

Apparent Stereo: The Cornsweet Illusion Can Enhance Perceived Depth

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Stereo in daily life

Stereo in daily life



Anaglyph



Shutter glasses



Autostereoscopic

Stereo in daily life



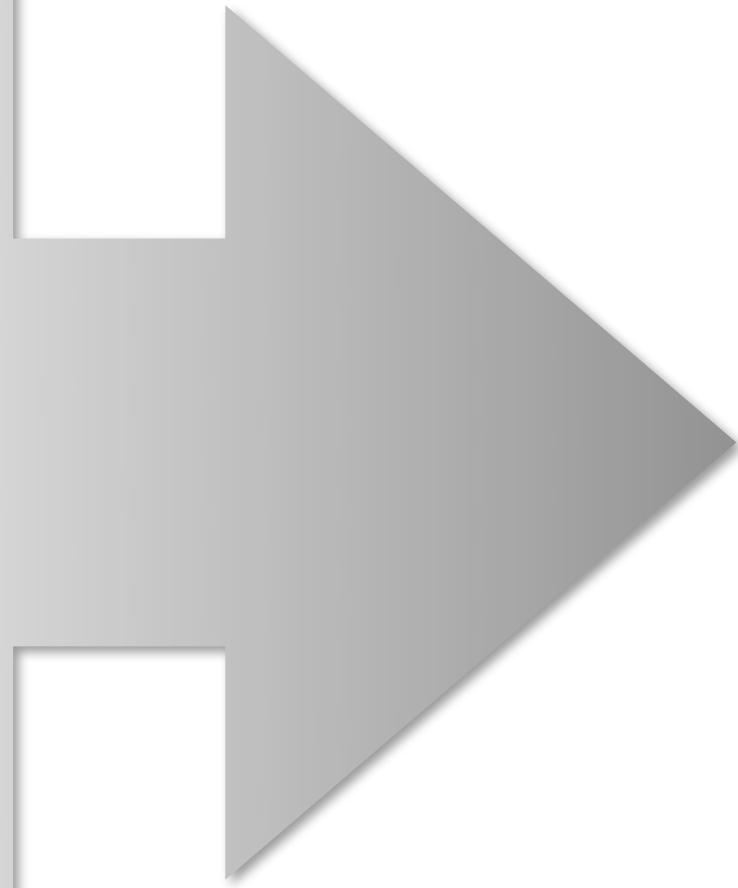
Anaglyph



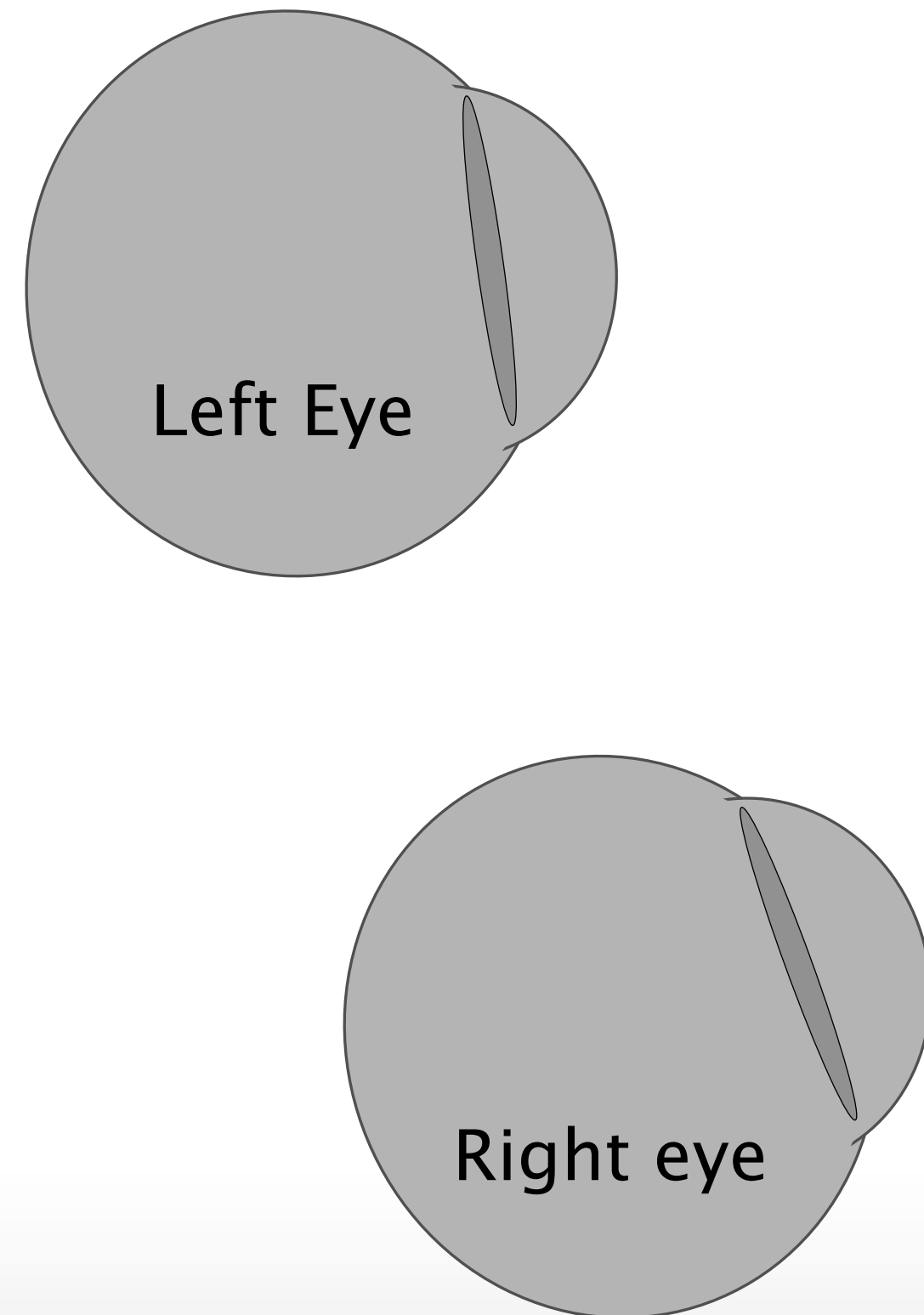
Shutter glasses



Autostereoscopic

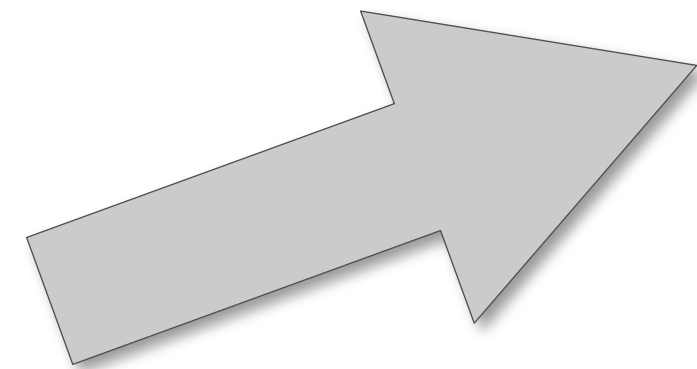
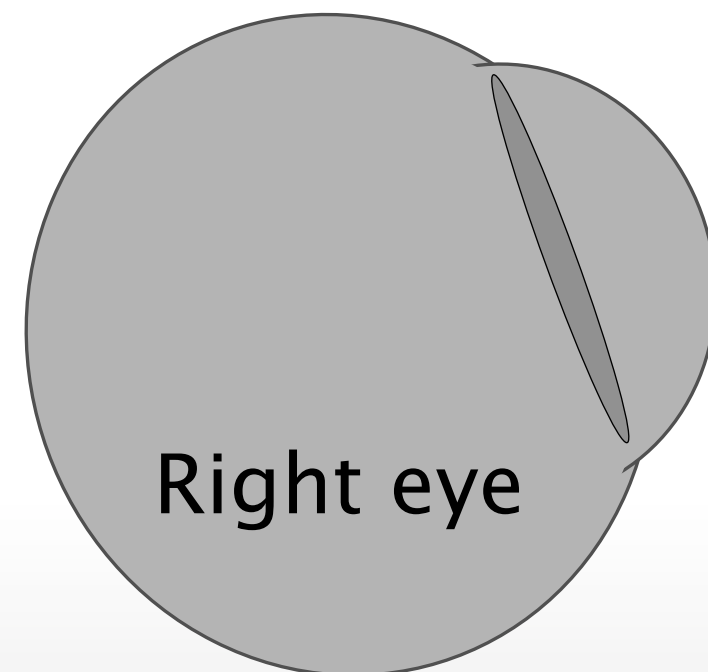
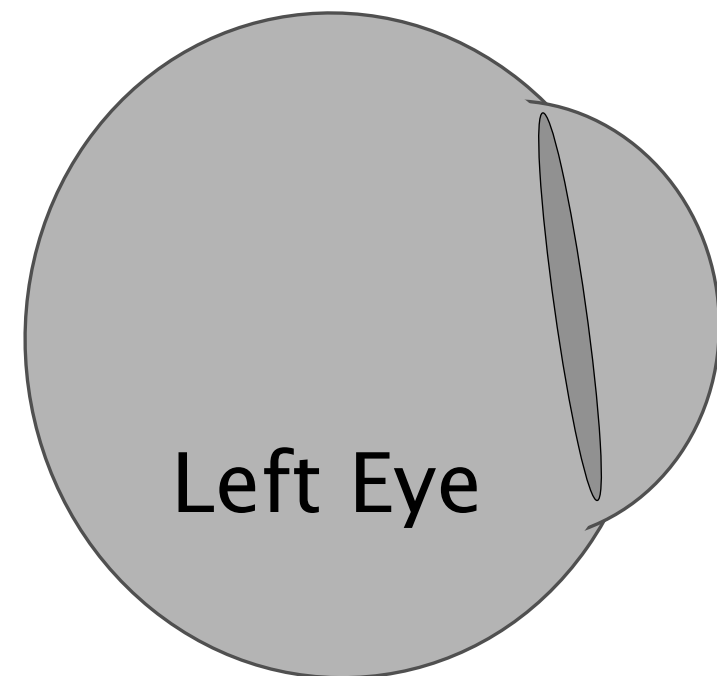


Stereo on a flat display



Stereo on a flat display

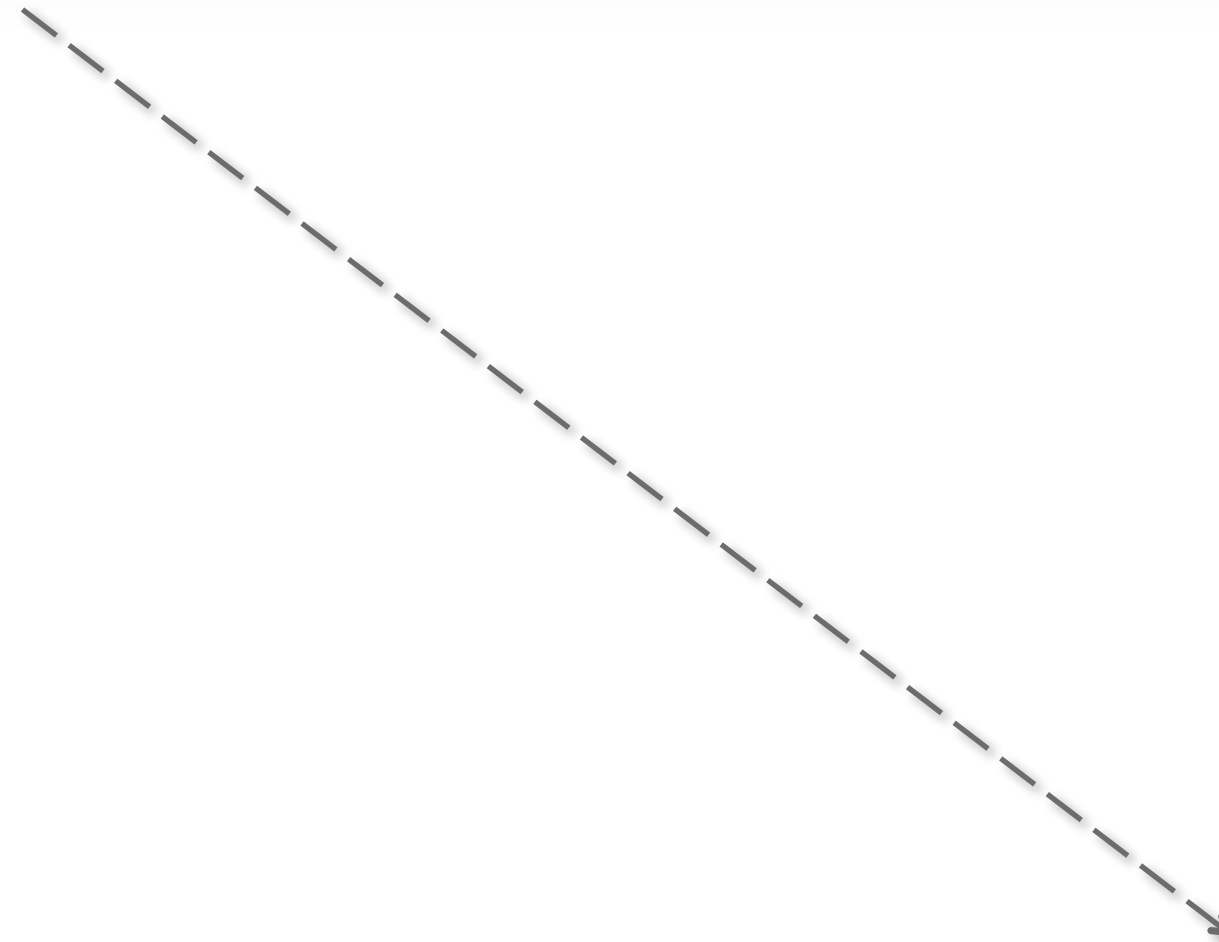
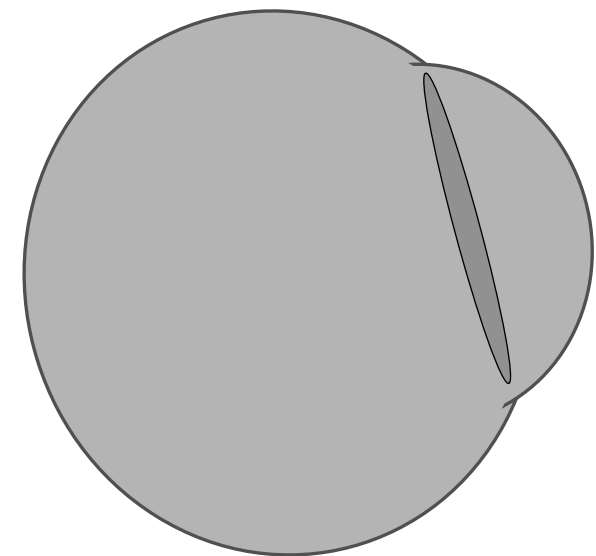
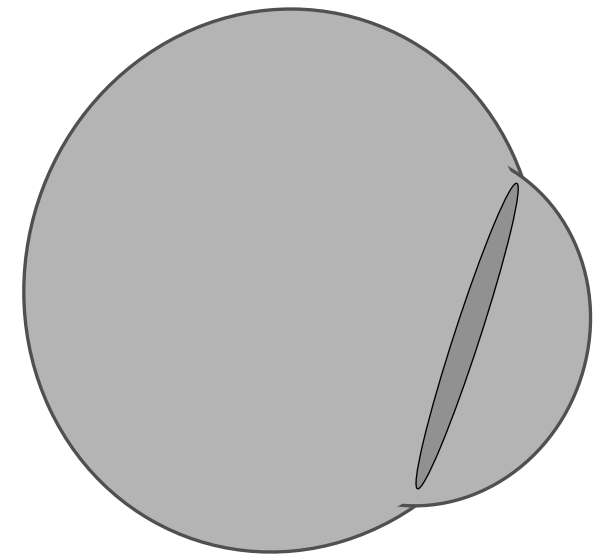
Different image for each eye



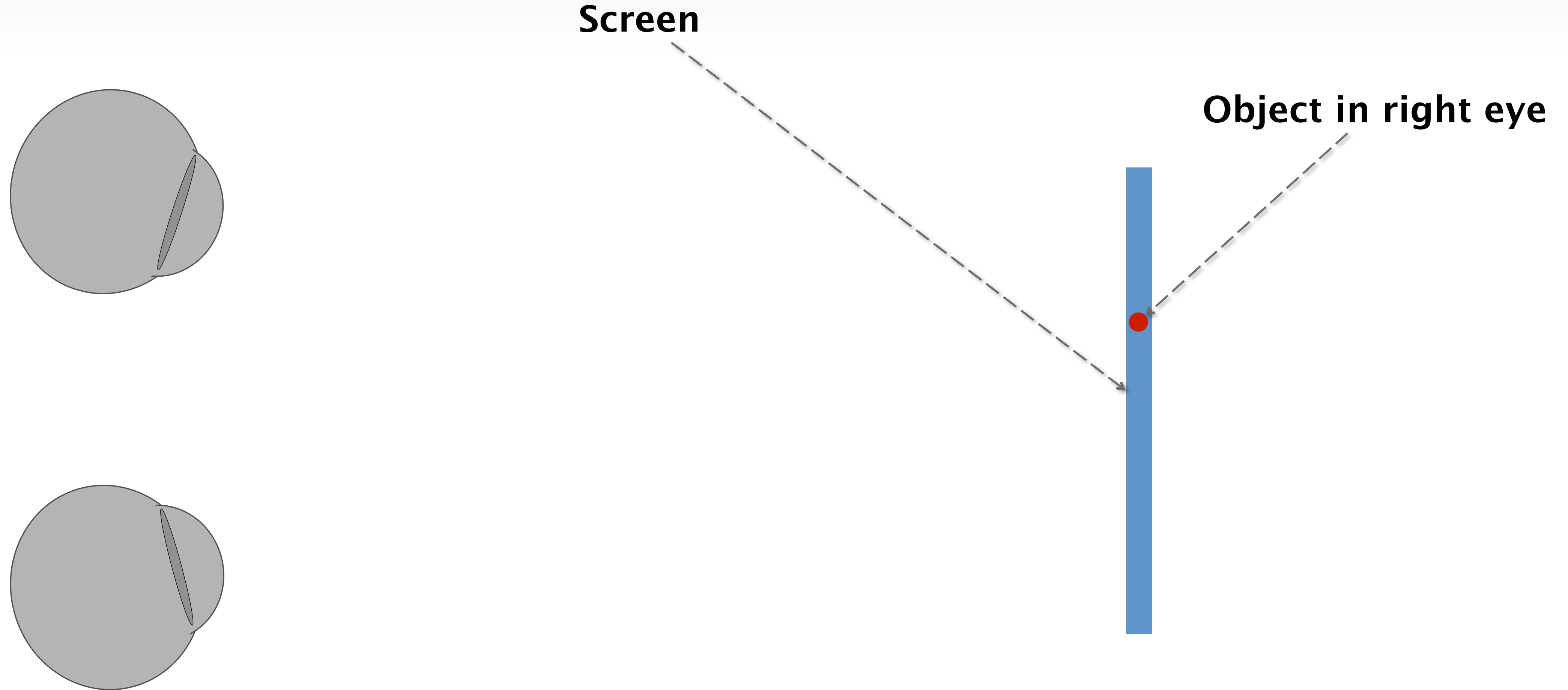
Cheating our HVS

Cheating our HVS

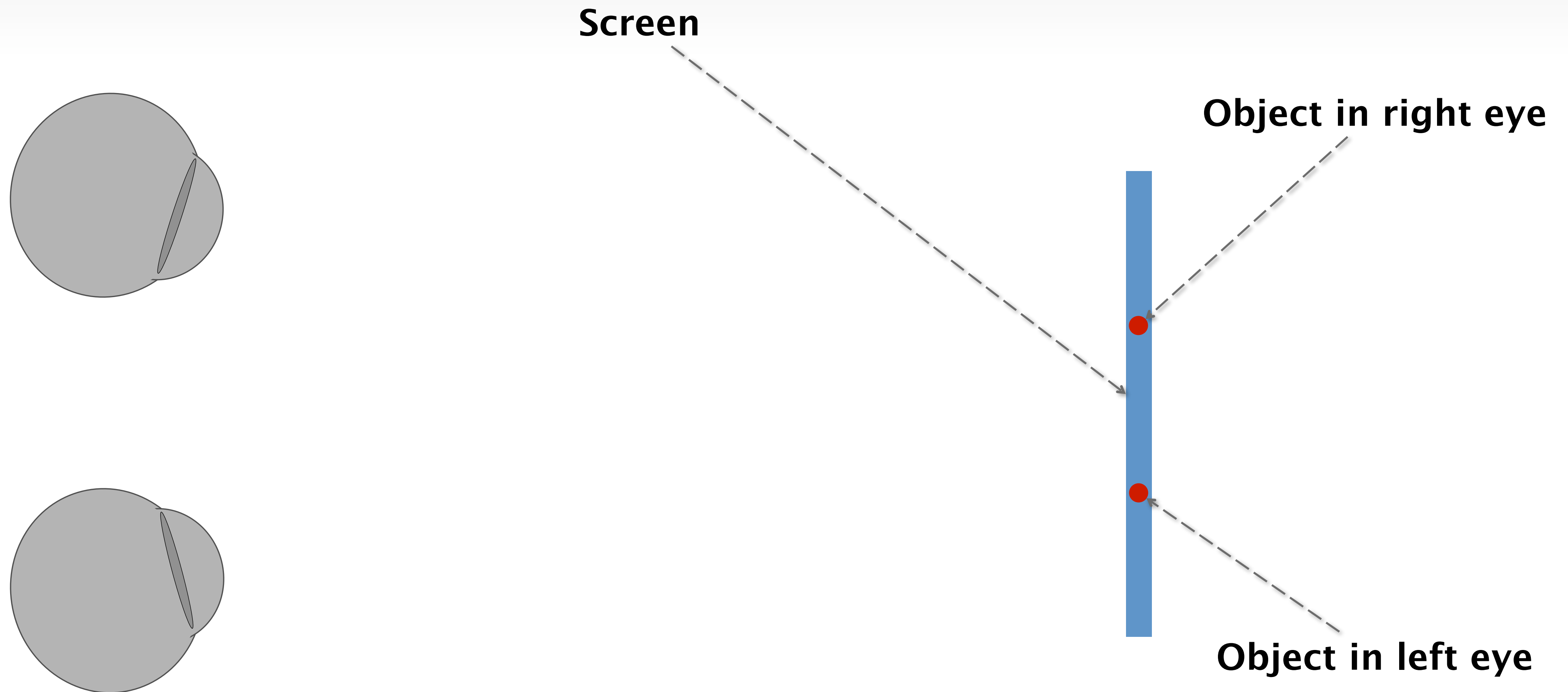
Screen



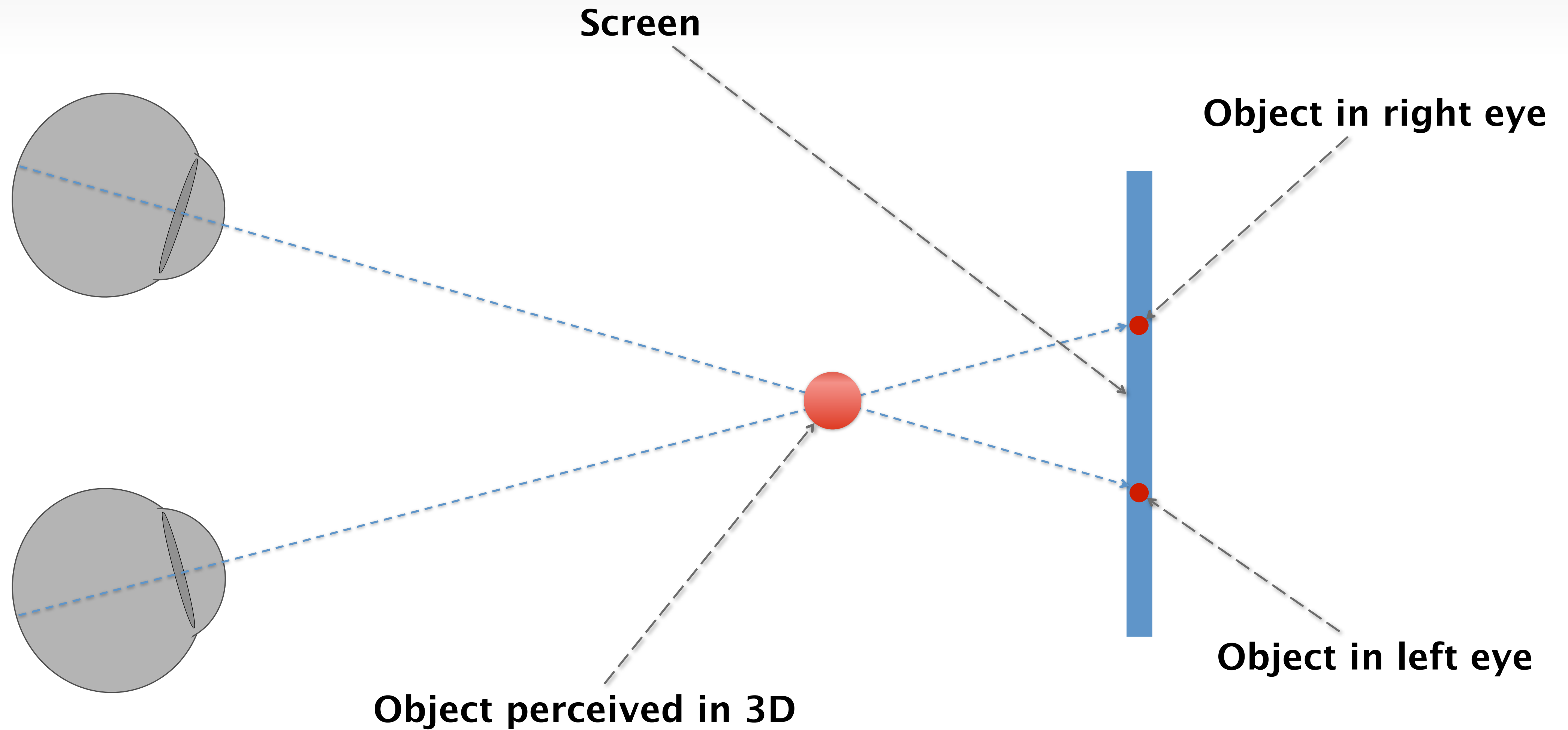
Cheating our HVS



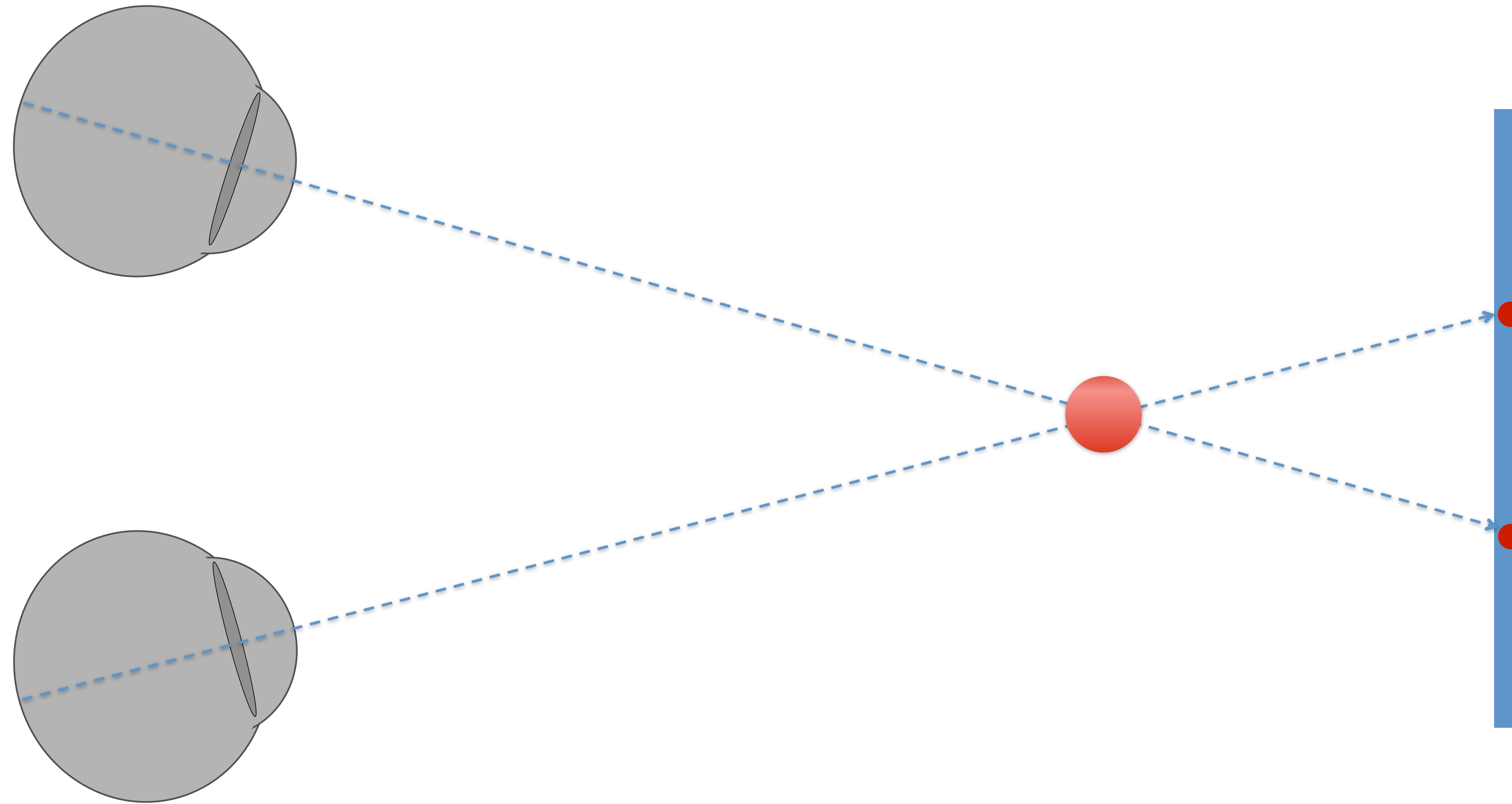
Cheating our HVS



Cheating our HVS

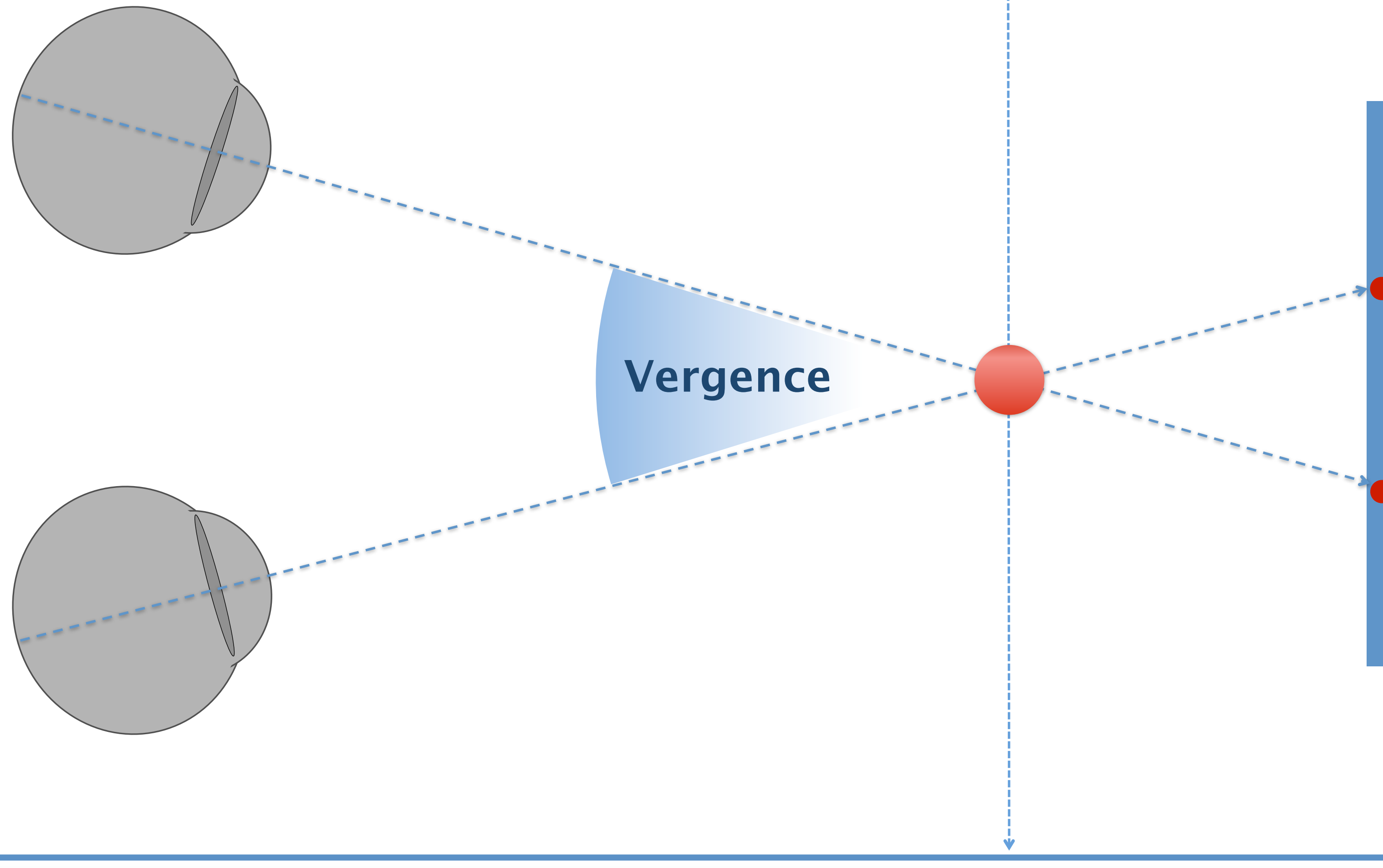


Cheating our HVS



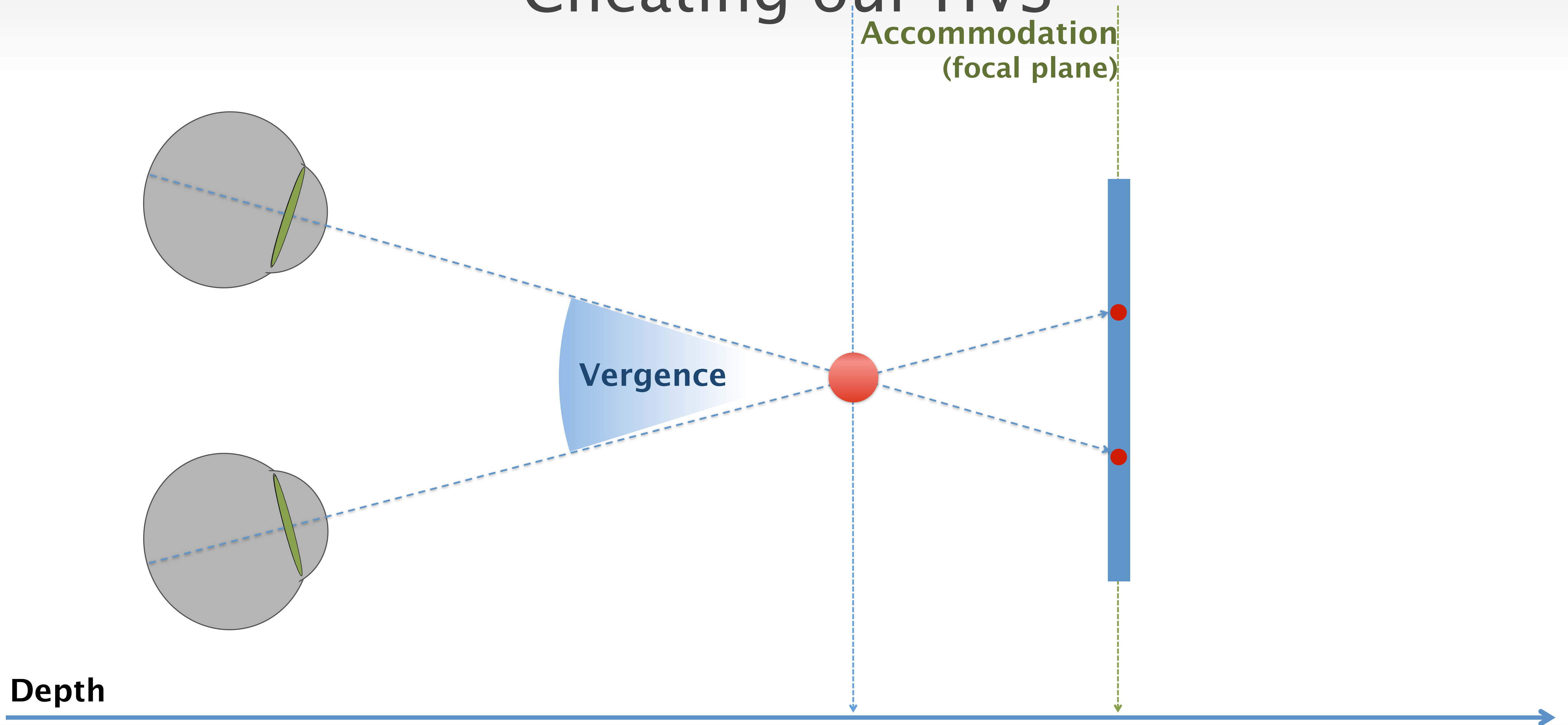
Depth

Cheating our HVS

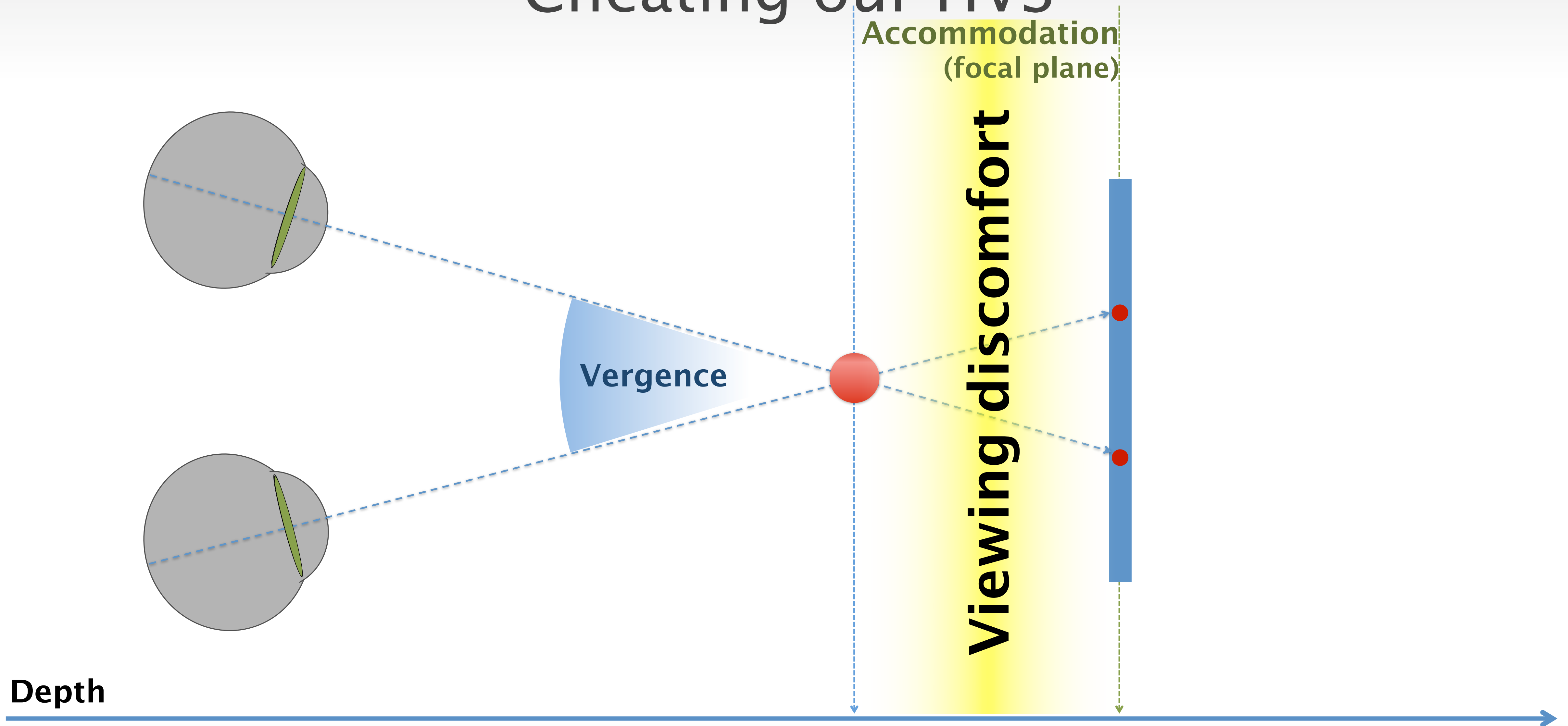


Depth

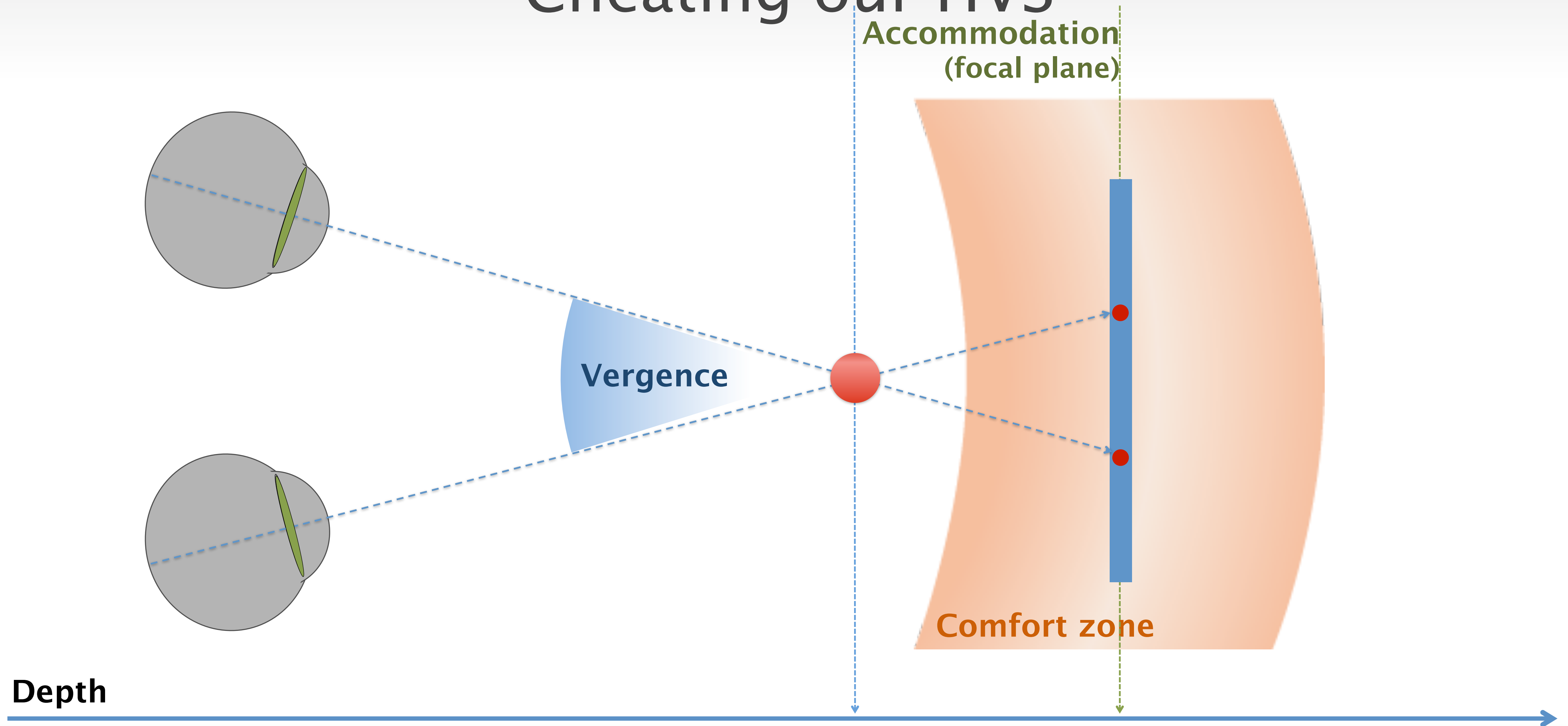
Cheating our HVS



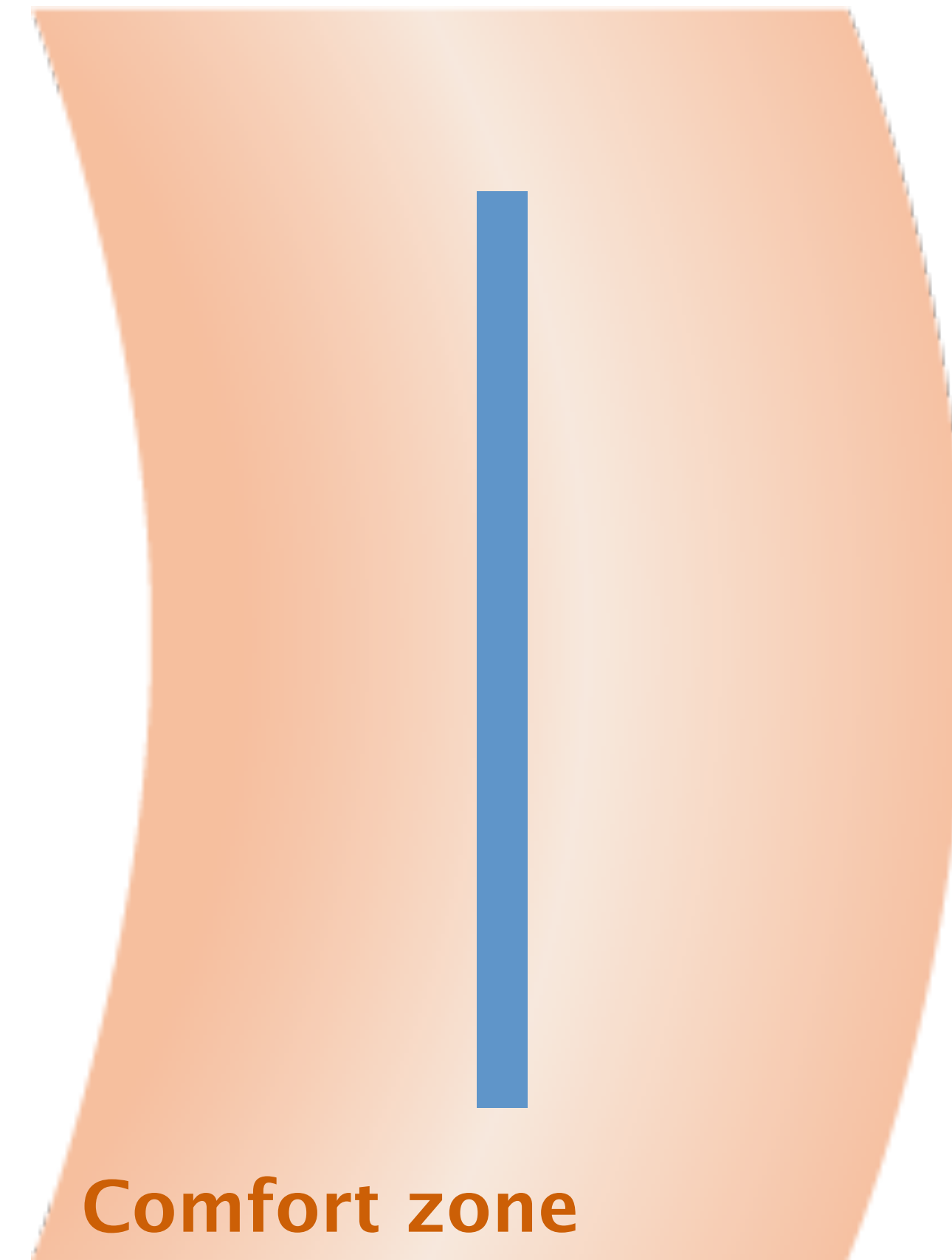
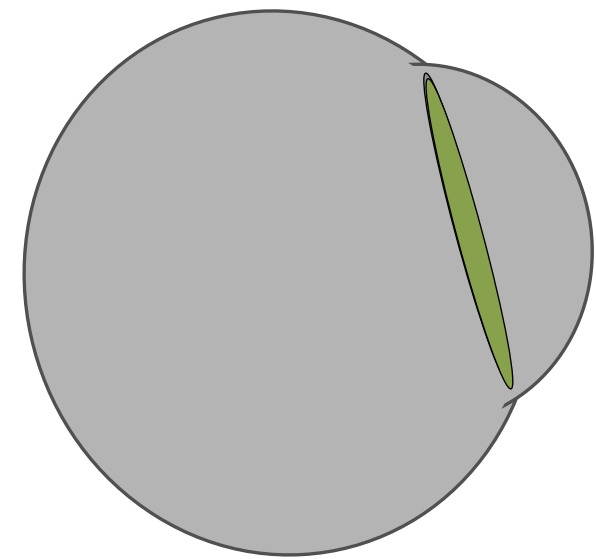
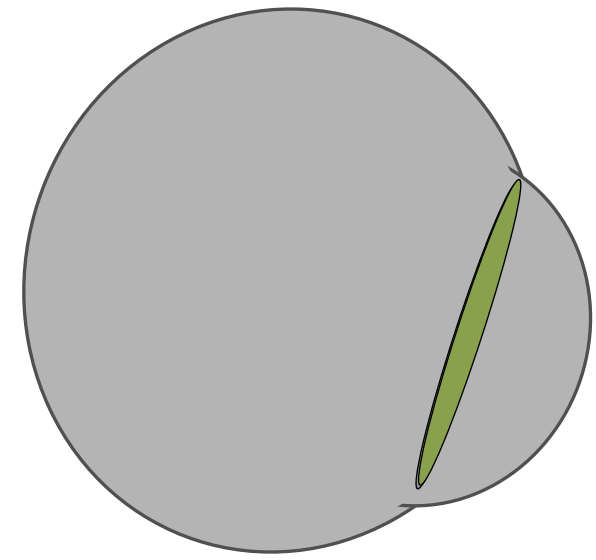
Cheating our HVS



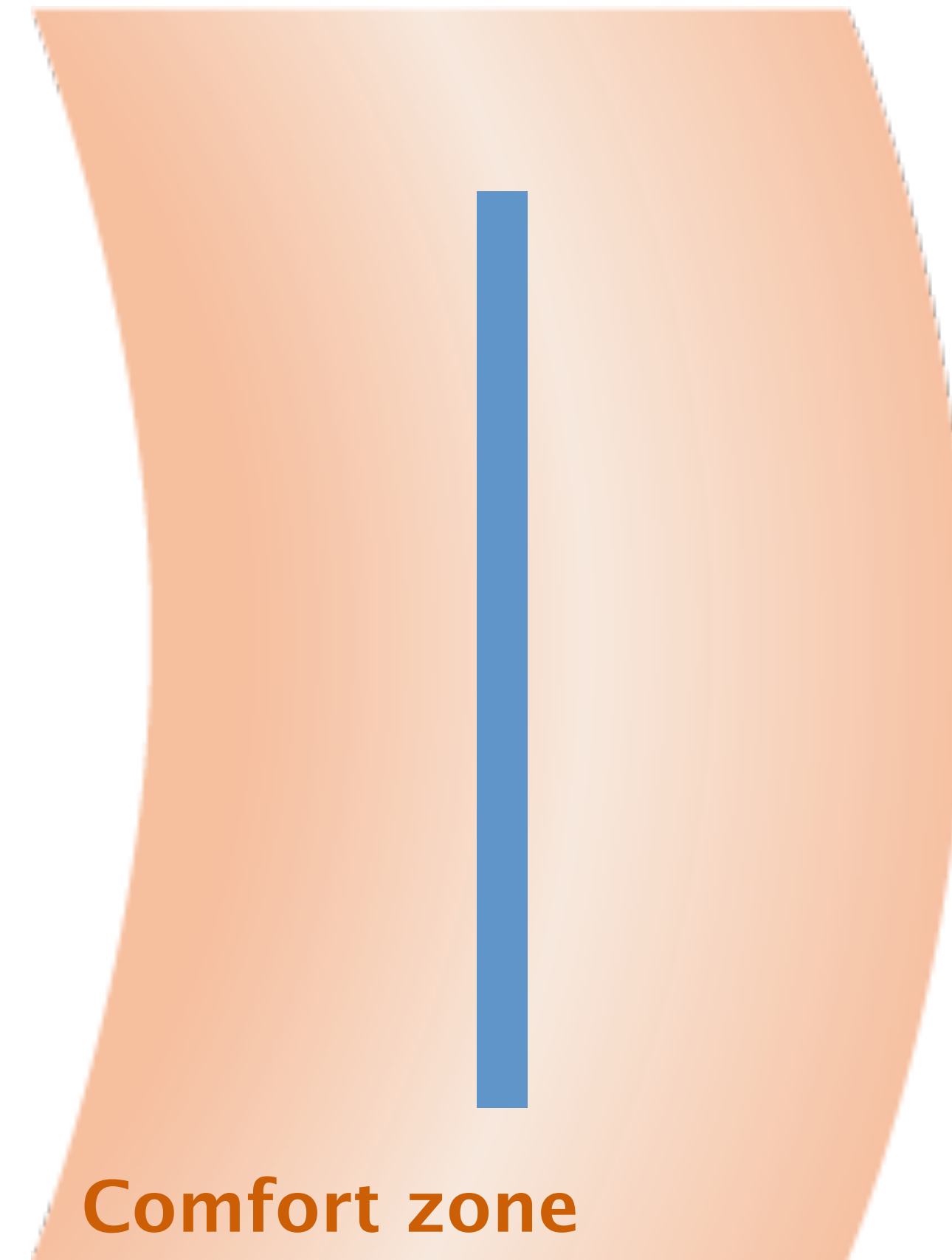
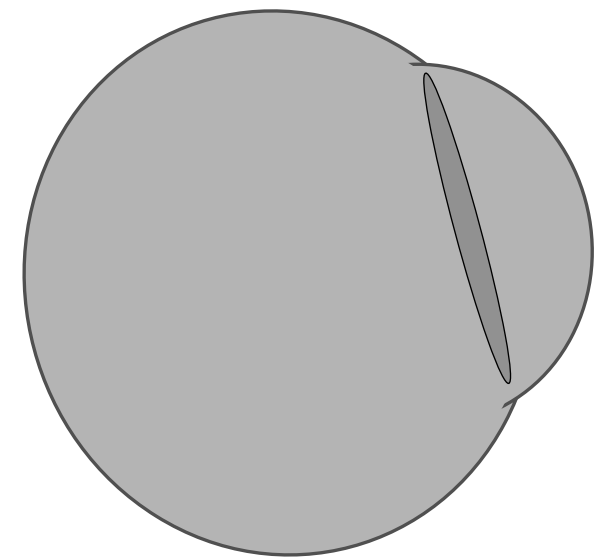
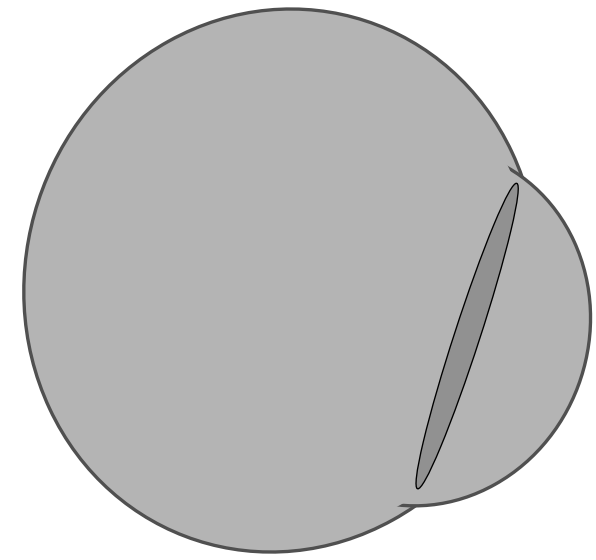
Cheating our HVS



