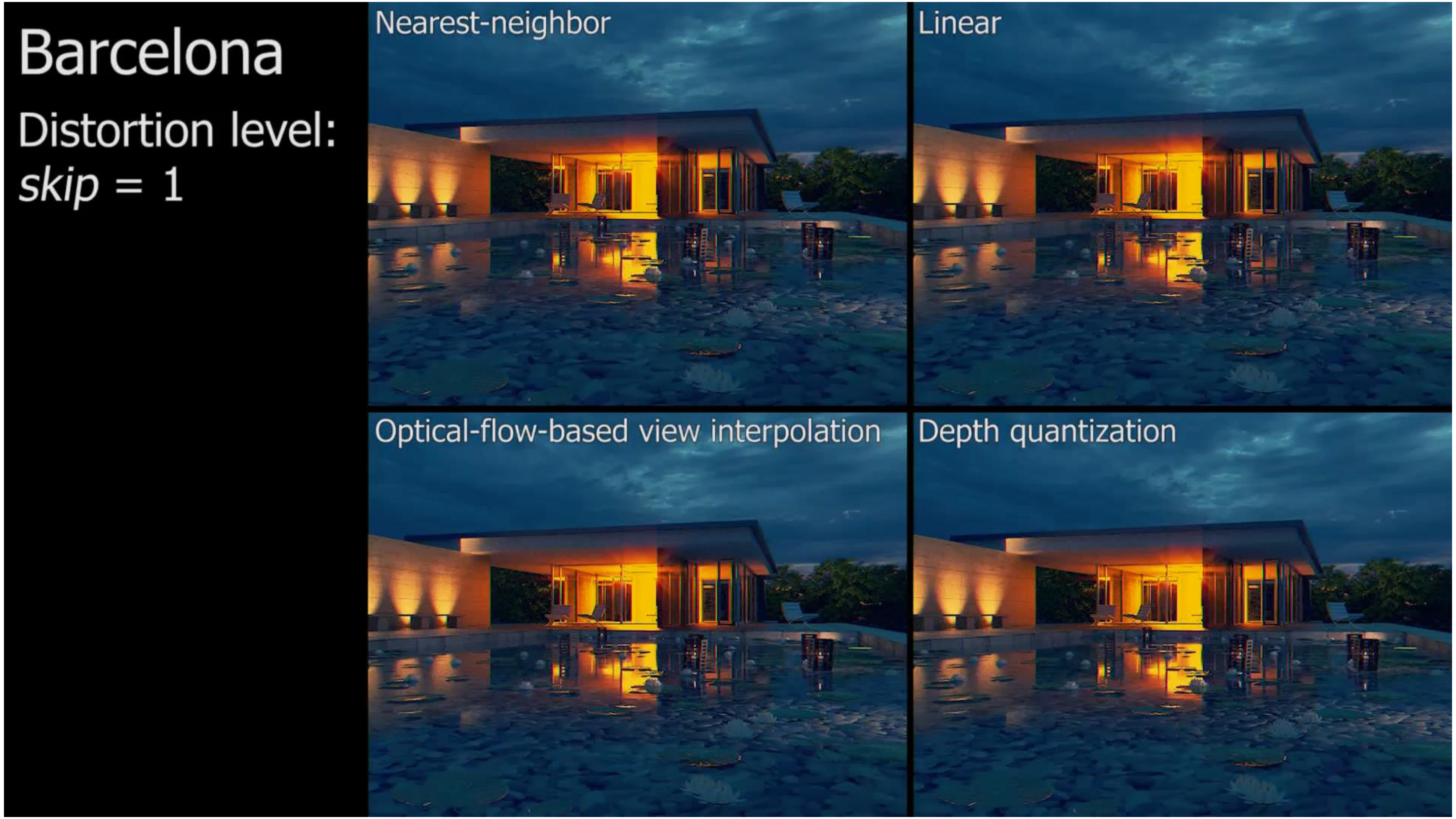
Visual Quality Difference

LF database

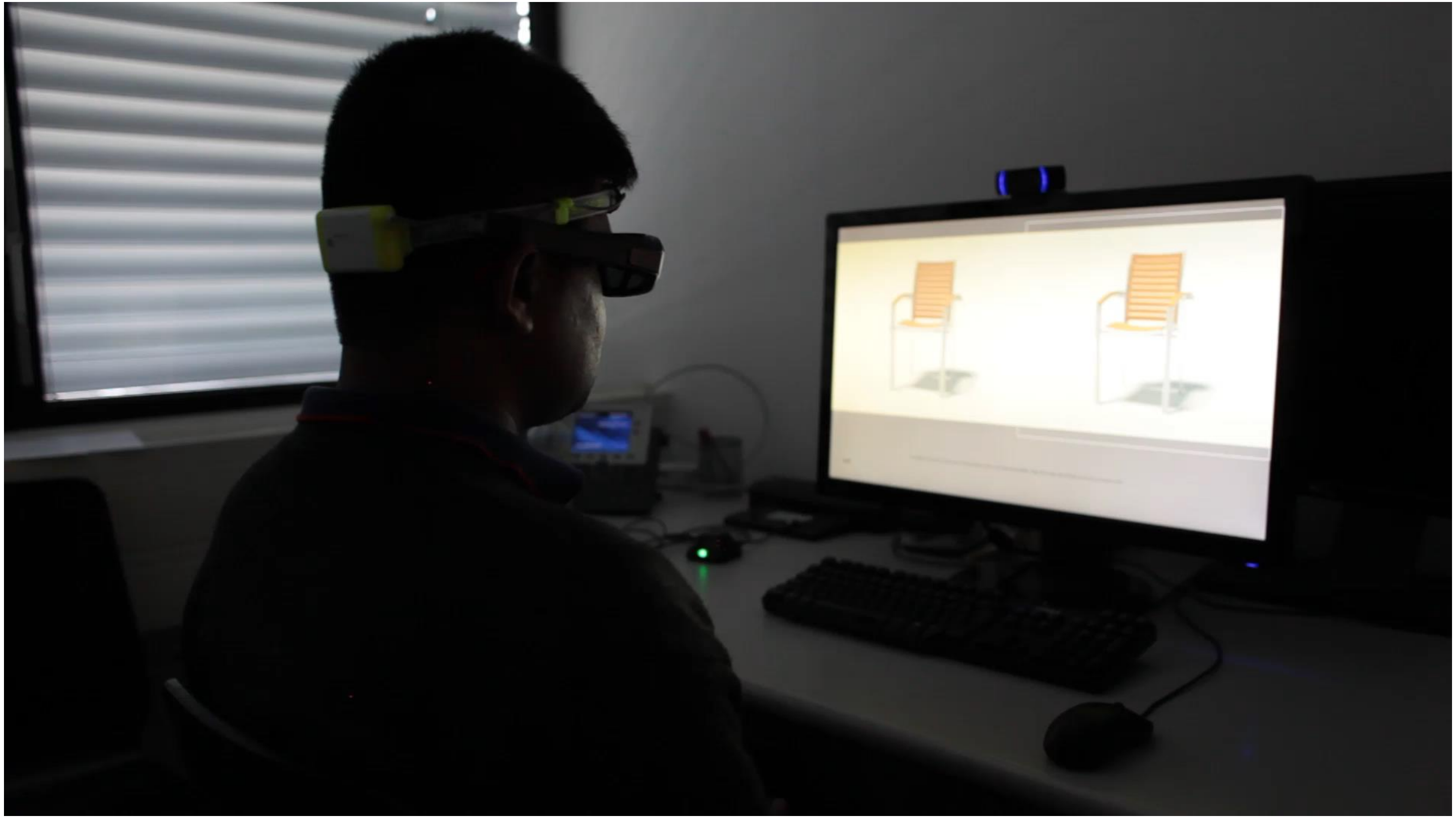

Room
Gallery
Corner
Barcelona
Cobblestone
Car
Blob
Furniture
Chair
Toys
Bikes
Mannequin
Livingroom
Workshop