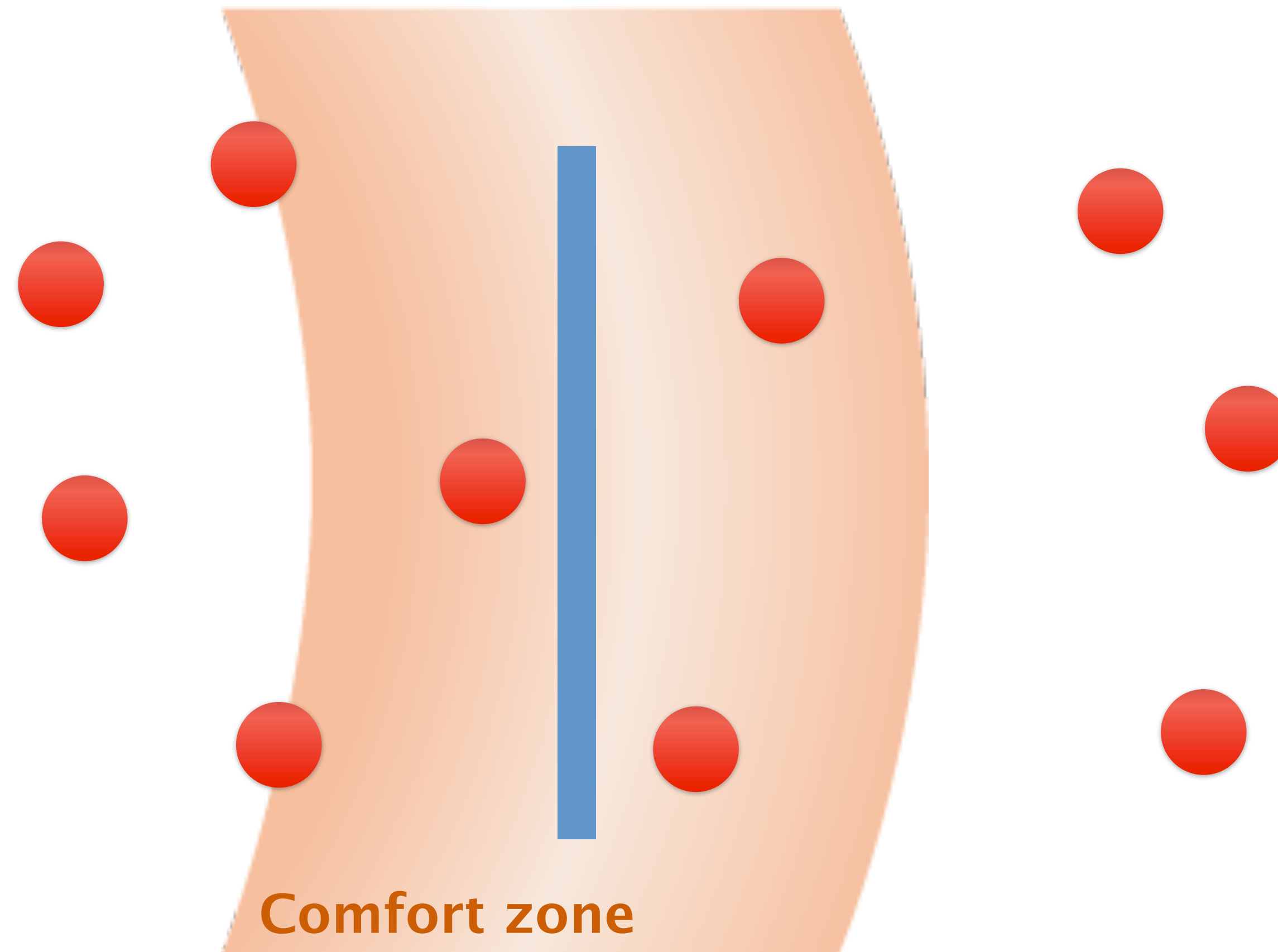
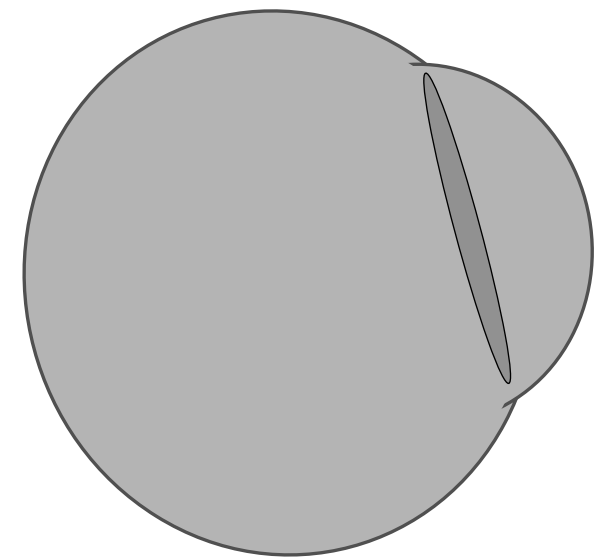
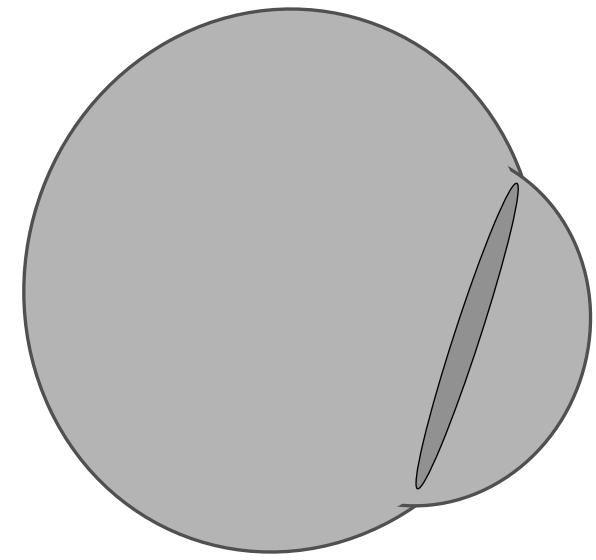
Cheating our HVS



Depth manipulation

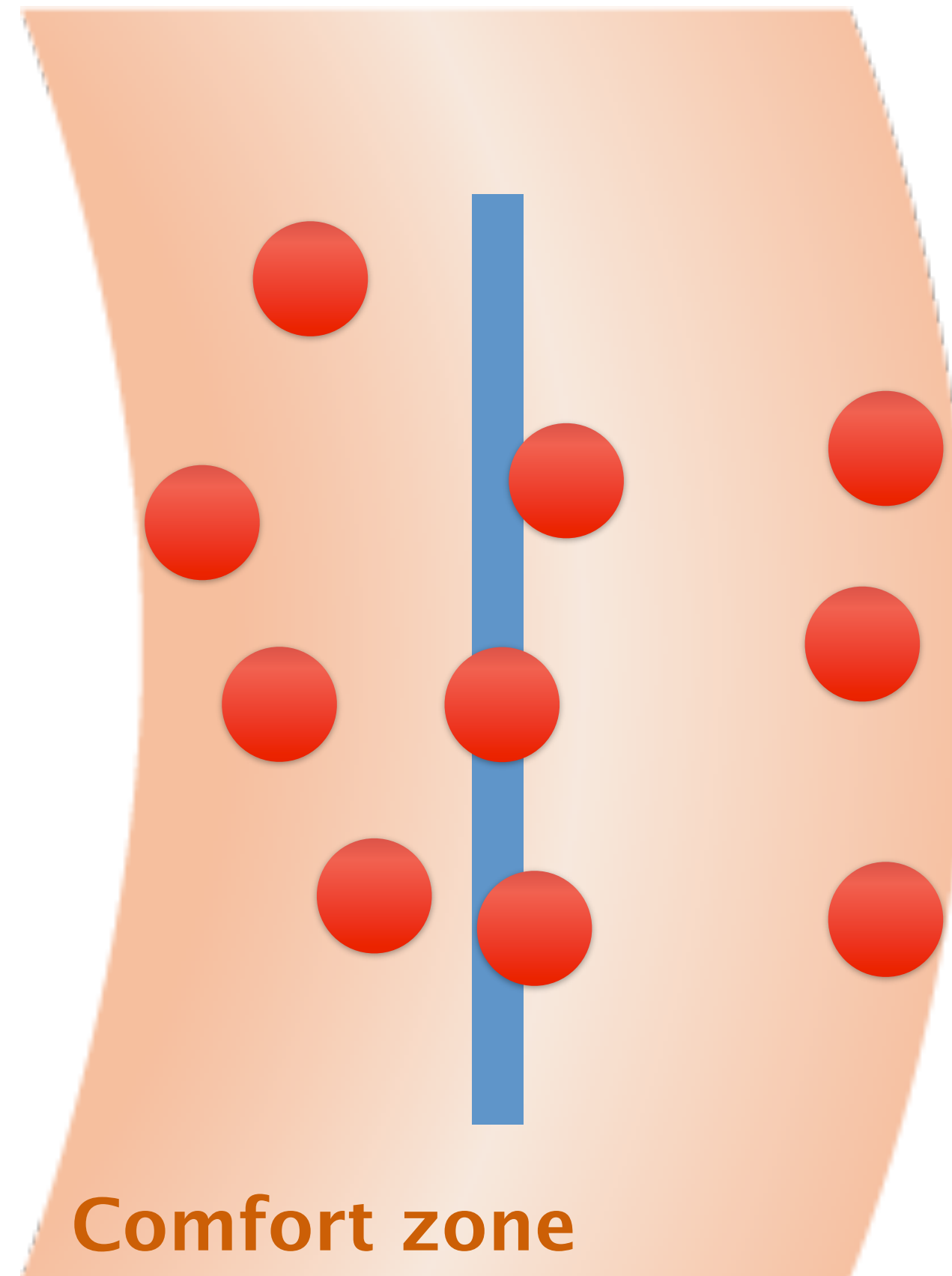
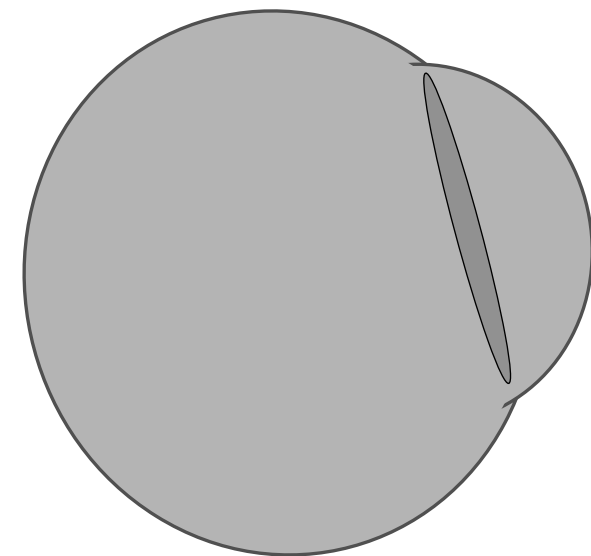
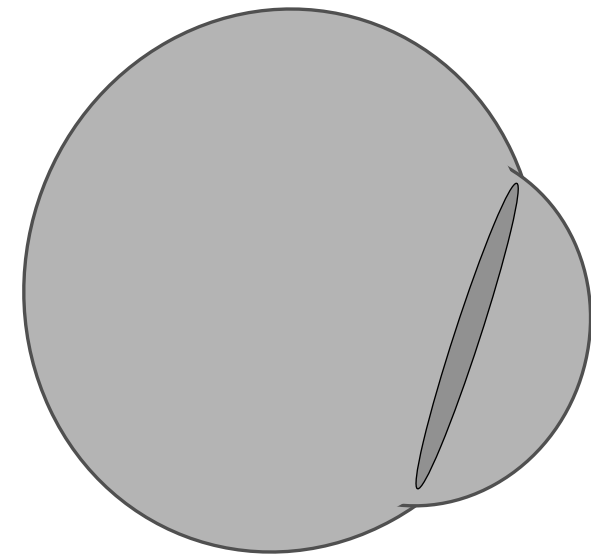


Depth manipulation



Viewing discomfort

Depth manipulation



Viewing discomfort

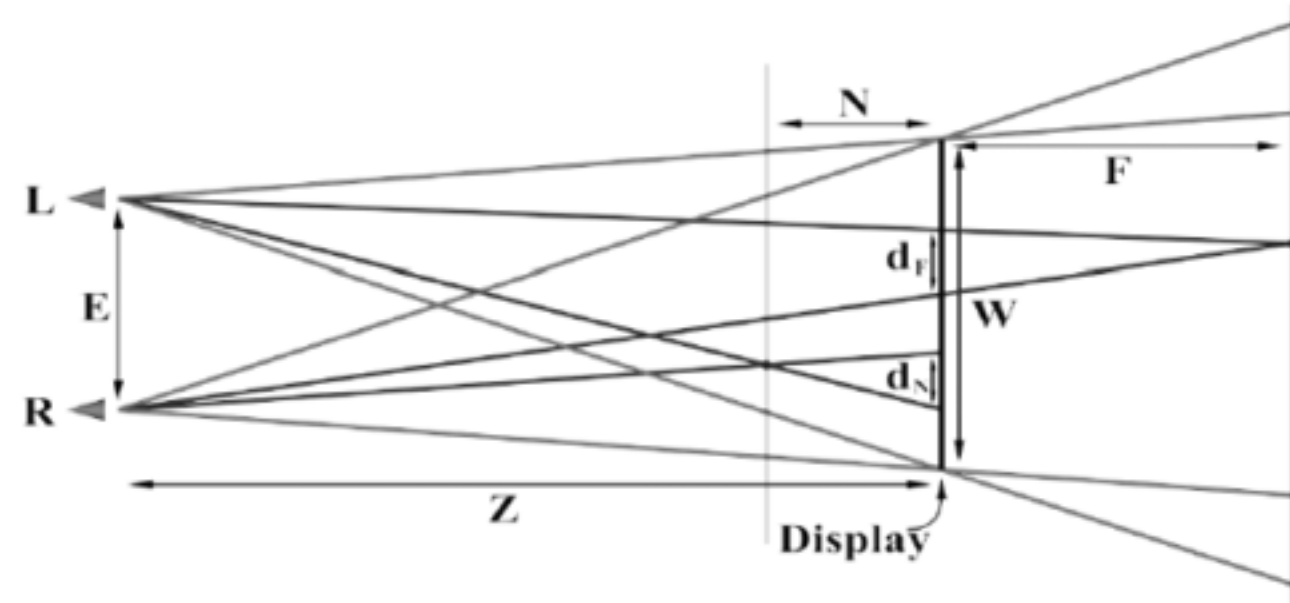
Scene manipulation →

Viewing comfort

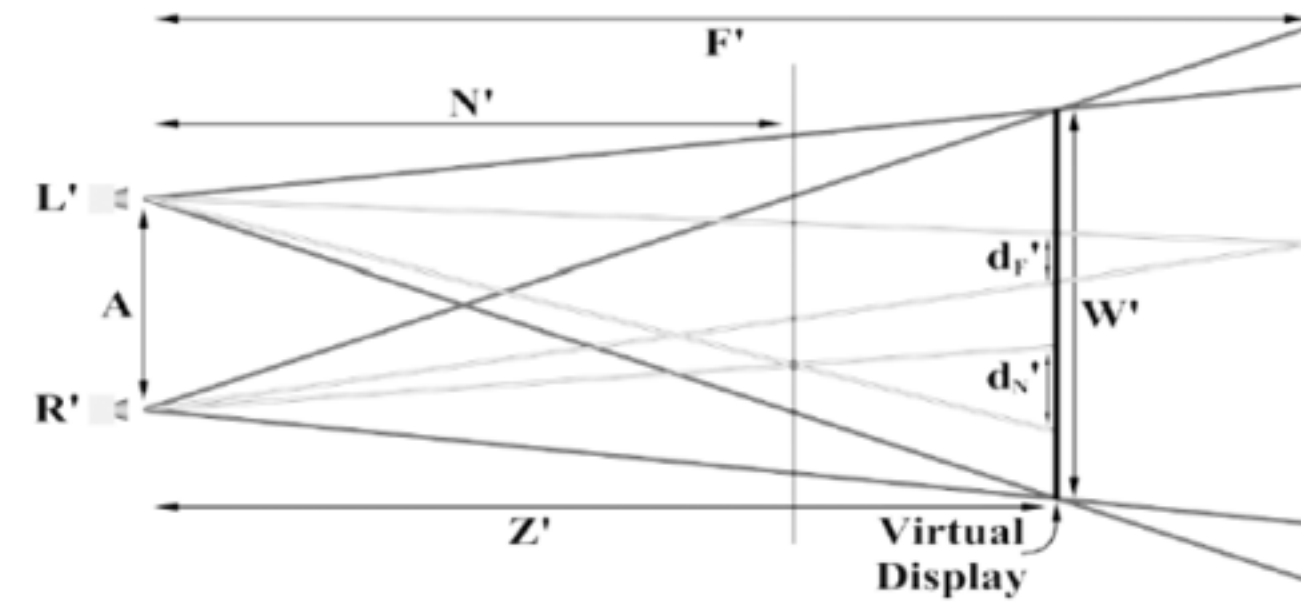
Scene manipulation

Scene manipulation

a) Viewer/Display space



b) Camera/Scene space

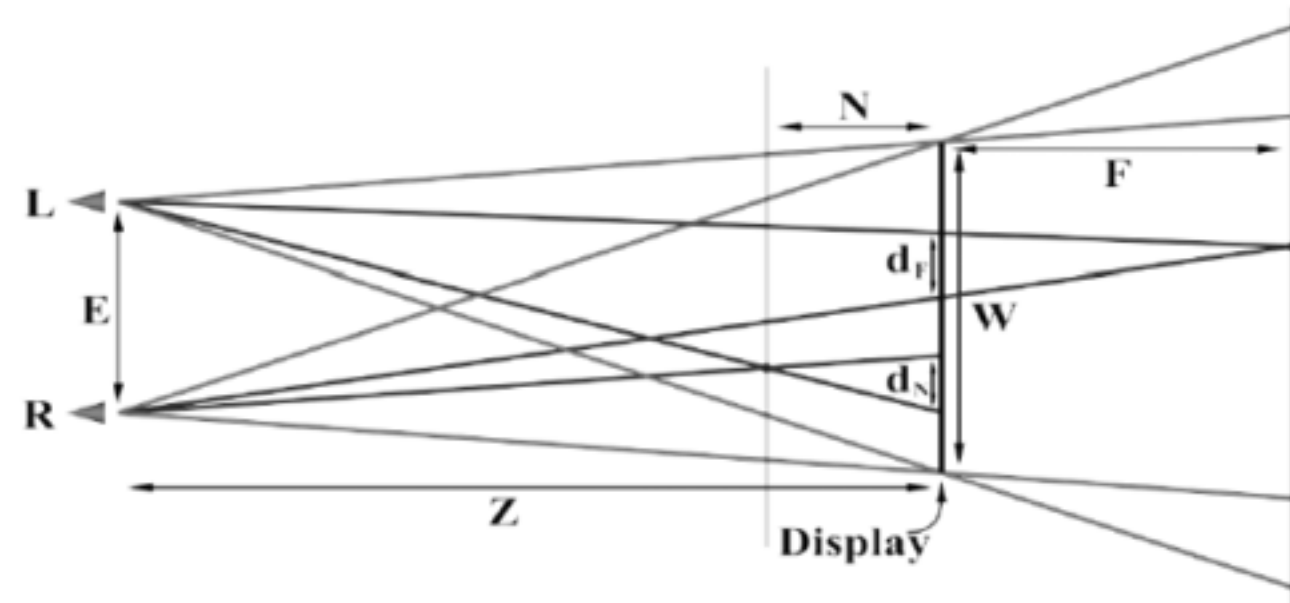


Camera manipulation

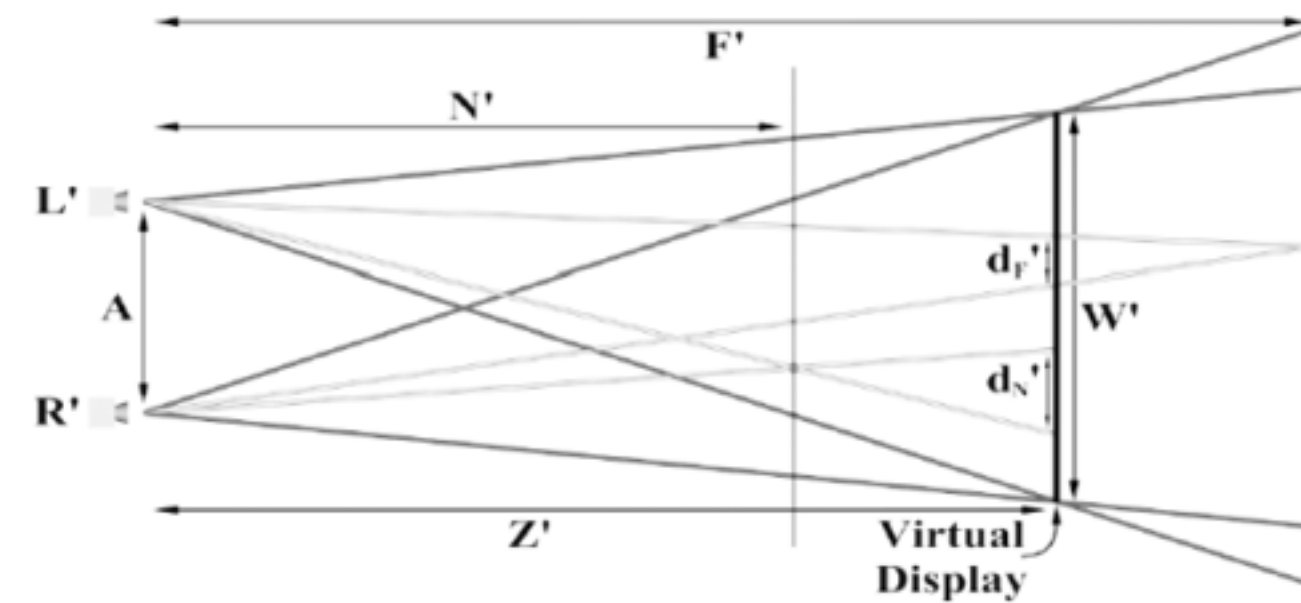
“Controlling Perceived Depth in Stereoscopic Images”
[Jones et al. 2001]

Scene manipulation

a) Viewer/Display space

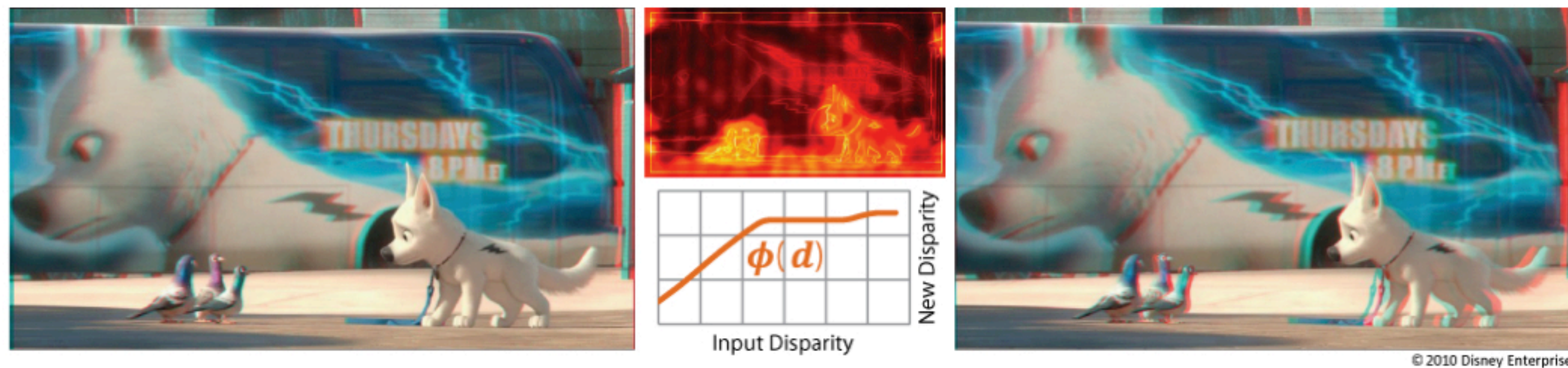


b) Camera/Scene space



Camera manipulation

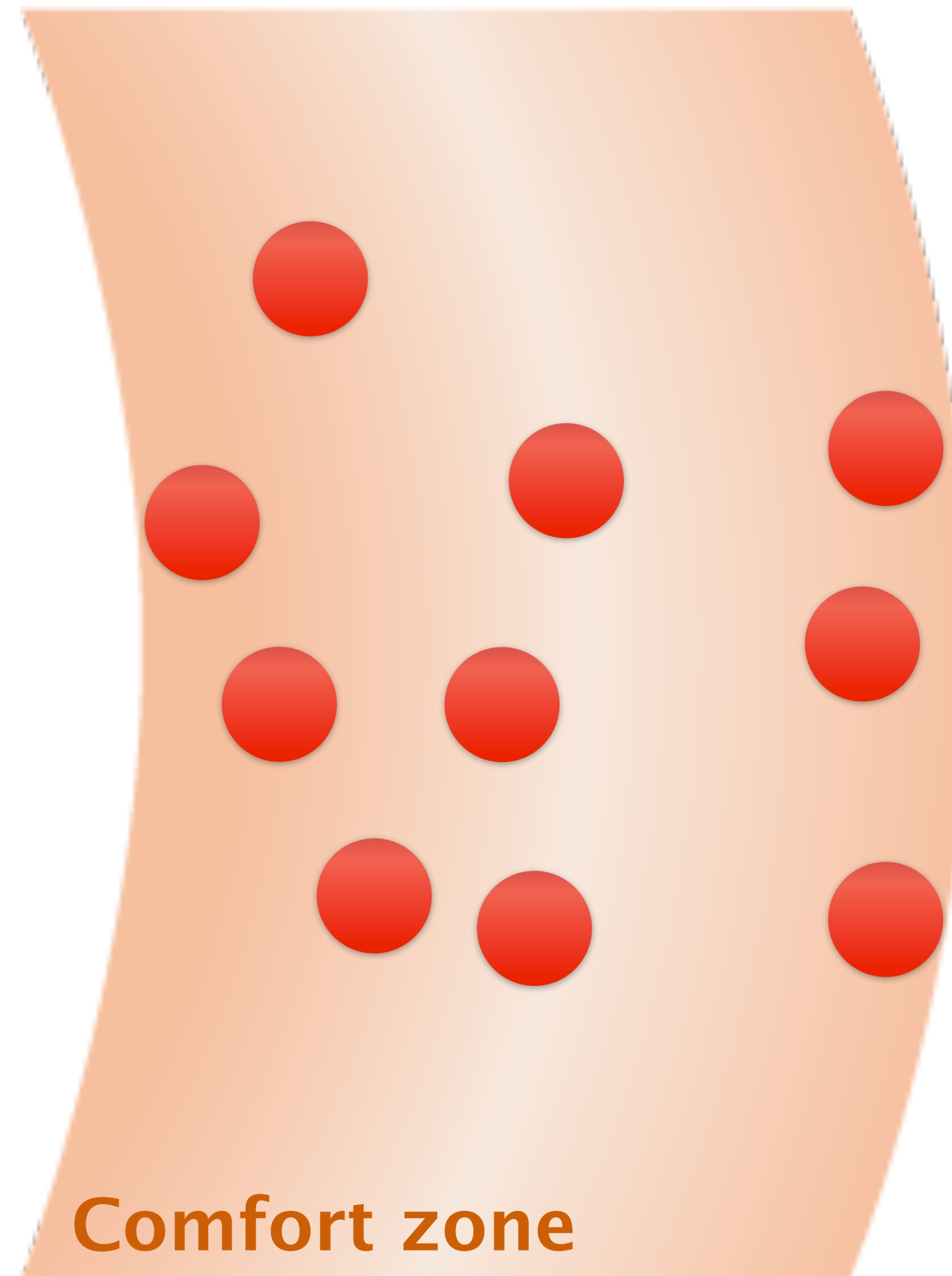
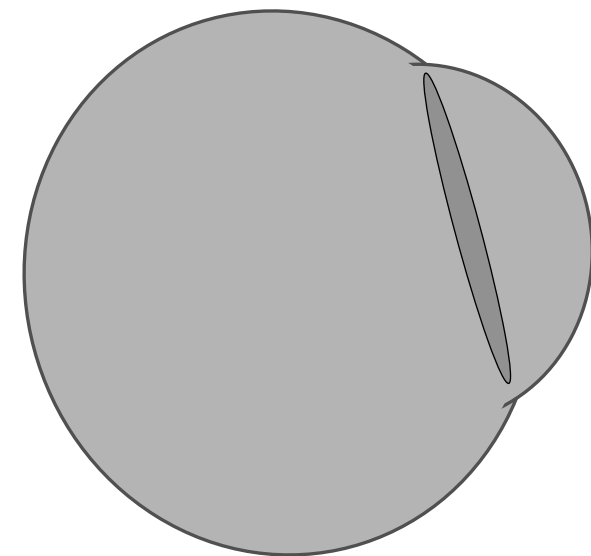
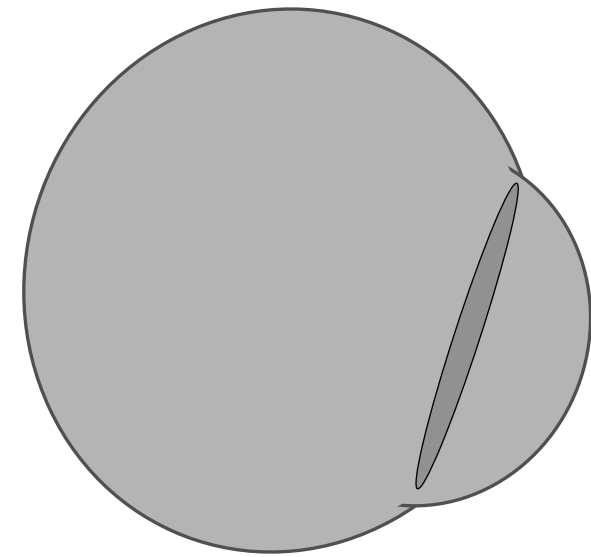
“Controlling Perceived Depth in Stereoscopic Images”
[Jones et al. 2001]



Disparity manipulation

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

Depth manipulation

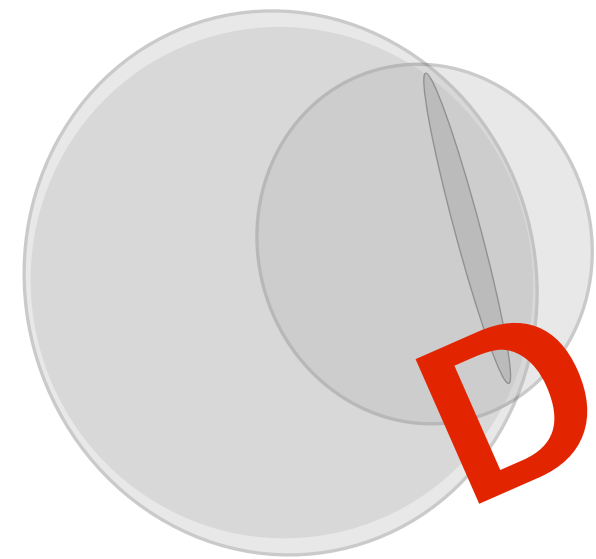
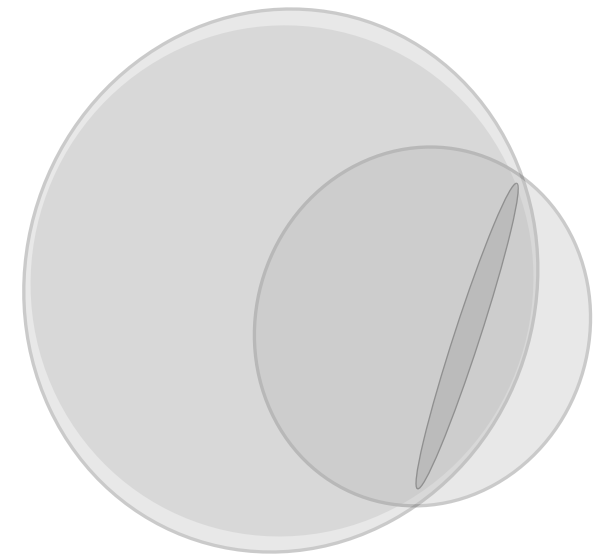


Viewing discomfort

Scene manipulation →

Viewing comfort

Depth manipulation



Depth impression suppressed!



Viewing discomfort

Scene manipulation →

Viewing comfort

Tone-mapping problem

Tone-mapping problem



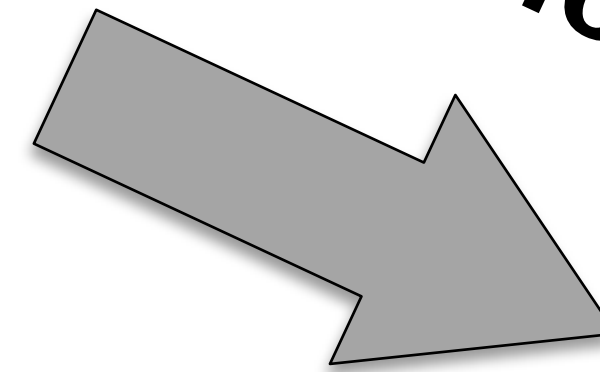
High dynamic range image

Tone-mapping problem



High dynamic range image

**Dynamic range
reduction**



Contrast Restoration

“Contrast Restoration by Adaptive Countershading”
[Krawczyk et al. 2007]

Contrast Restoration



Tone mapped

“Contrast Restoration by Adaptive Countershading”
[Krawczyk et al. 2007]

Contrast Restoration



Tone mapped

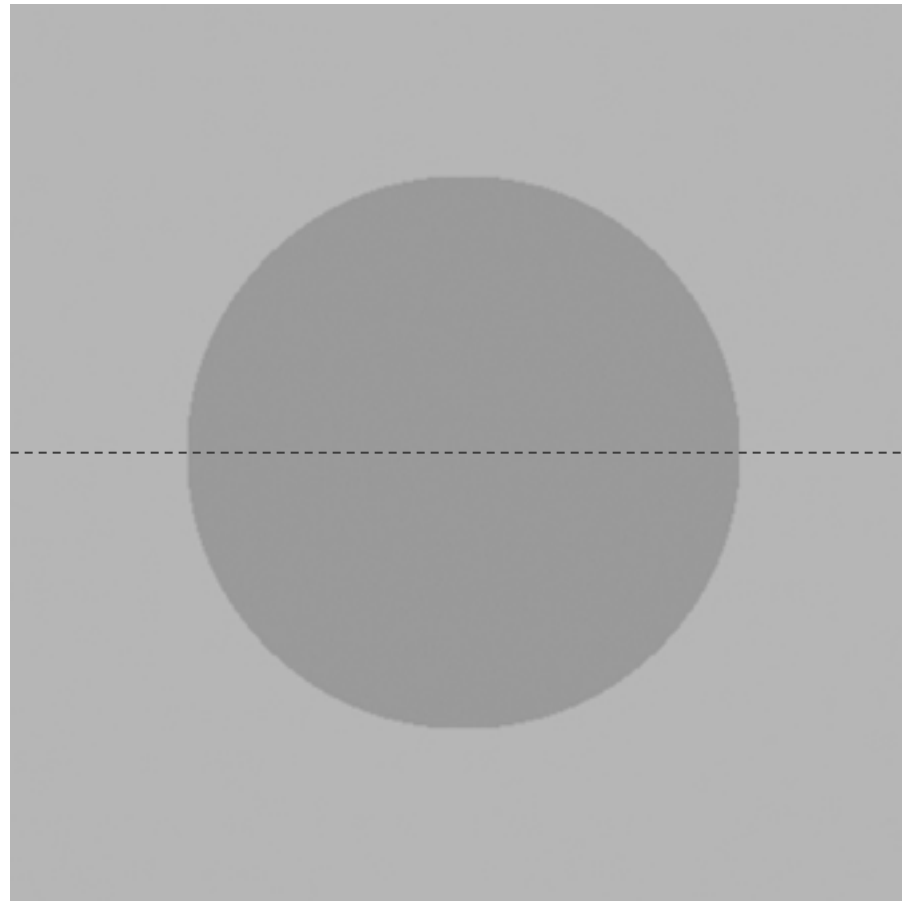


Enhanced

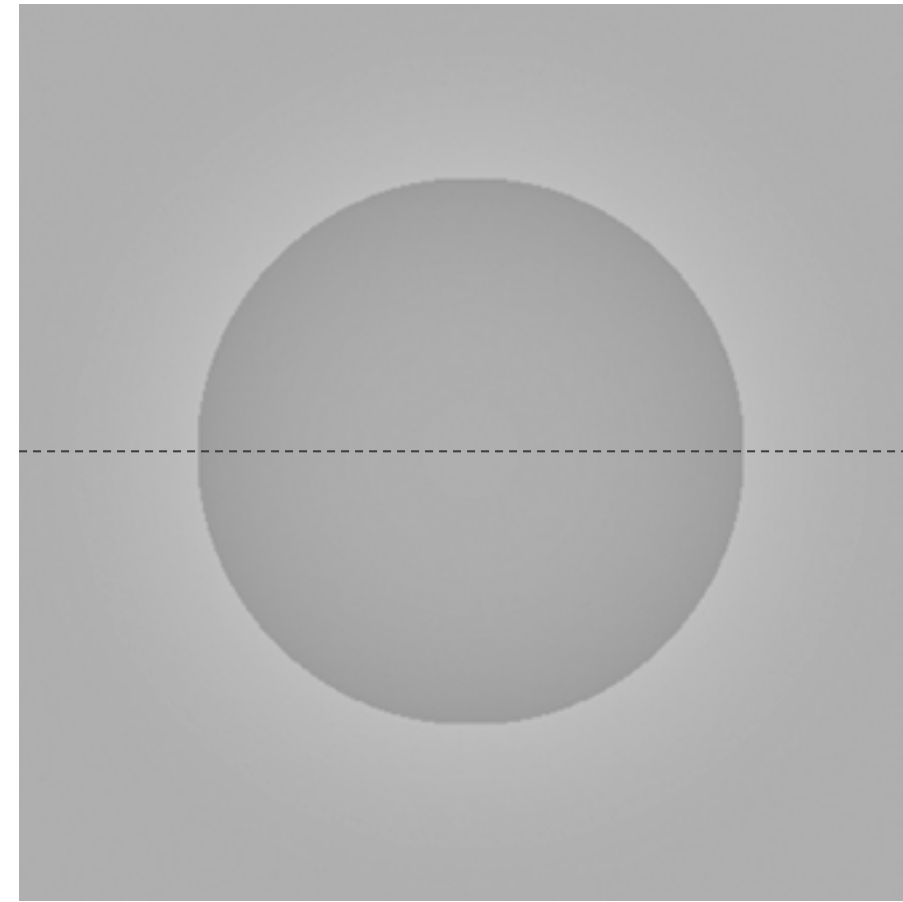
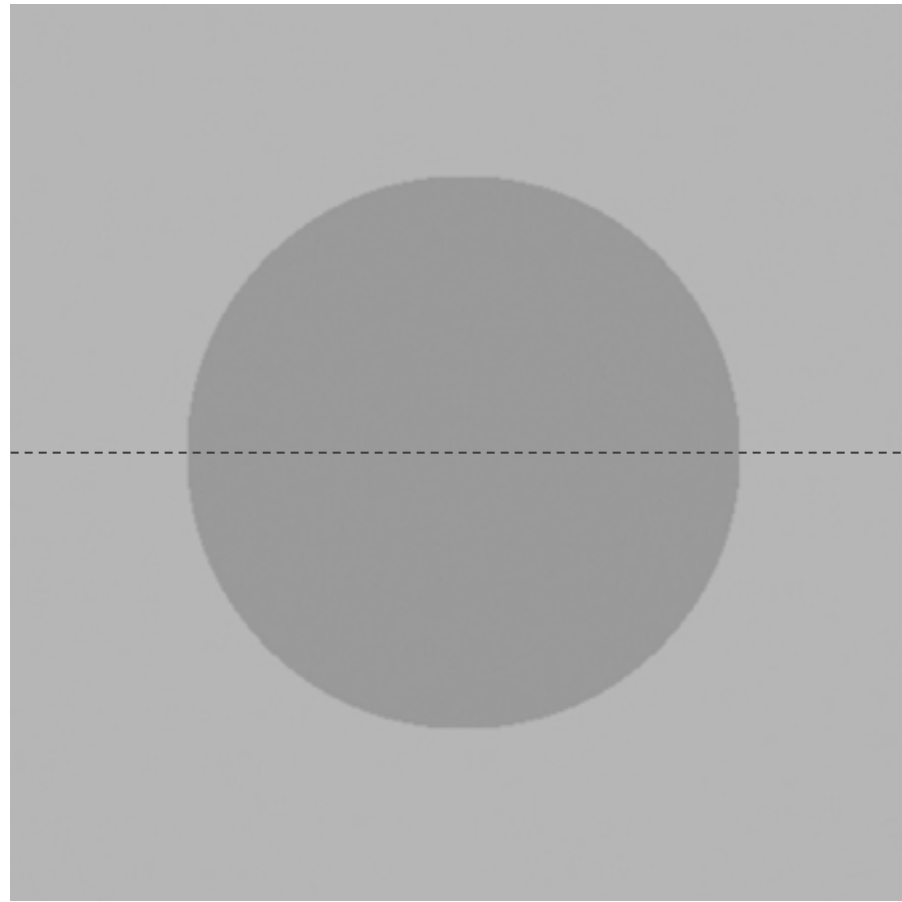
“Contrast Restoration by Adaptive Countershading”
[Krawczyk et al. 2007]

Cornsweet illusion

Cornsweet illusion

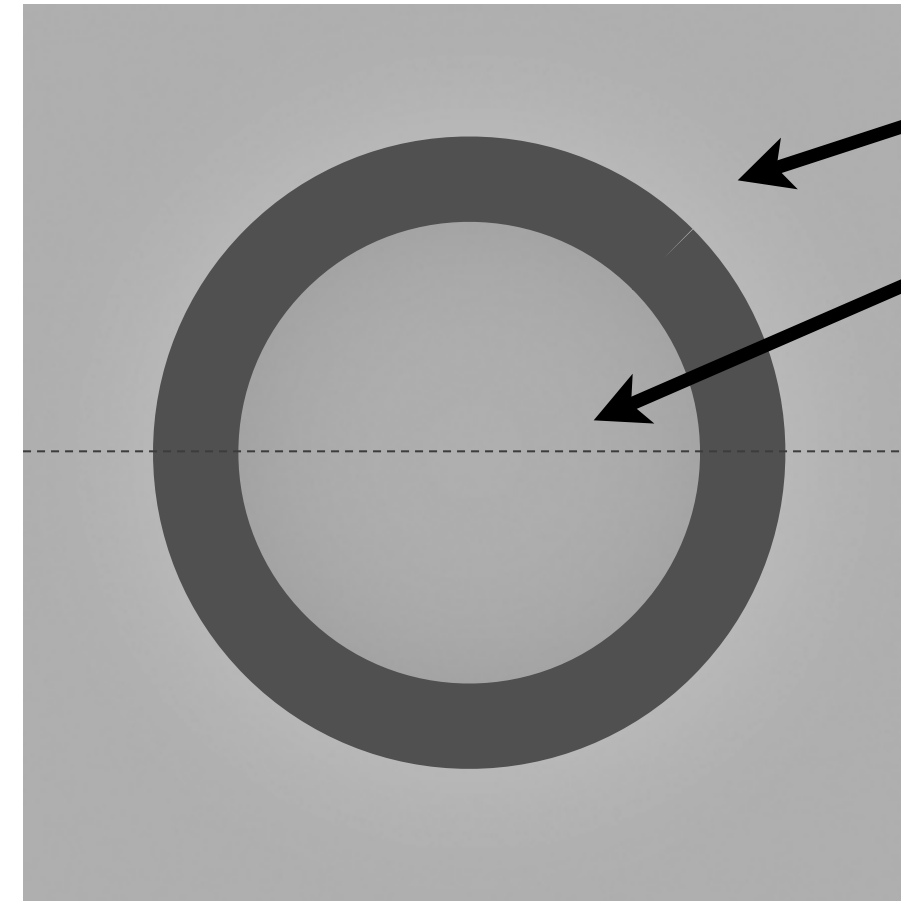
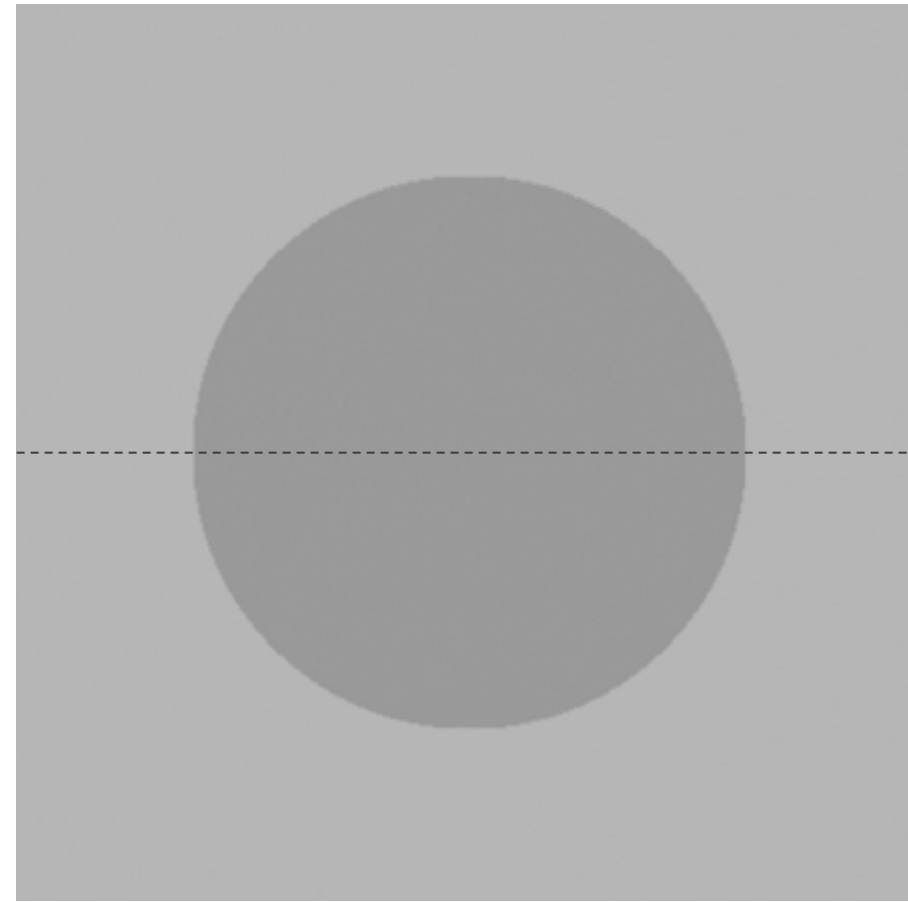


Cornsweet illusion



- Perceived contrast similar

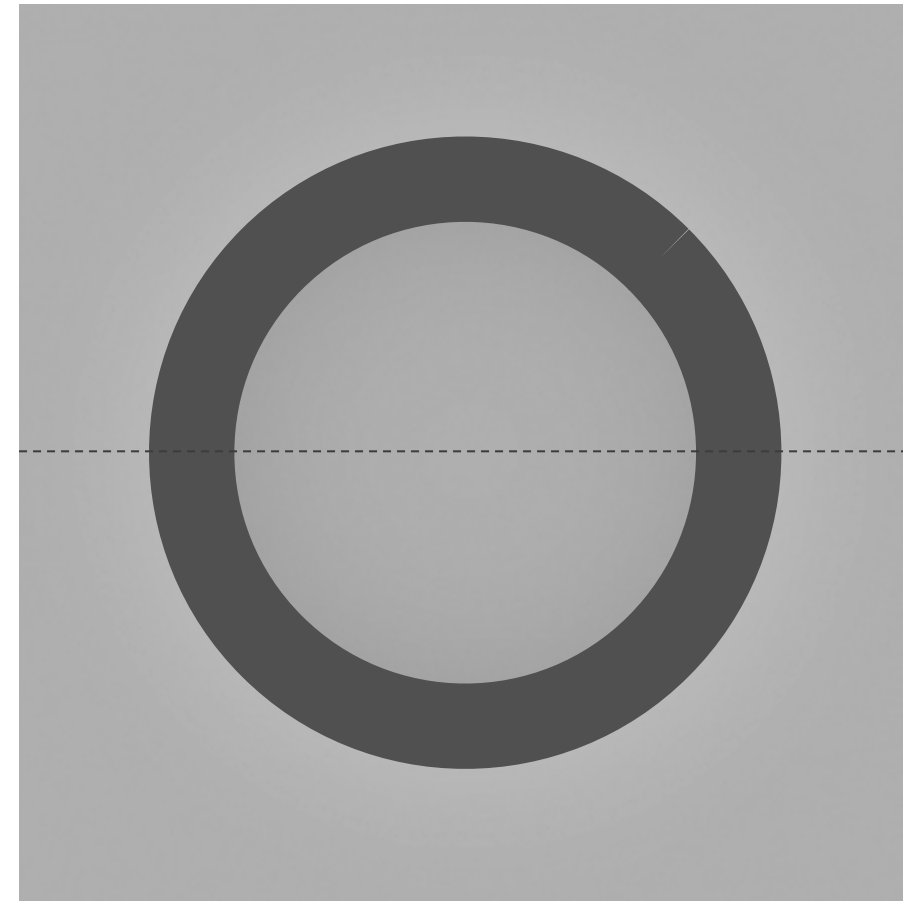
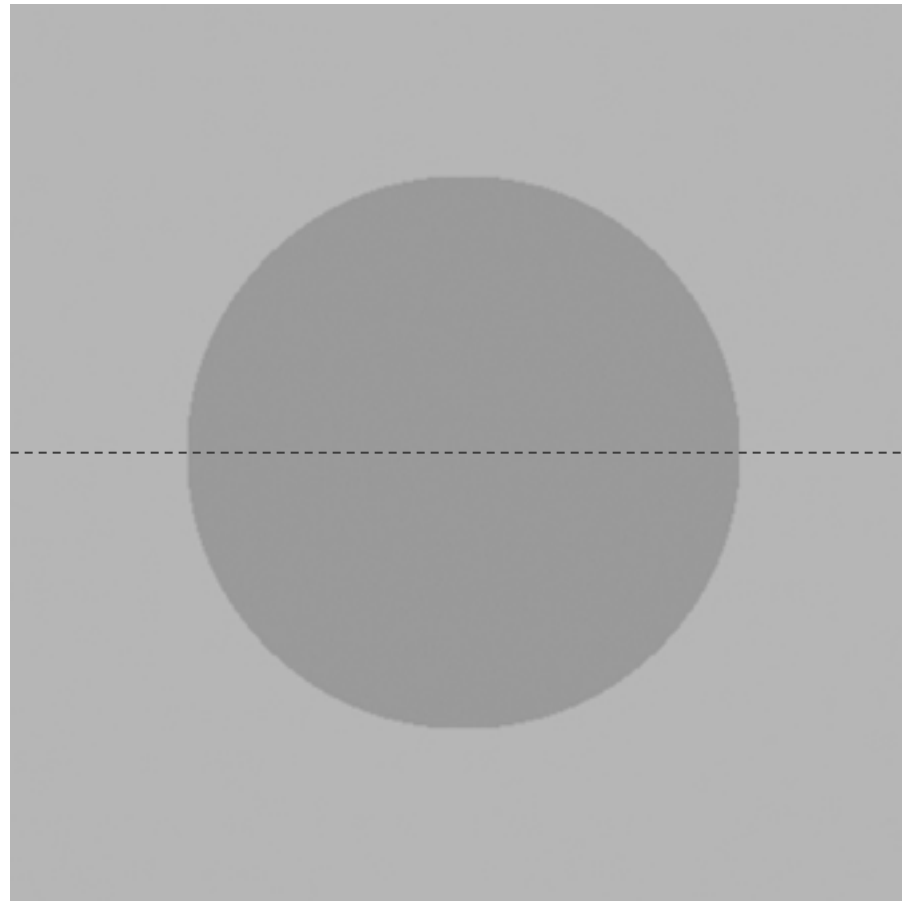
Cornsweet illusion



the same

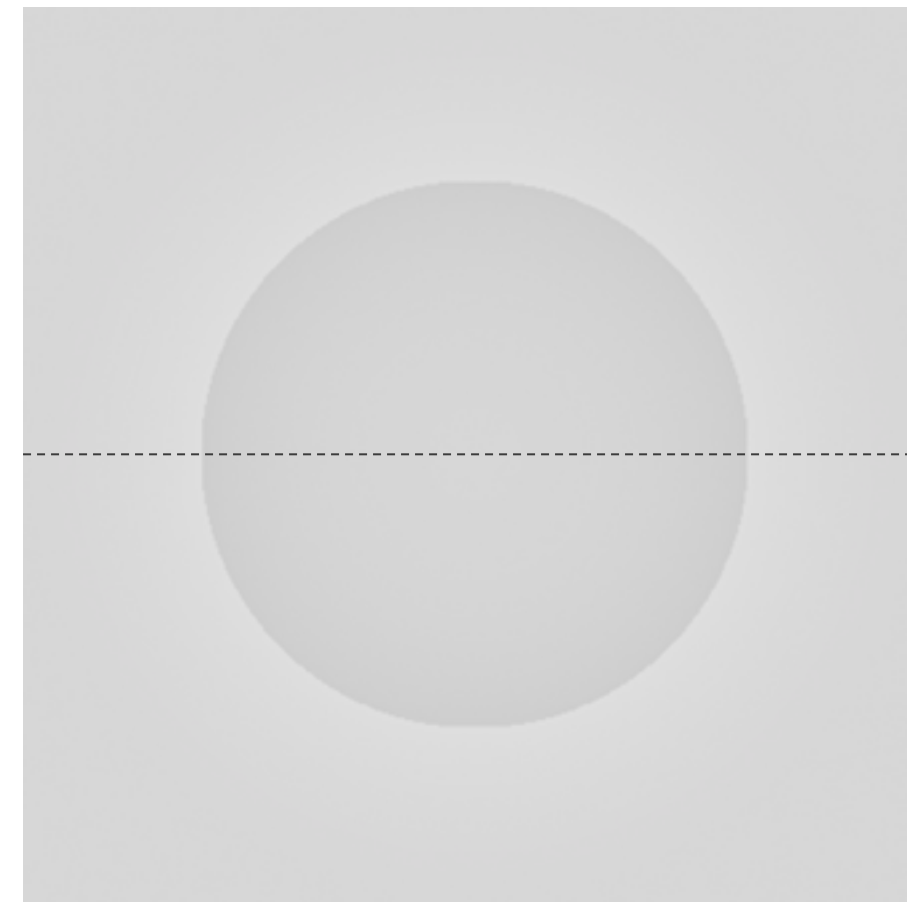
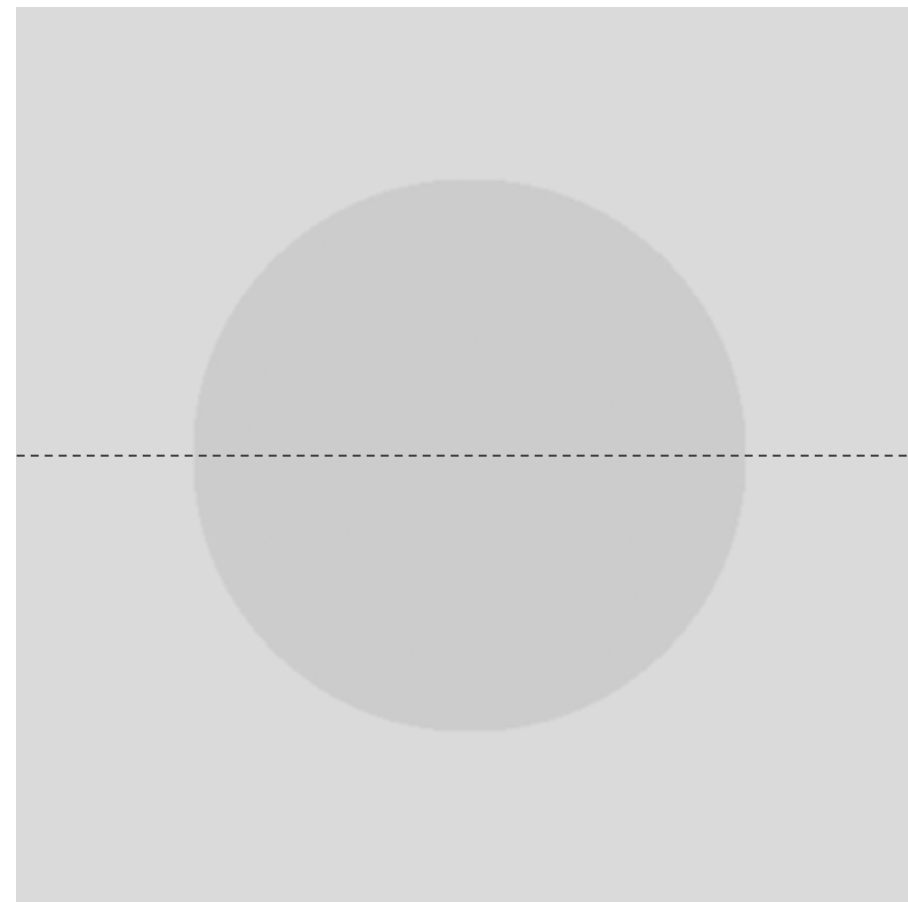
- Perceived contrast similar
- Luminance range reduced

Cornsweet illusion



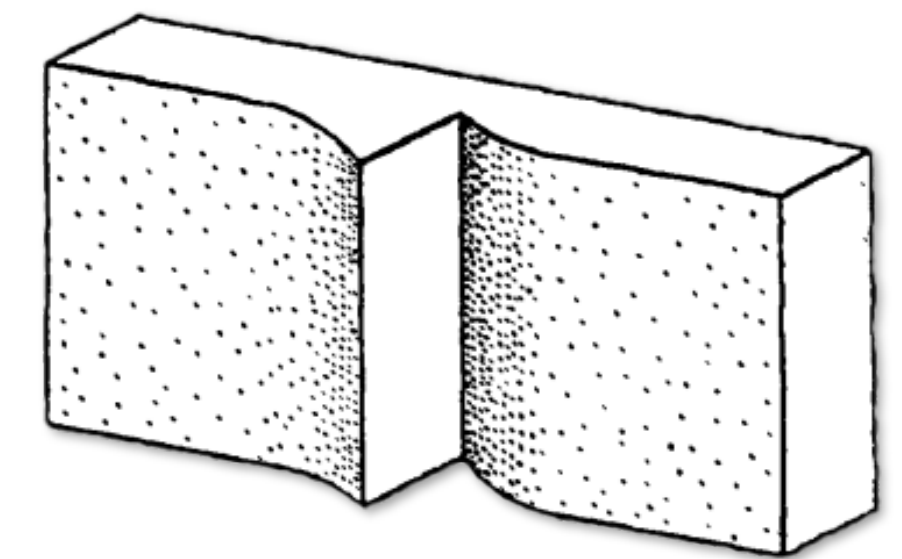
- Perceived contrast similar
- Luminance range reduced

Cornsweet illusion



- Perceived contrast similar
- Luminance range reduced

Cornsweet illusion works for depth:

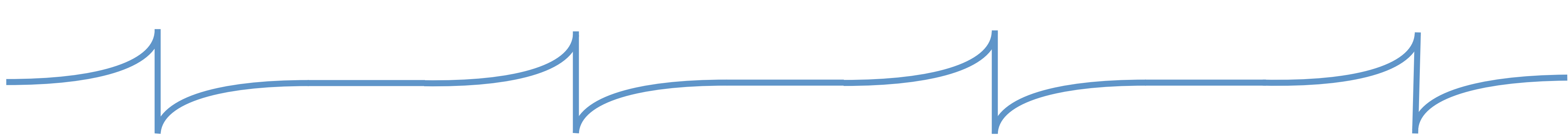


“A Craik–O'Brien–Cornsweet illusion for visual depth” [Anstis et al. 1978]

Profiles cascading

Profiles cascading

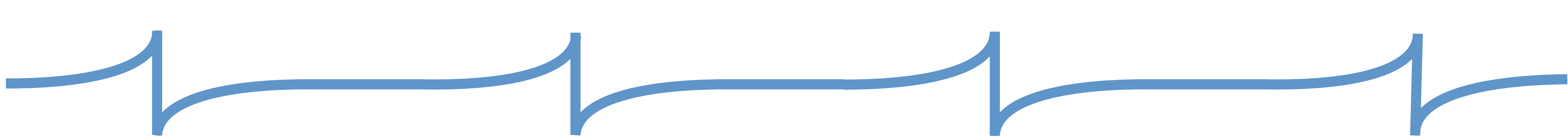
Cornsweet profile



Depth ↑

Profiles cascading

Cornsweet profile

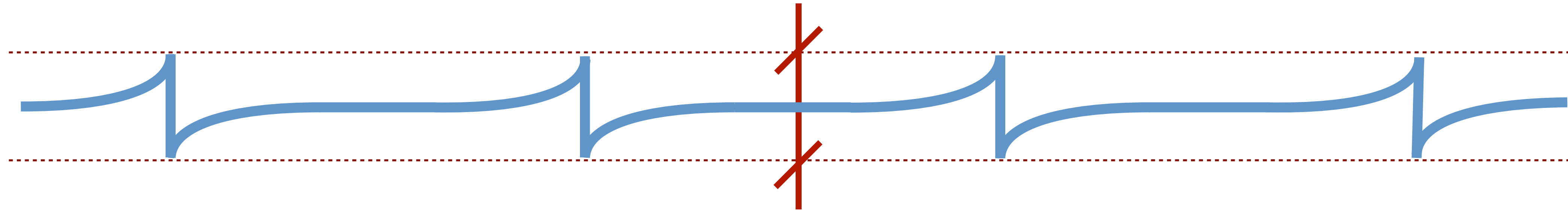


Perceived profile



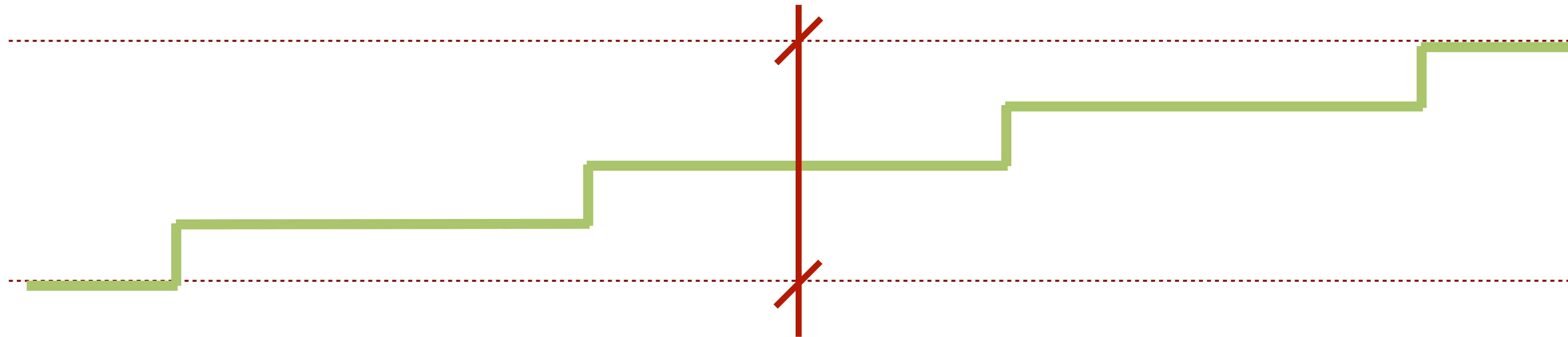
Profiles cascading

Cornsweet profile



Depth ↑

Perceived profile

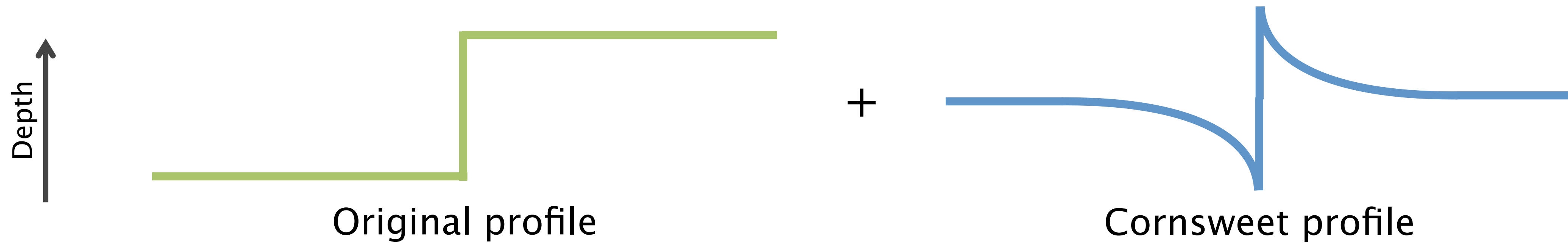


Depth ↑

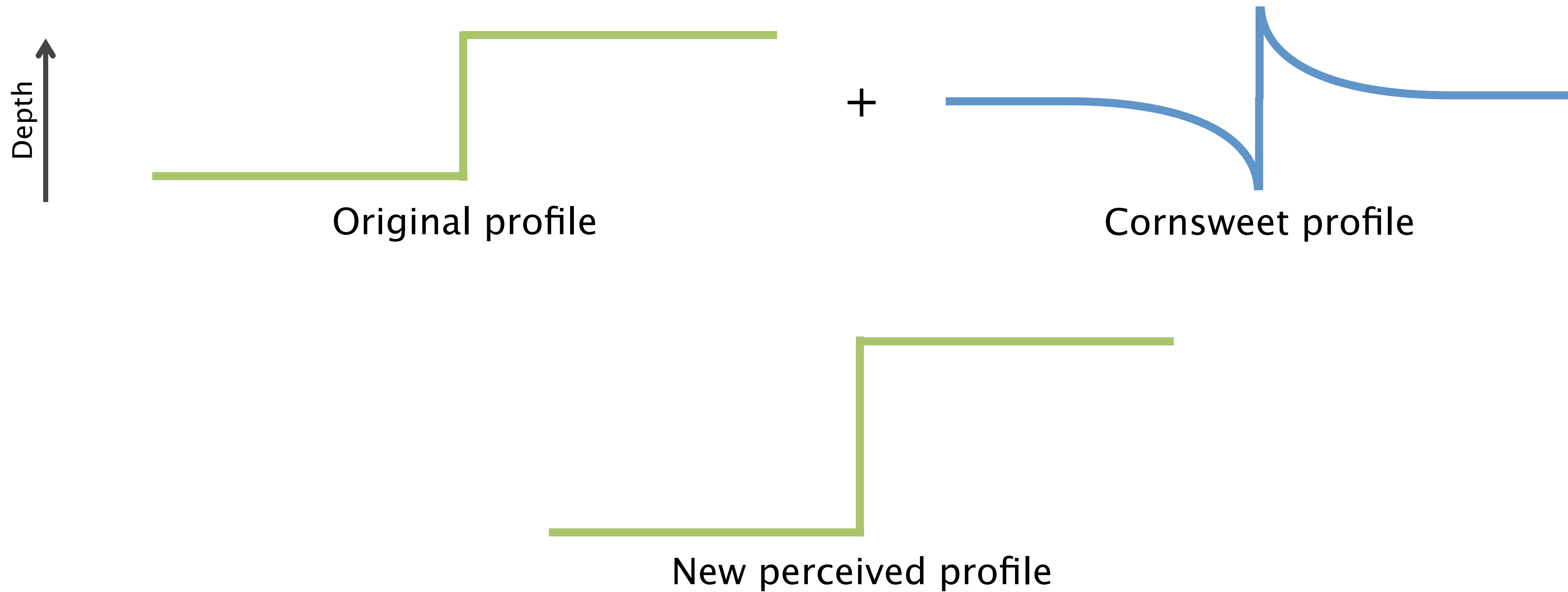
Enhancement using Conrsweet profiles



Enhancement using Cornsweet profiles



Enhancement using Cornsweet profiles



Cornsweet profiles computation

Cornsweet profiles computation

Original disparity



Cornsweet profiles computation

Original disparity



Modified disparity

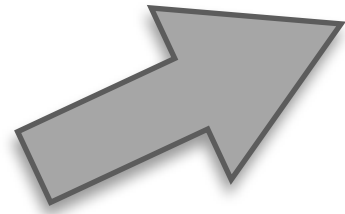
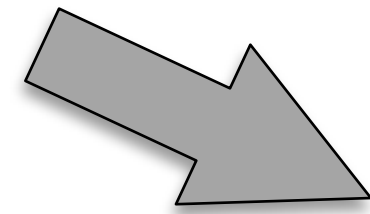


Cornsweet profiles computation

Original disparity



Modified disparity



Difference

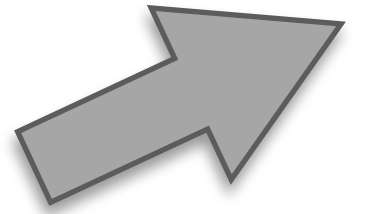
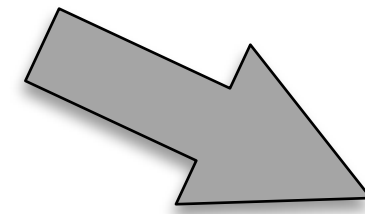


Cornsweet profiles computation

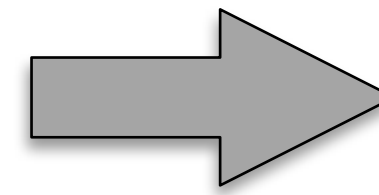
Original disparity



Modified disparity



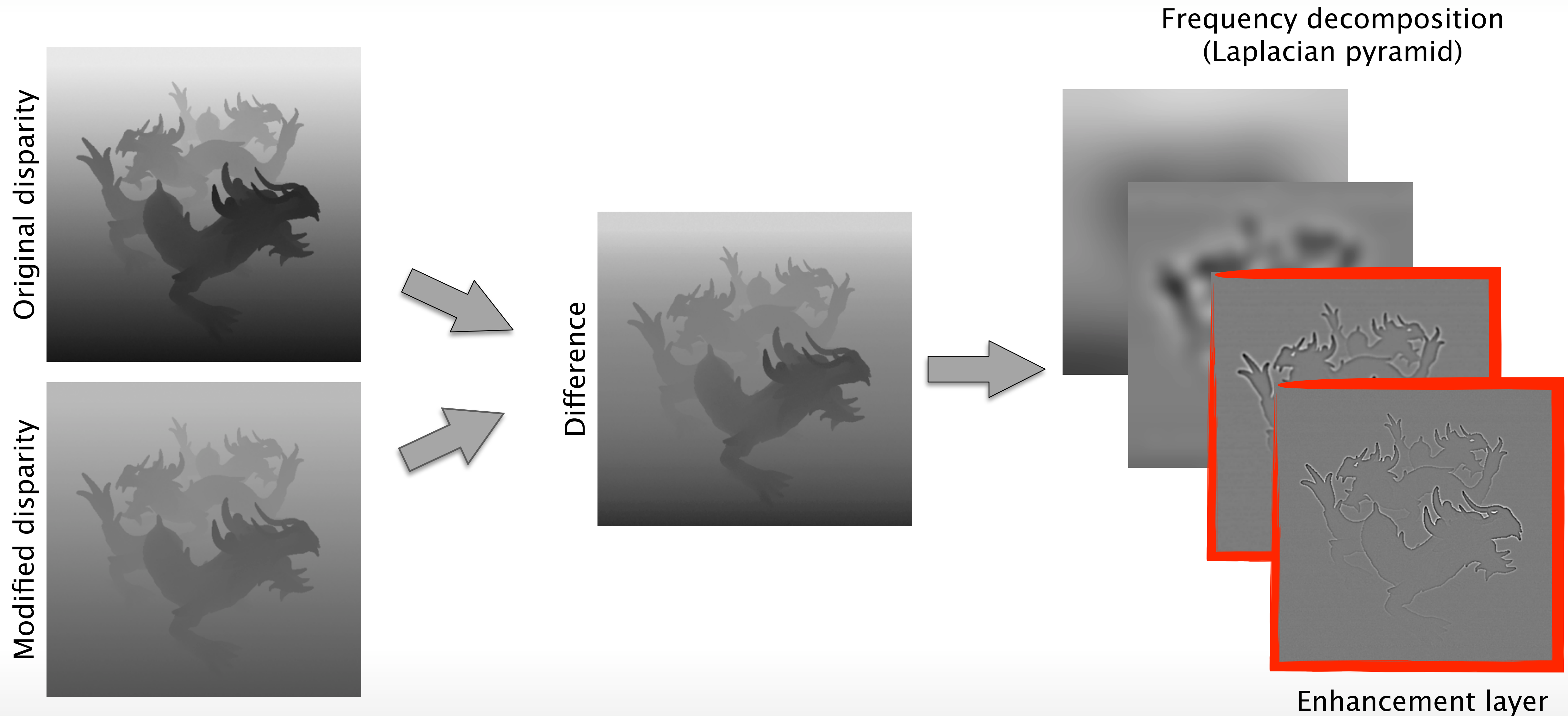
Difference



Frequency decomposition
(Laplacian pyramid)



Cornsweet profiles computation



Cornsweet profiles computation

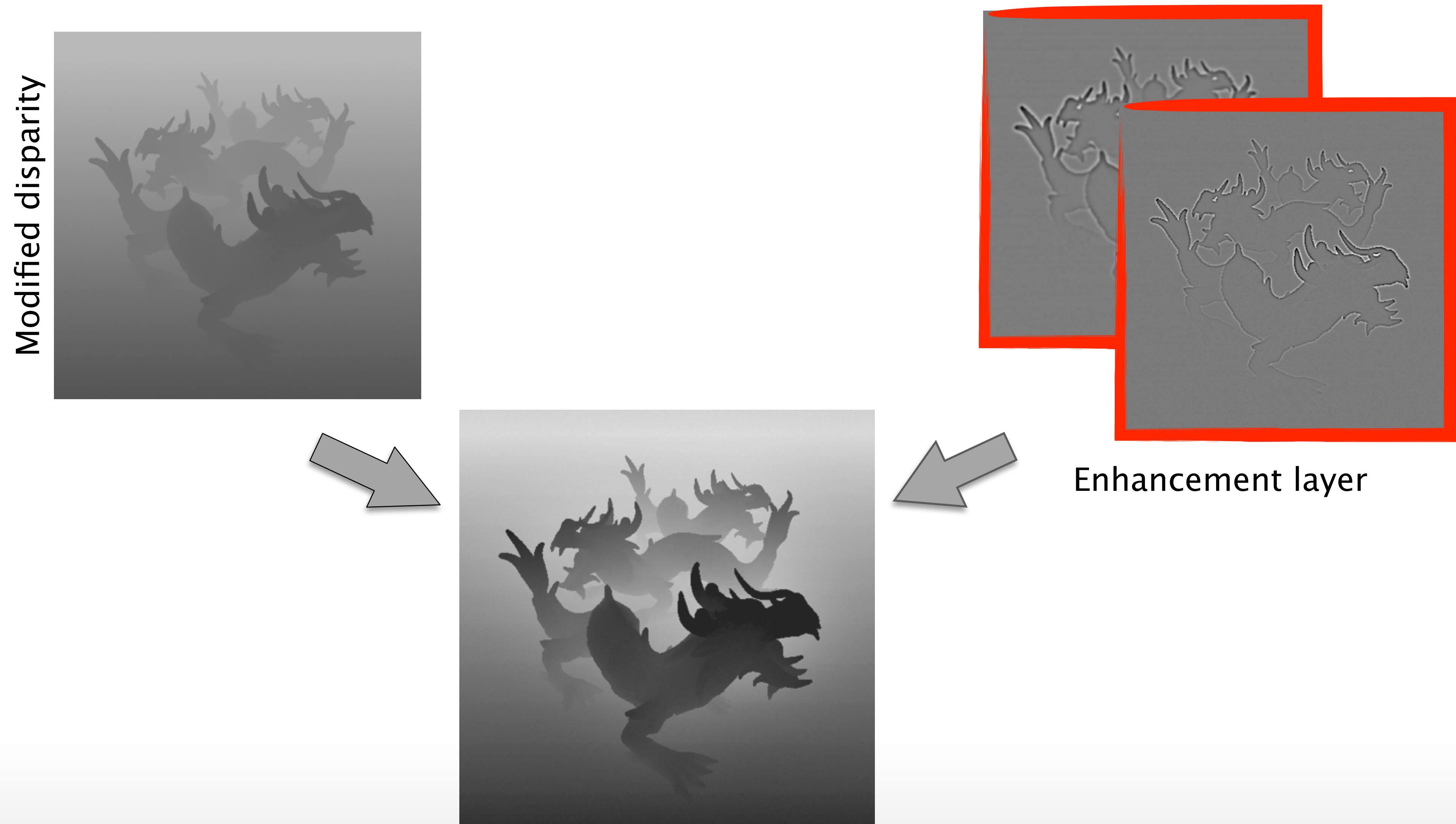
Cornsweet profiles computation

Modified disparity



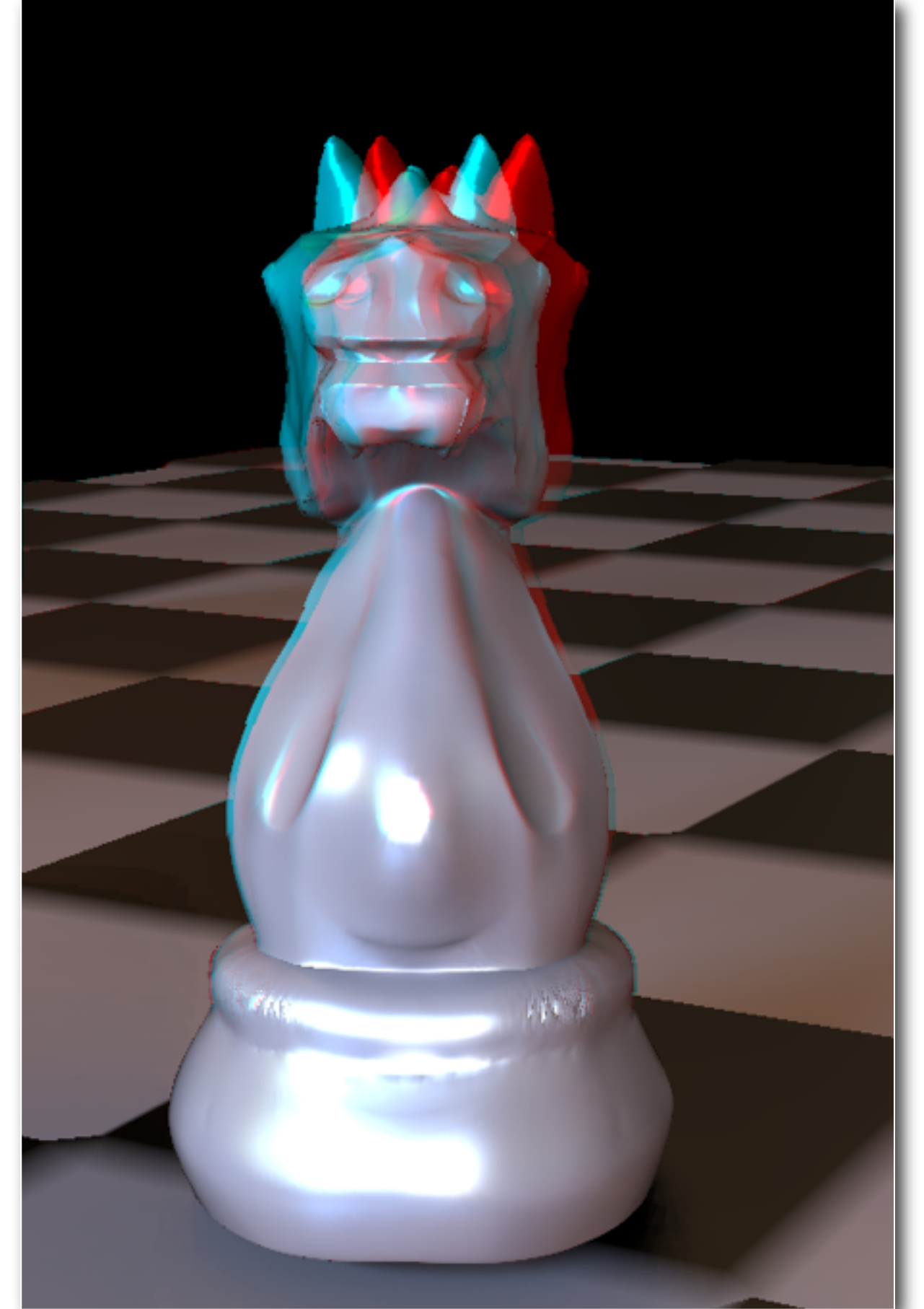
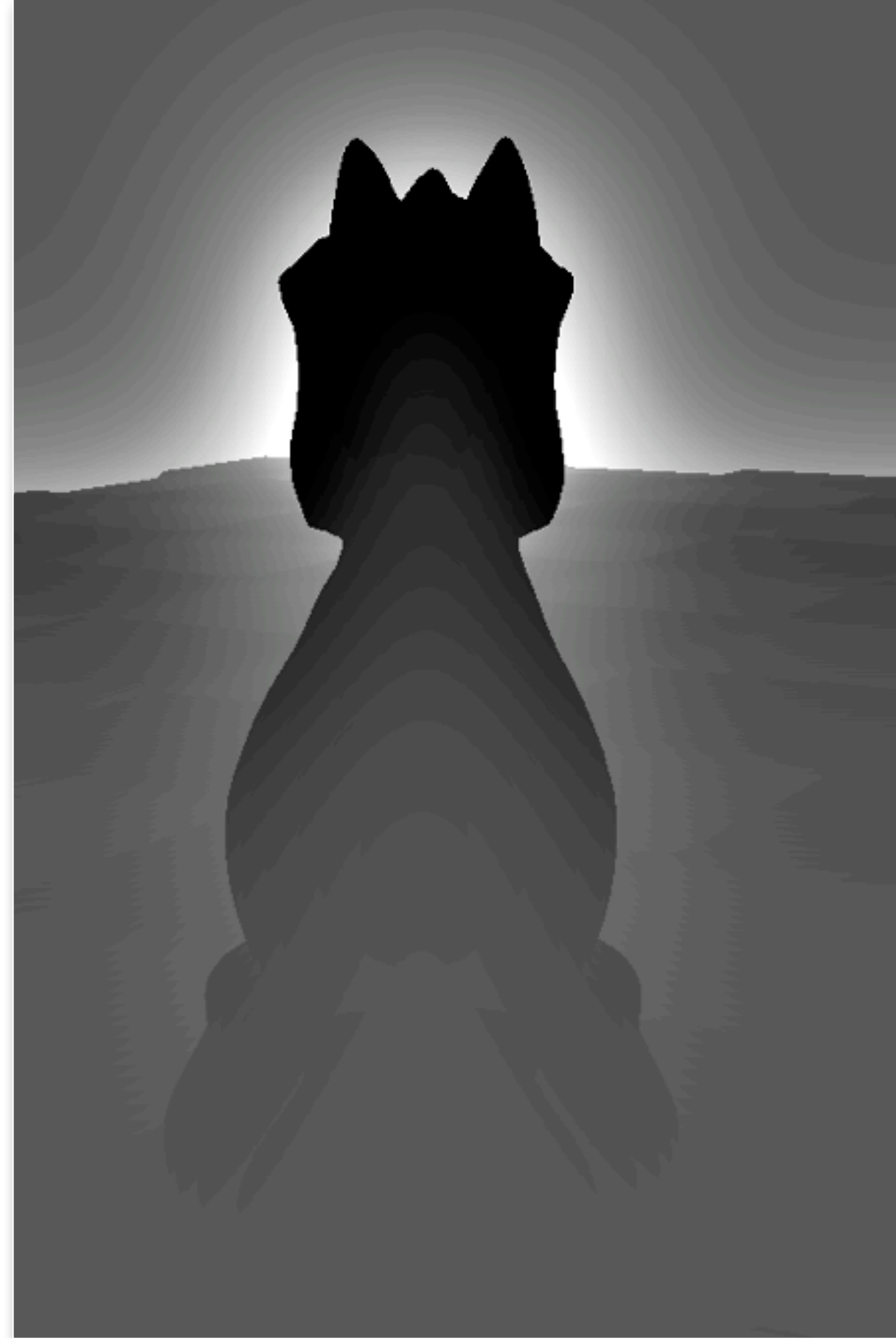
Enhancement layer

Cornsweet profiles computation



Naive solution

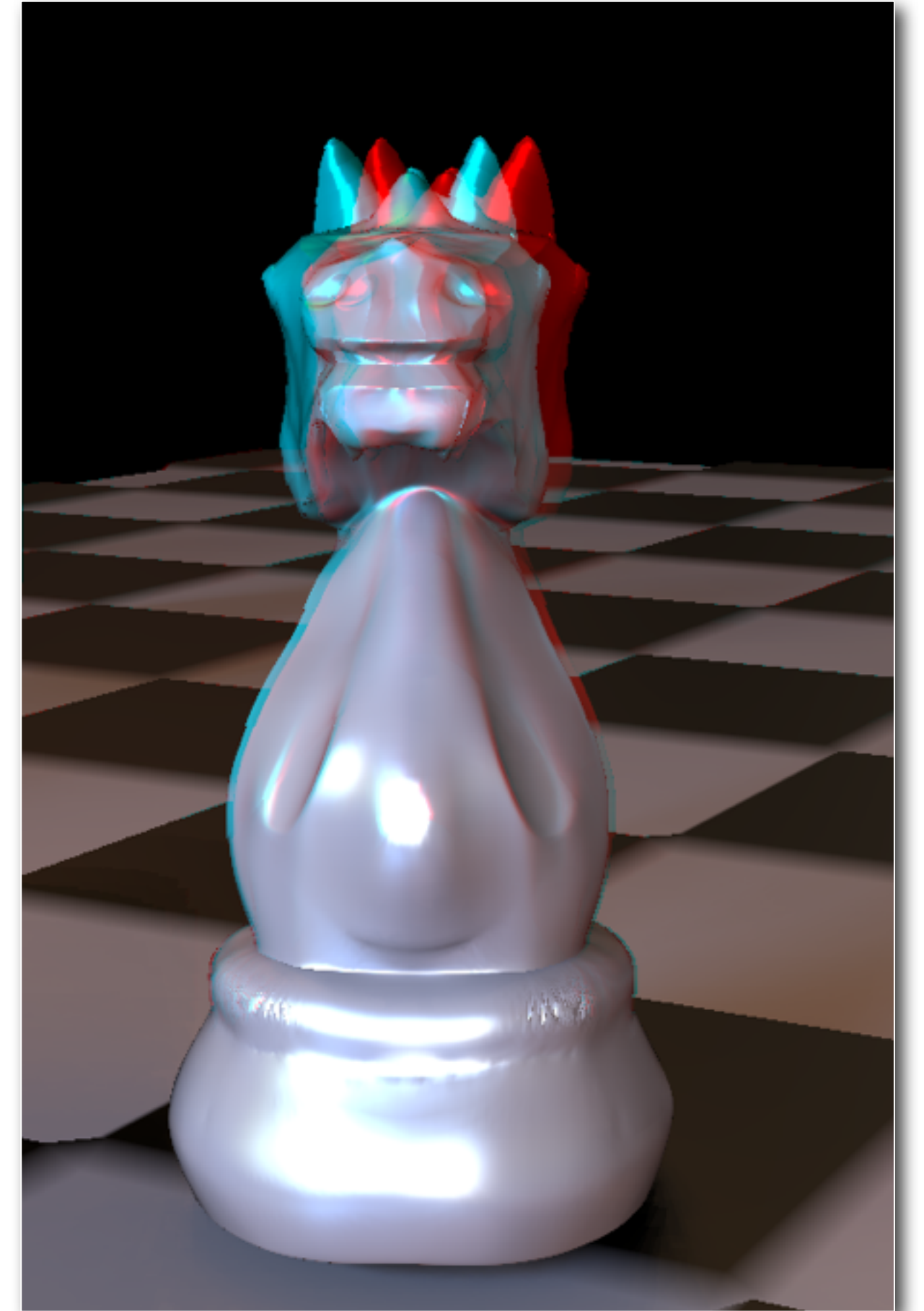
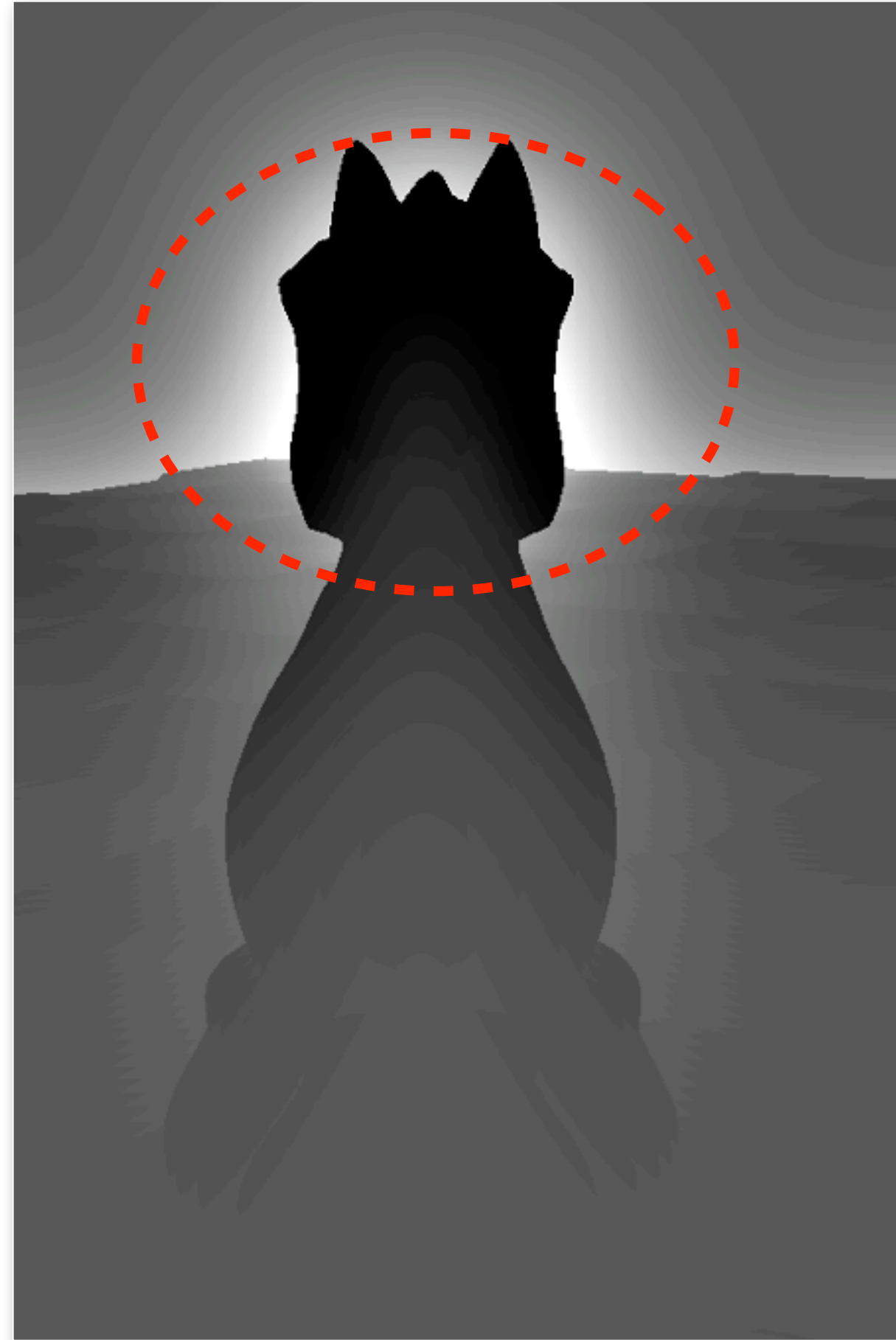
Problems:



Naive solution

Problems:

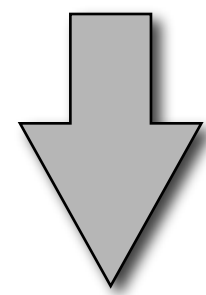
- Geometry deformation
- Comfort zone violation



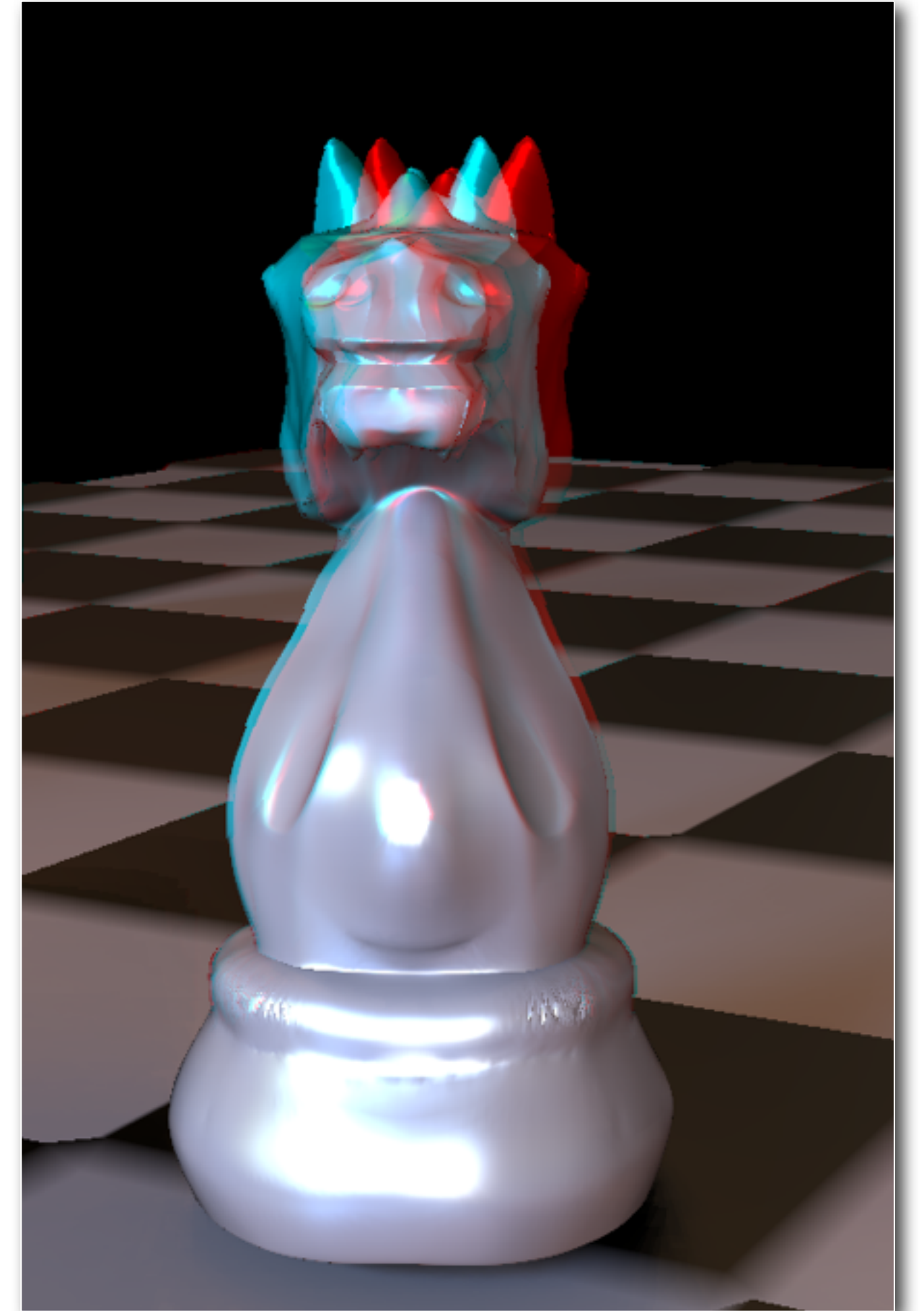
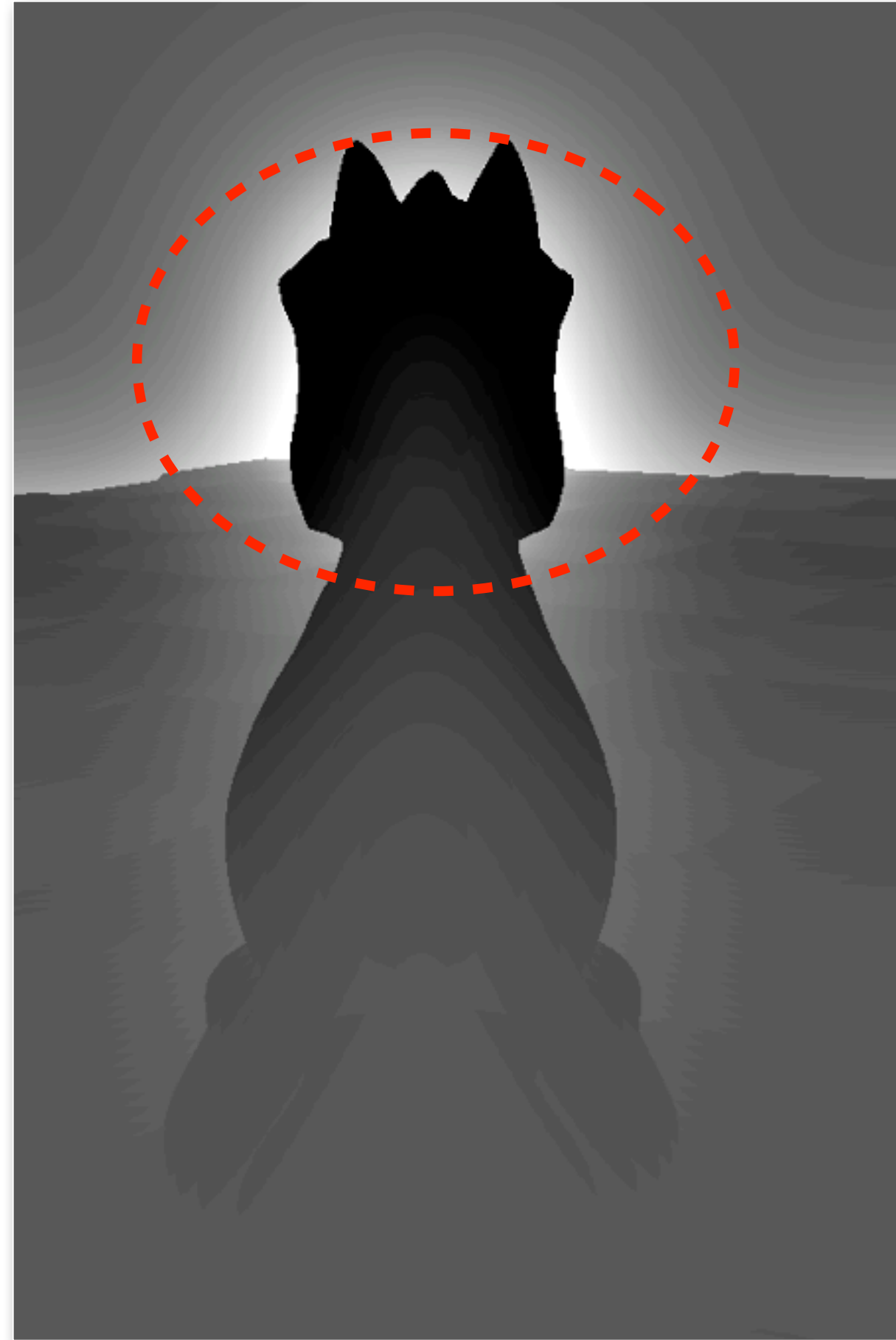
Naive solution

Problems:

- Geometry deformation
- Comfort zone violation



Perceptual space



Perceptual model

“A Perceptual Model for Disparity”
[Didyk et al. 2012]

Perceptual model



“A Perceptual Model for Disparity”
[Didyk et al. 2012]

Perceptual model



“A Perceptual Model for Disparity”
[Didyk et al. 2012]

Luminance

Luminance

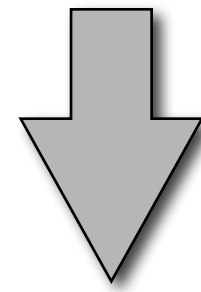
- Such models exist for luminance

Luminance

- Such models exist for luminance
- The HVS processes different frequencies separately

Luminance

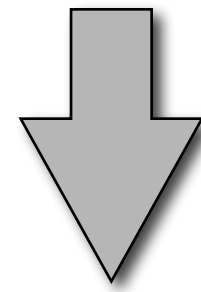
- Such models exist for luminance
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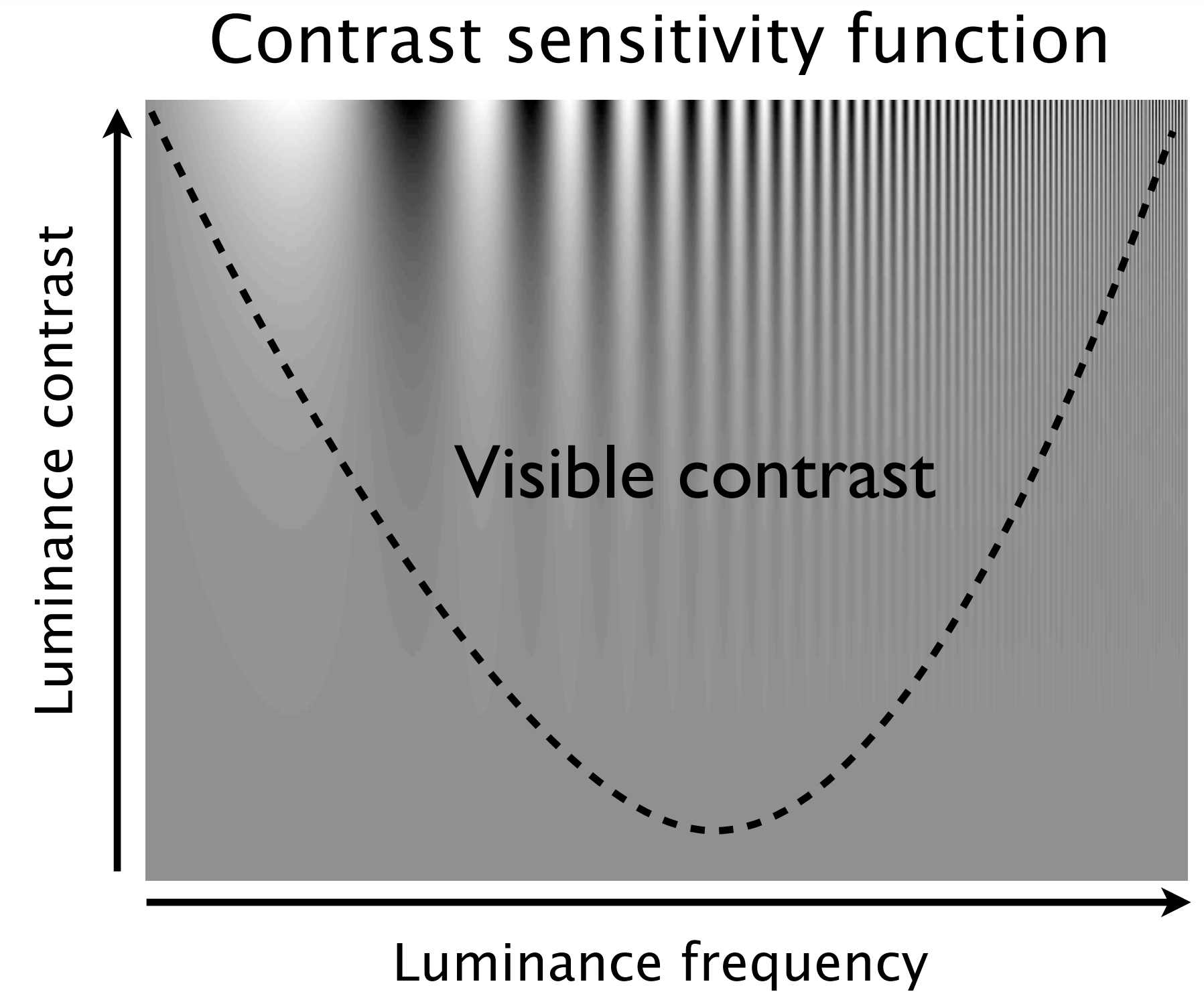
Sinusoidal patterns considered

Luminance

- Such models exist for luminance
- The HVS processes different frequencies separately

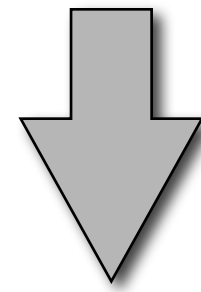


Sinusoidal patterns considered

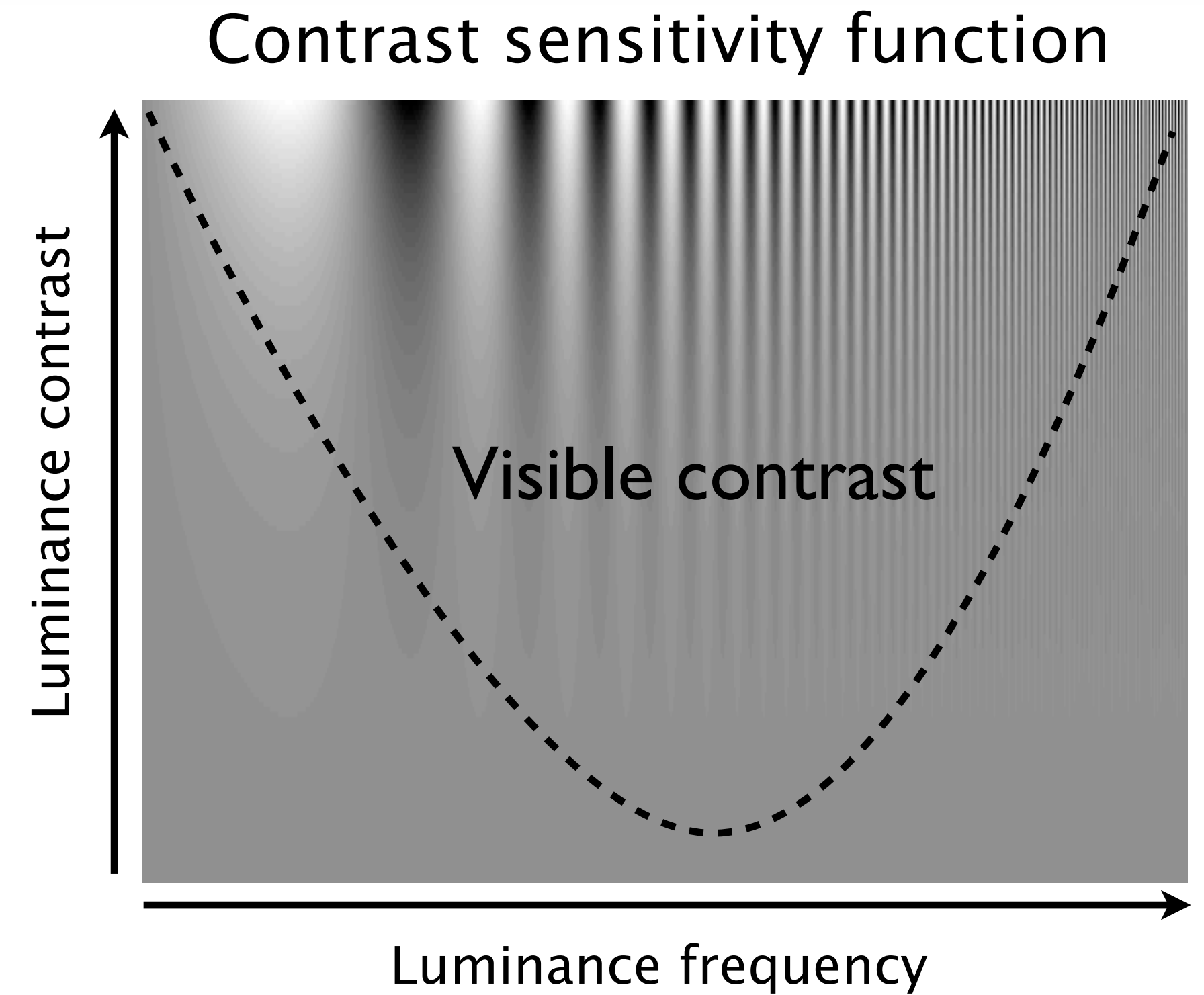


Luminance

- Such models exist for luminance
- The HVS processes different frequencies separately



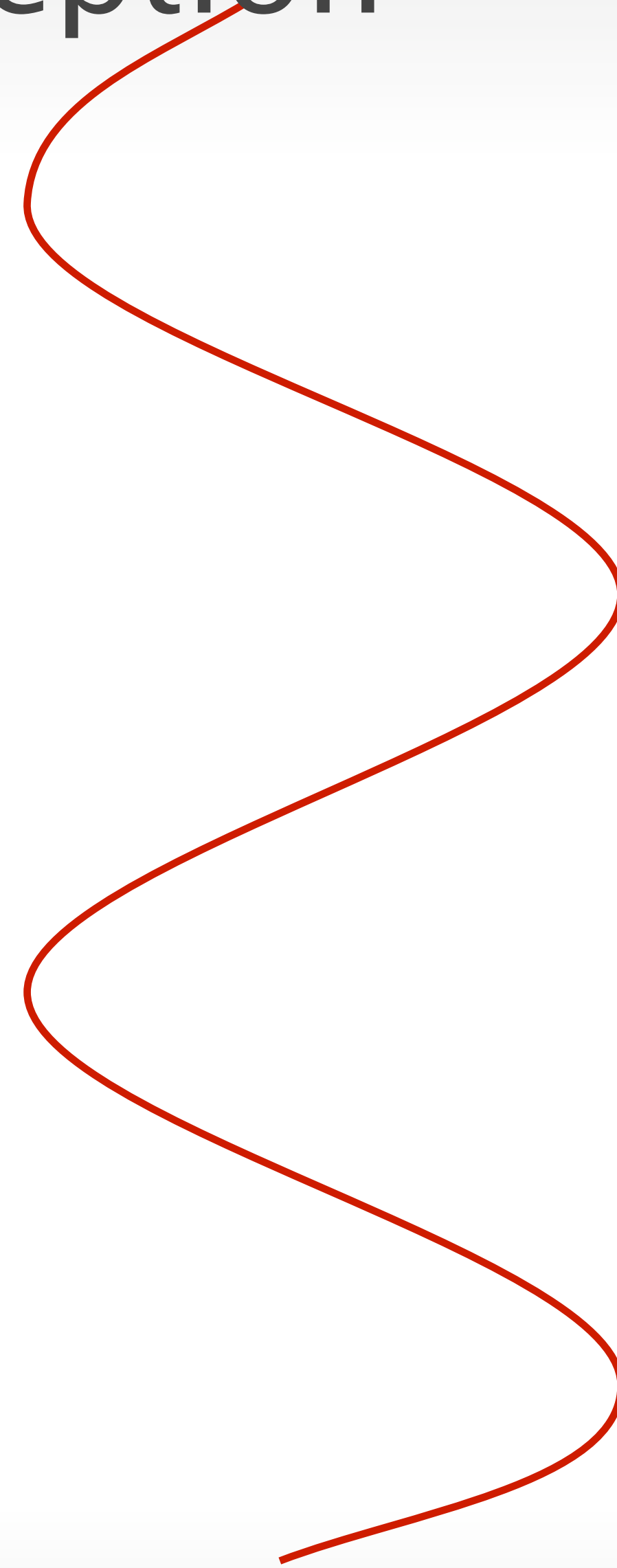
Sinusoidal patterns considered



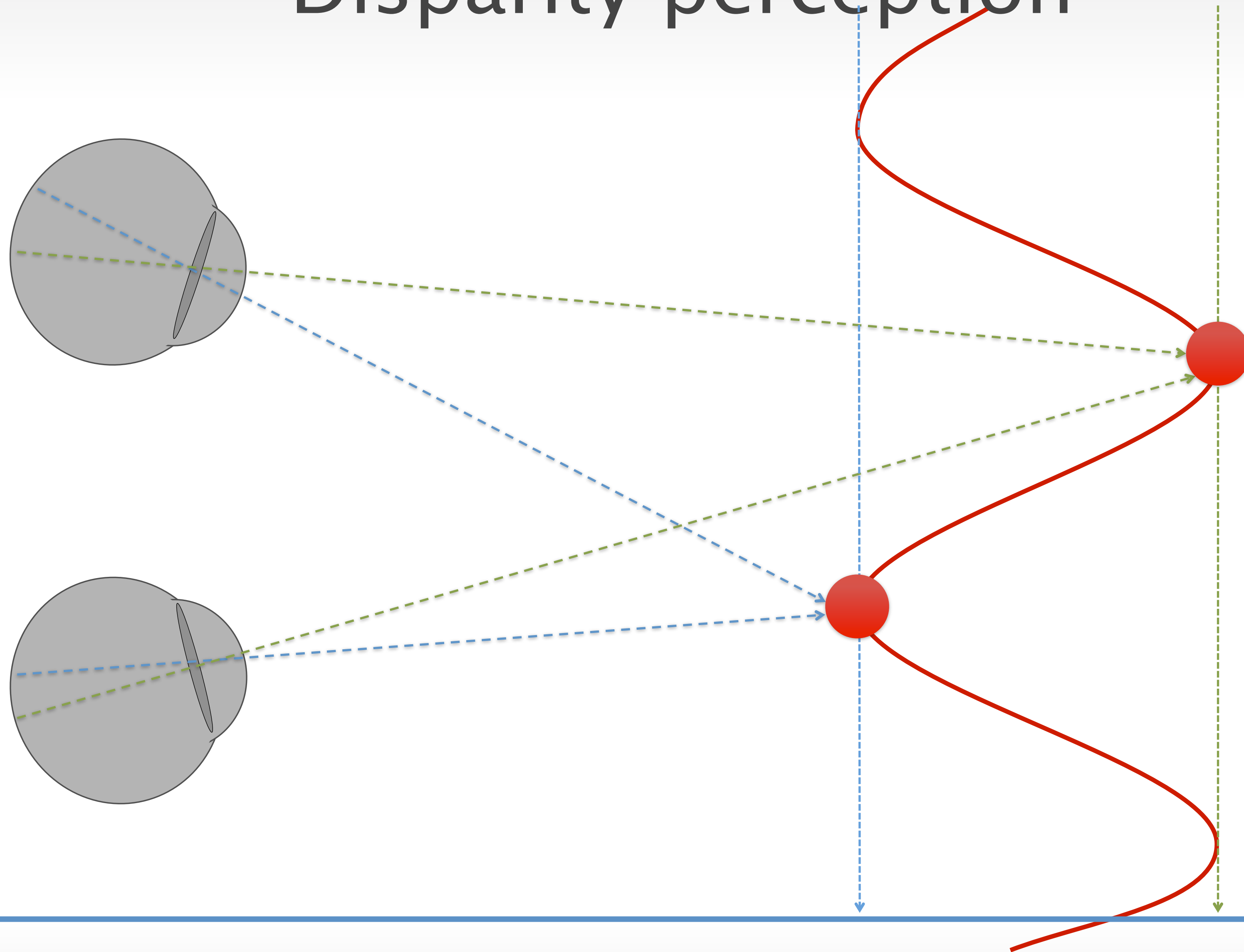
Disparity perception follows similar mechanisms