Distortions

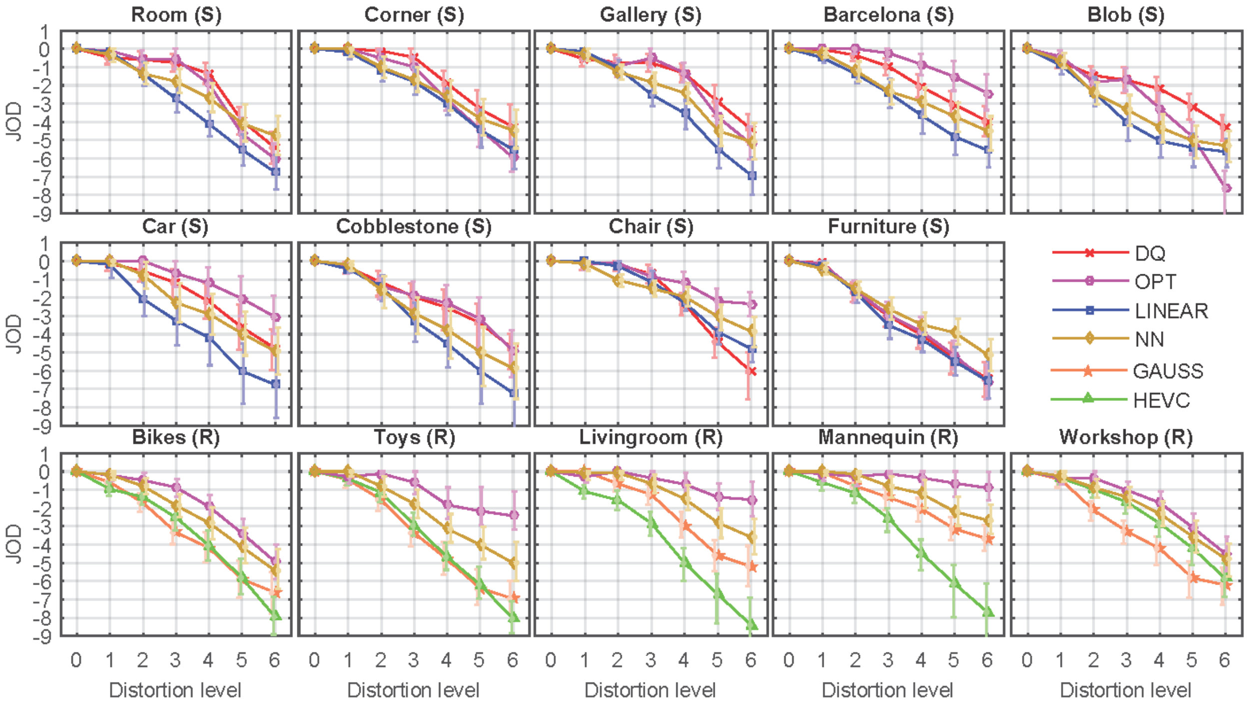
Distortions



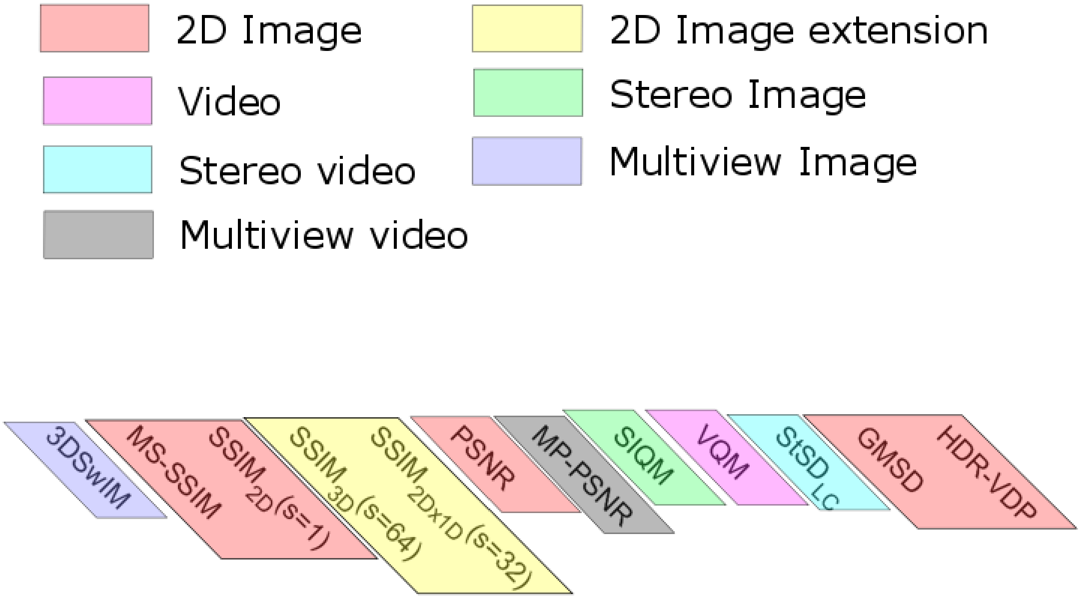
Subjective study



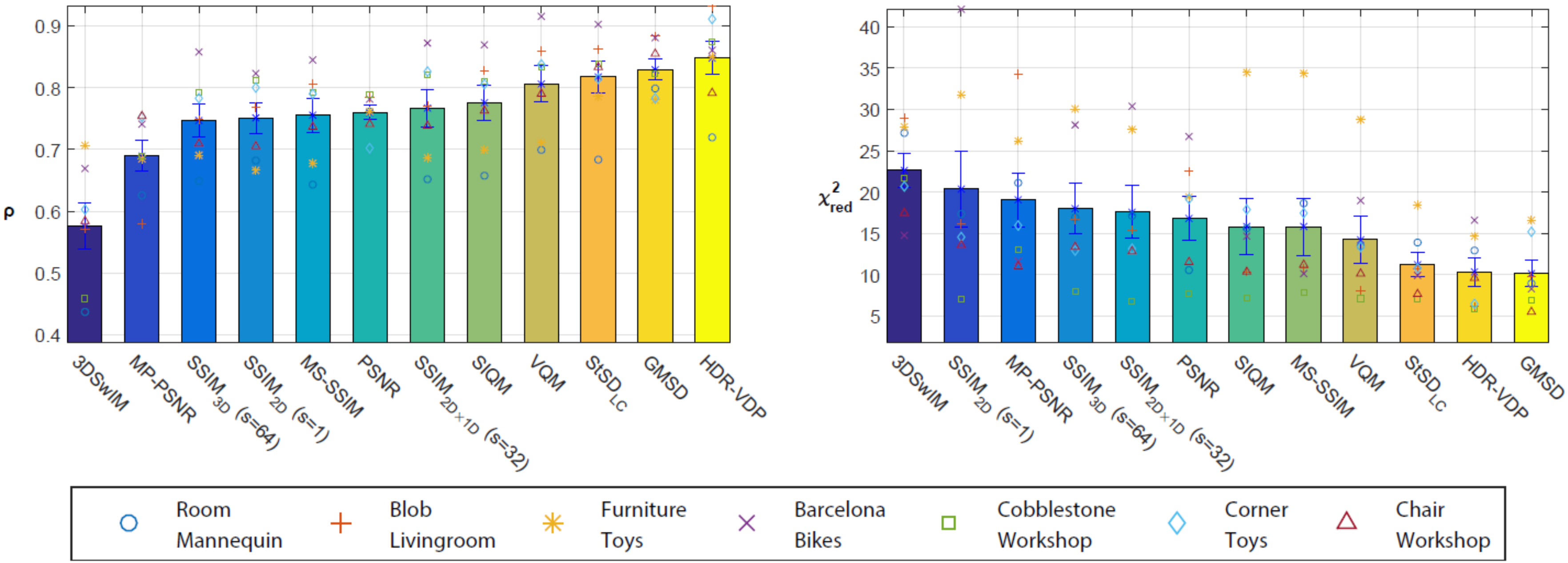
Subjective scaling



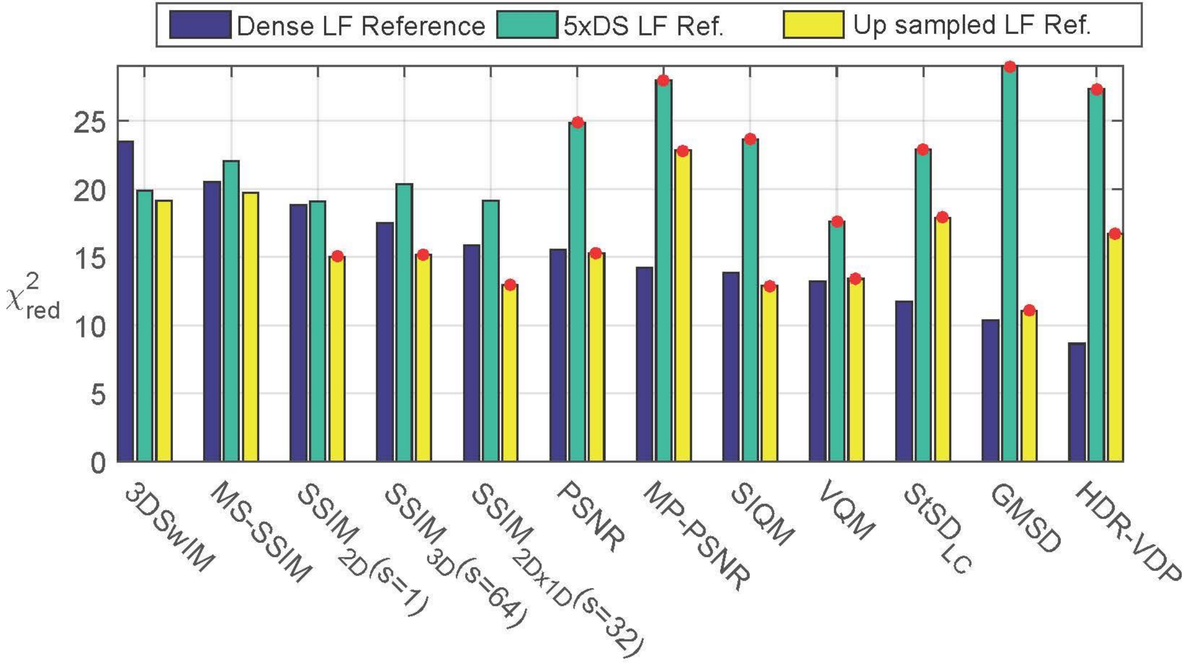
Predicting subjective scores



Metric Performance



Predicting subjective scores



Conclusions

- We need metrics that are tuned to light field specific artifacts
- 2D metrics to a certain extent address the quality issue, but need dense light fields as reference. In many cases, this not a possibility
- A more relevant metric for light fields must provide the quality when there is no reference at all
- Learning based approaches must be explored with good training data to see the usefulness of such approaches

Collaborators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Martin Čadík


Vamsi Kiran Adhikarla


Grzegorz Krawczyk


Elmar Eisemann


Dawid Pająk


Piotr Didyk


Petr Kellnhofer


Yulia Gryaditskaya