“Seeing in depth” [Howard and Rogers 2002]

Disparity perception

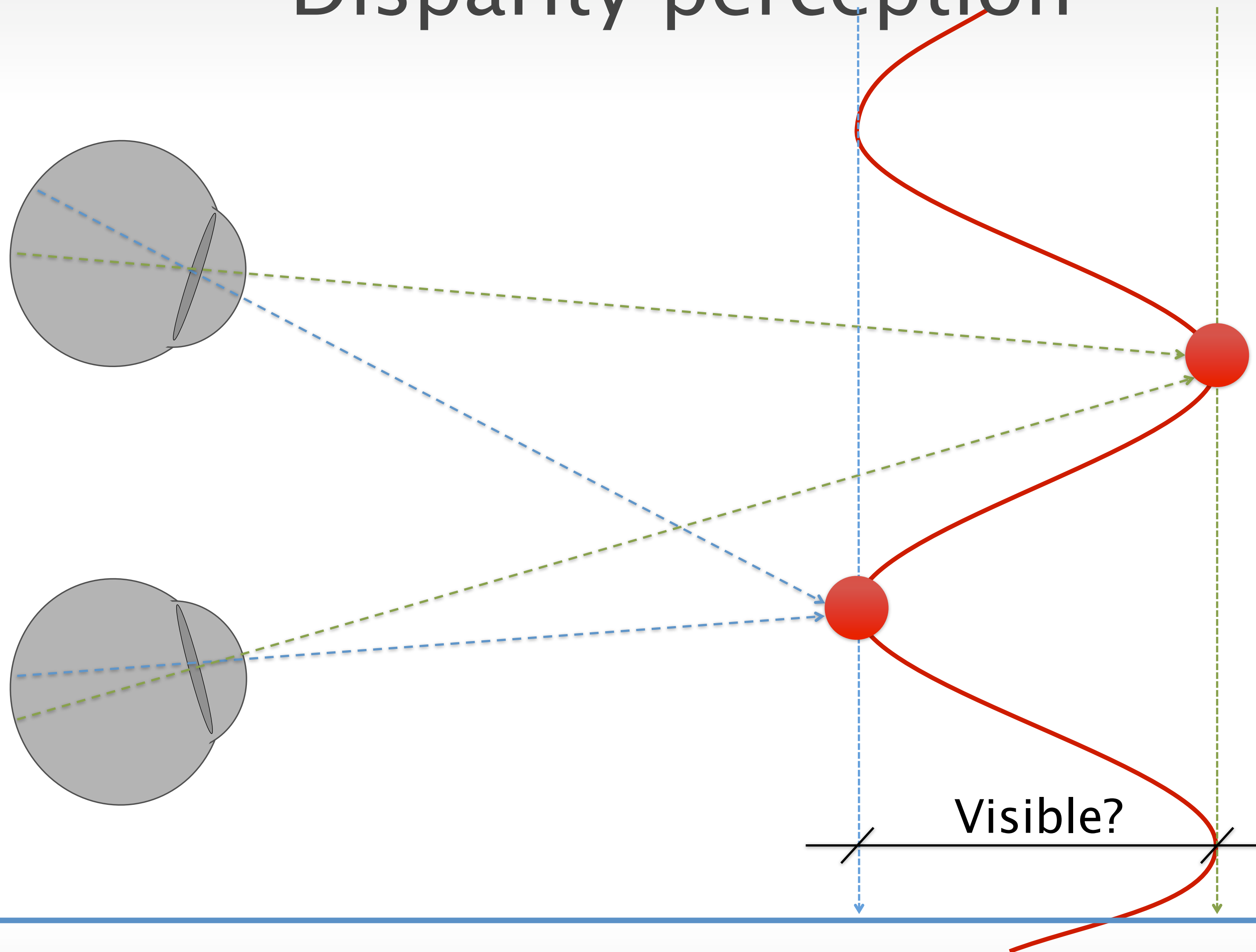


Disparity perception

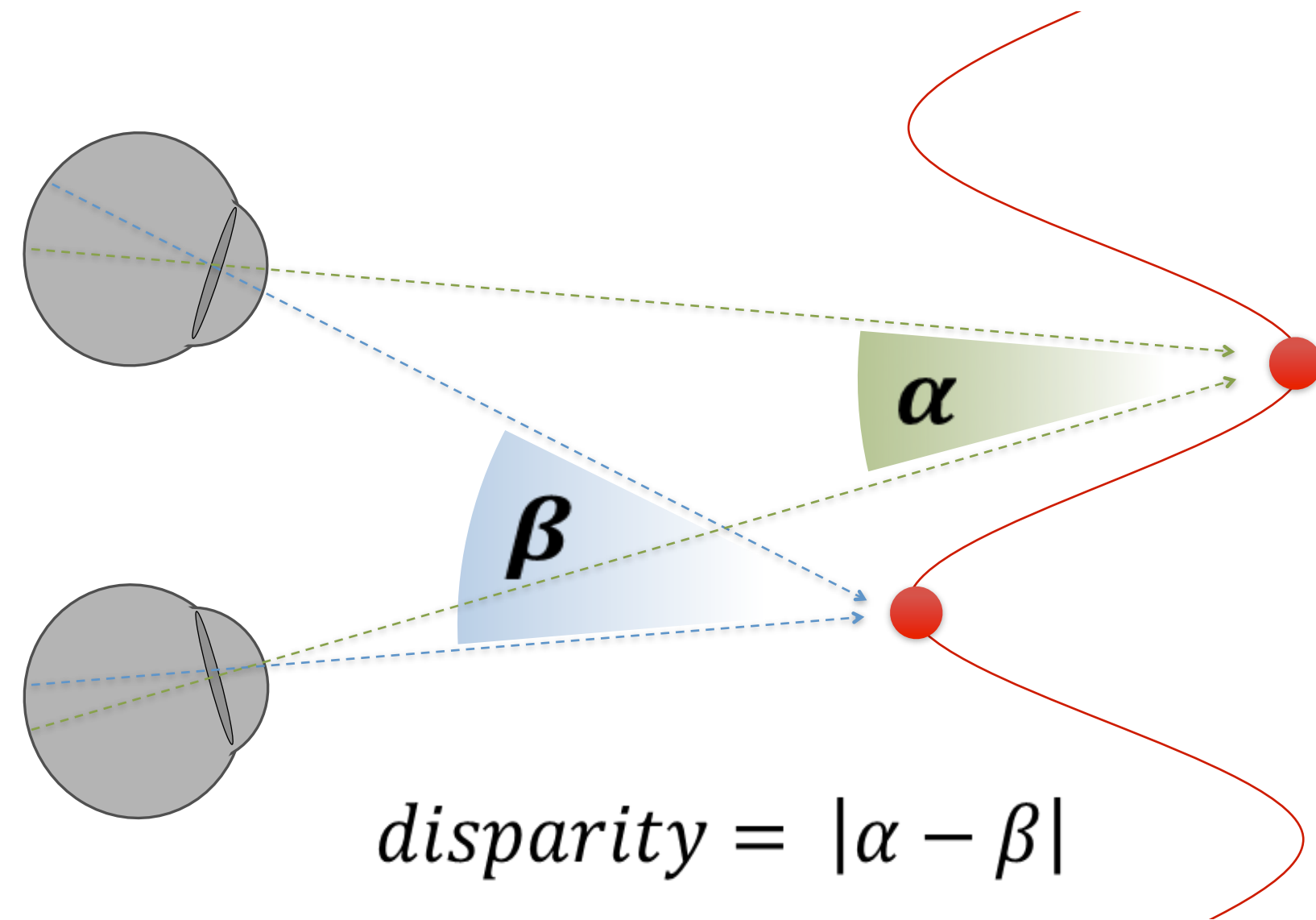


Depth

Disparity perception

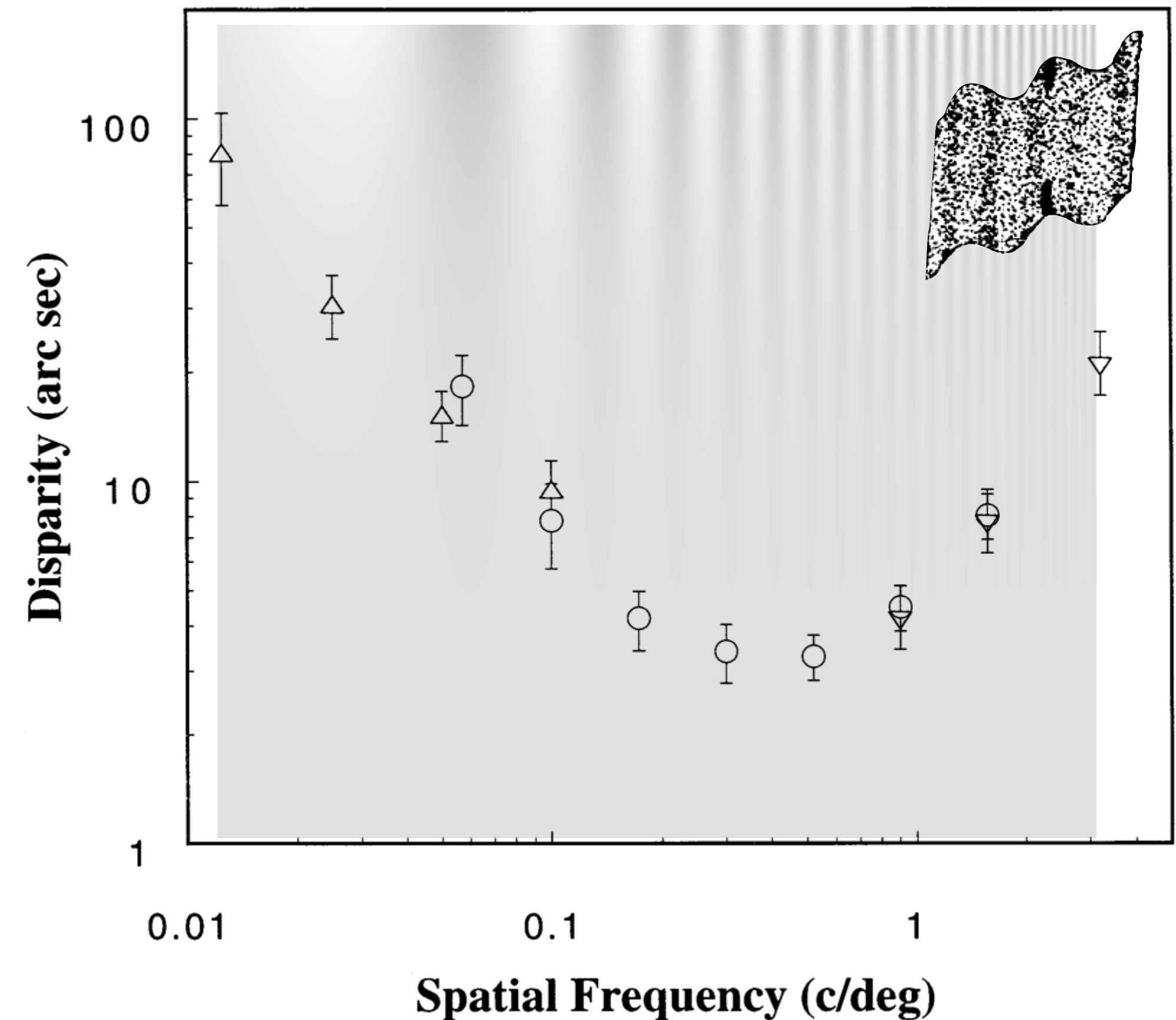


Disparity sensitivity function

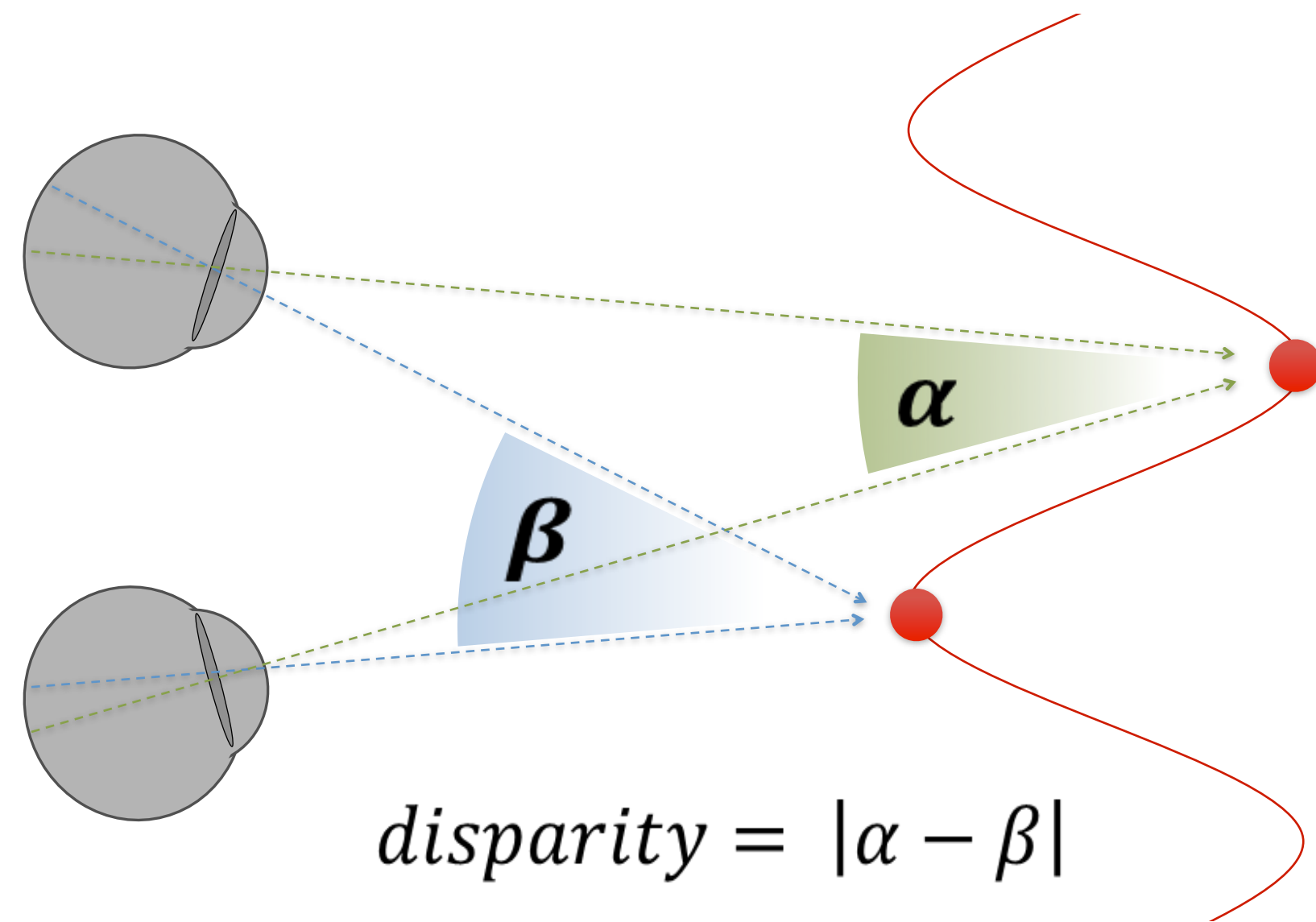


For sinusoidal depth corrugation

“Sensitivity to horizontal and vertical corrugations
defined by binocular disparity”
[Bradshaw et al. 1999]

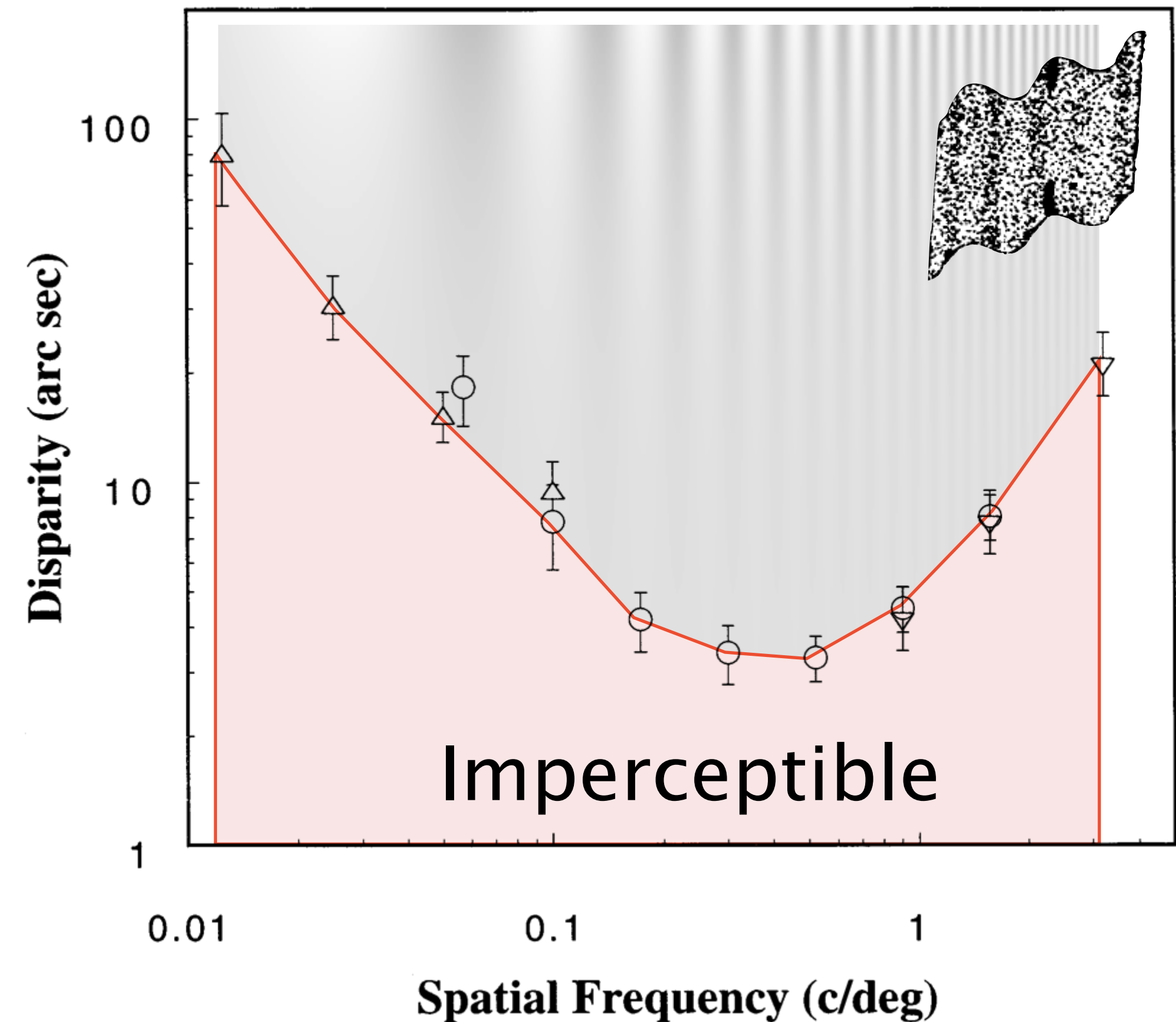


Disparity sensitivity function

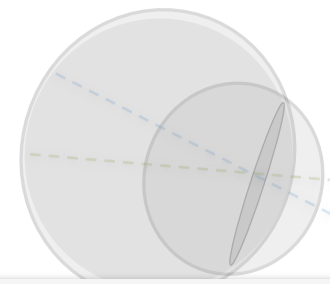


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[Bradshaw et al. 1999]



Disparity sensitivity function

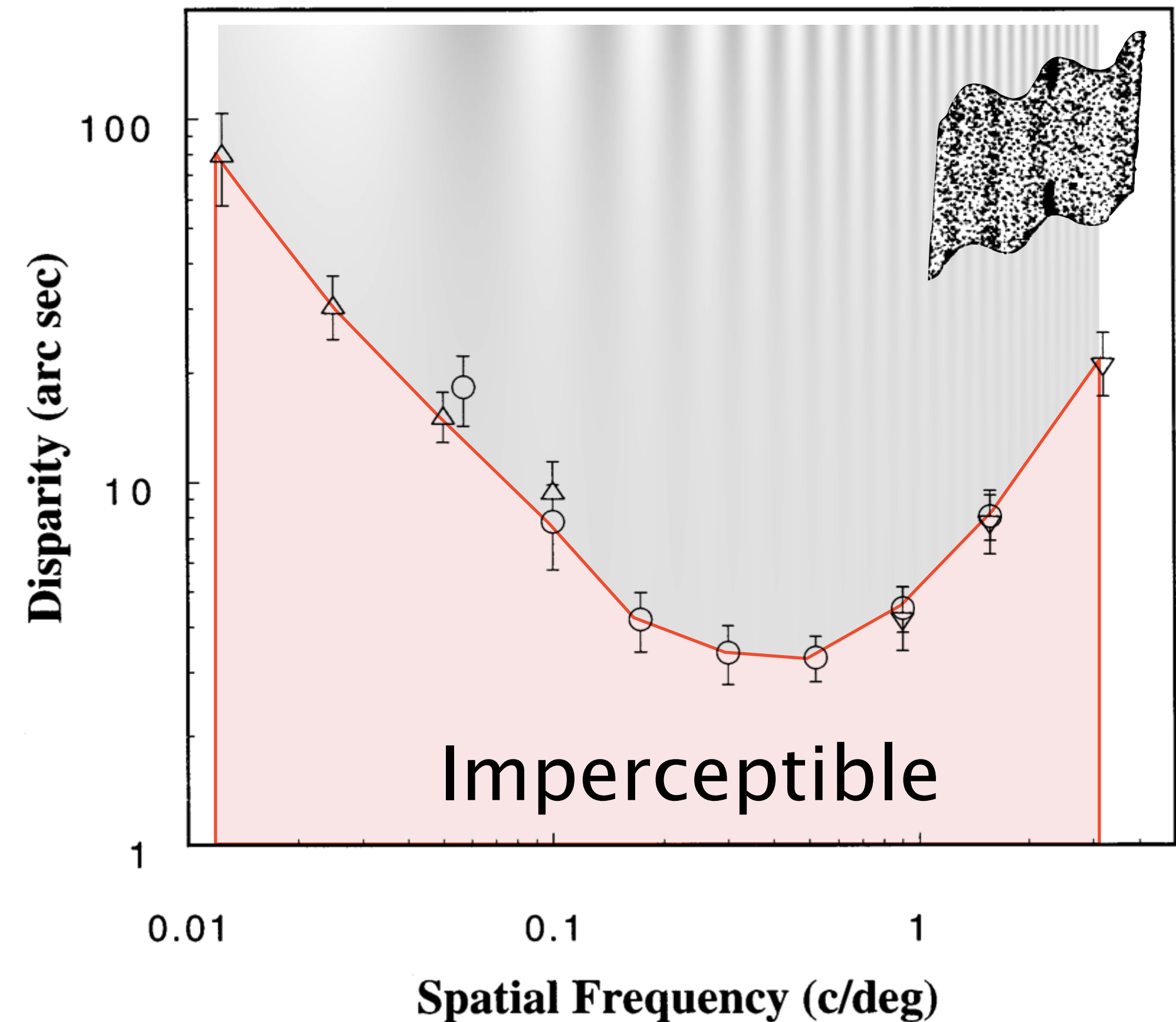


- This tells only the visibility
- Magnitude is equally interesting

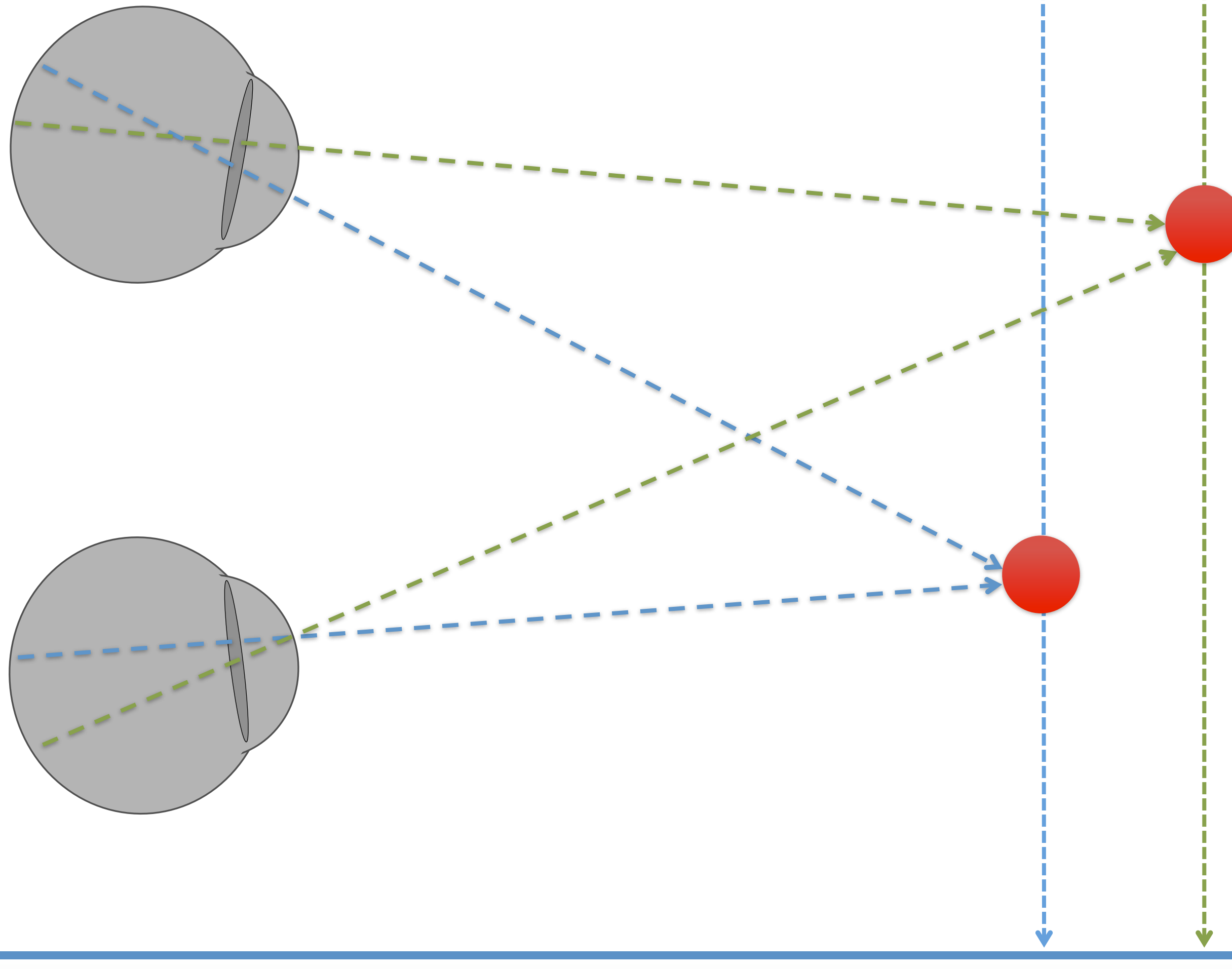
$$\text{disparity} = |\alpha - \beta|$$

For sinusoidal depth corrugation

“Sensitivity to horizontal and vertical corrugations
defined by binocular disparity”
[Bradshaw et al. 1999]

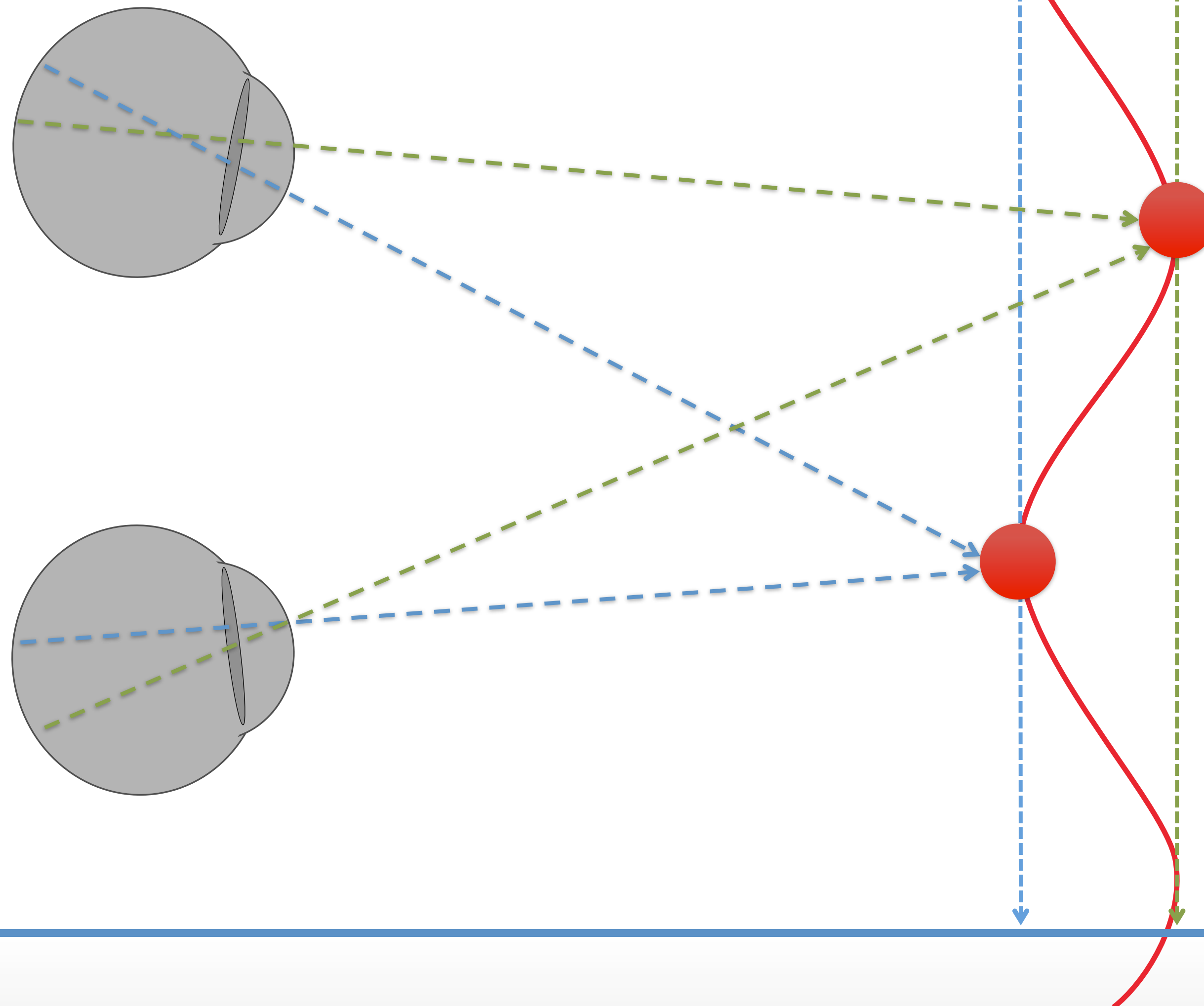


Discrimination threshold

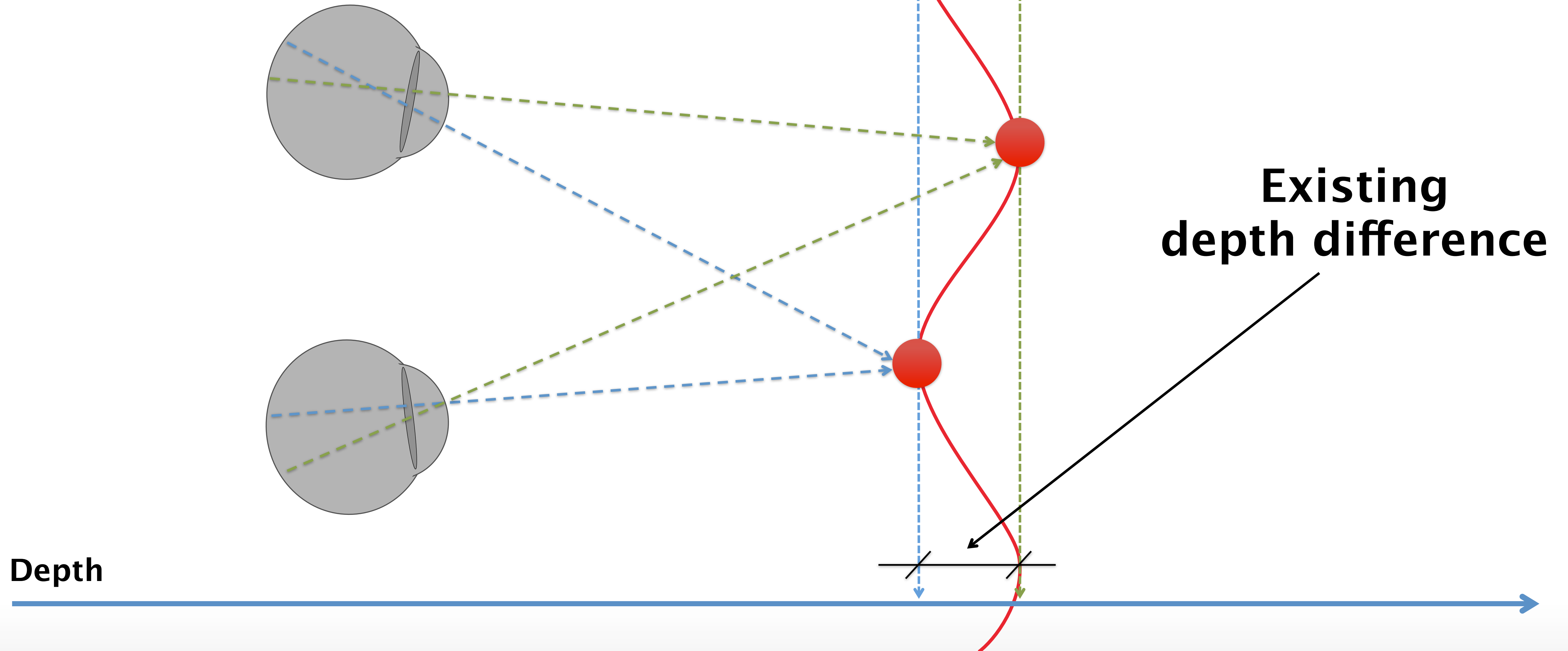


Depth

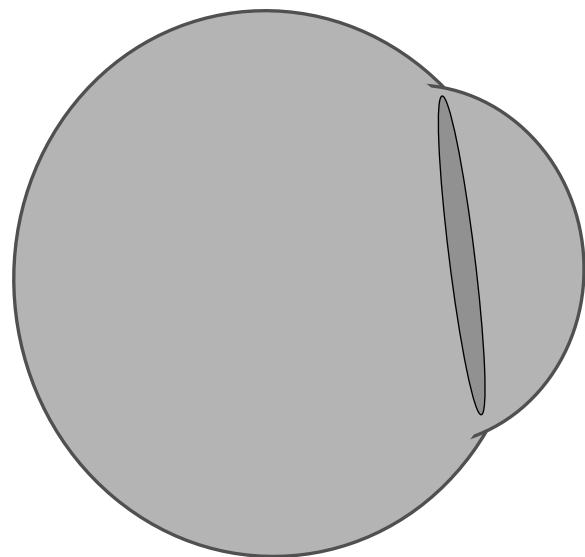
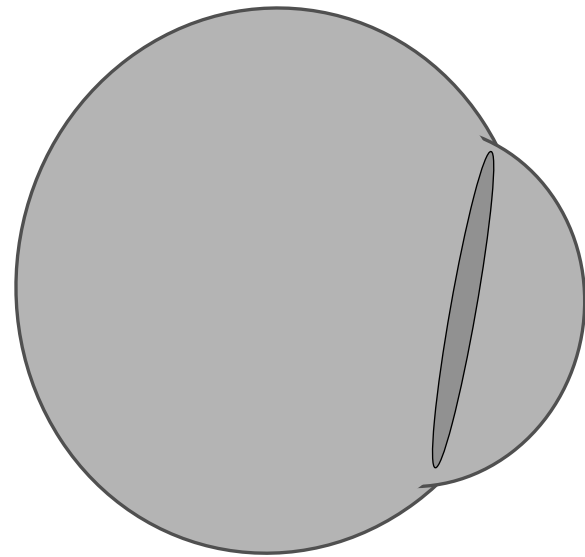
Discrimination threshold



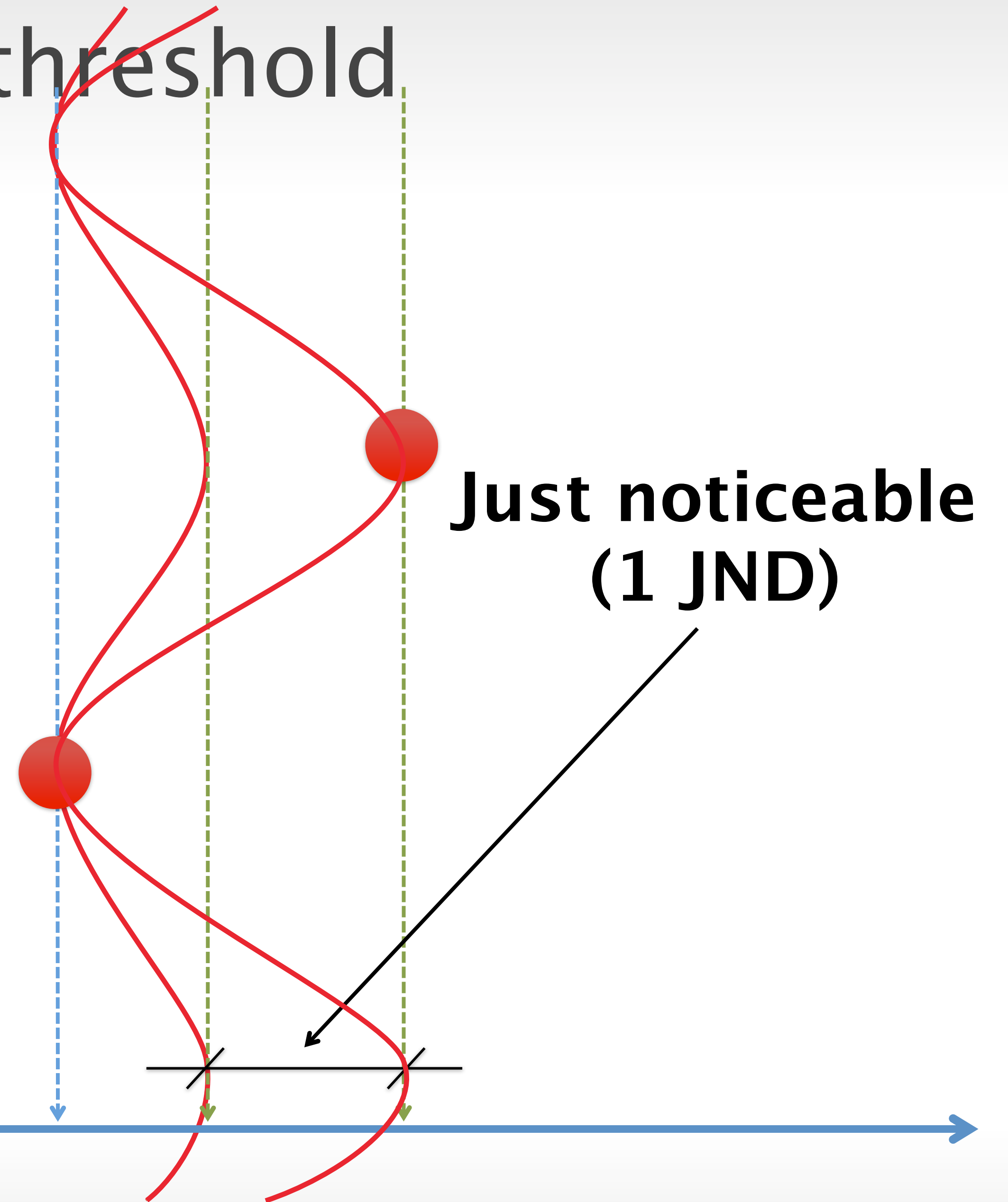
Discrimination threshold



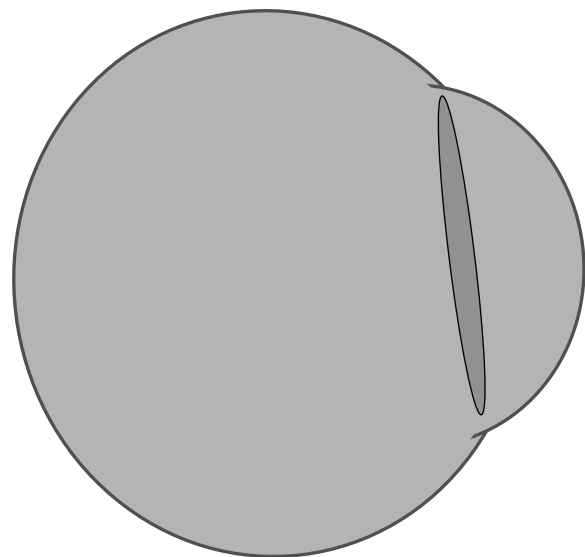
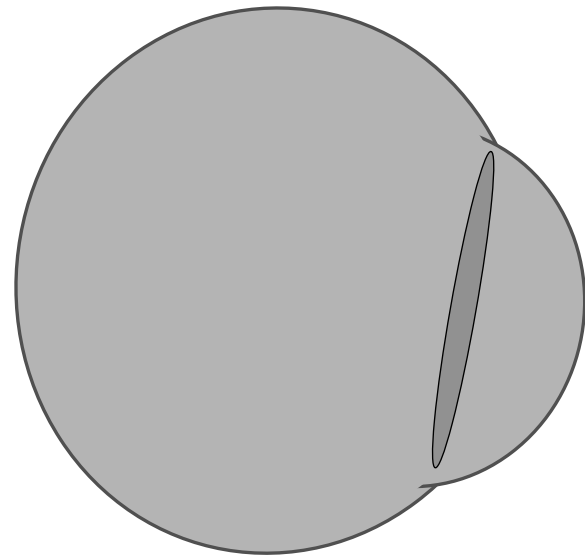
Discrimination threshold



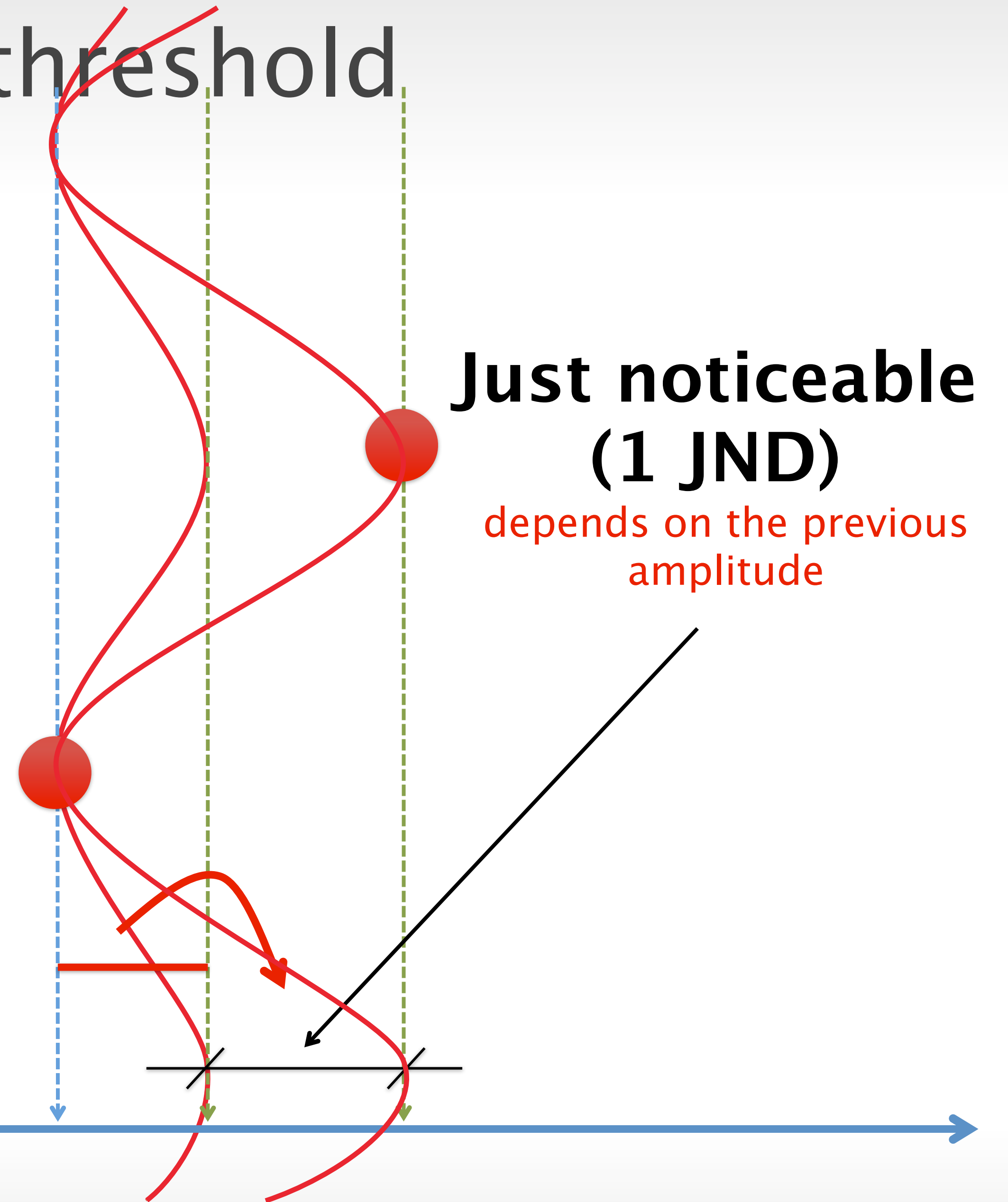
Depth



Discrimination threshold



Depth



Disparity perception

Sensitivity to depth changes depends on:

Disparity perception

Sensitivity to depth changes depends on:

- Spatial frequency of disparity corrugation

Disparity perception

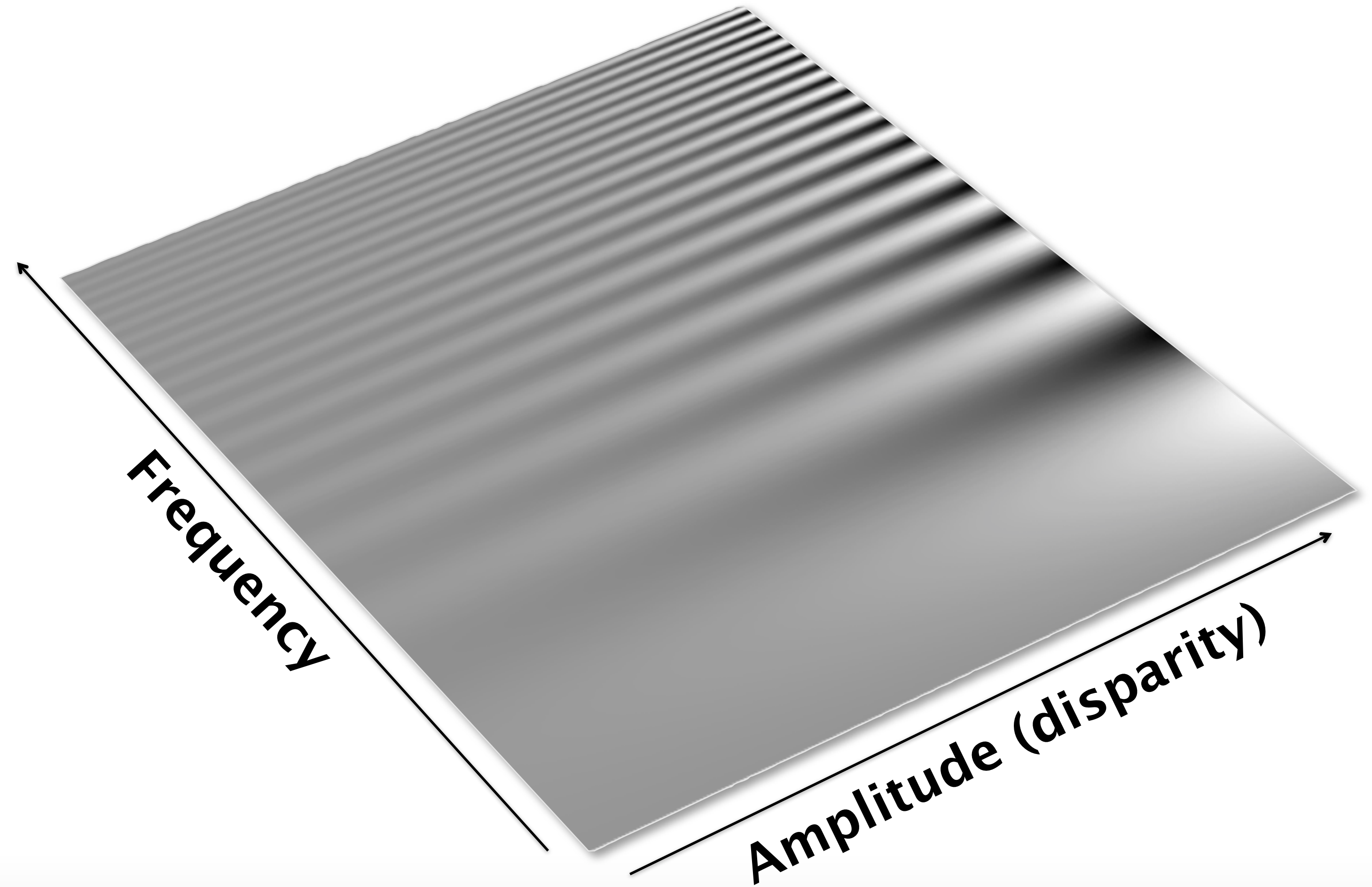
Sensitivity to depth changes depends on:

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

Measurements

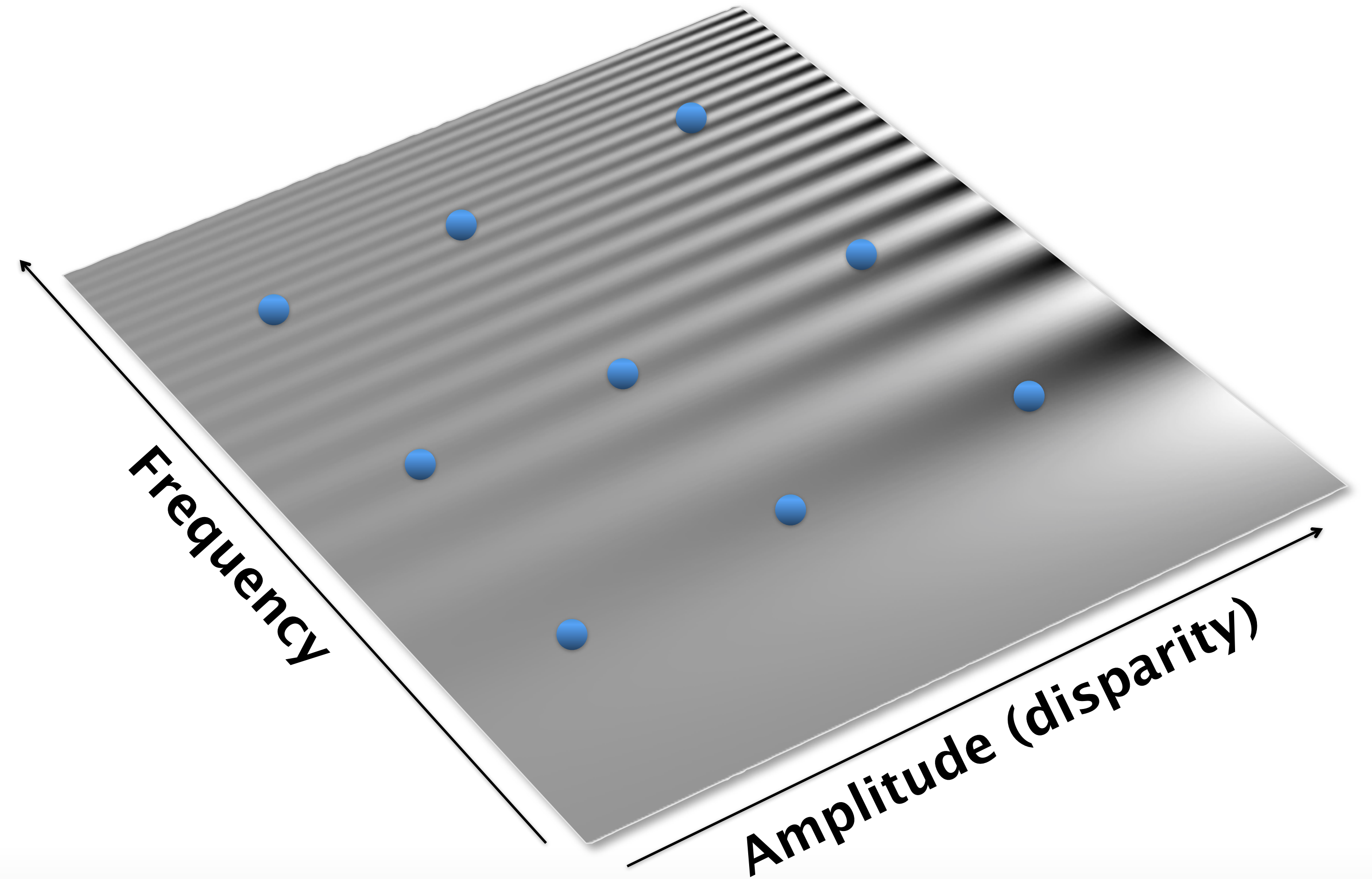
Measurements

Parameter space:



Measurements

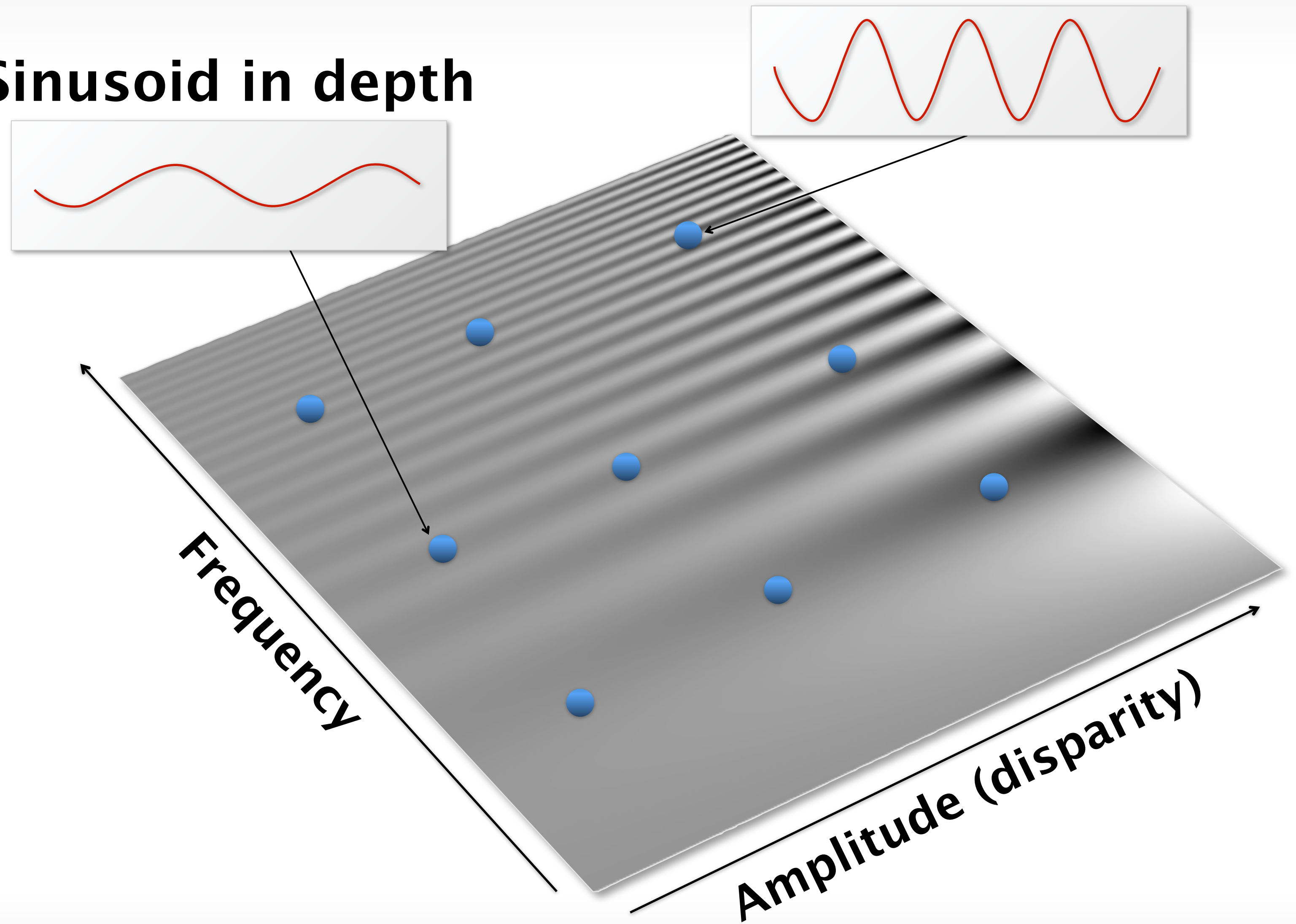
1. Sample the space



Measurements

Sinusoid in depth

1. Sample the space

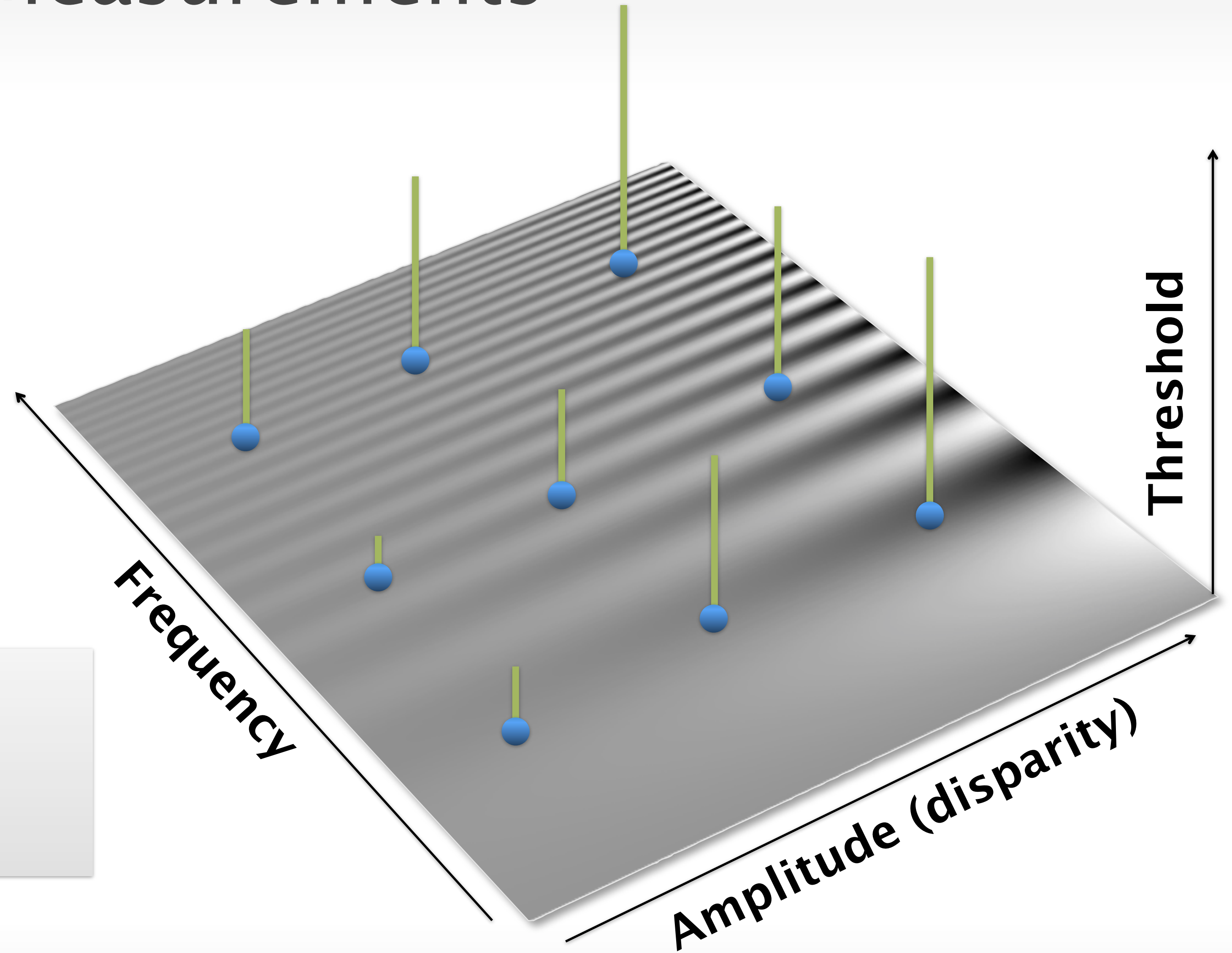


Measurements

1. Sample the space

2. Measure thresholds

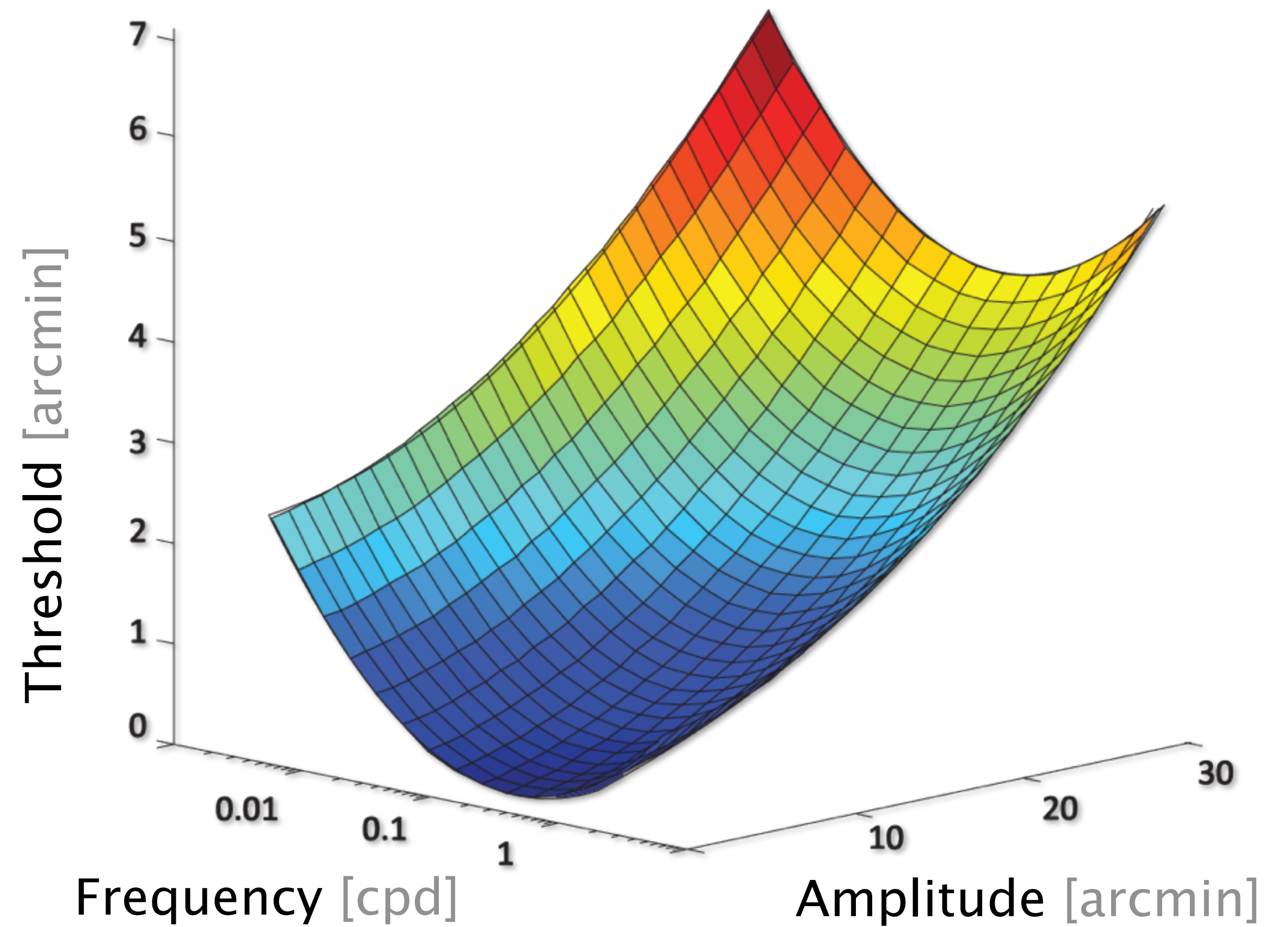
➡ Threshold estimation



Model

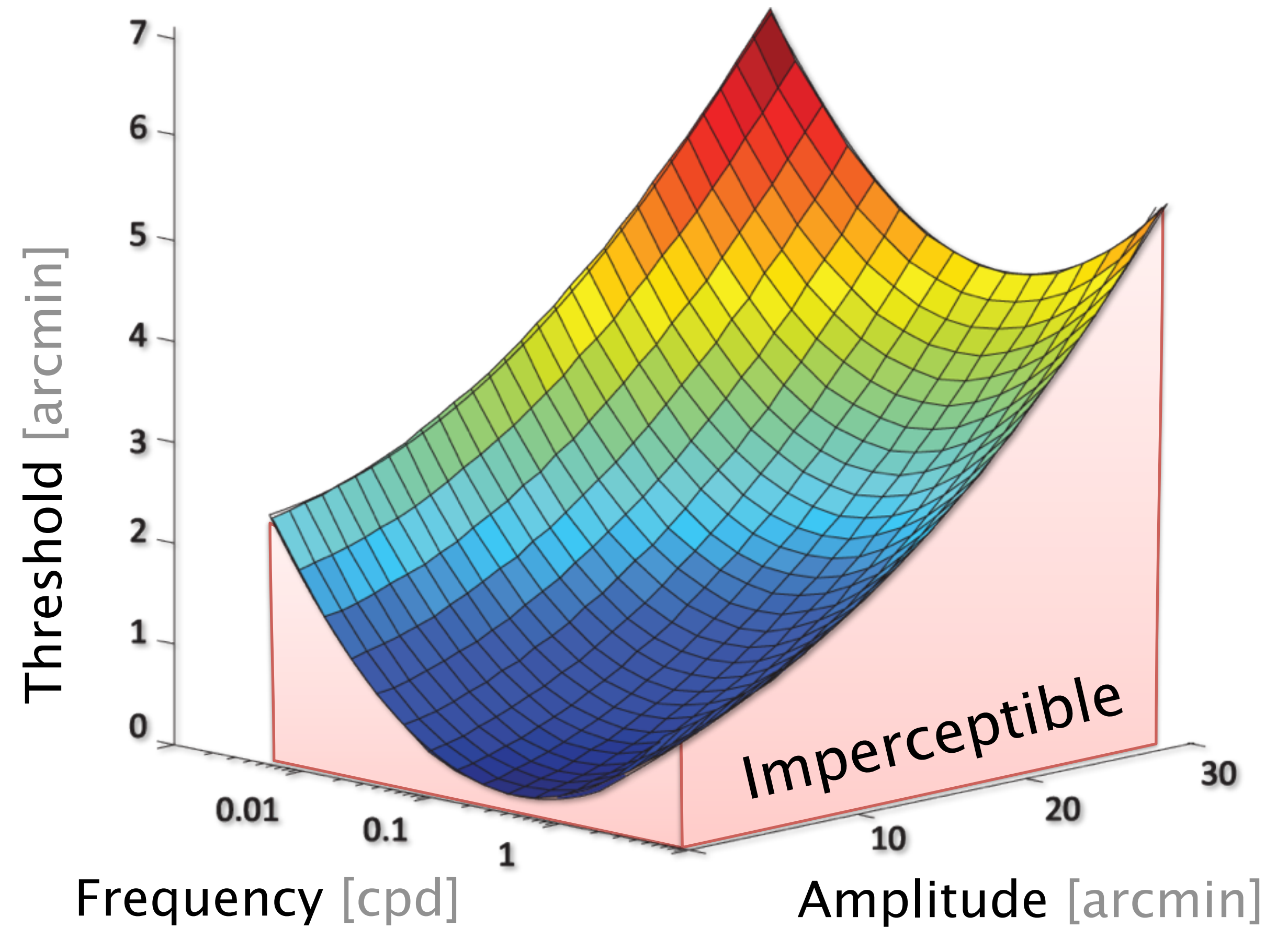
Model

3. Fit analytic function



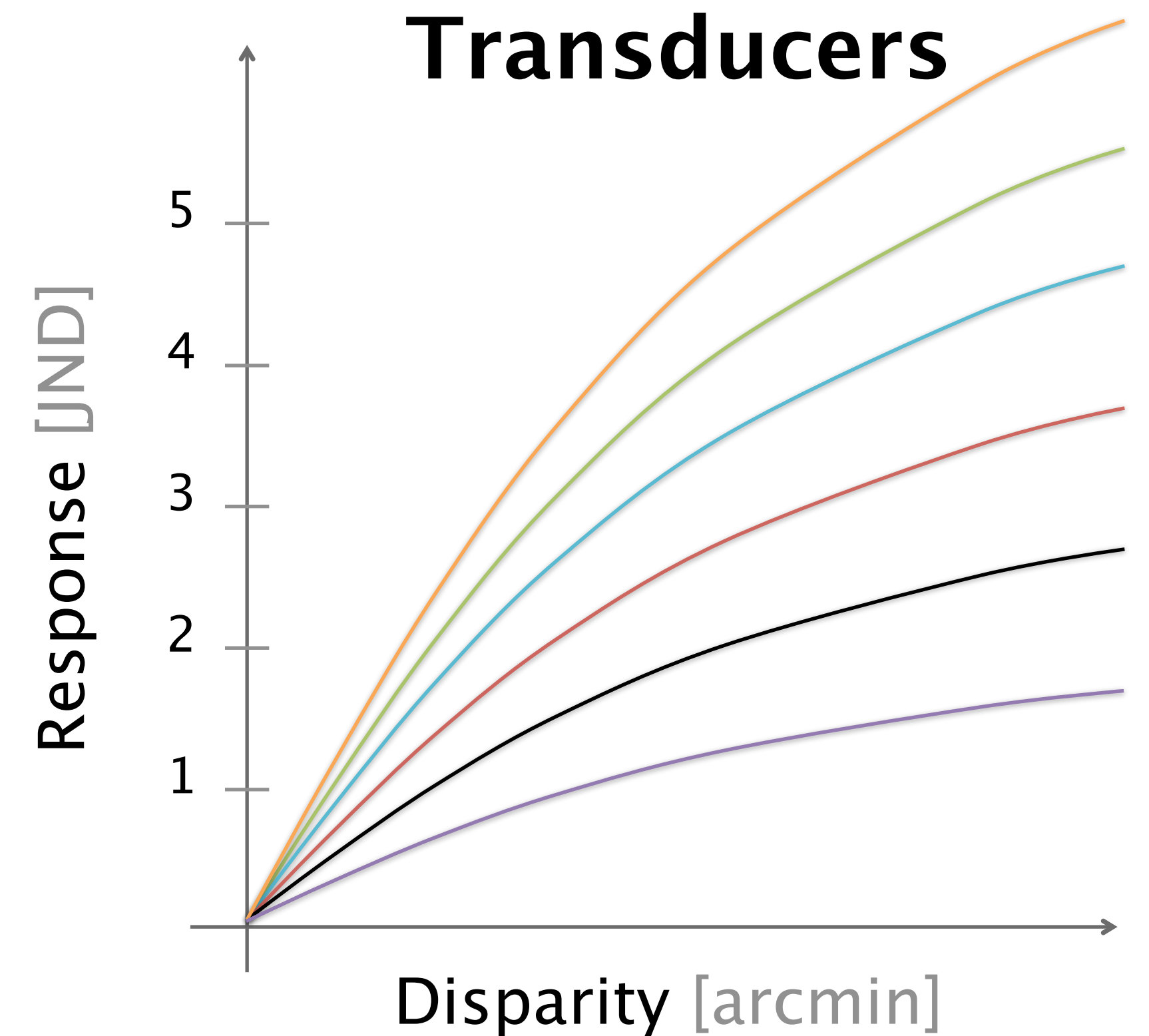
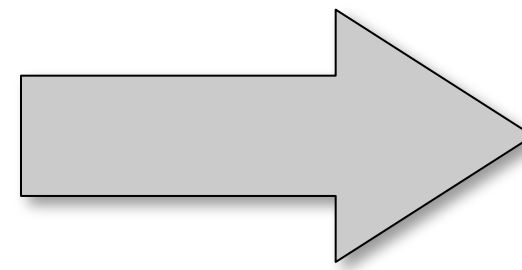
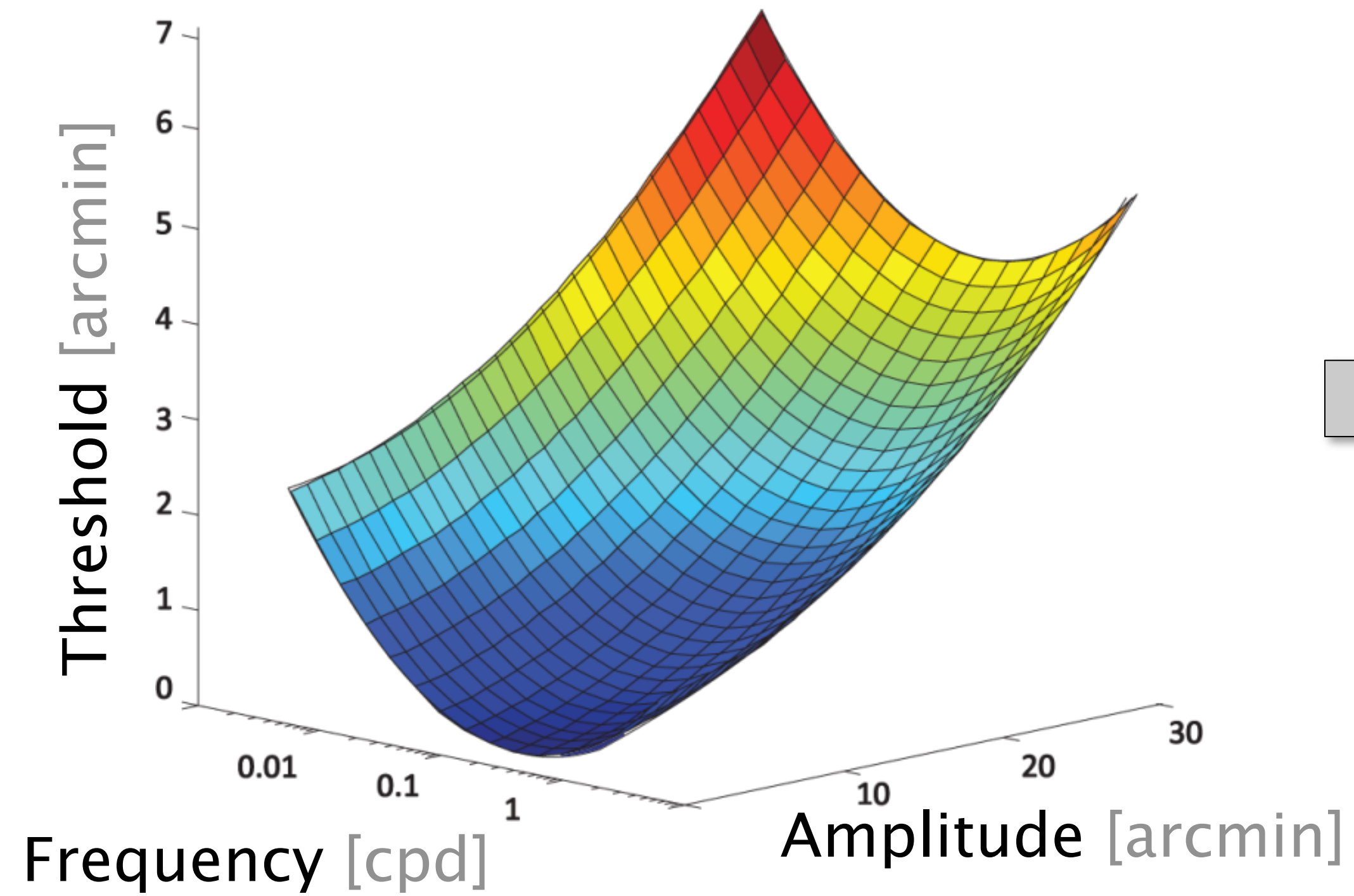
Model

3. Fit analytic function



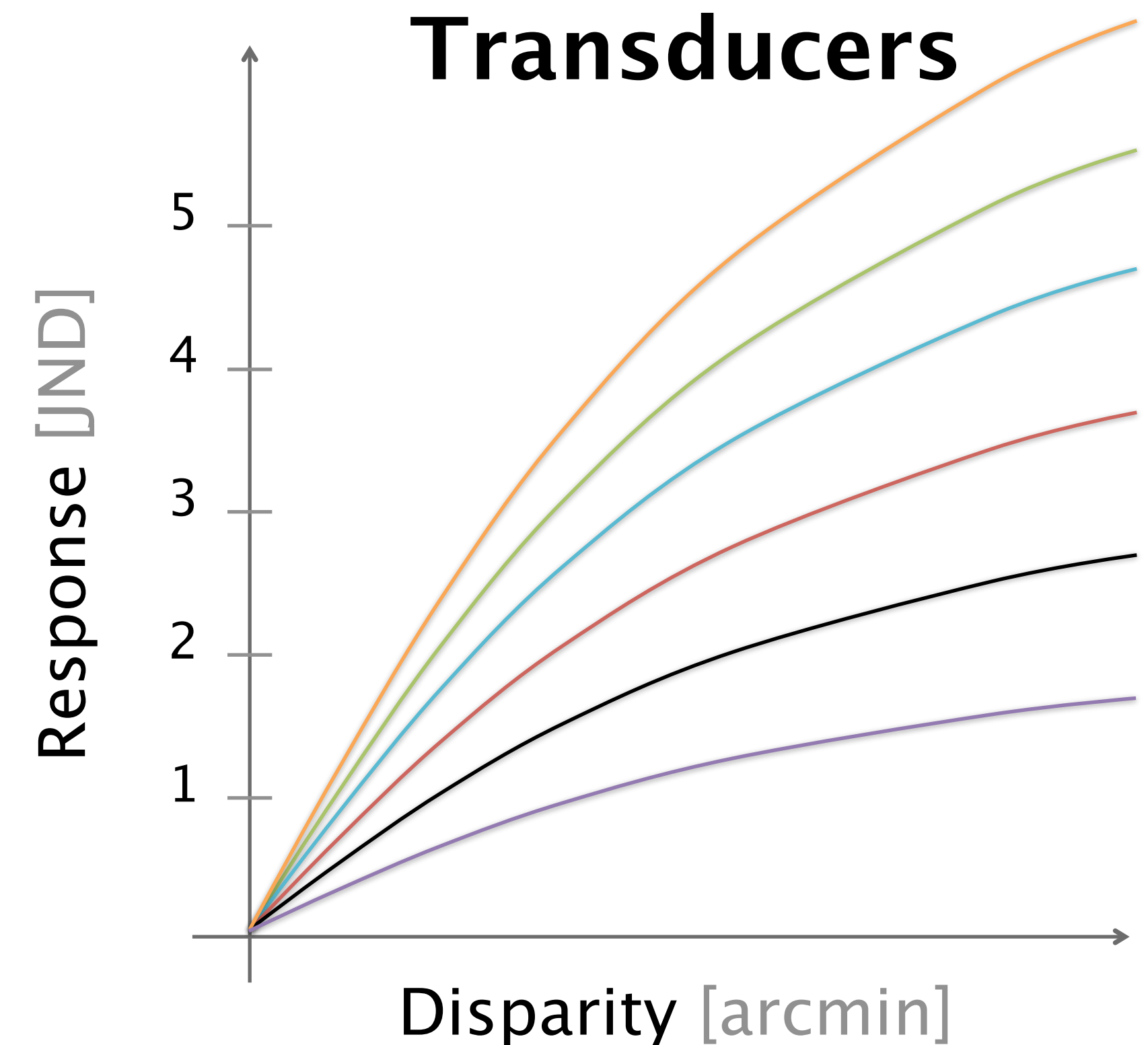
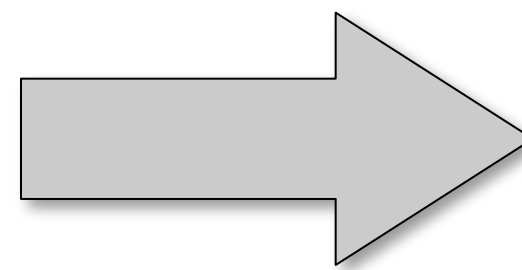
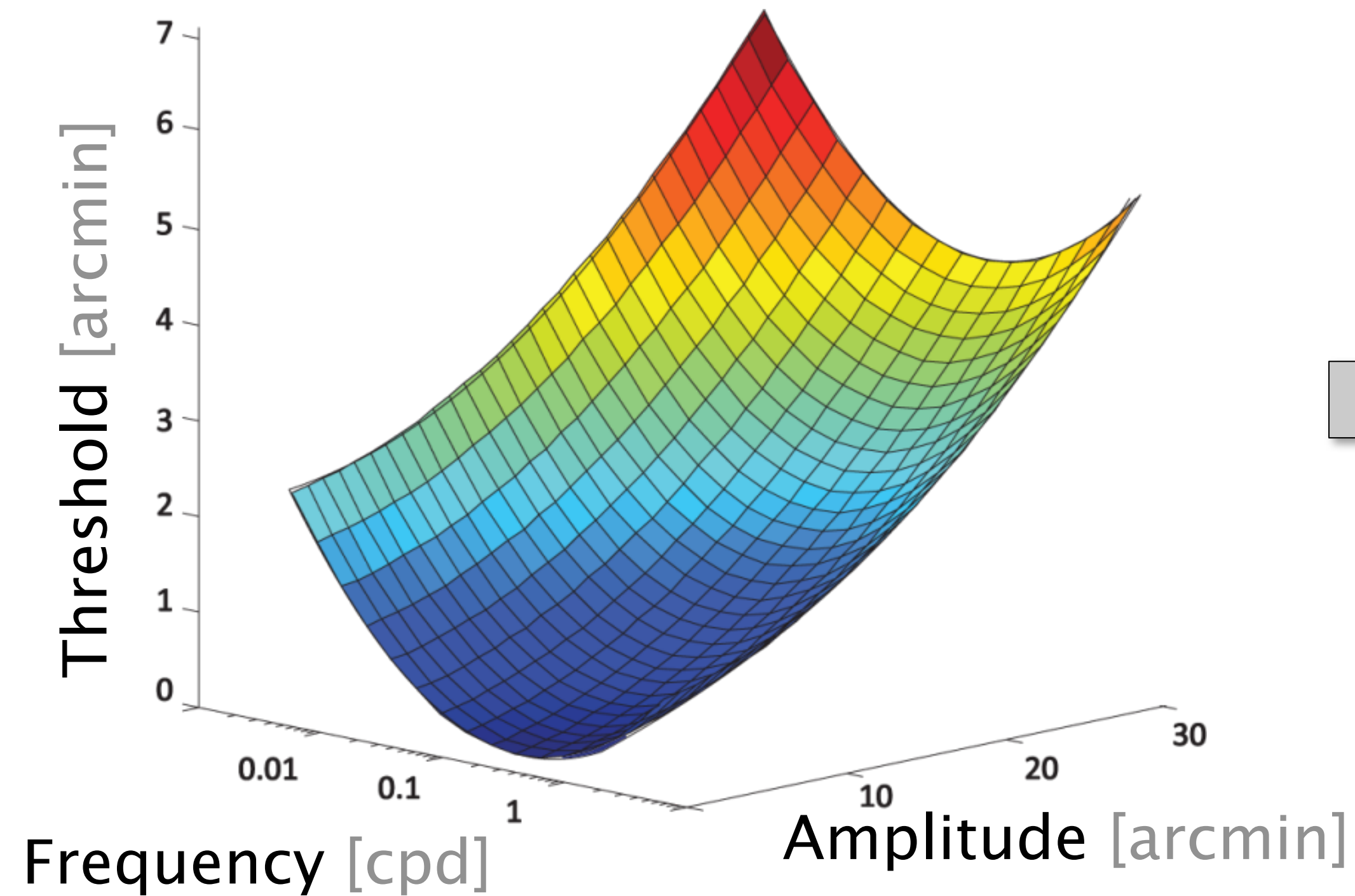
The HVS response

The HVS response



Each curve corresponds to different frequency

The HVS response



Each curve corresponds to different frequency

“A transducer function for threshold and suprathreshold human vision” [Wilson 1980]

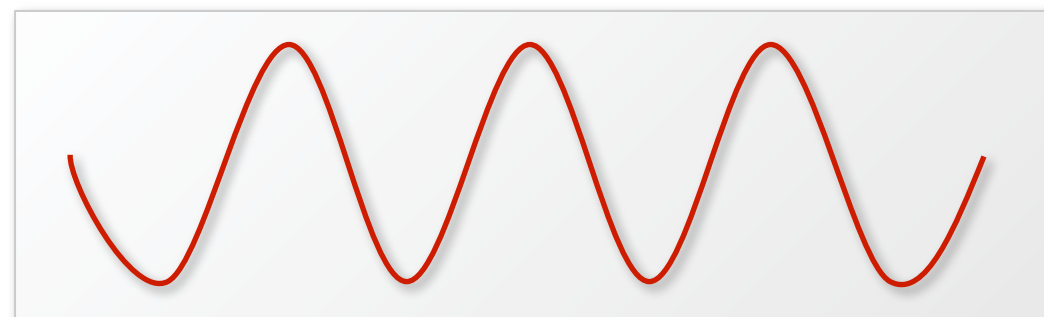
“A perceptual framework for contrast processing of high dynamic range images” [Mantiuk et al. 2005]

Perceptual space

Shown so far:

Perceptual space

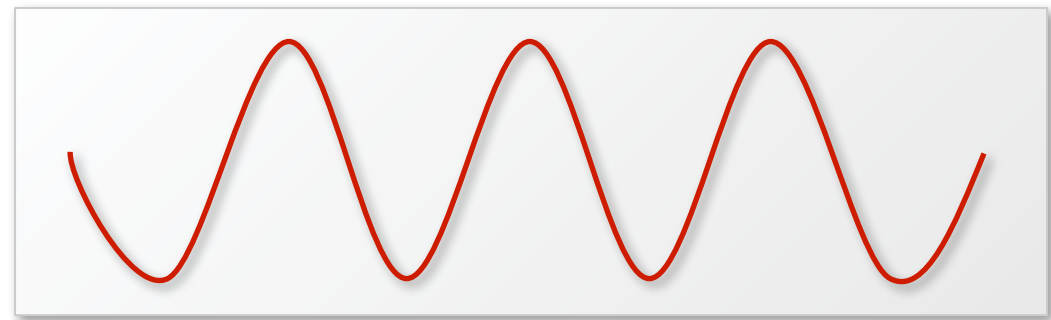
Shown so far:



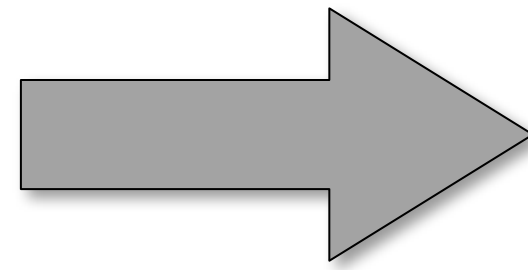
(disparity, frequency)
[arcmin, cpd]

Perceptual space

Shown so far:



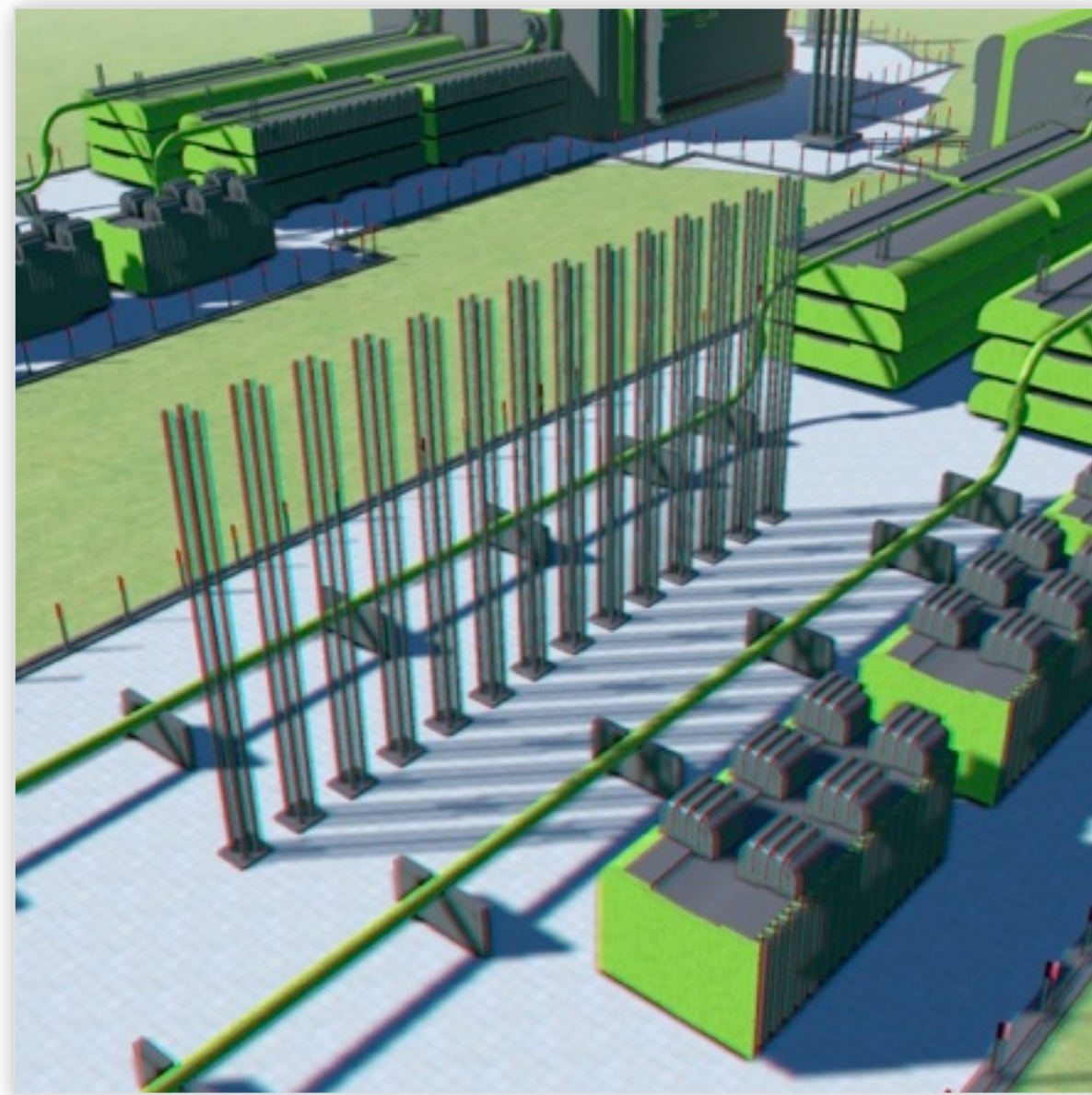
(disparity, frequency)
[arcmin, cpd]



HVS response
[JND]

Perceptual space

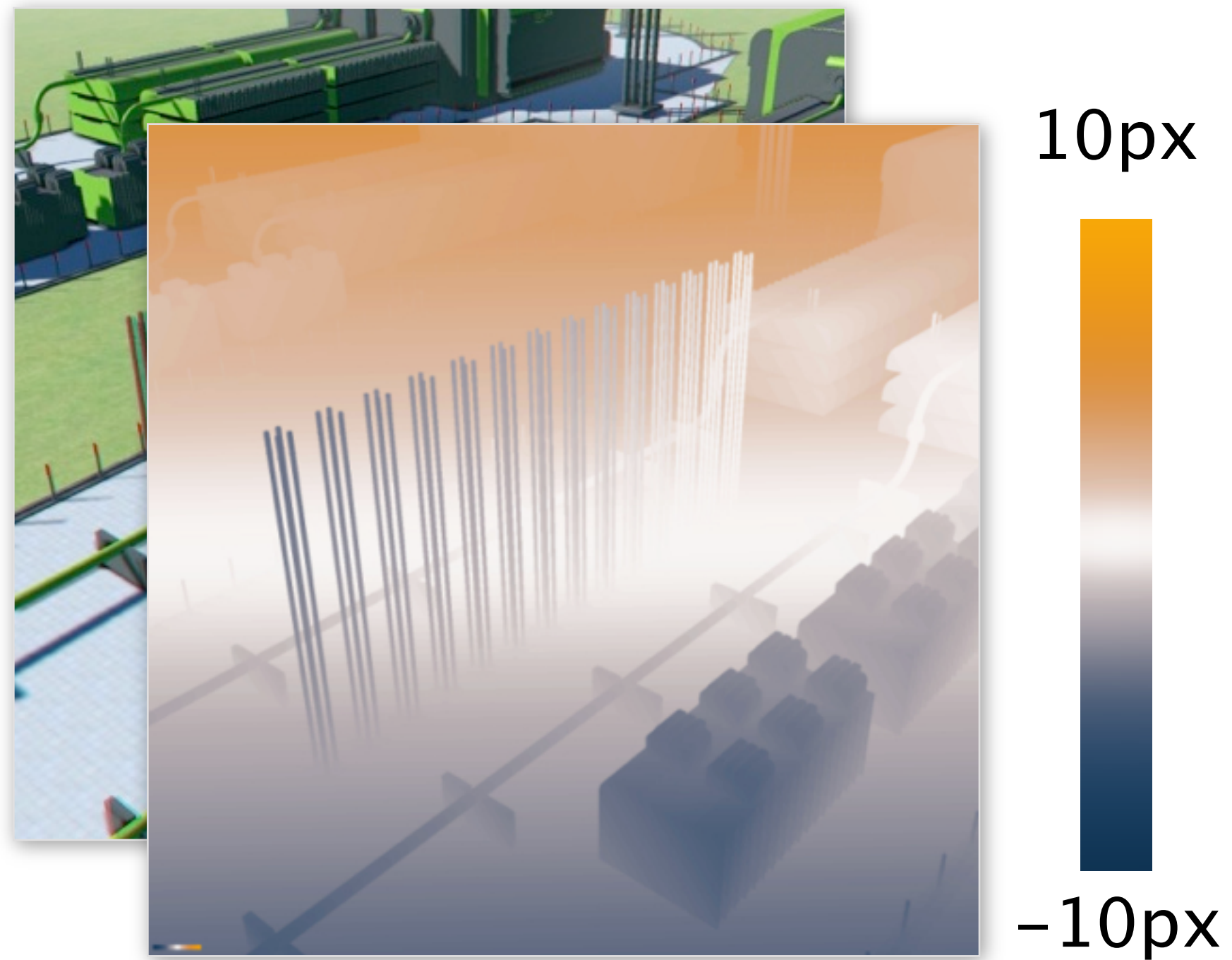
Our problem:



3D scene with pixel disparity
[pixels]

Perceptual space

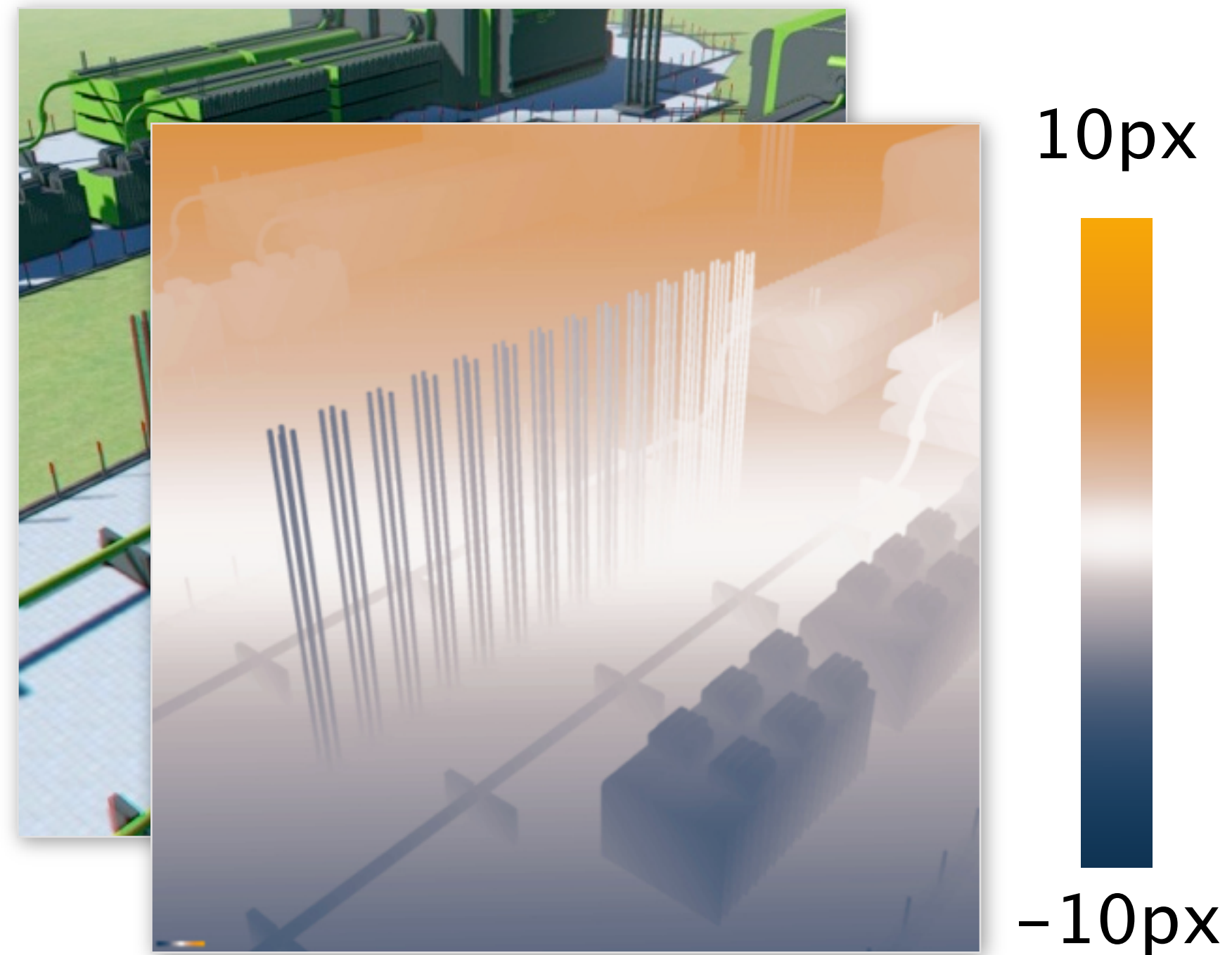
Our problem:



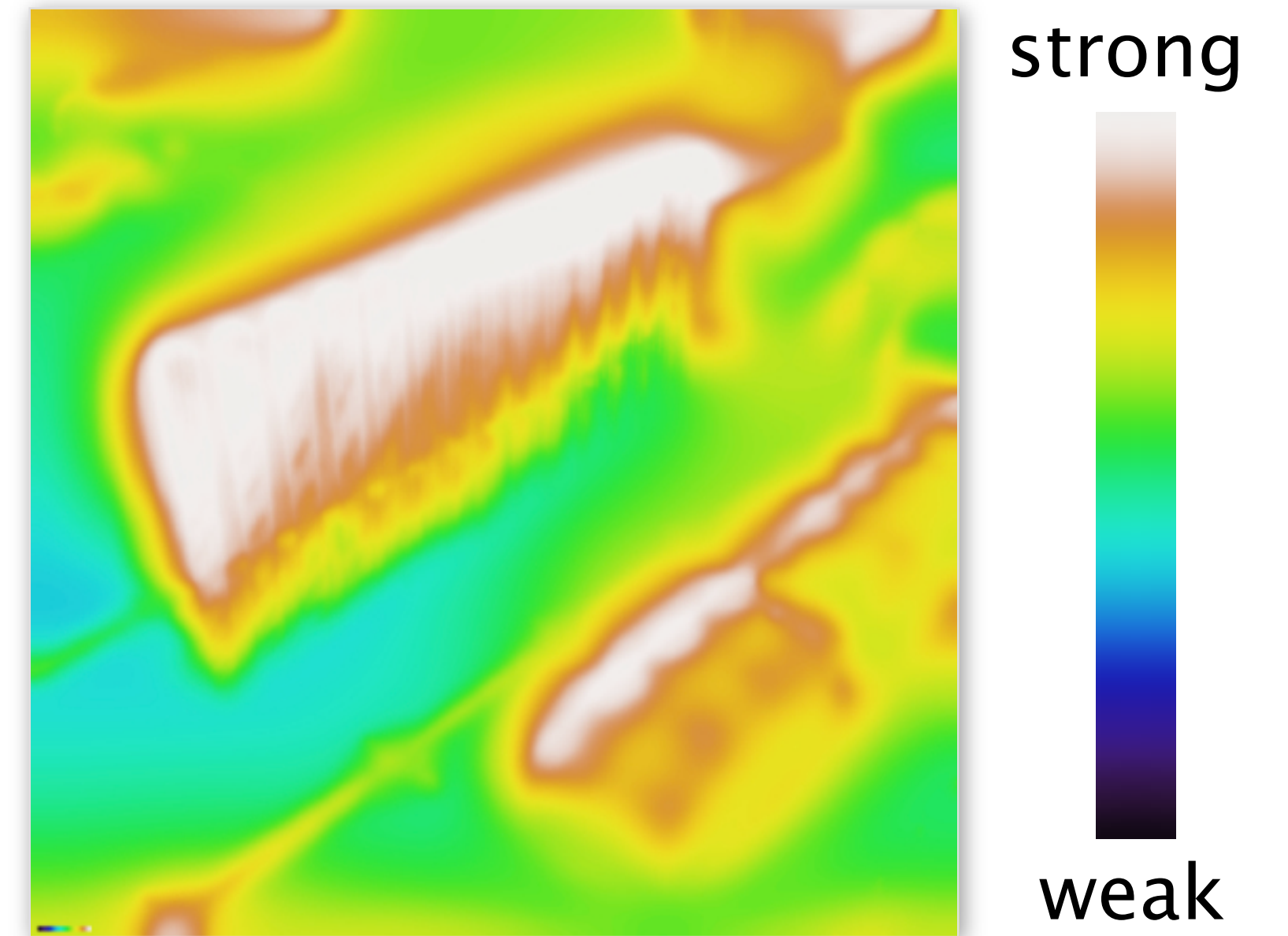
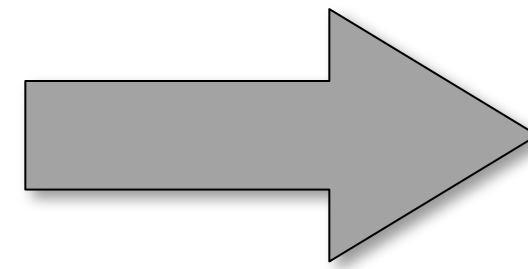
3D scene with pixel disparity
[pixels]

Perceptual space

Our problem:



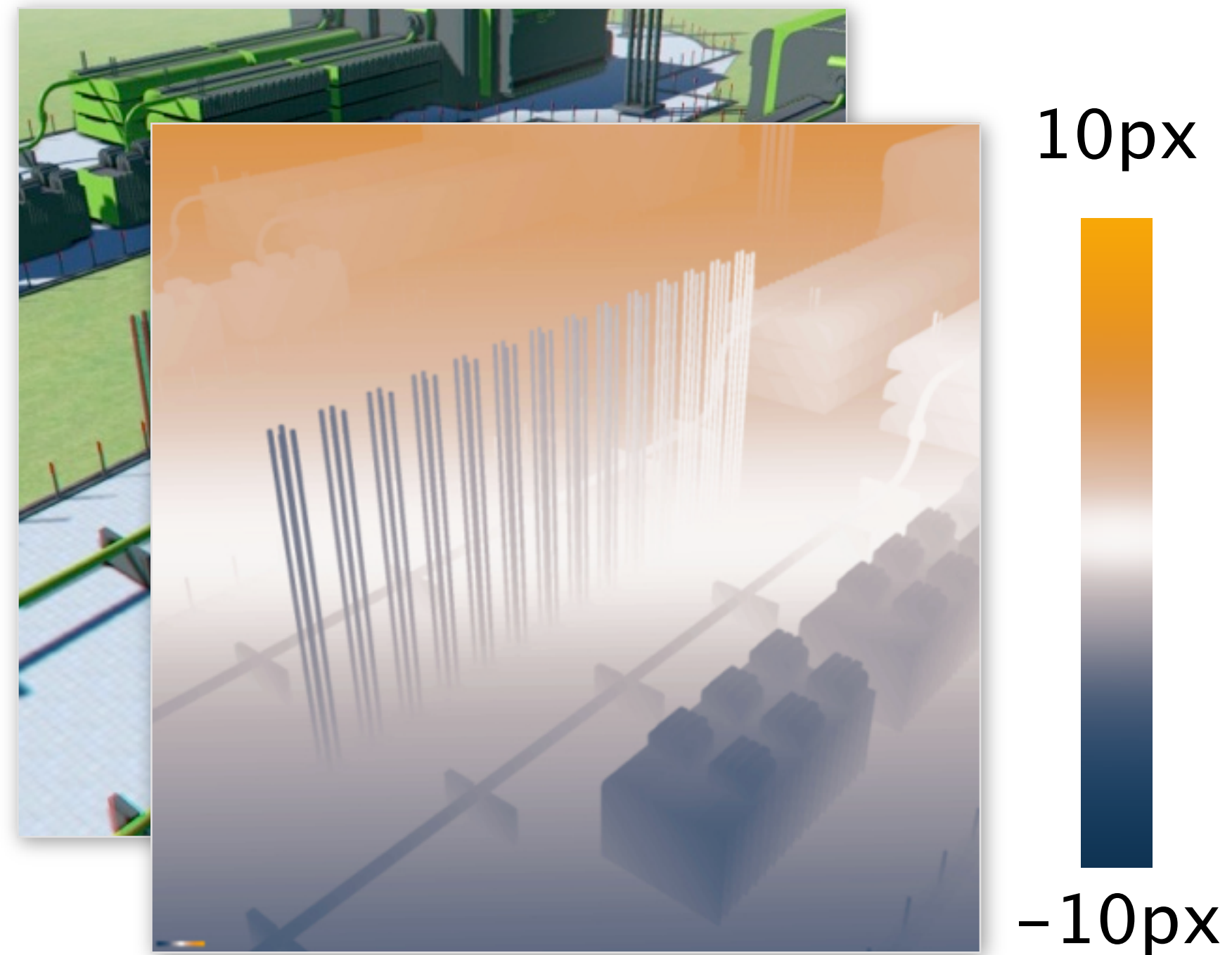
3D scene with pixel disparity
[pixels]



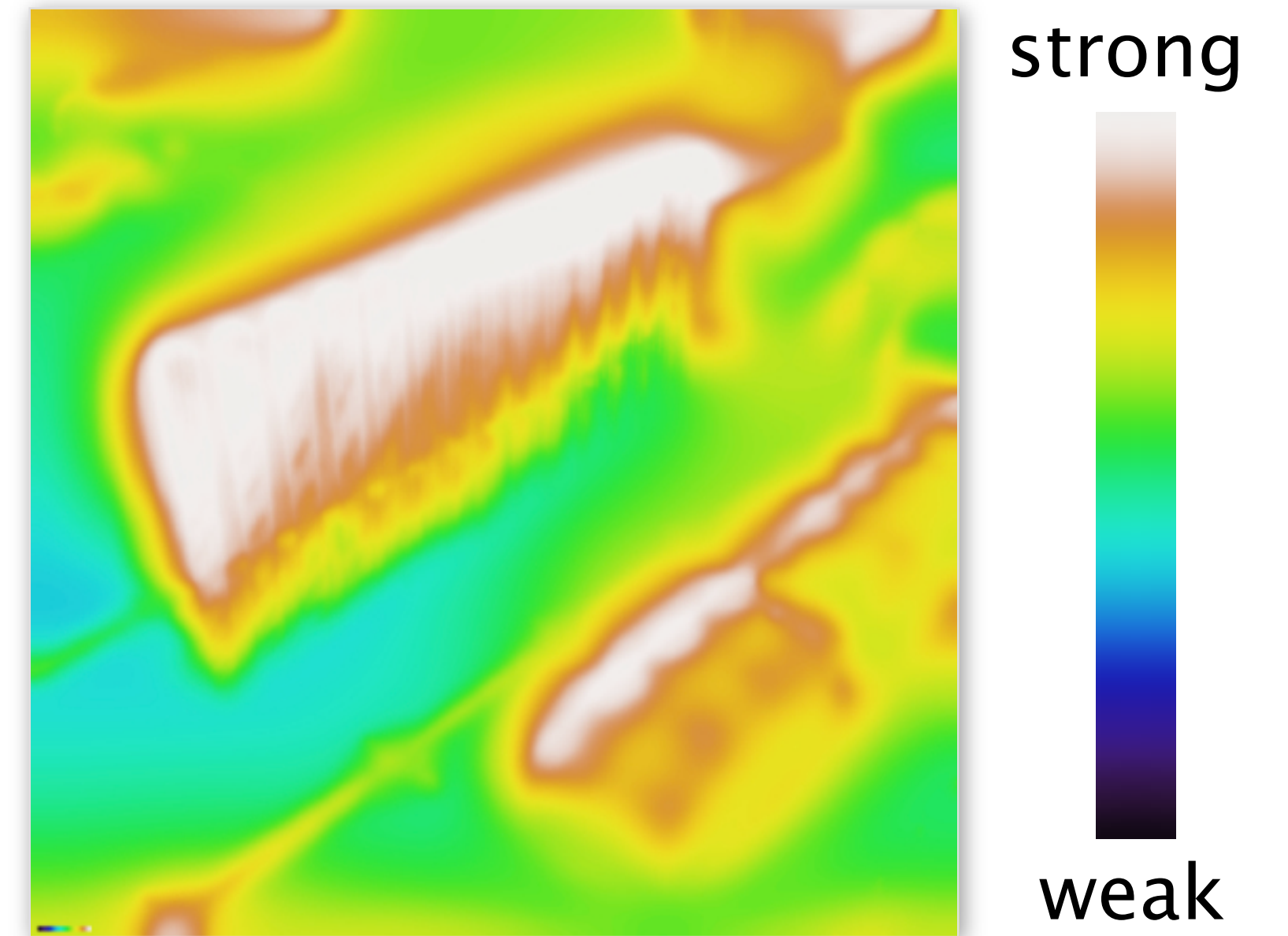
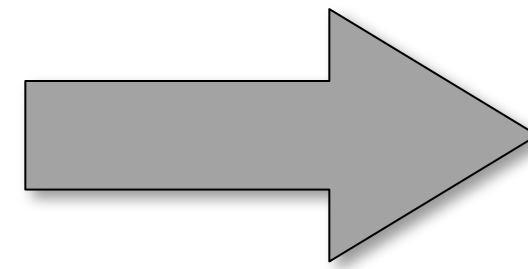
Map of HVS response
[JND]

Perceptual space

Our problem:



3D scene with pixel disparity
[pixels]



Map of HVS response
[JND]

Perceptual space

Our problem:

Problems:

pixel disparity [pixels]	→	disparity [arcmin]
sinusoidal patterns	→	complex images

strong



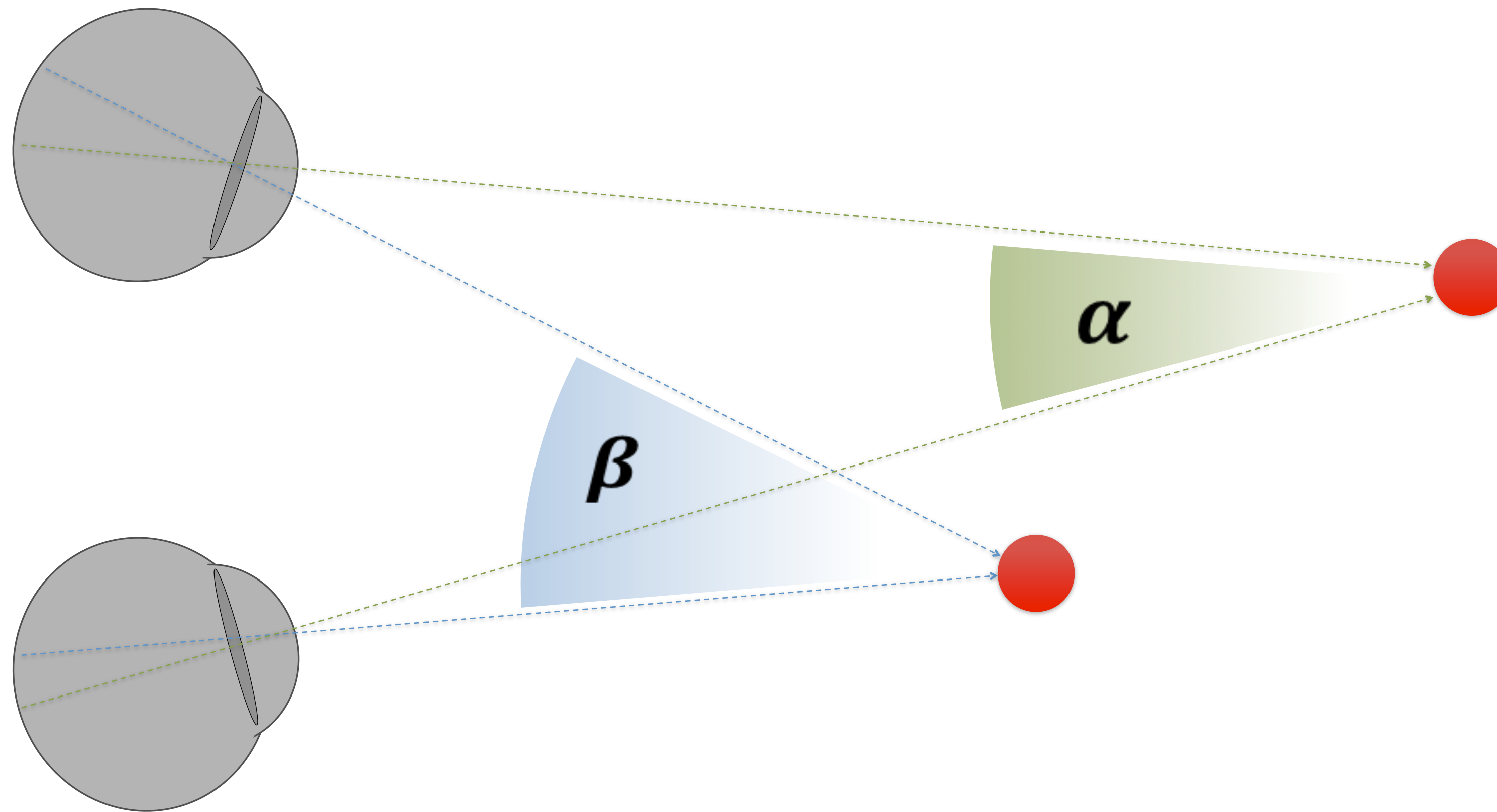
weak

3D scene with pixel disparity
[pixels]

Map of HVS response
[JND]

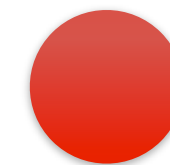
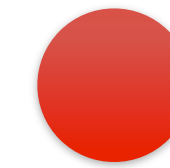
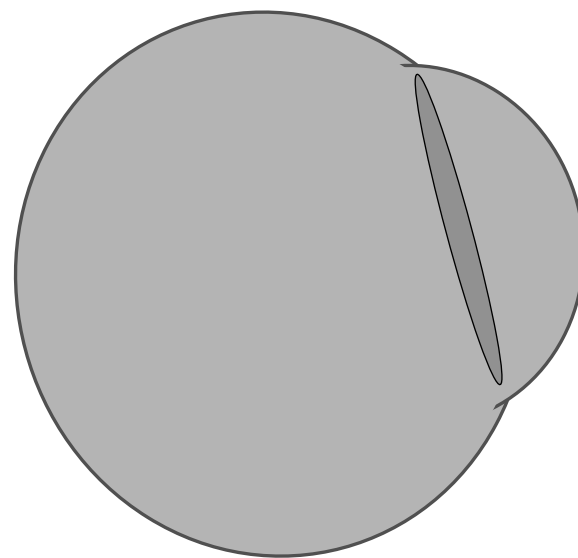
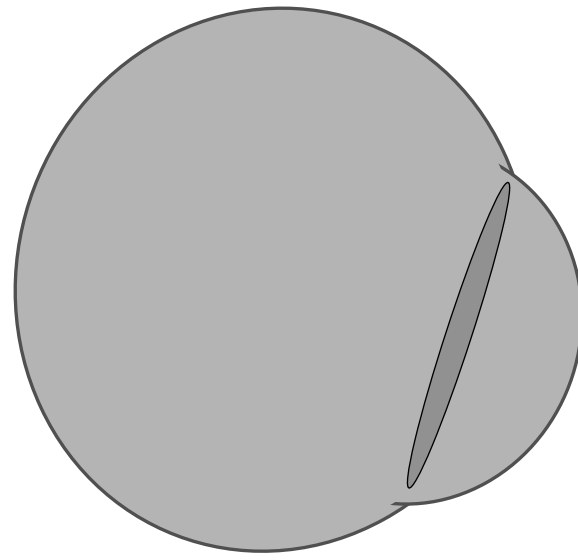
Disparity

Disparity

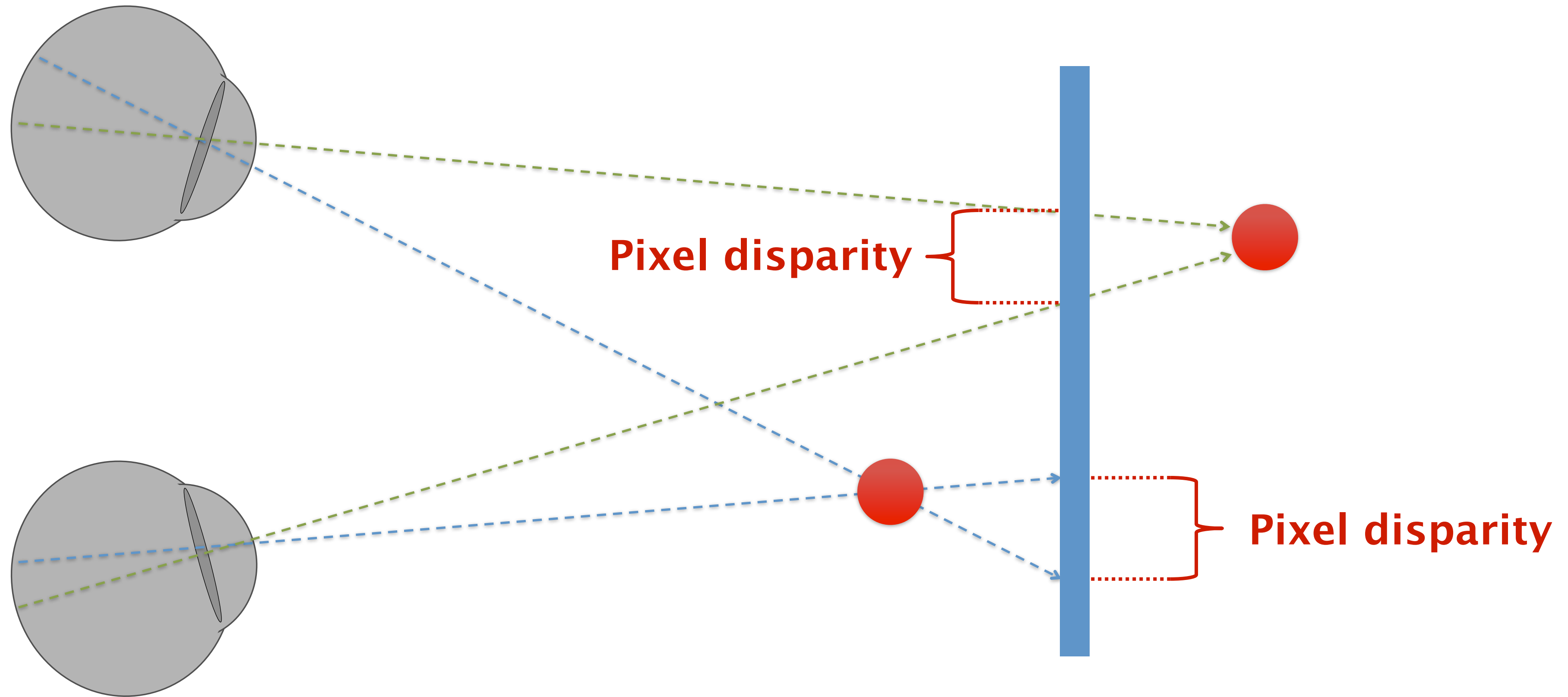


$$\text{disparity} = |\alpha - \beta|$$

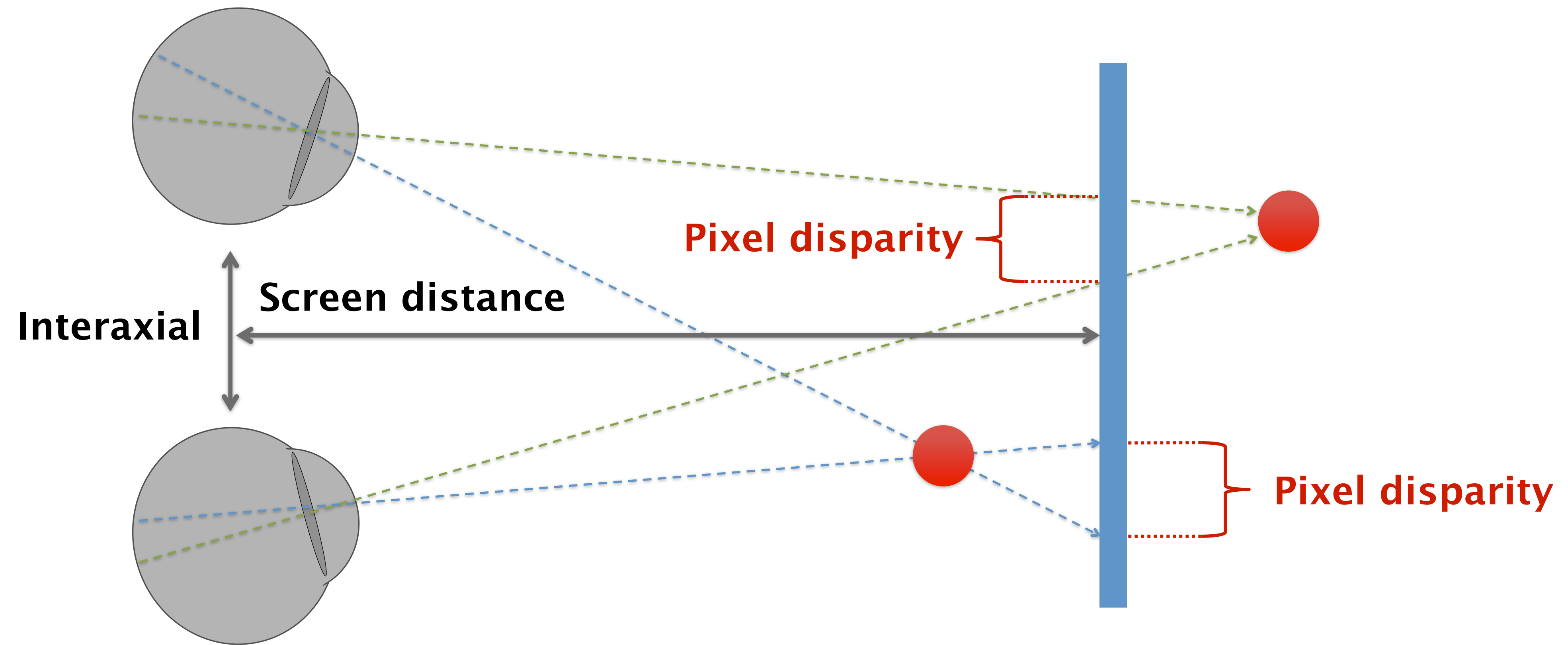
Pixel disparity to disparity



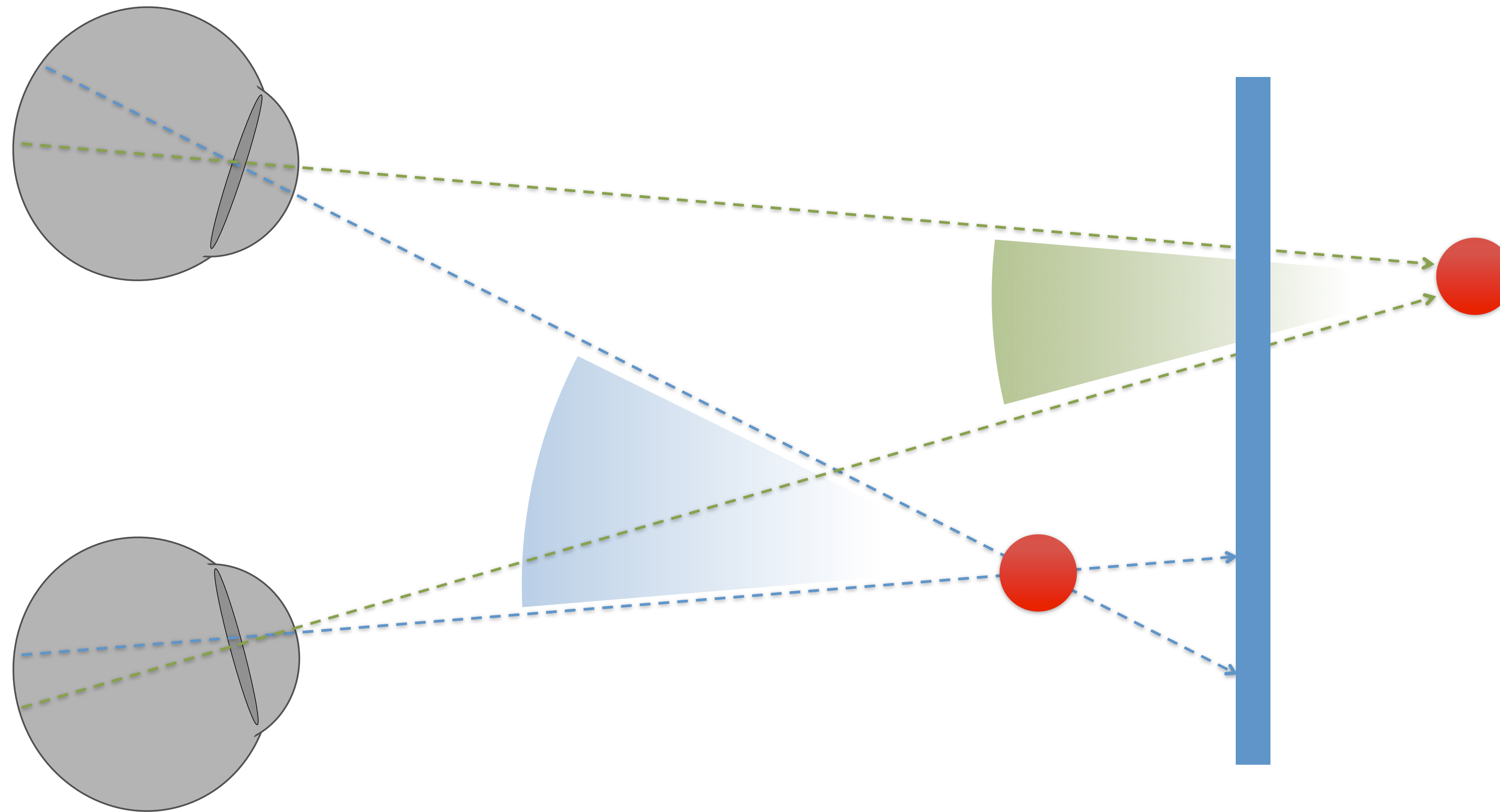
Pixel disparity to disparity



Pixel disparity to disparity



Pixel disparity to disparity

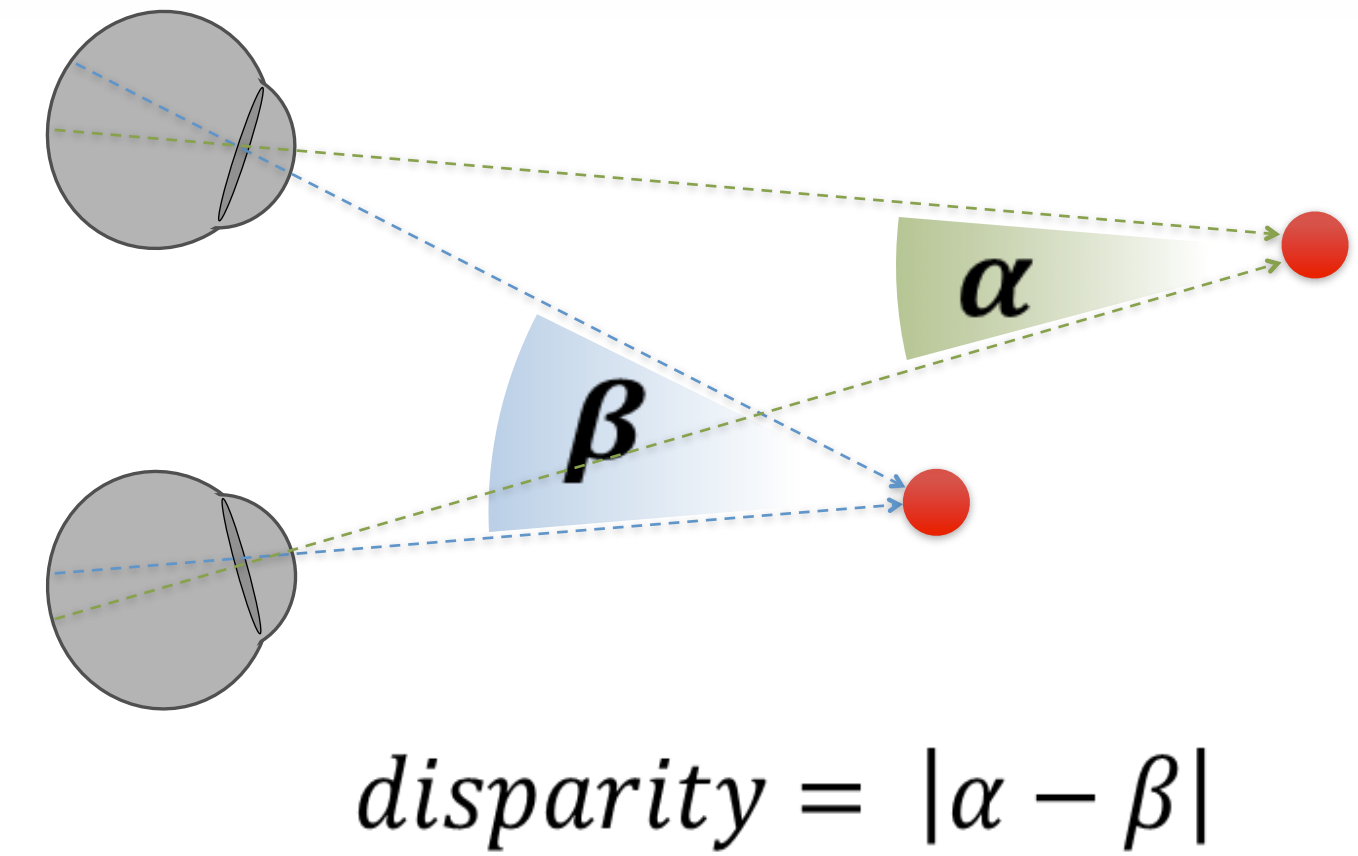


(viewing conditions, pixel disparity) $\rightarrow$ vergence

Vergence to disparity

Vergence to disparity

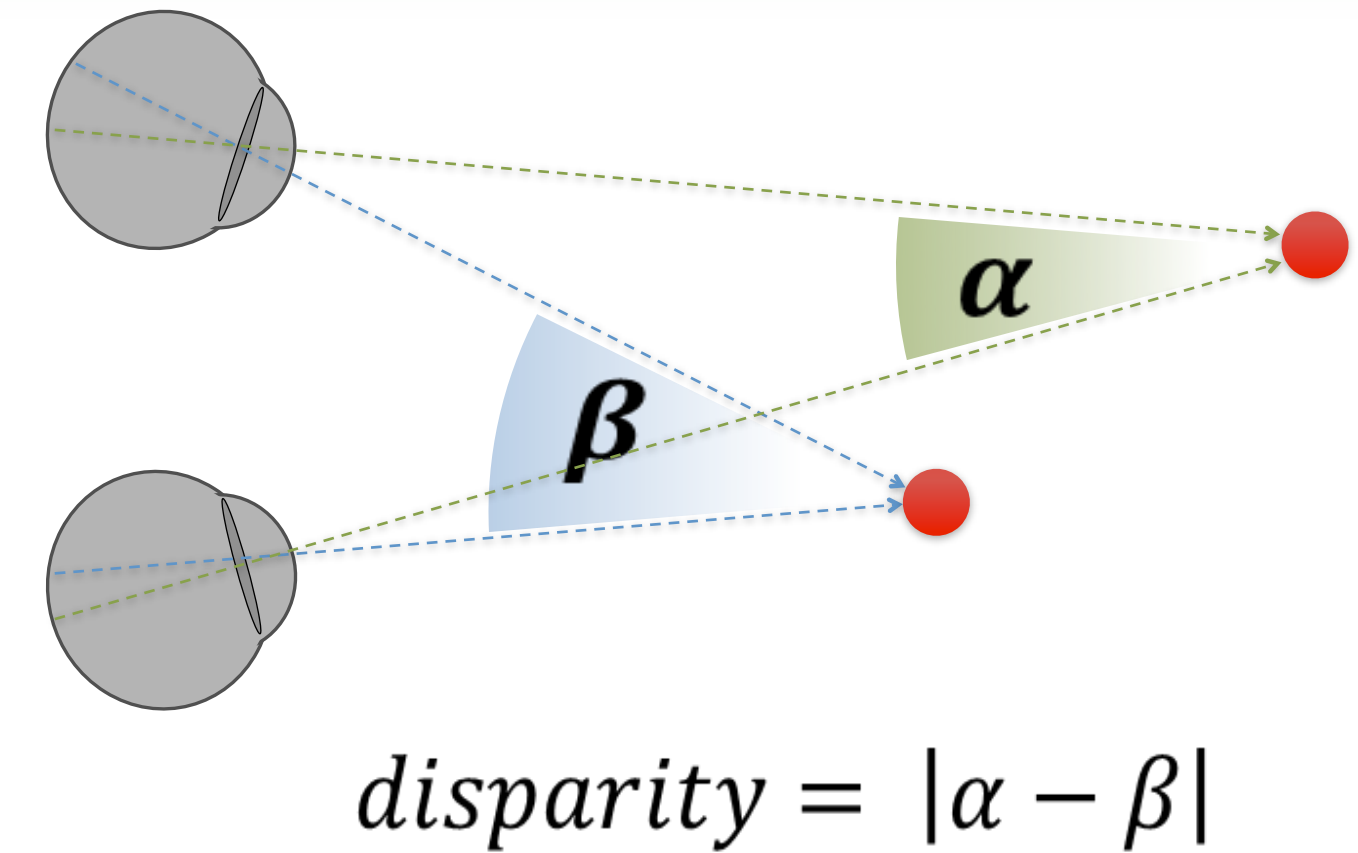
Disparity is a difference of vergence angles



Vergence to disparity

Disparity is a difference of vergence angles

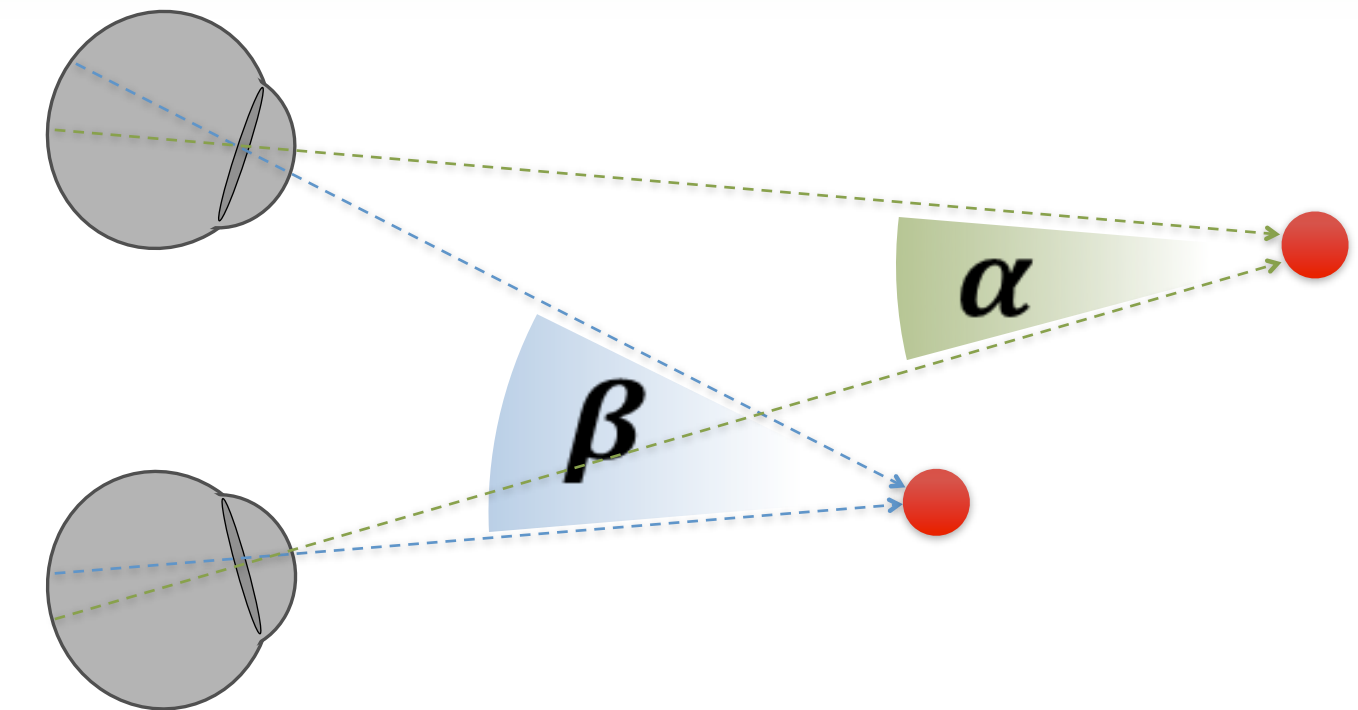
Disparity = Vergence “contrast”



Vergence to disparity

Disparity is a difference of vergence angles

Disparity = Vergence “contrast”



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

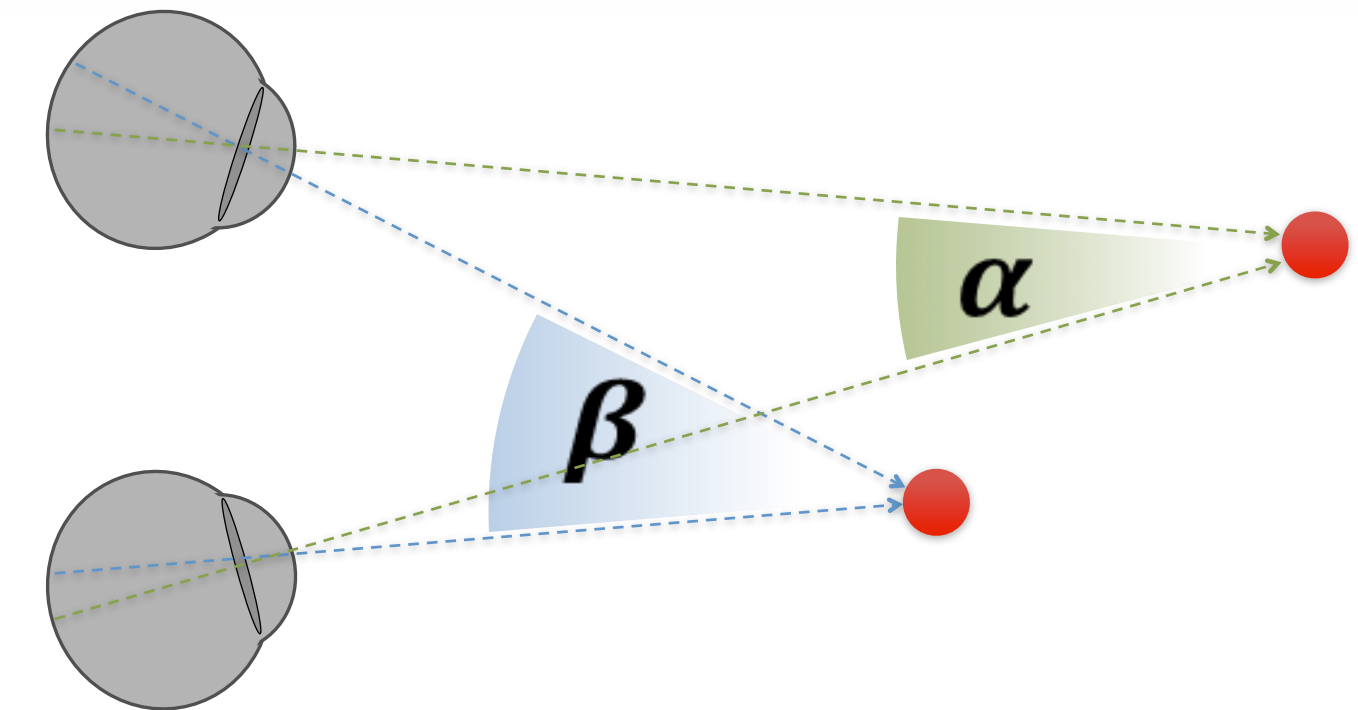
Analogy to luminance:

Luminance	↔	Vergence
Luminance contrast	↔	Disparity

Vergence to disparity

Disparity is a difference of vergence angles

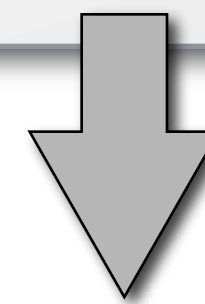
Disparity = Vergence “contrast”



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

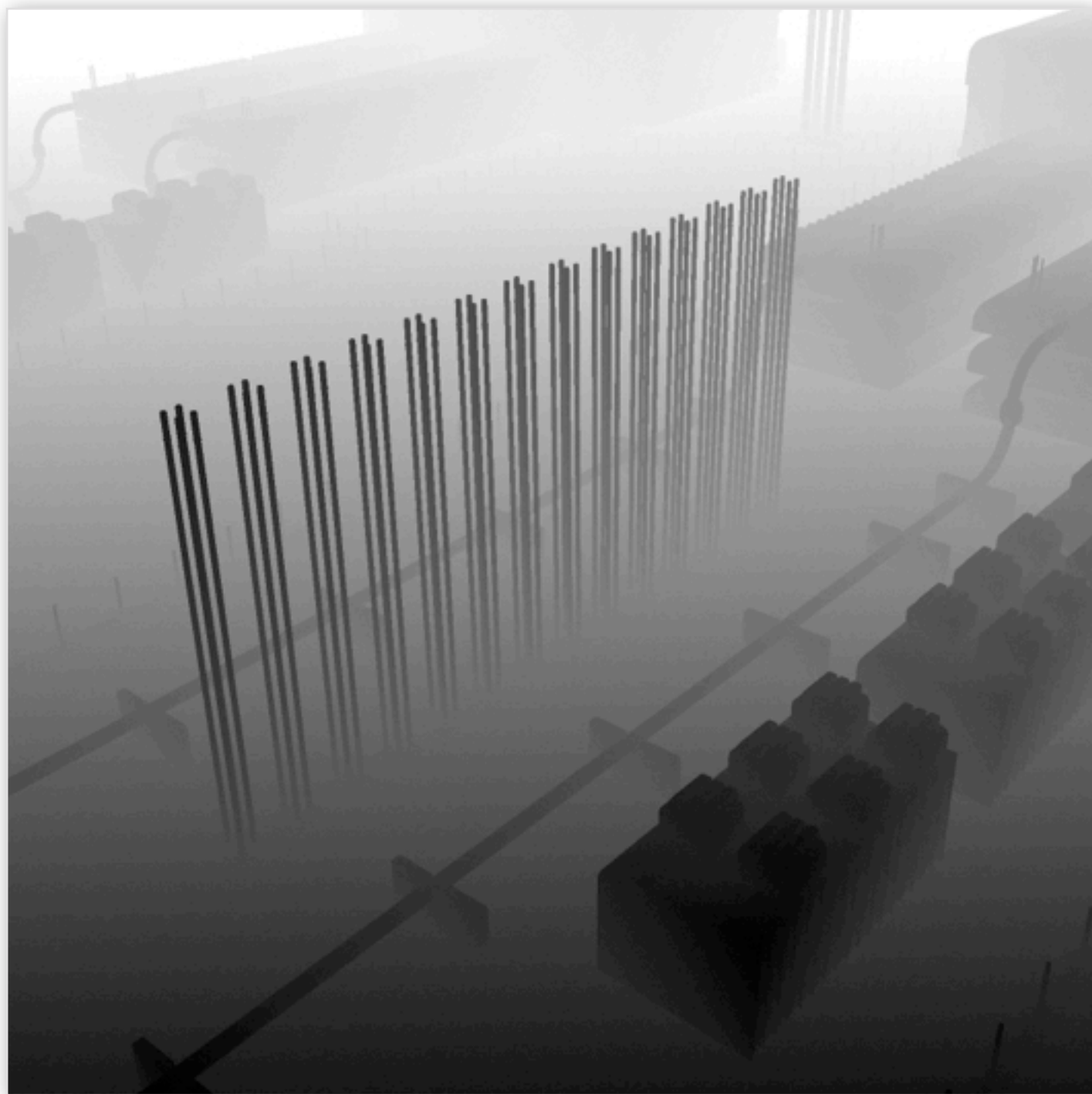
Analogy to luminance:

Luminance	↔	Vergence
Luminance contrast	↔	Disparity



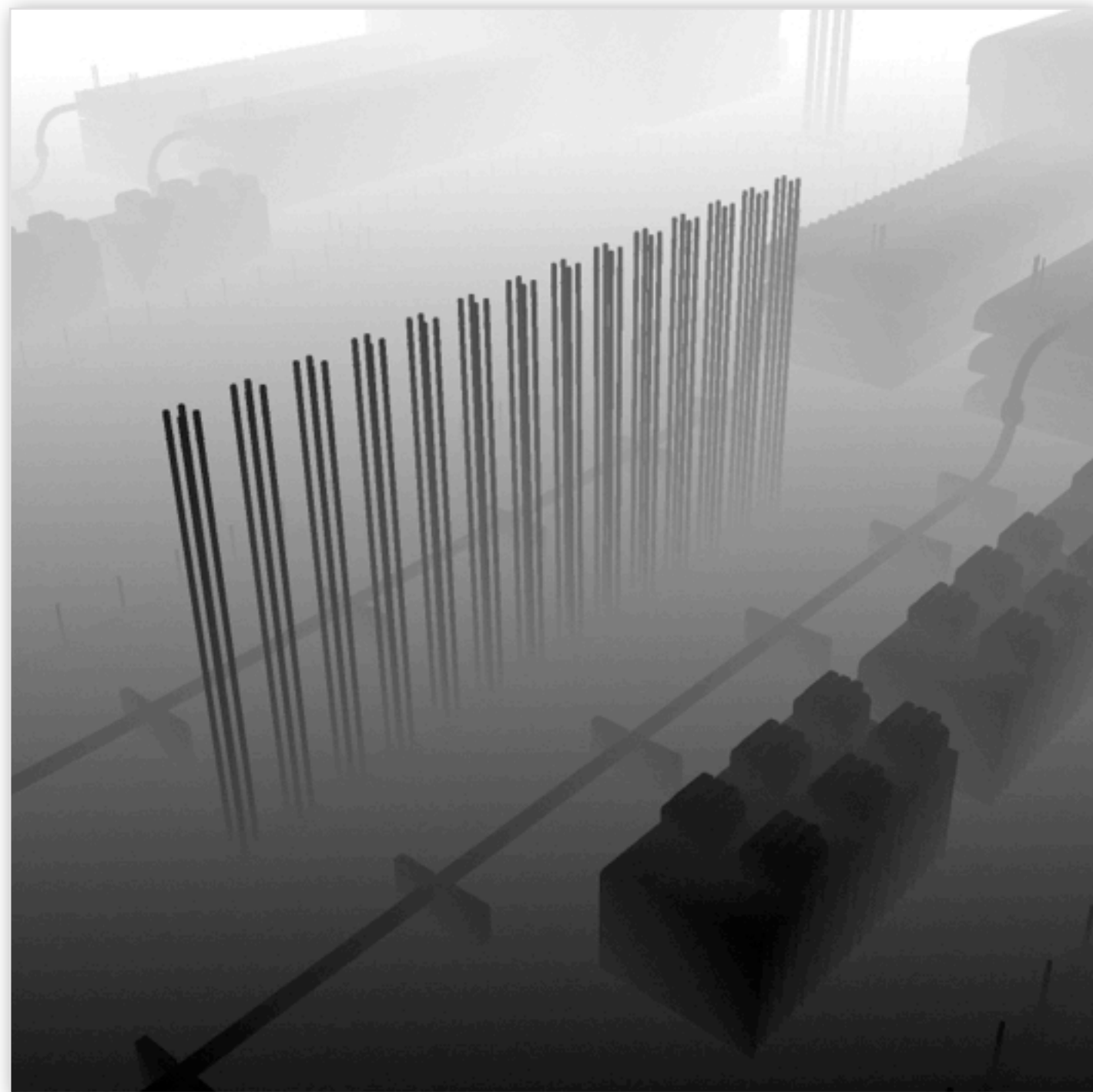
Similar processing to luminance

Vergence to disparity

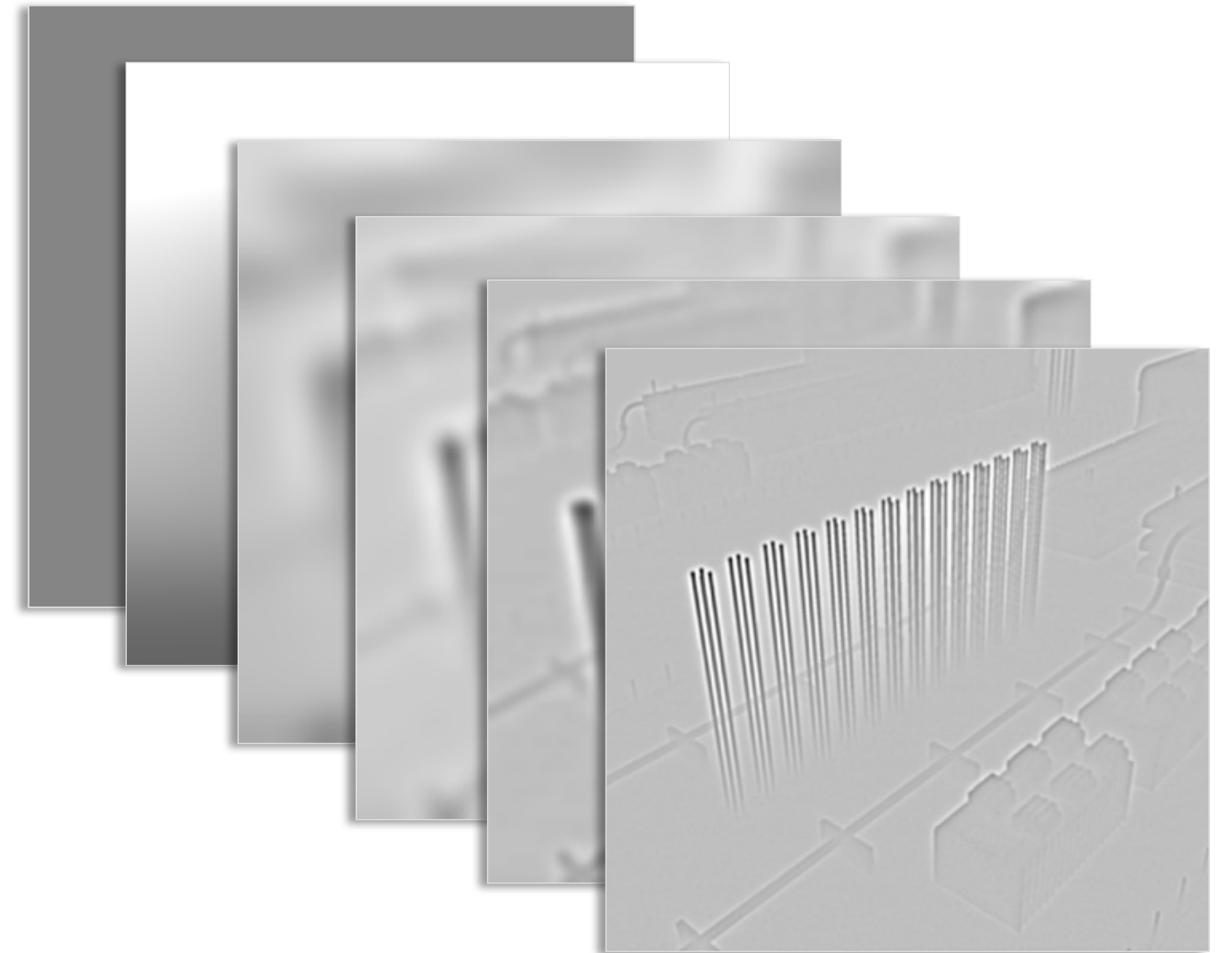
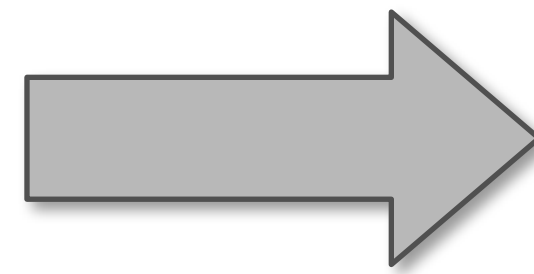


Vergence [arcmin]

Vergence to disparity

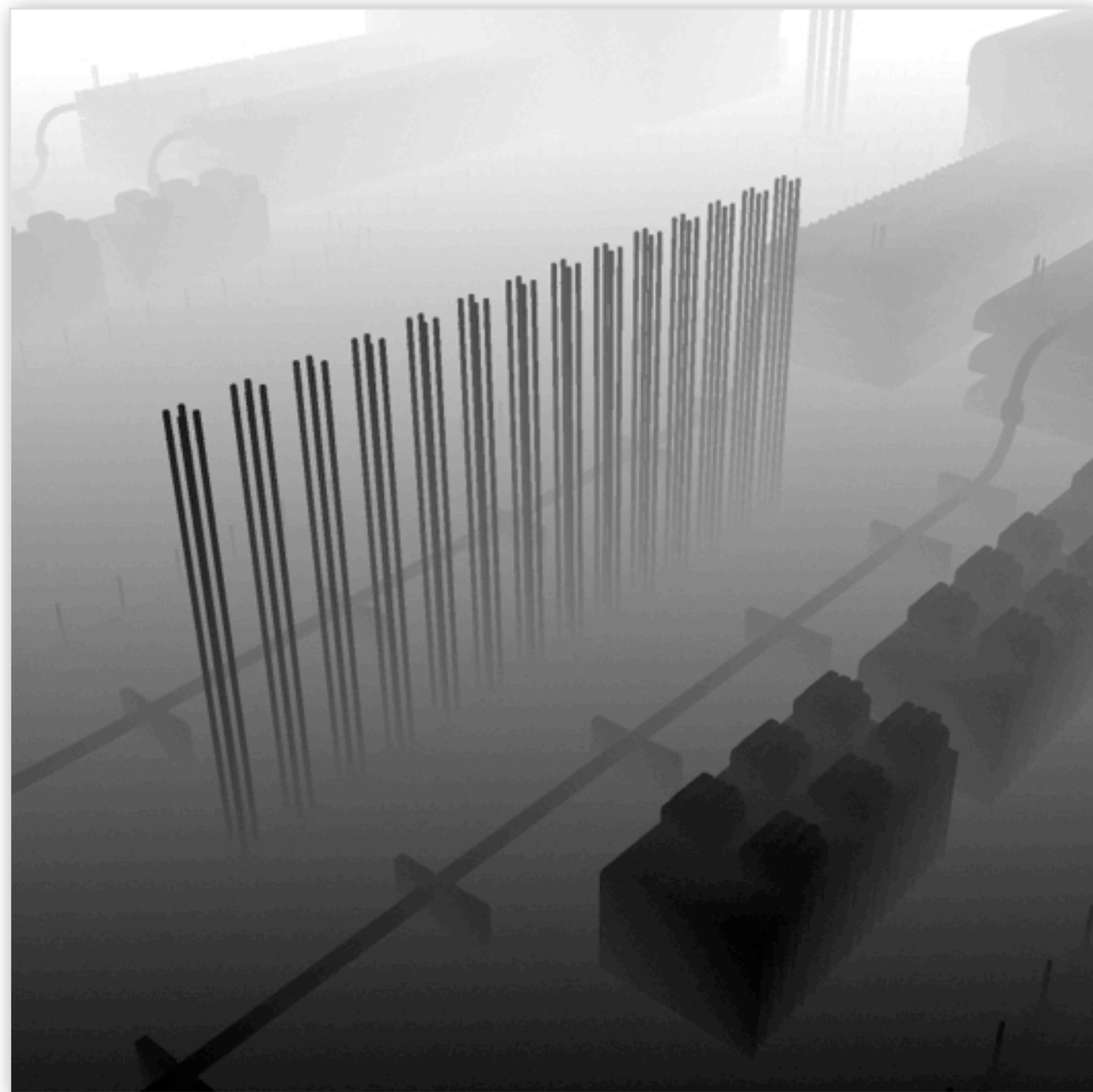


Vergence [arcmin]

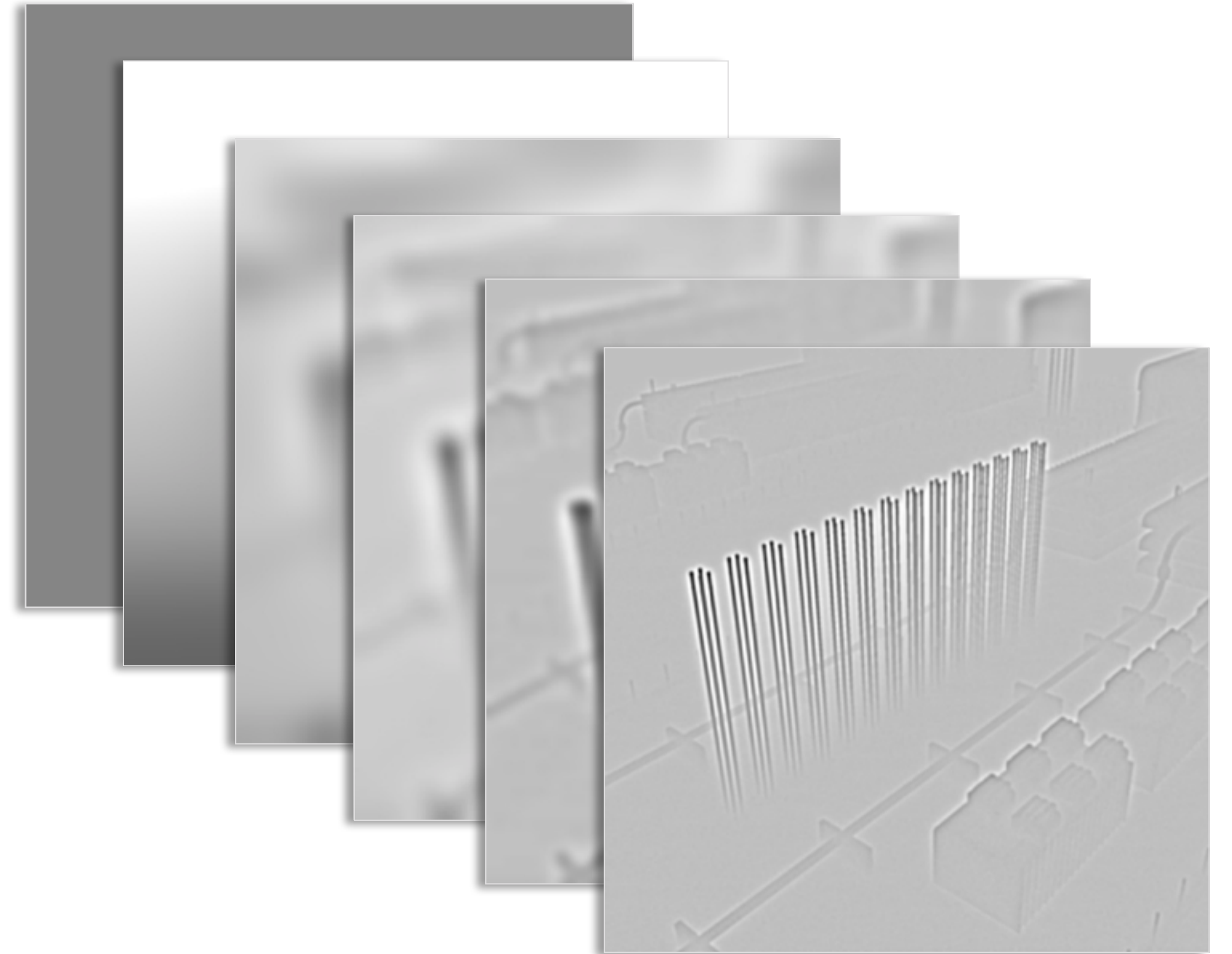
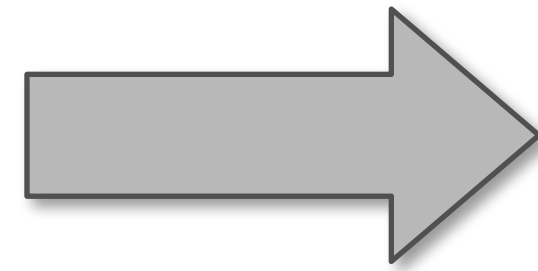


Frequency decomposition

Vergence to disparity

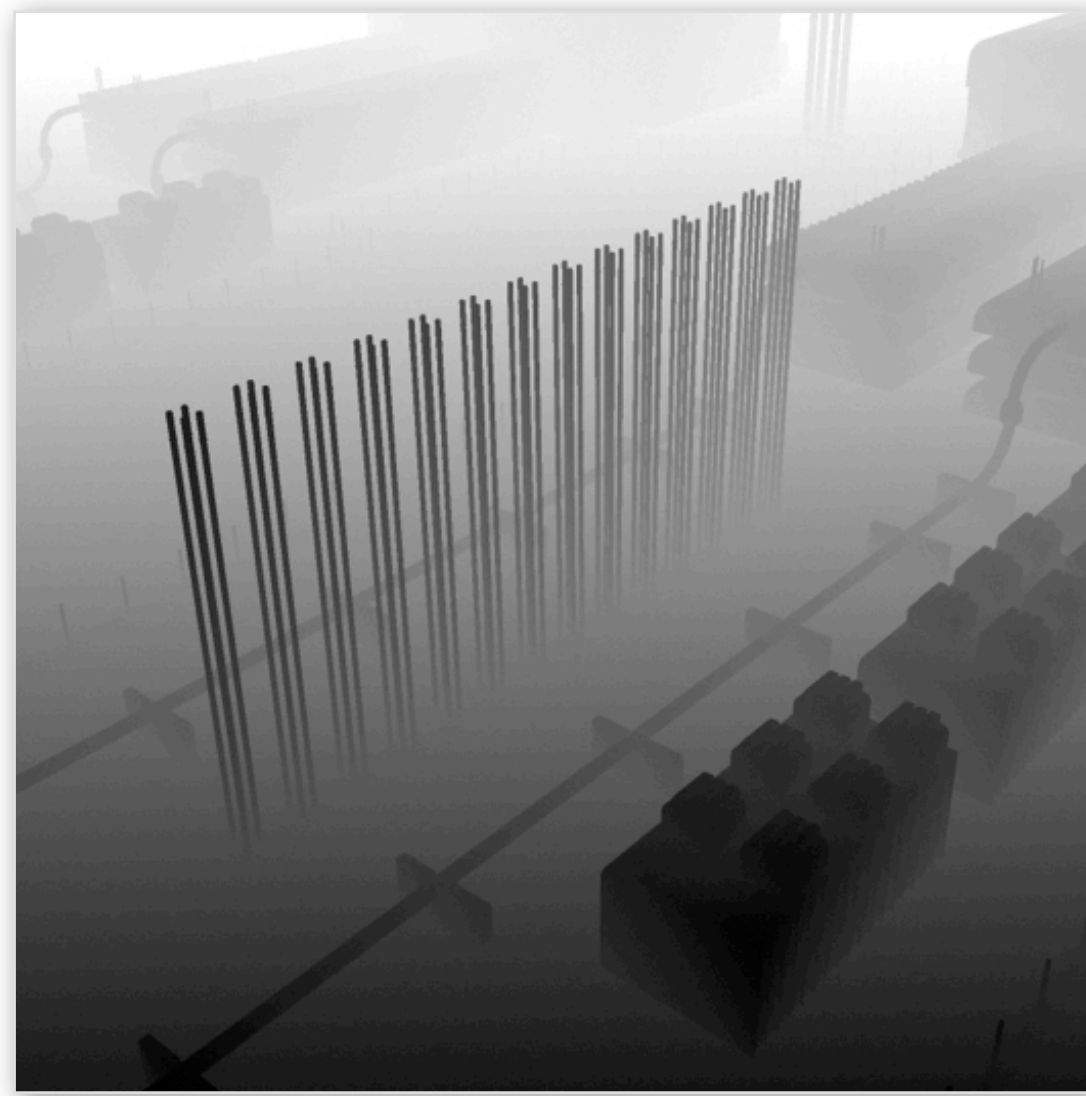


Vergence [arcmin]

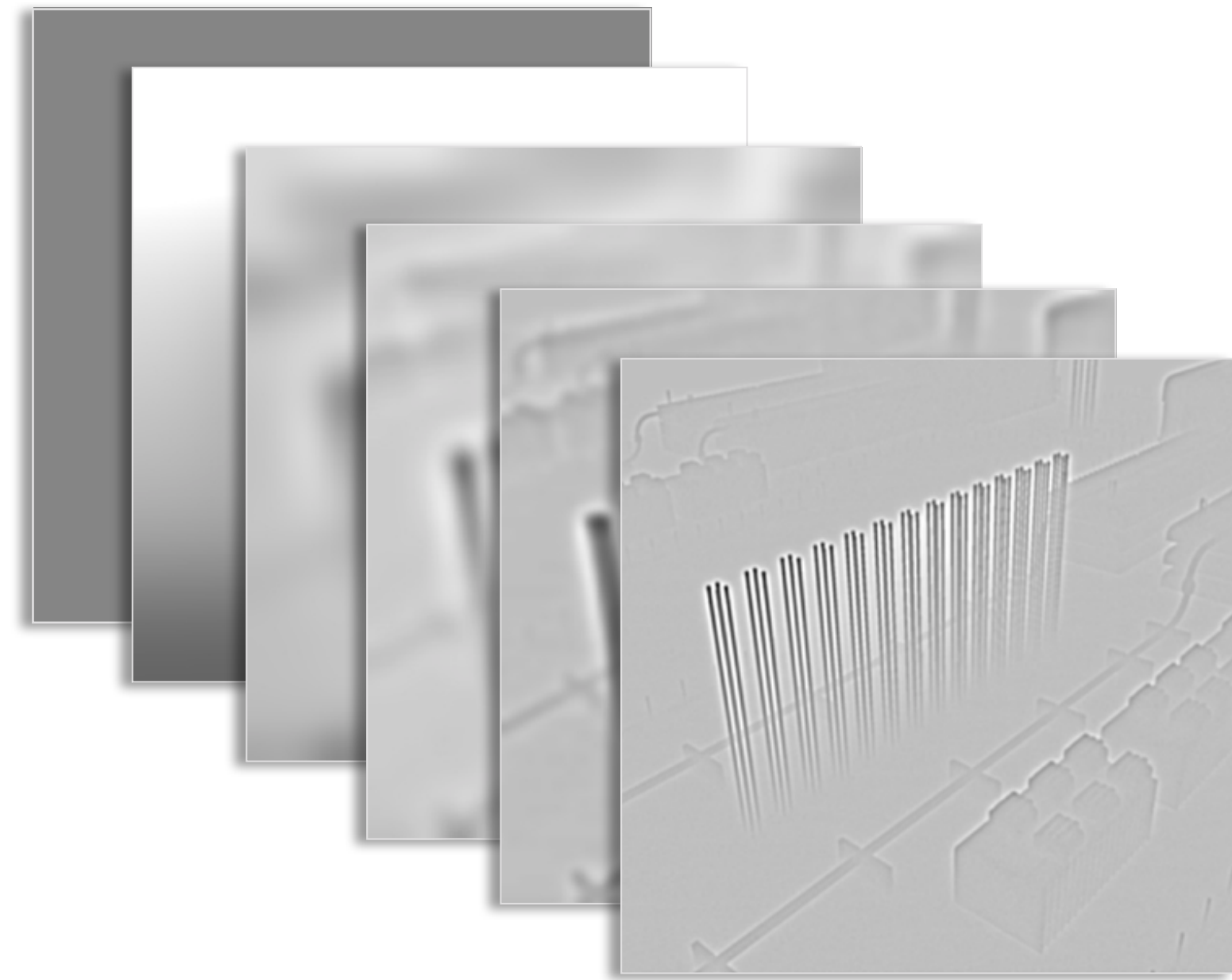
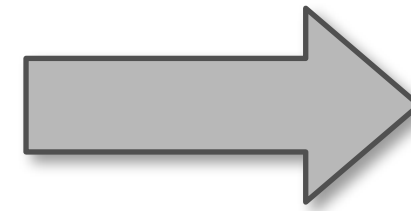


Frequency decomposition

Vergence to disparity



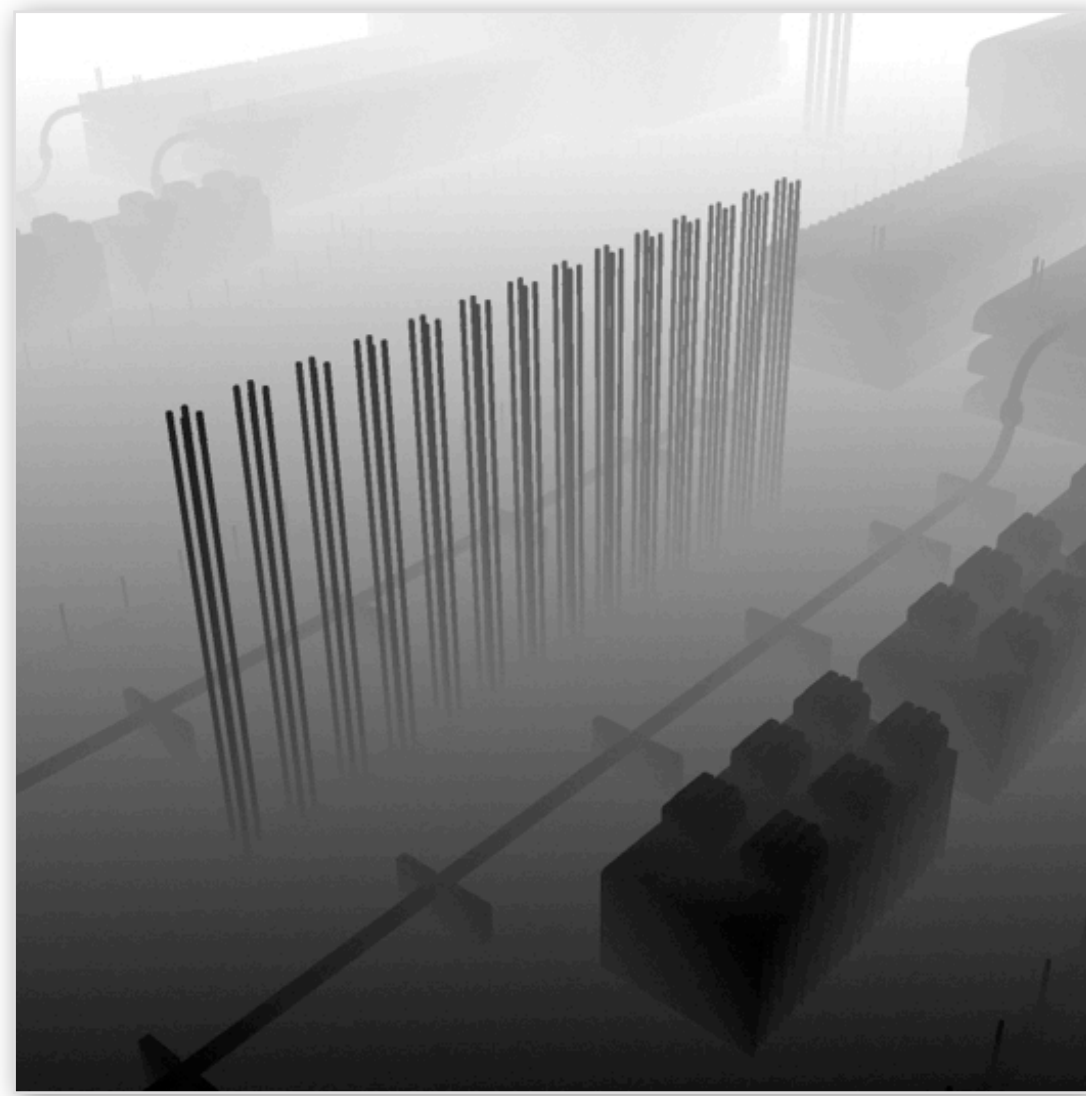
Vergence [arcmin]



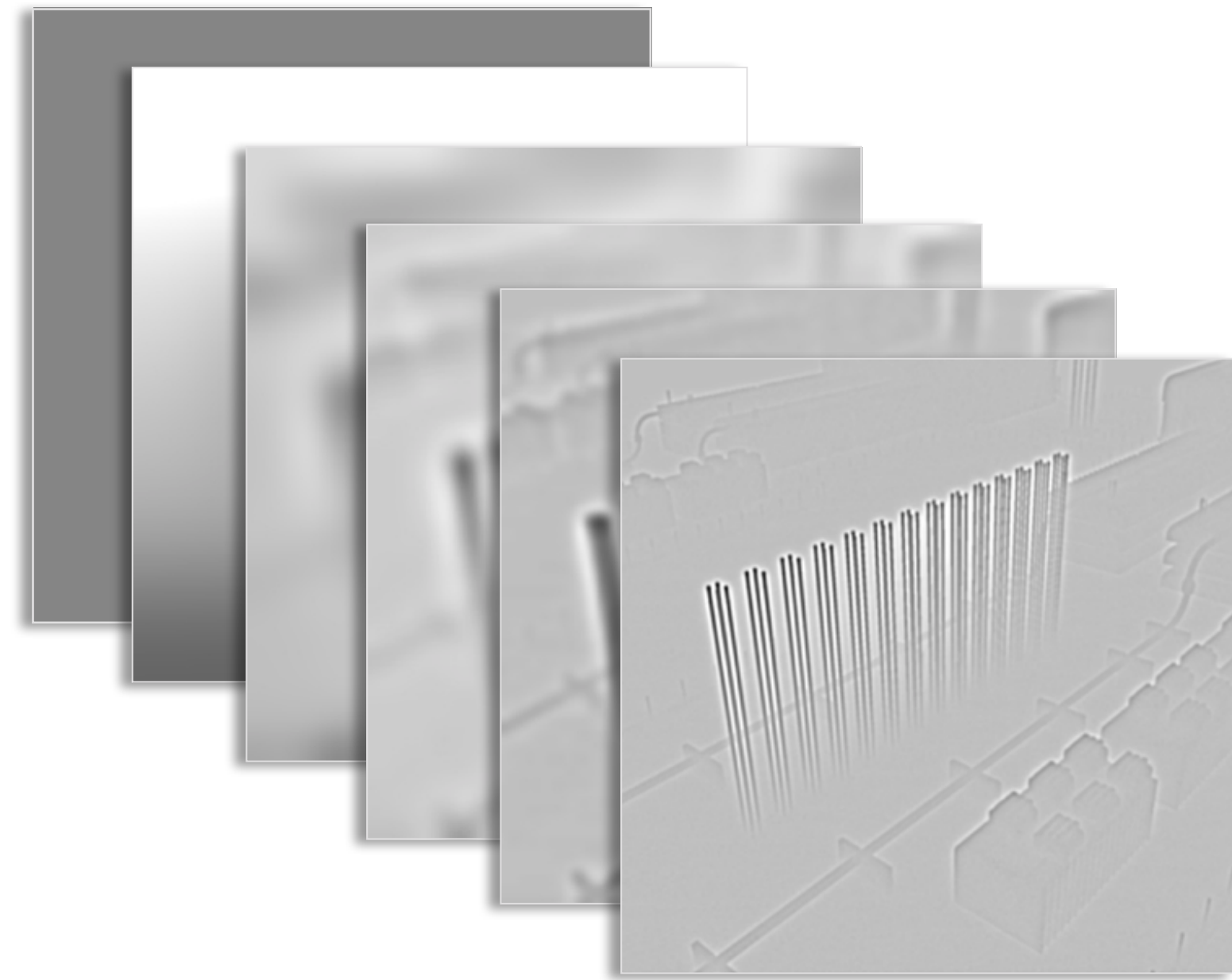
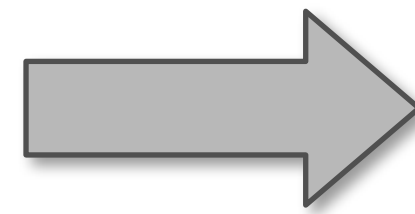
Frequency decomposition

- We can process frequencies independently

Vergence to disparity



Vergence [arcmin]

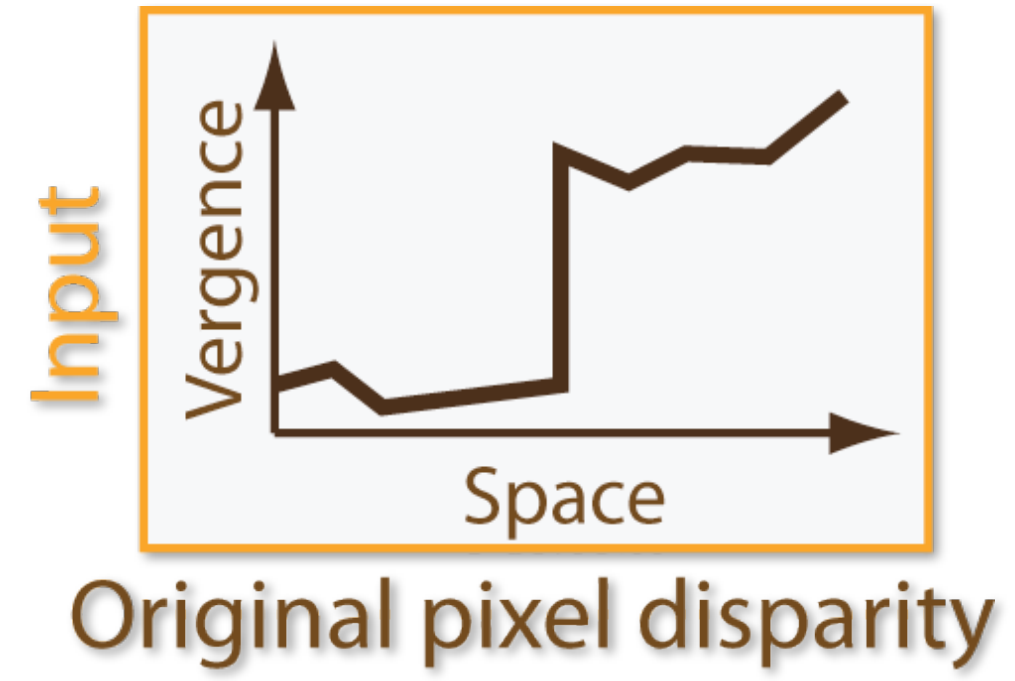


Frequency decomposition

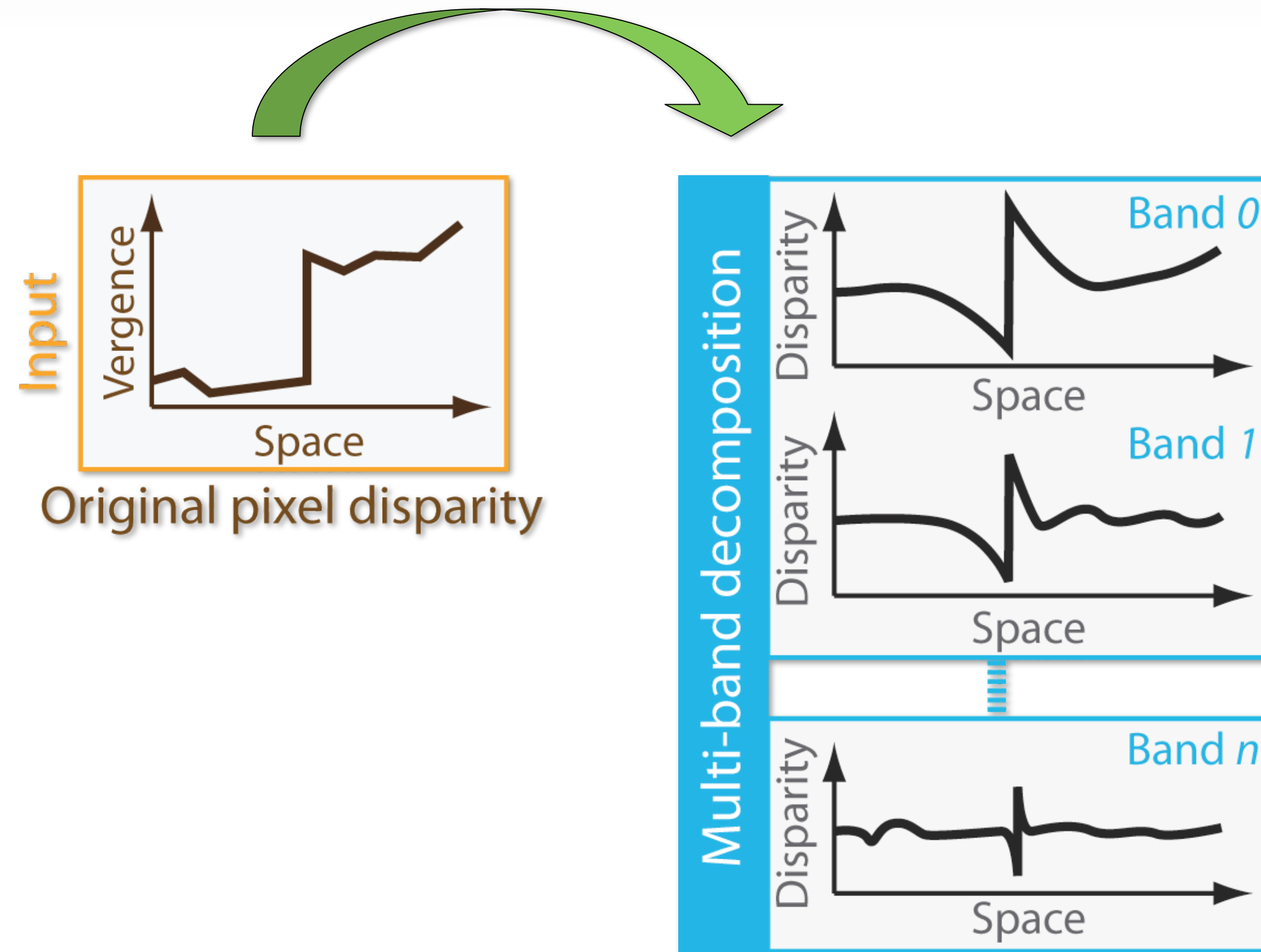
- We can process frequencies independently
- Vergence $\rightarrow$ disparity

Perceptual model

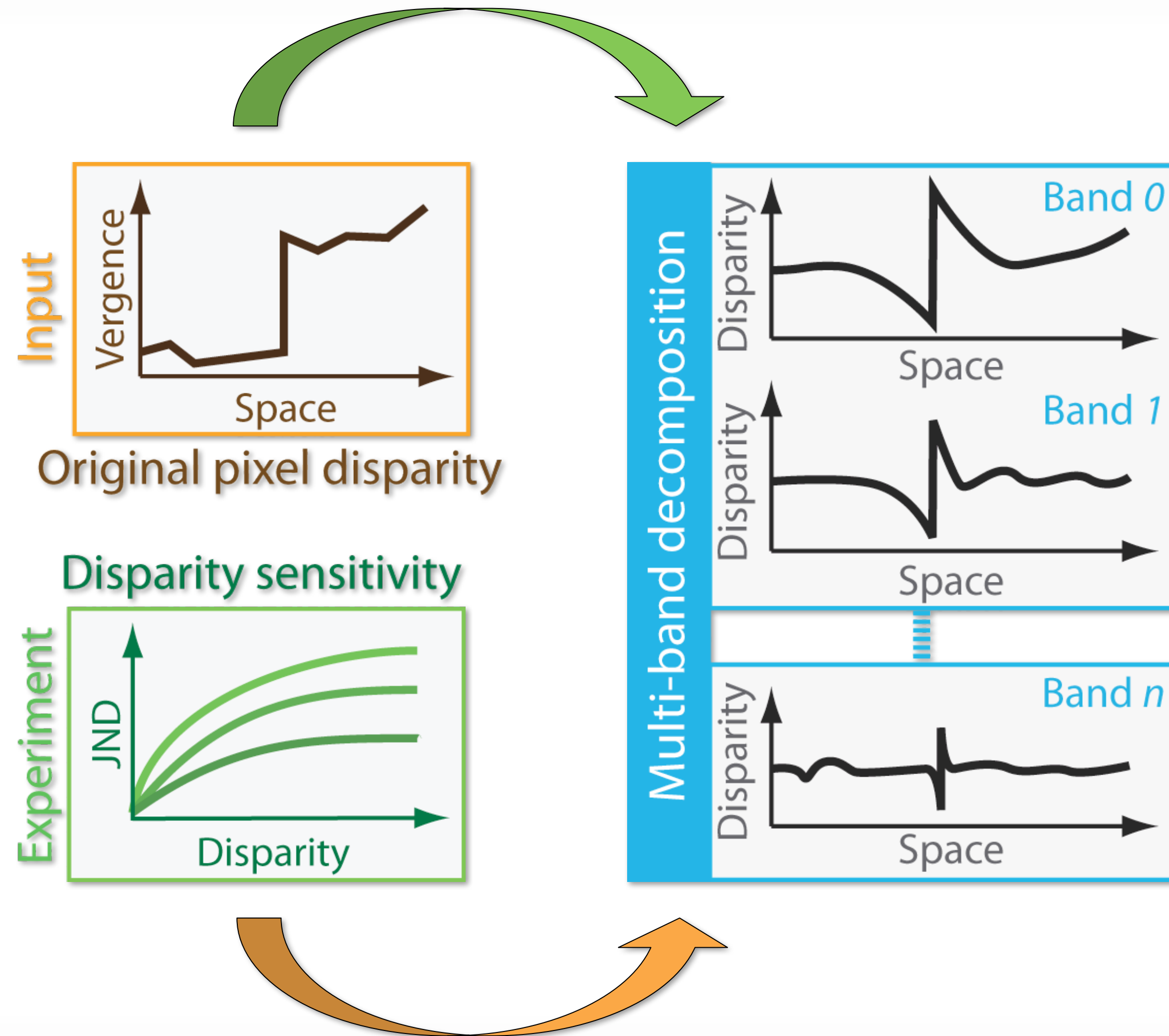
Perceptual model



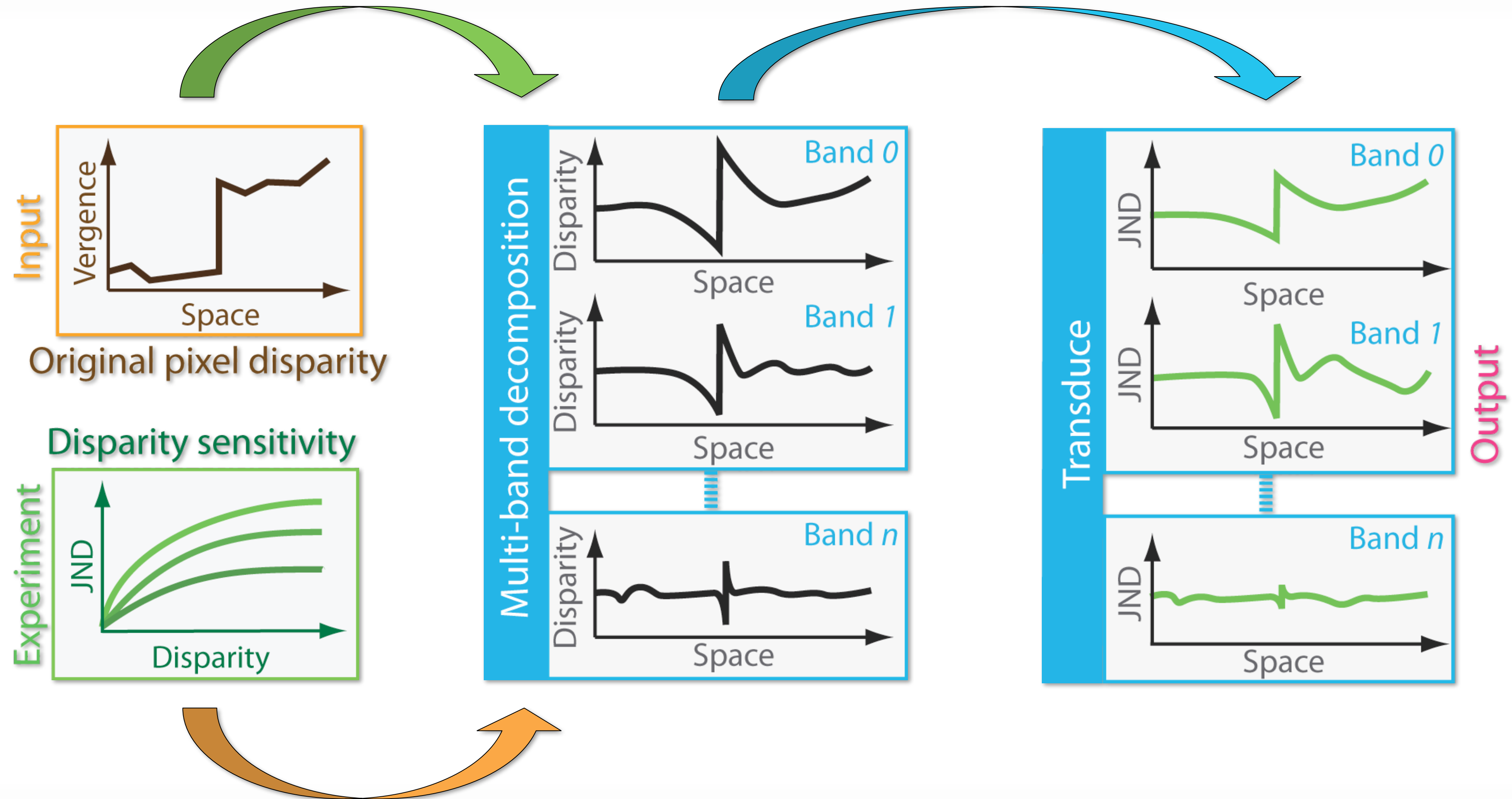
Perceptual model



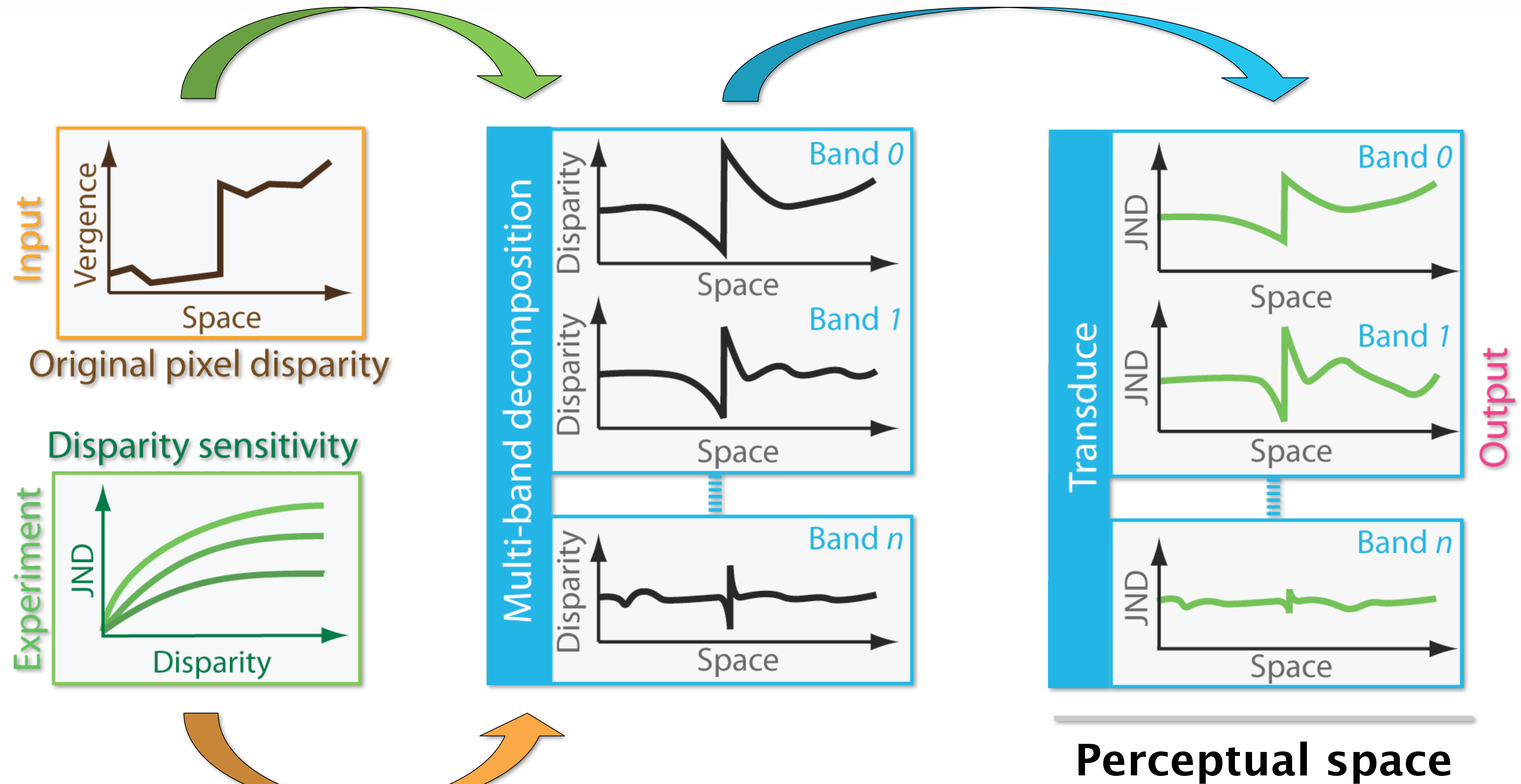
Perceptual model



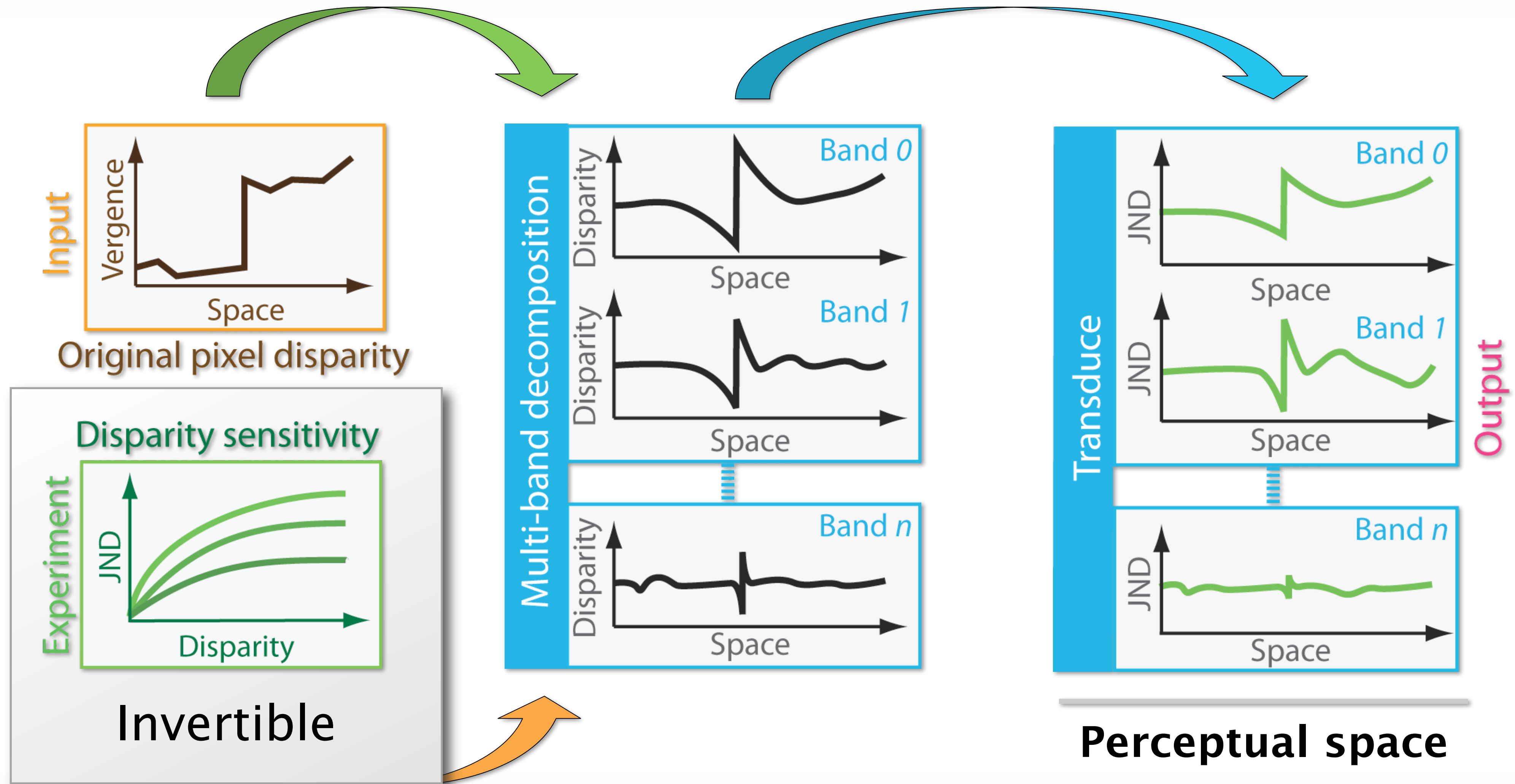
Perceptual model



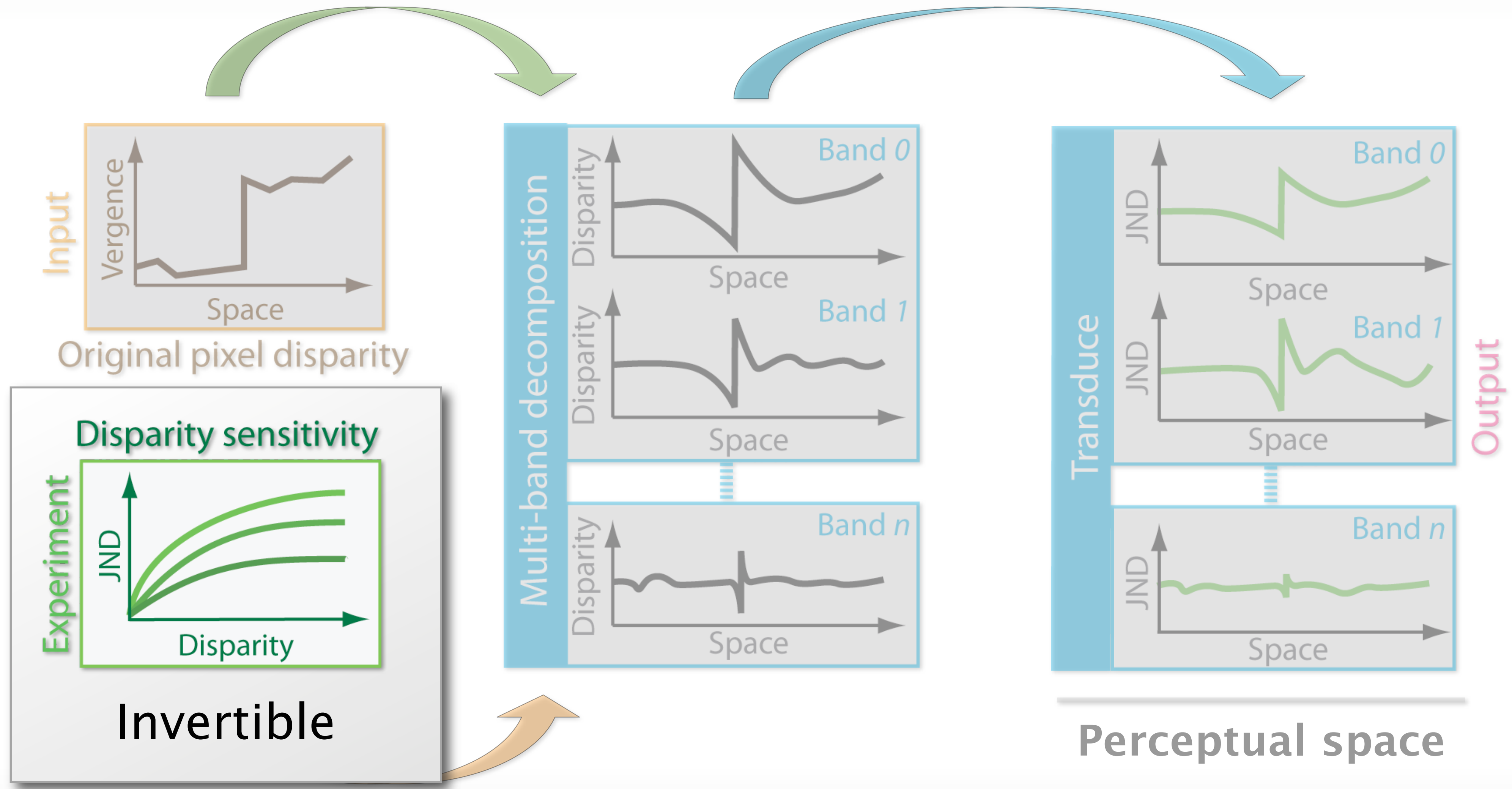
Perceptual model



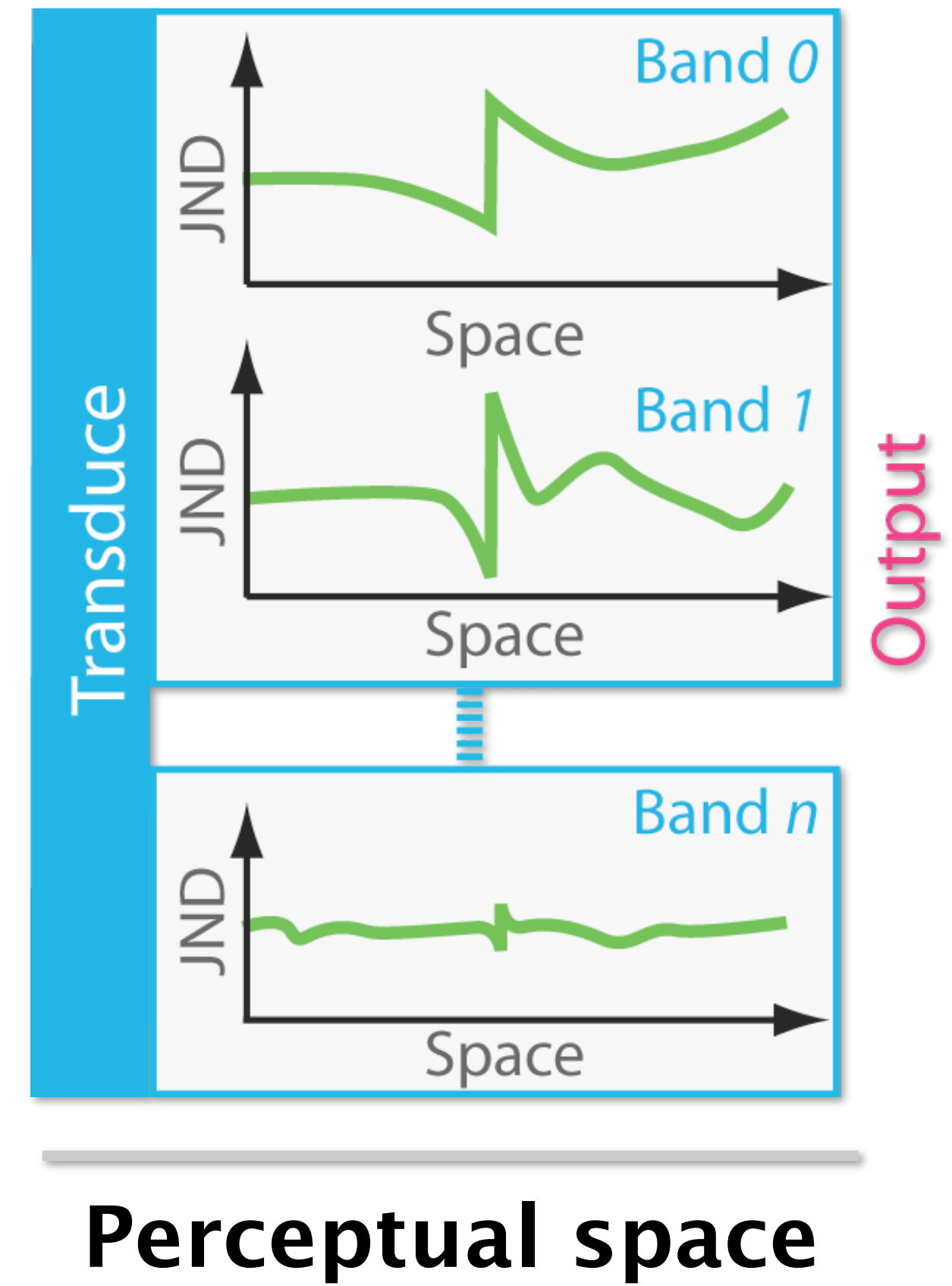
Perceptual model



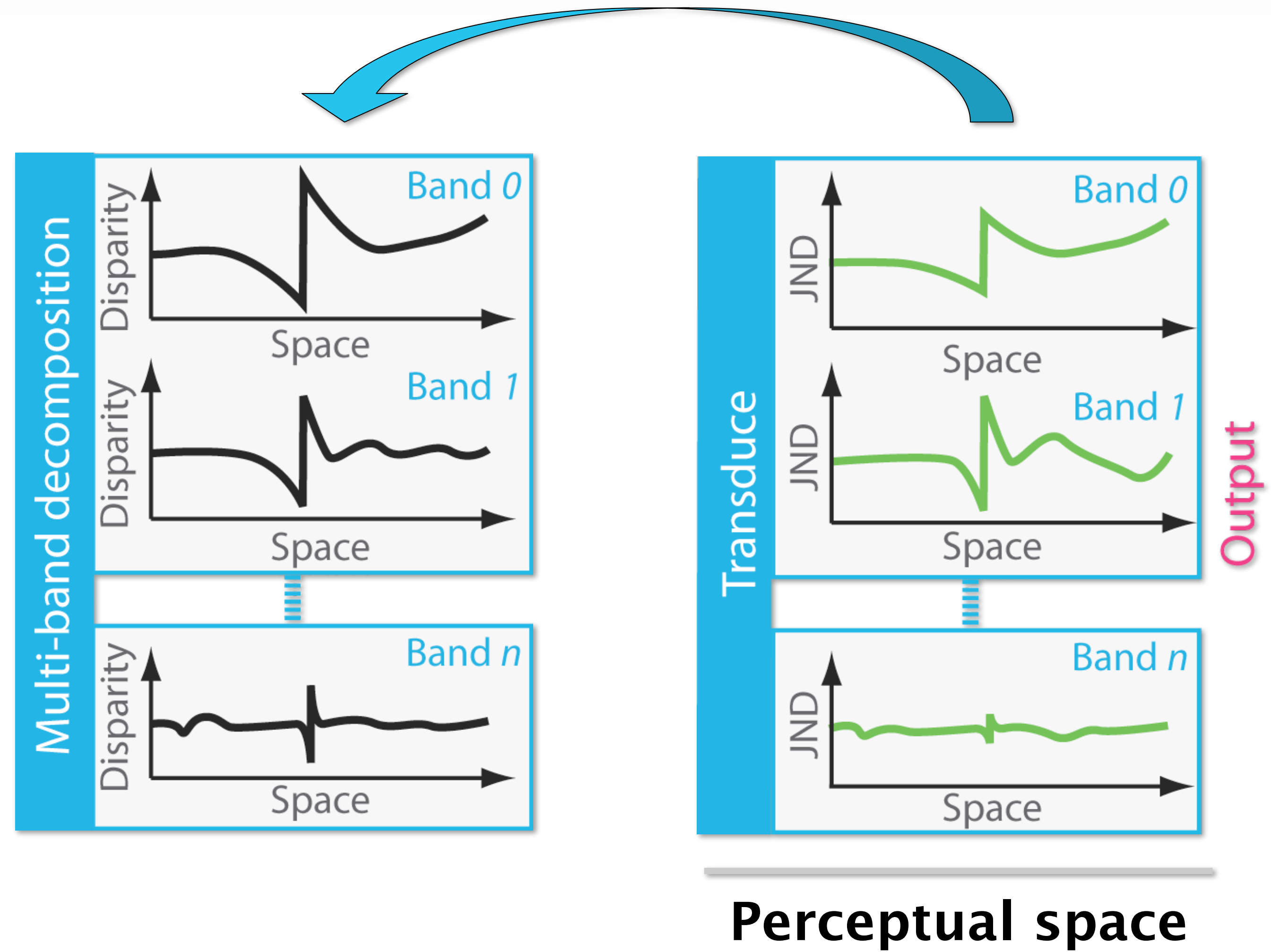
Perceptual model



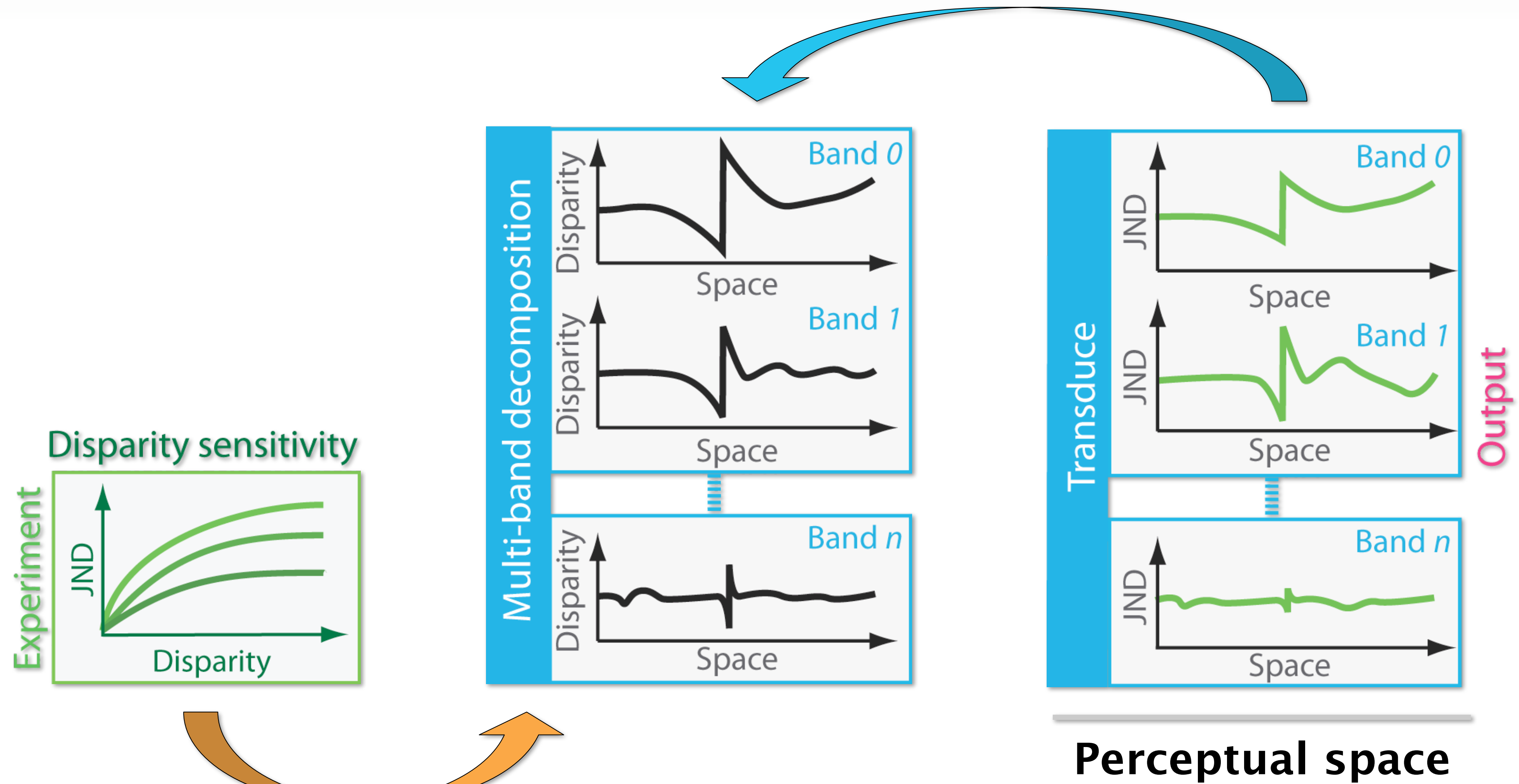
Inverse model



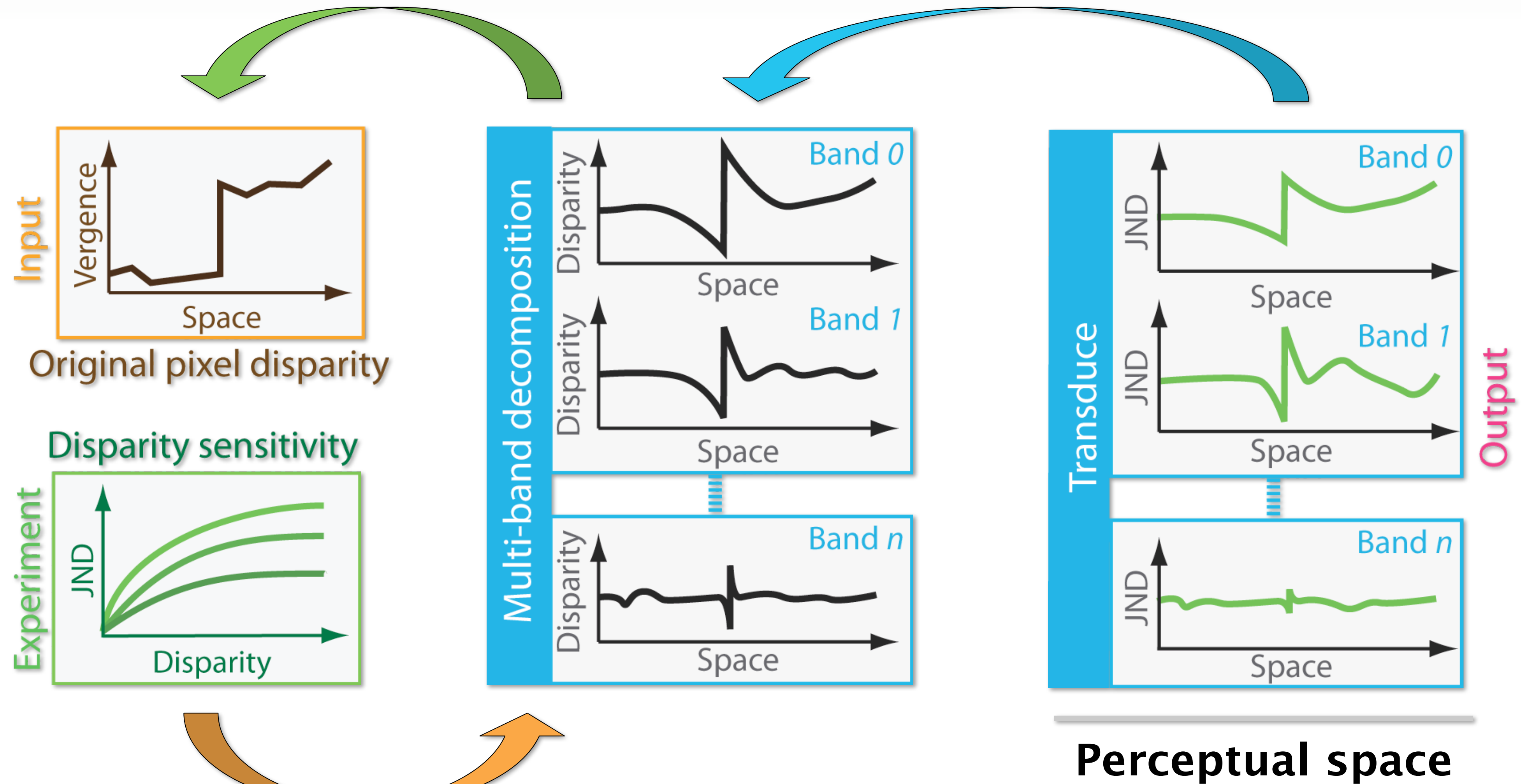
Inverse model



Inverse model



Inverse model



Our profiles computation

Our profiles computation

Original pixel disparity



Our profiles computation

Original pixel disparity

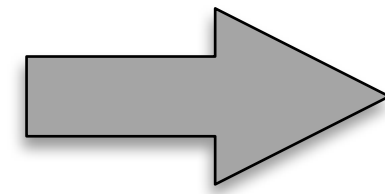


Modified pixel disparity

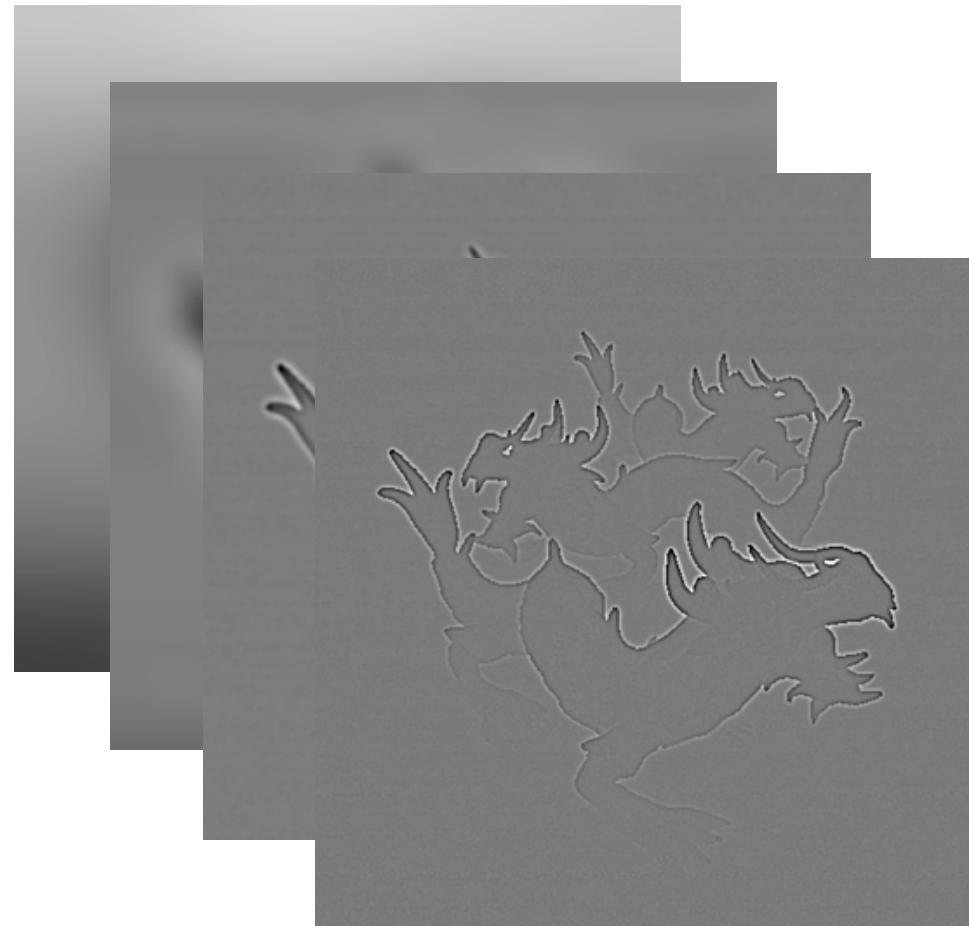


Our profiles computation

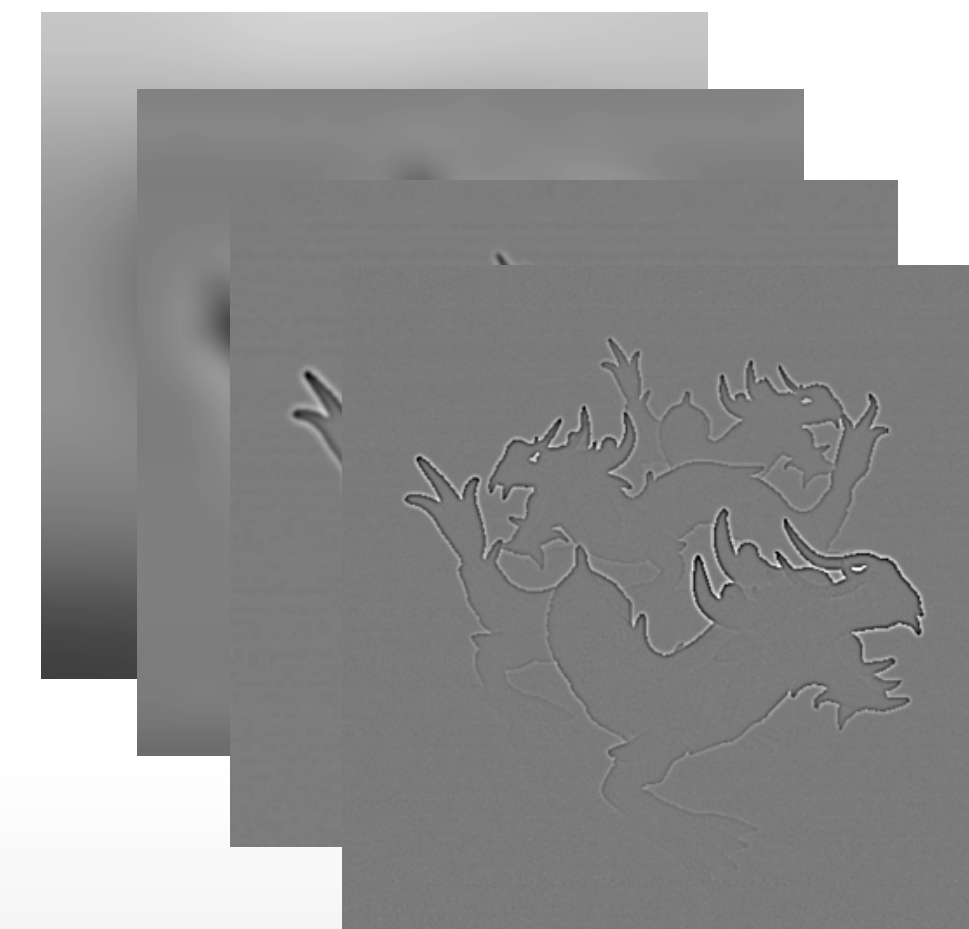
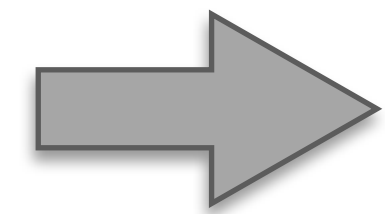
Original pixel disparity



Perceptual space
(Laplacian pyramid)

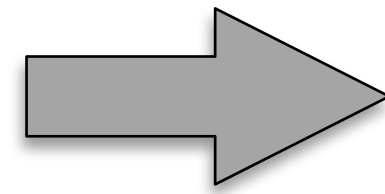


Modified pixel disparity

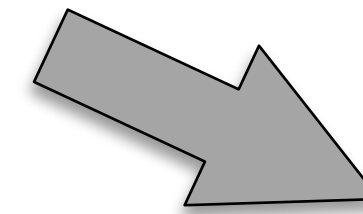
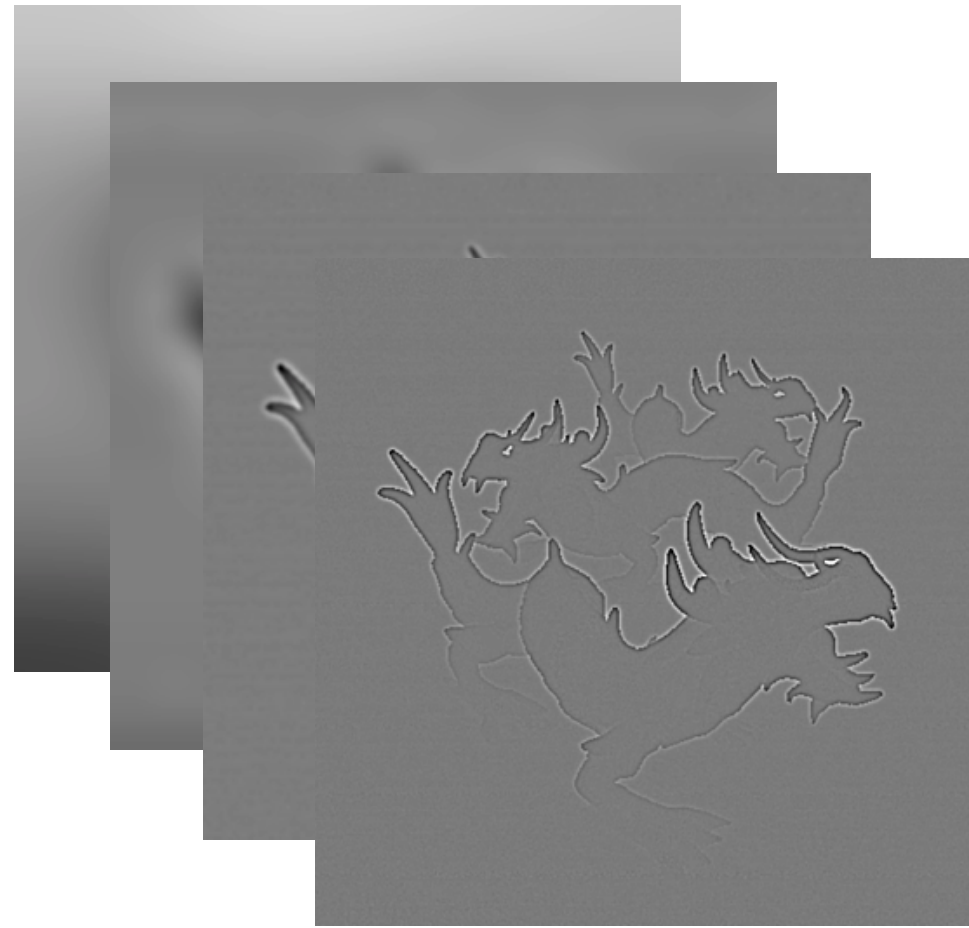


Our profiles computation

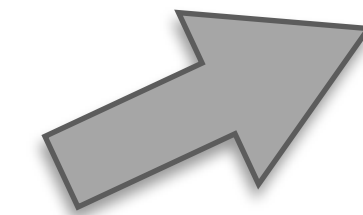
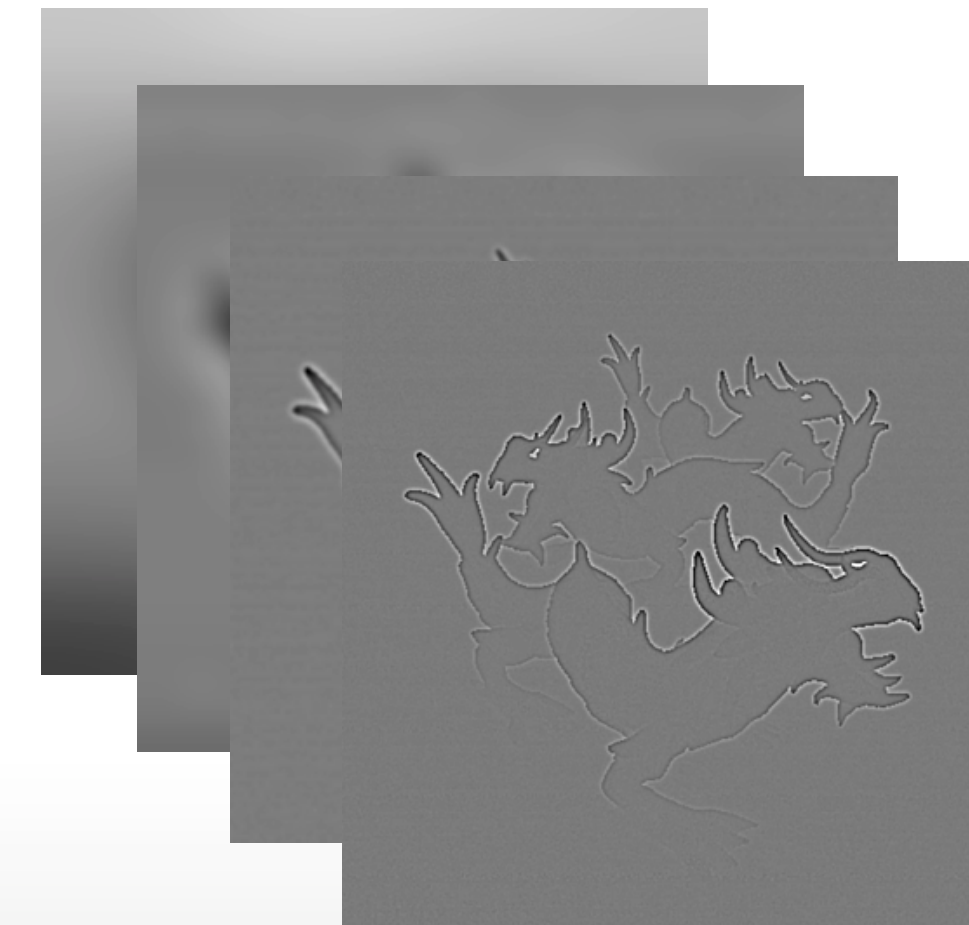
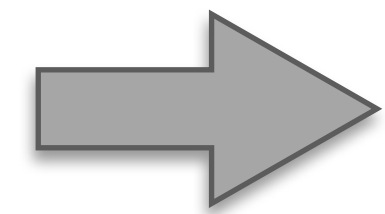
Original pixel disparity



Perceptual space
(Laplacian pyramid)

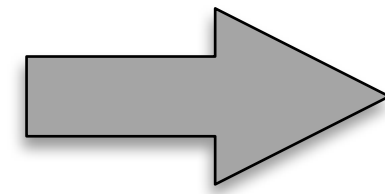


Modified pixel disparity

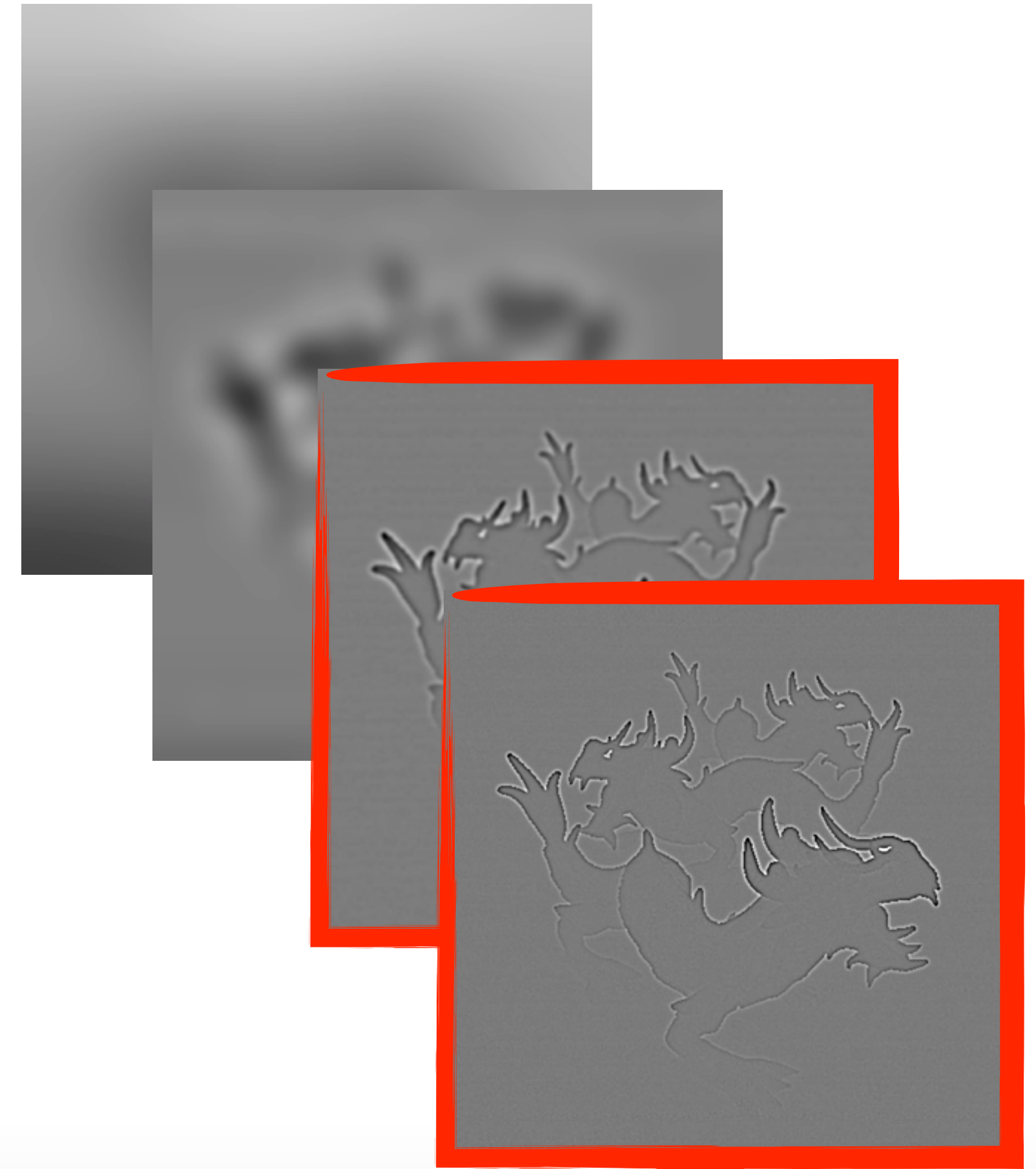
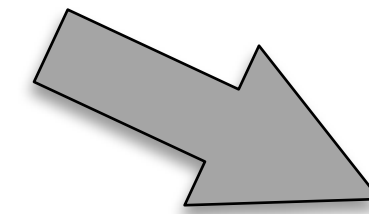
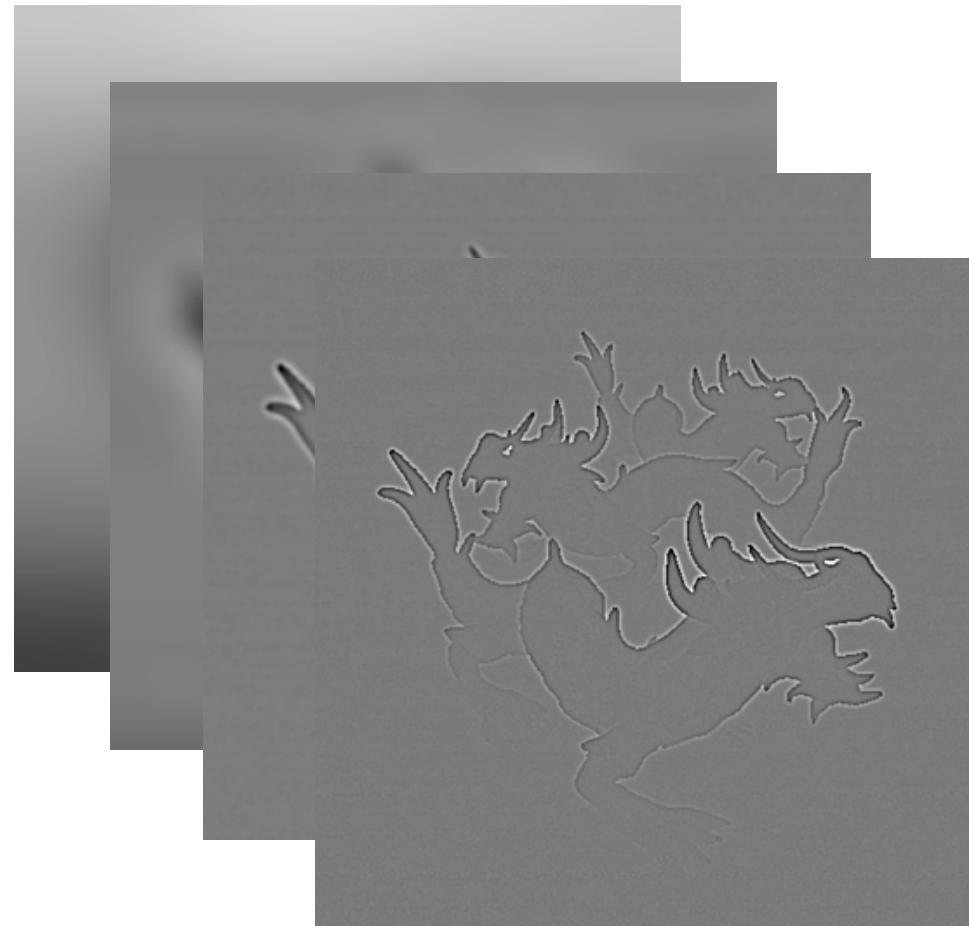


Our profiles computation

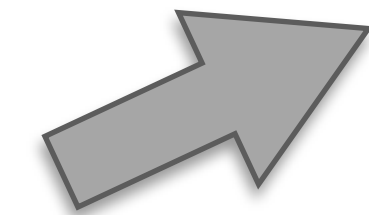
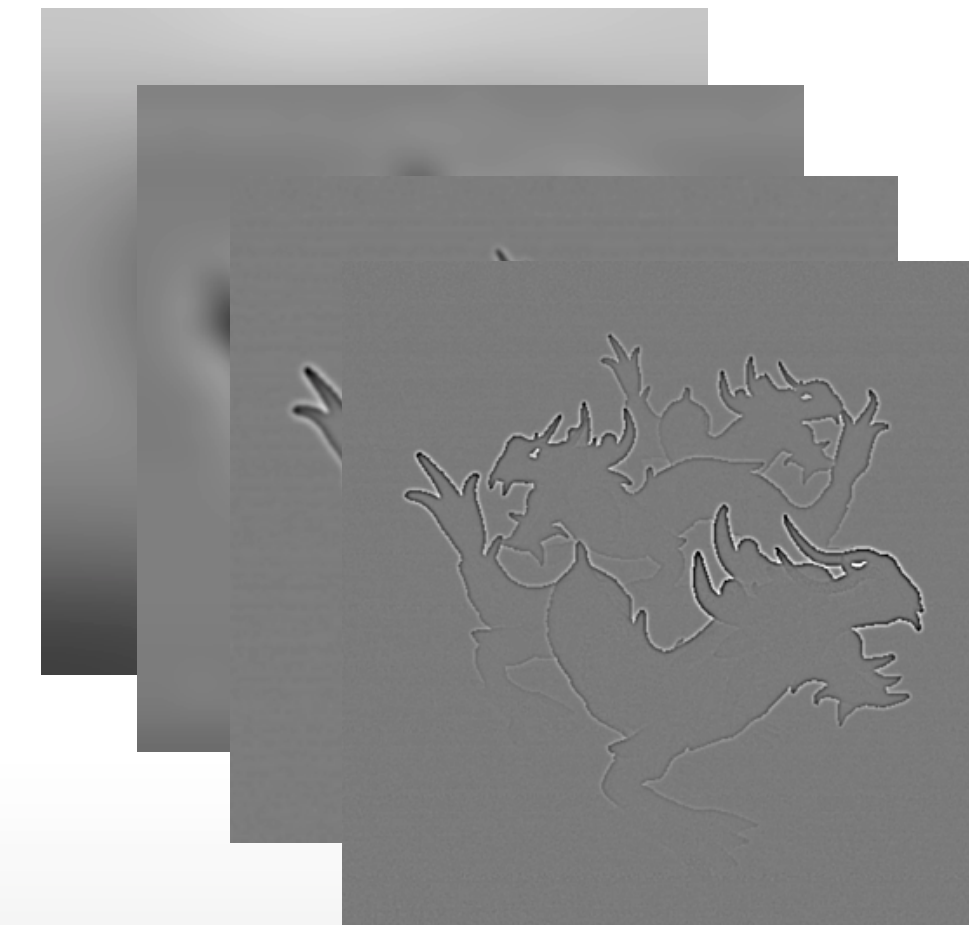
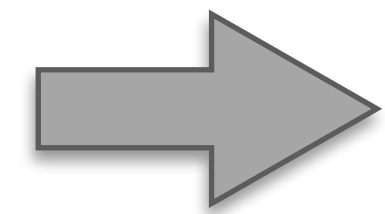
Original pixel disparity



Perceptual space
(Laplacian pyramid)

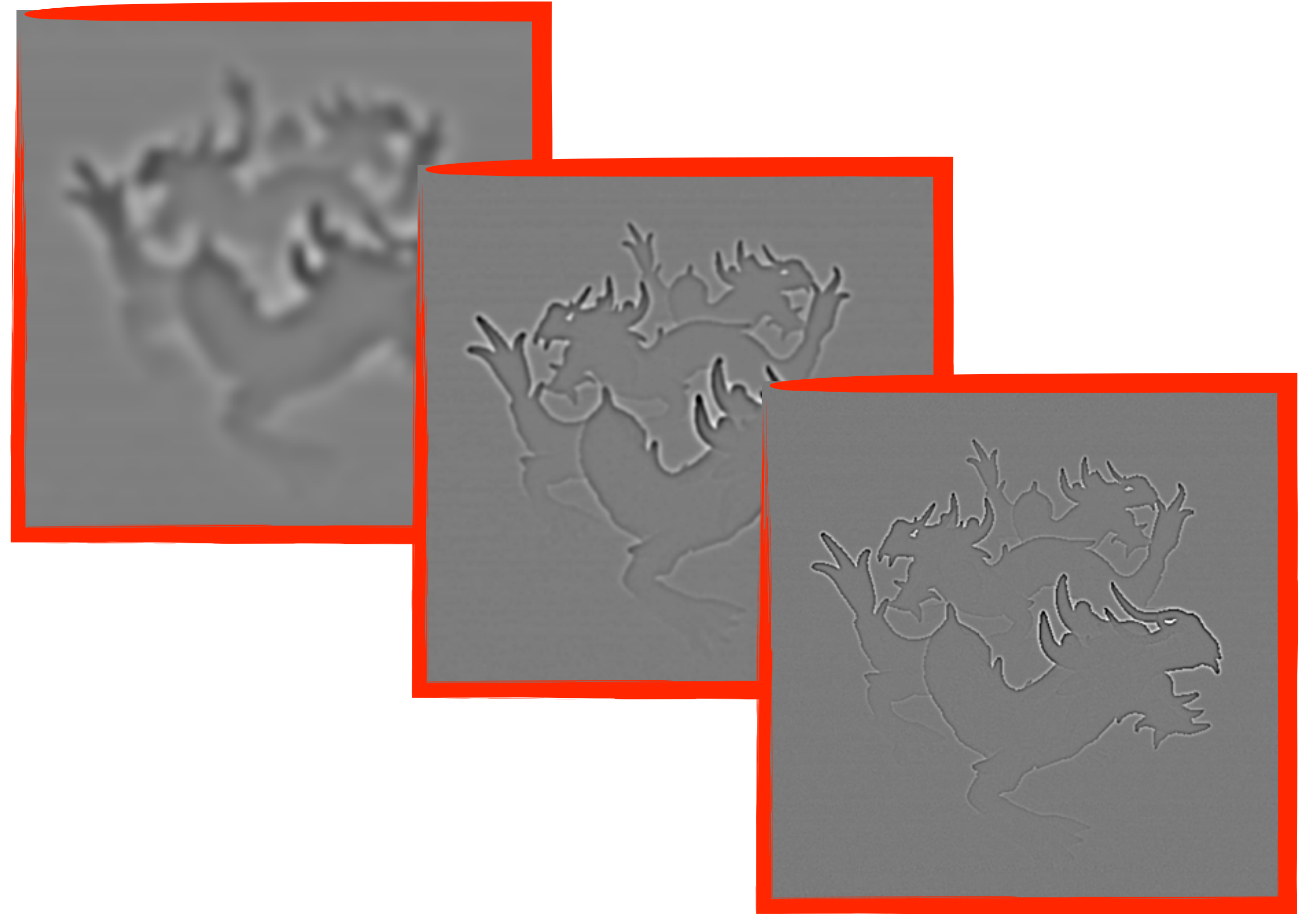


Modified pixel disparity



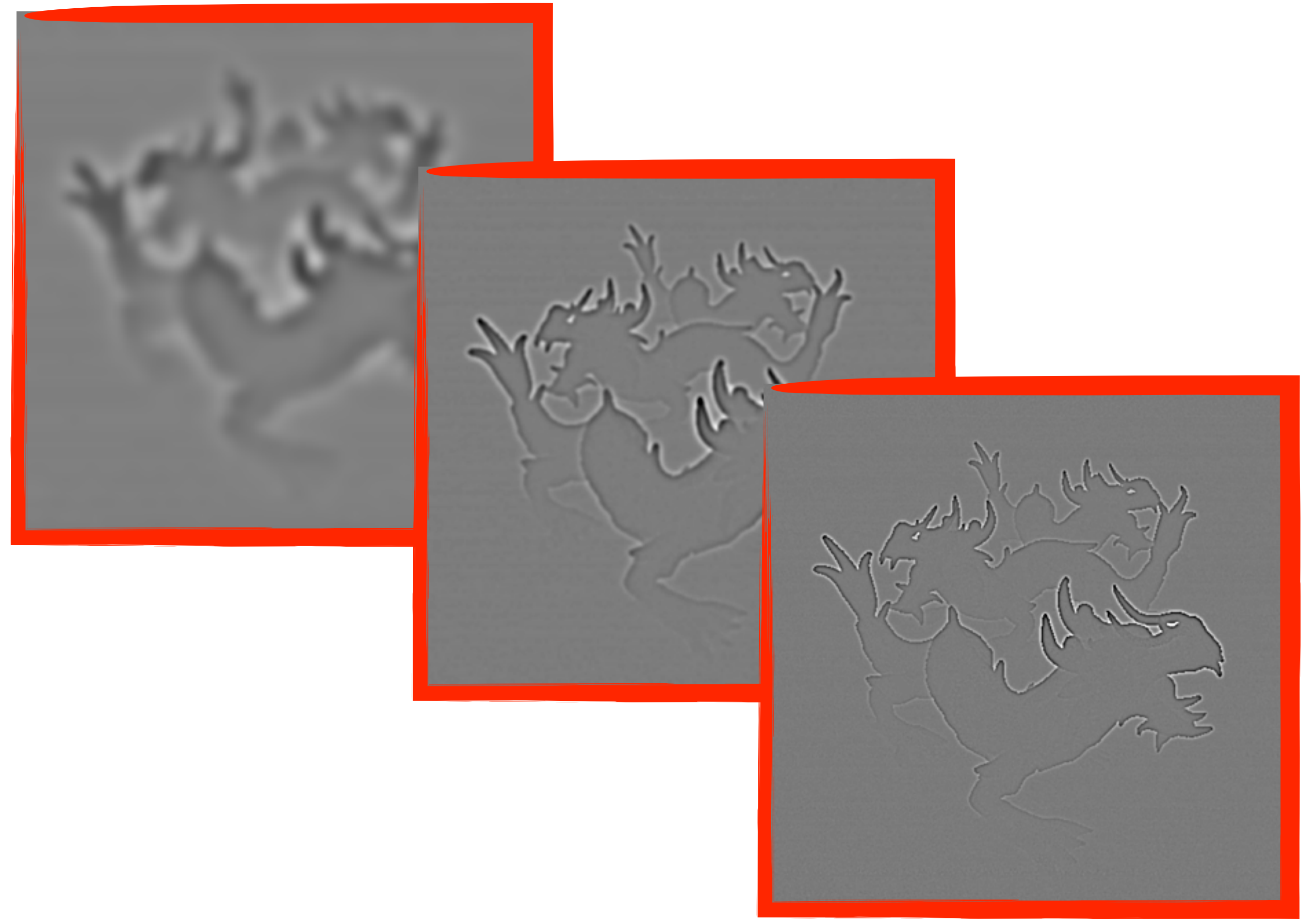
Enhancement layer
in JND units

Cornsweet profiles limiting



Cornsweet profiles limiting

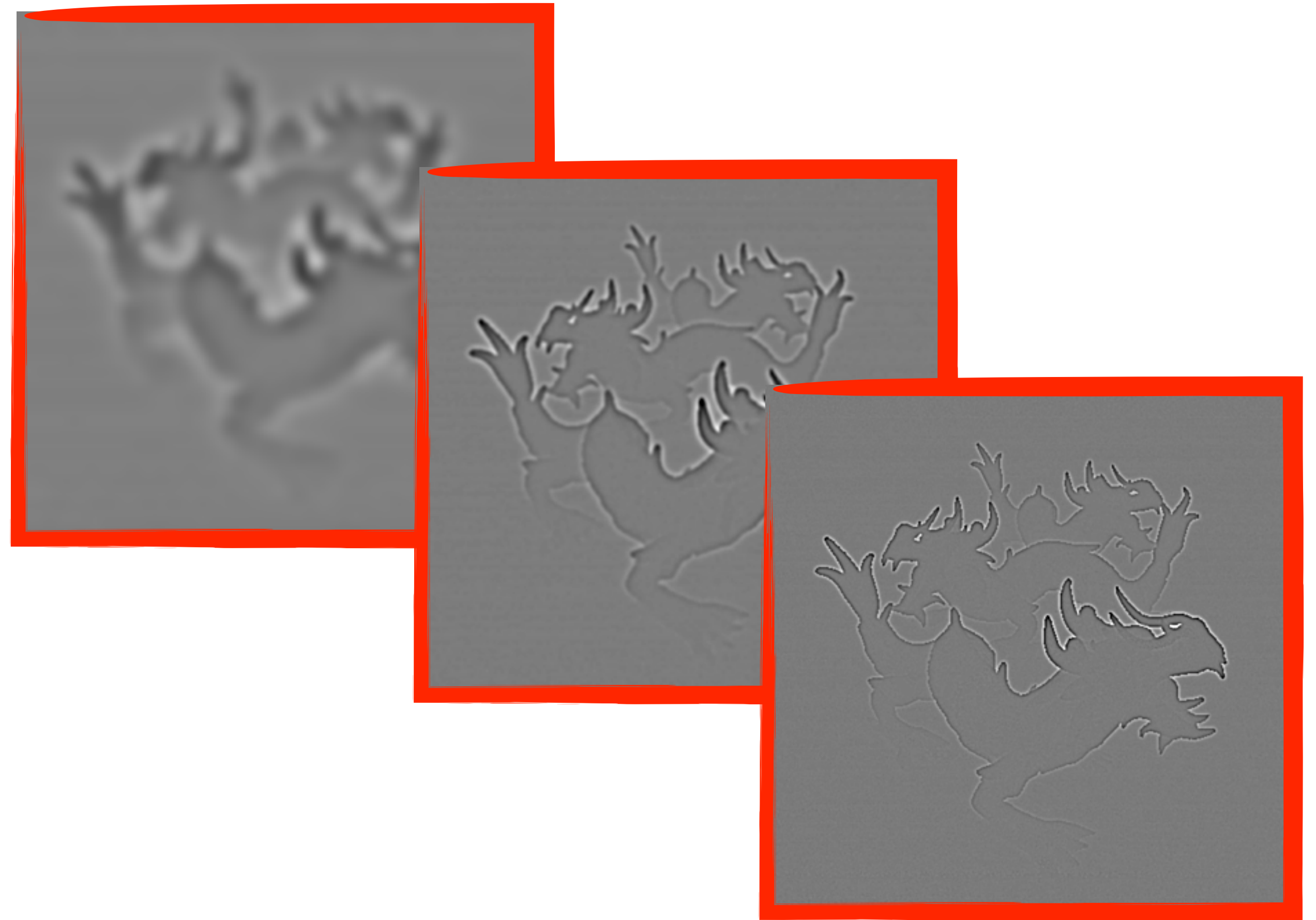
- Limiting profiles in JND space



Enhancement layer in JND units
(Laplacian pyramid)

Cornsweet profiles limiting

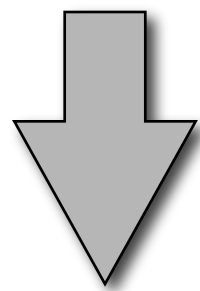
- Limiting profiles in JND space
- Simple clipping works well



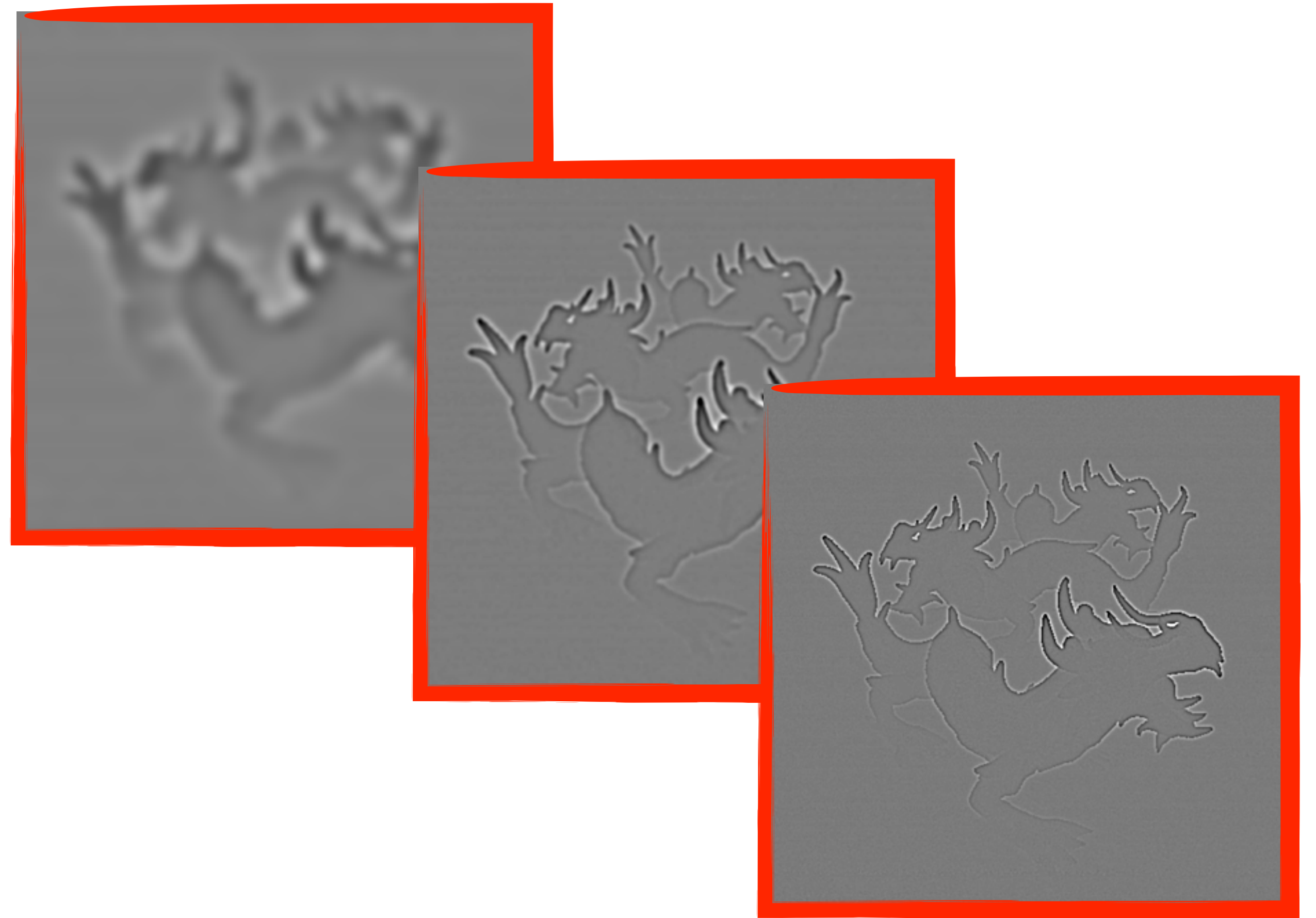
Enhancement layer in JND units
(Laplacian pyramid)

Cornsweet profiles limiting

- Limiting profiles in JND space
- Simple clipping works well



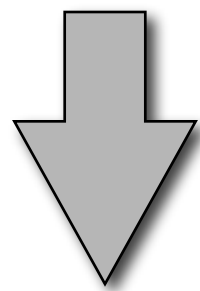
- Similar impact regardless location



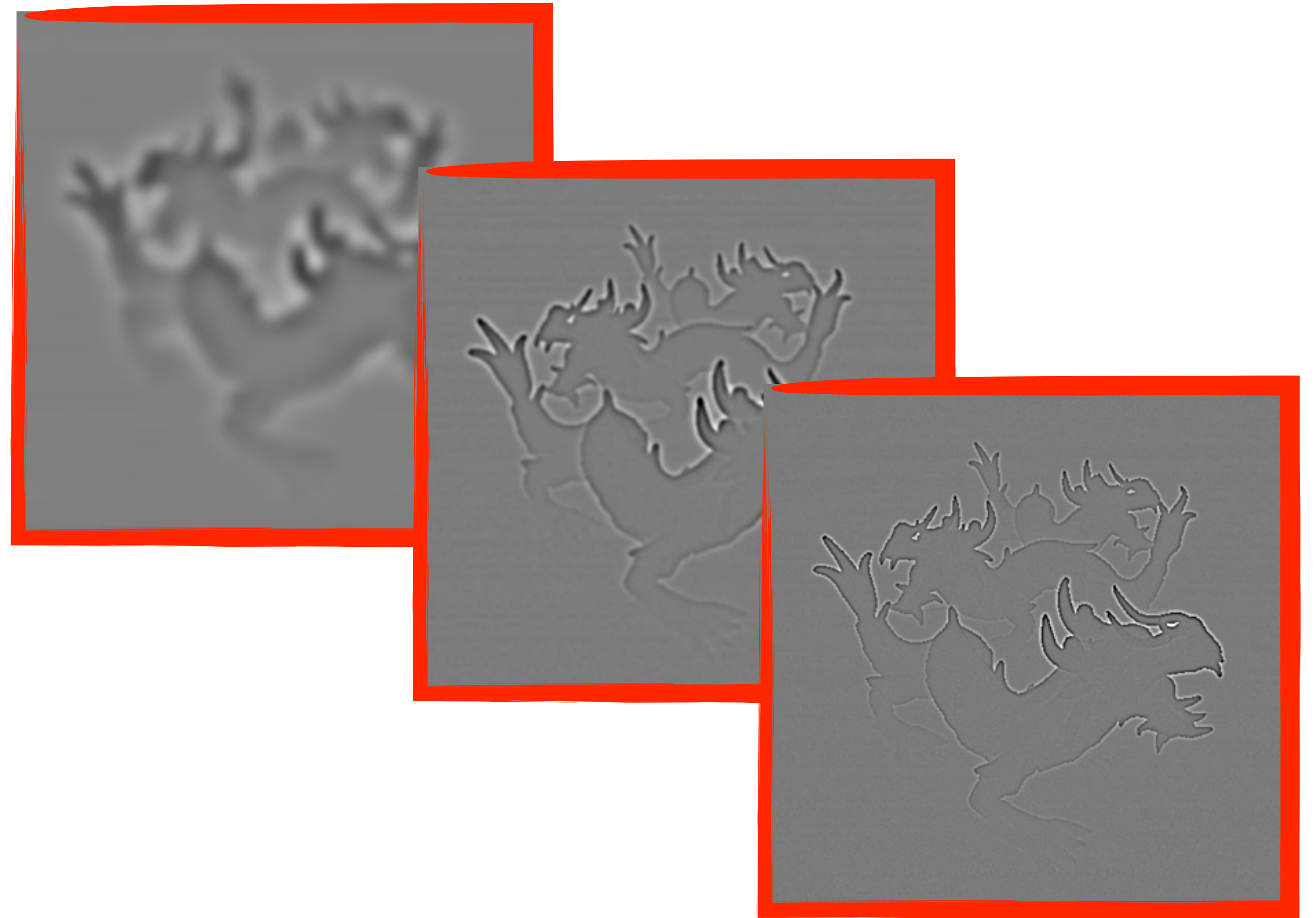
Enhancement layer in JND units
(Laplacian pyramid)

Cornsweet profiles limiting

- Limiting profiles in JND space
- Simple clipping works well



- Similar impact regardless location
- Geometry distortion under control



Enhancement layer in JND units
(Laplacian pyramid)

Cornsweet profiles computation



Modified pixel disparity

Cornsweet profiles computation



Modified pixel disparity

+



Enhancement layer

Cornsweet profiles computation



Modified pixel disparity

+



Enhancement layer

It can still exceed
comfort limits

Cornsweet profiles computation



Modified pixel disparity

+



Scaling map

x



Enhancement layer

Within
comfort limits

Cornsweet profiles computation



Modified pixel disparity

+



Scaling map

x

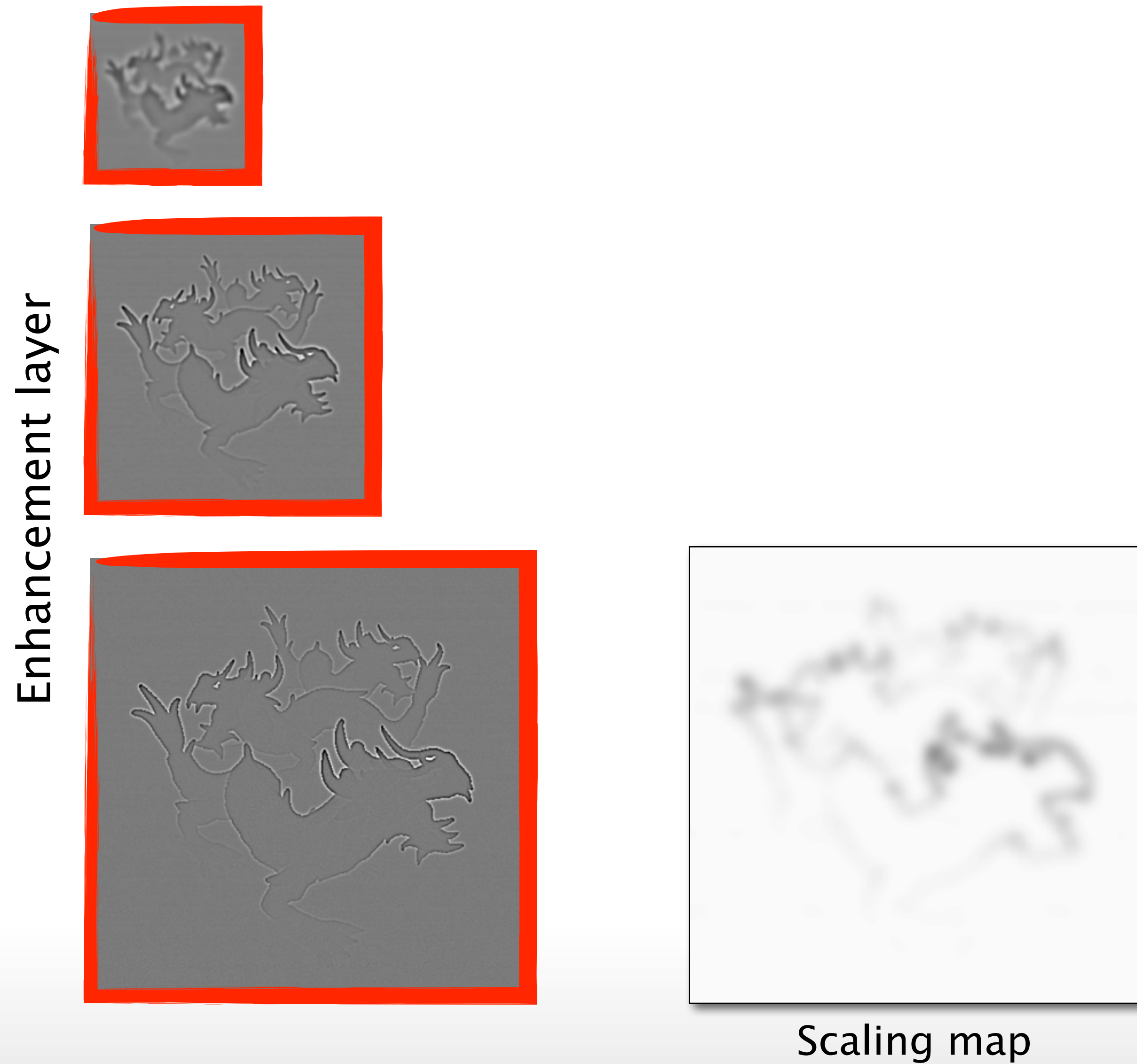


Enhancement layer

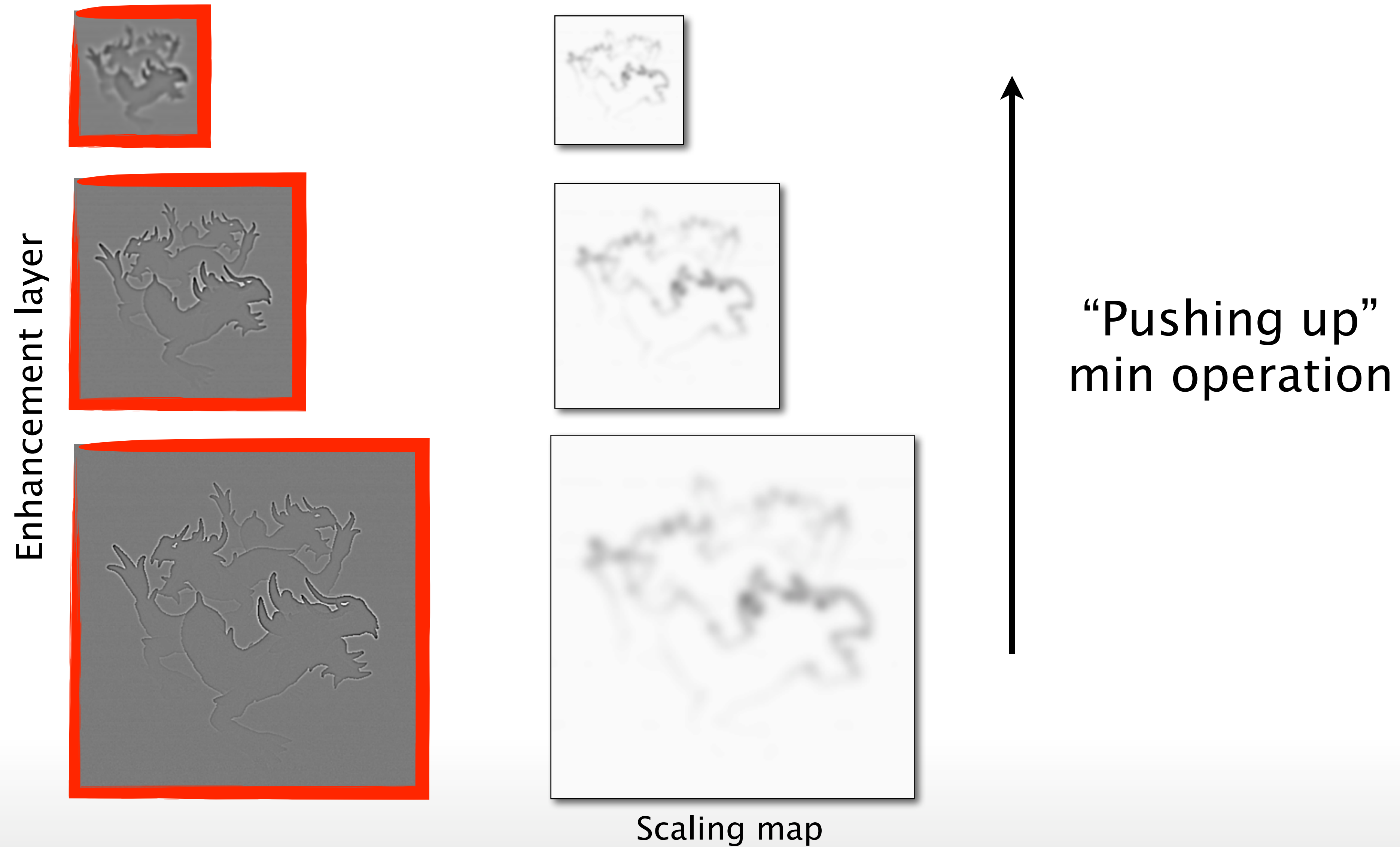
Within
comfort limits

Resulting profiles may loose the shape

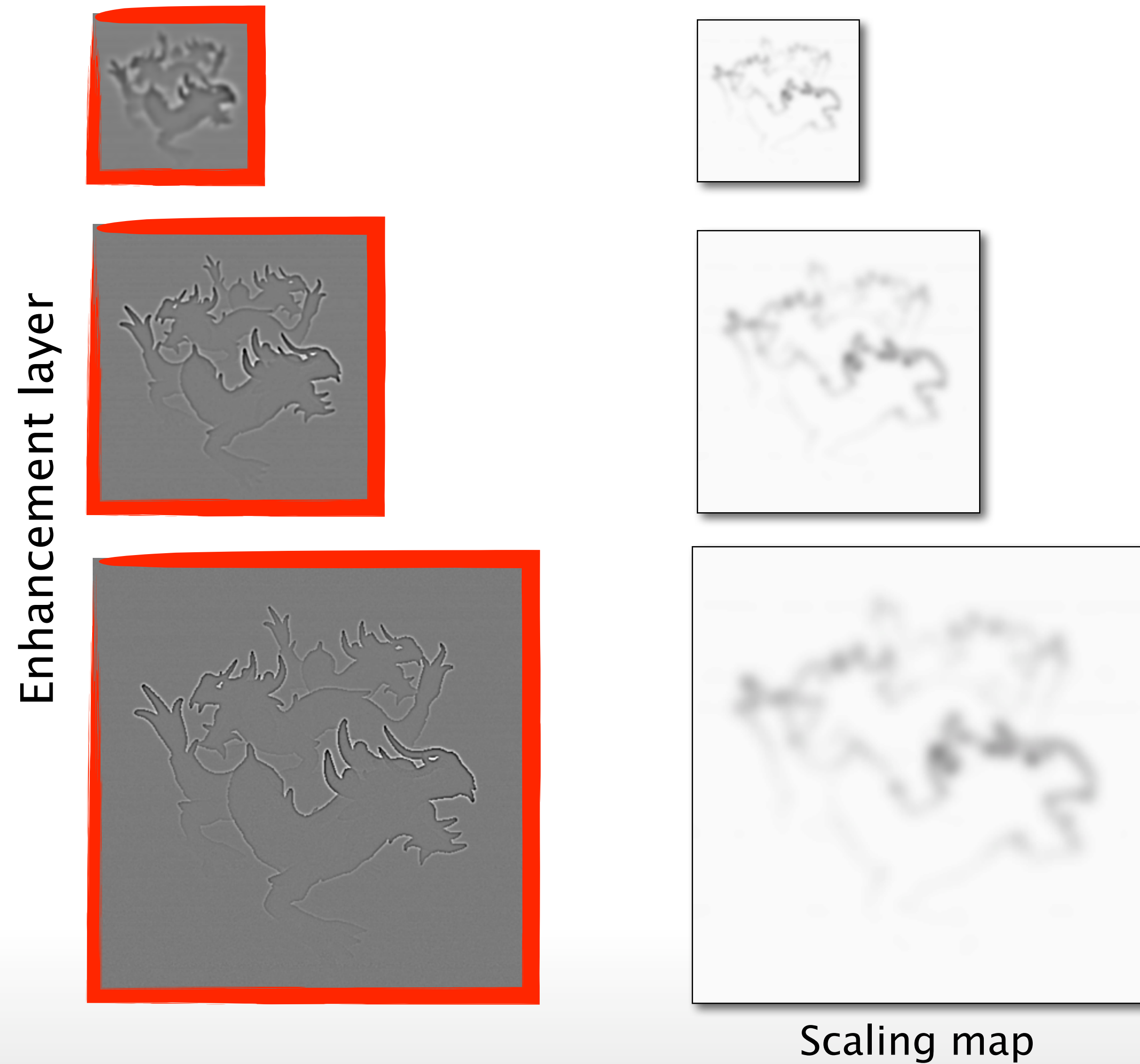
Cornsweet profiles computation



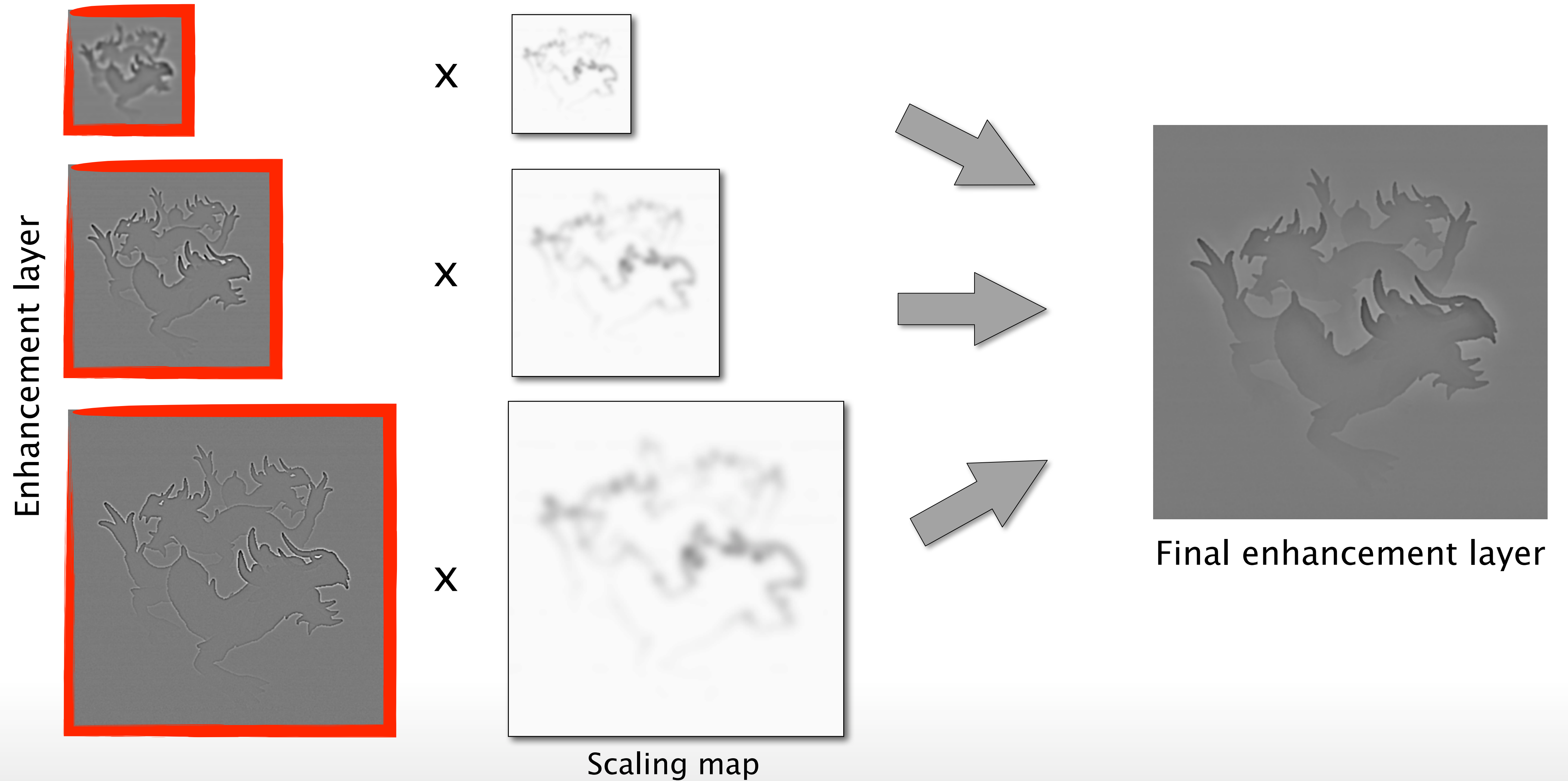
Cornsweet profiles computation



Cornsweet profiles computation



Cornsweet profiles computation



Different strategies



Simple Cornsweet profile



Logarithmically scaled



Our limiting

Enhancement example

Original



Enhancement example

Original



+2 JND



Enhancement example

Original



+2 JND



+4 JND



Enhancement example

Original



+2 JND



+4 JND

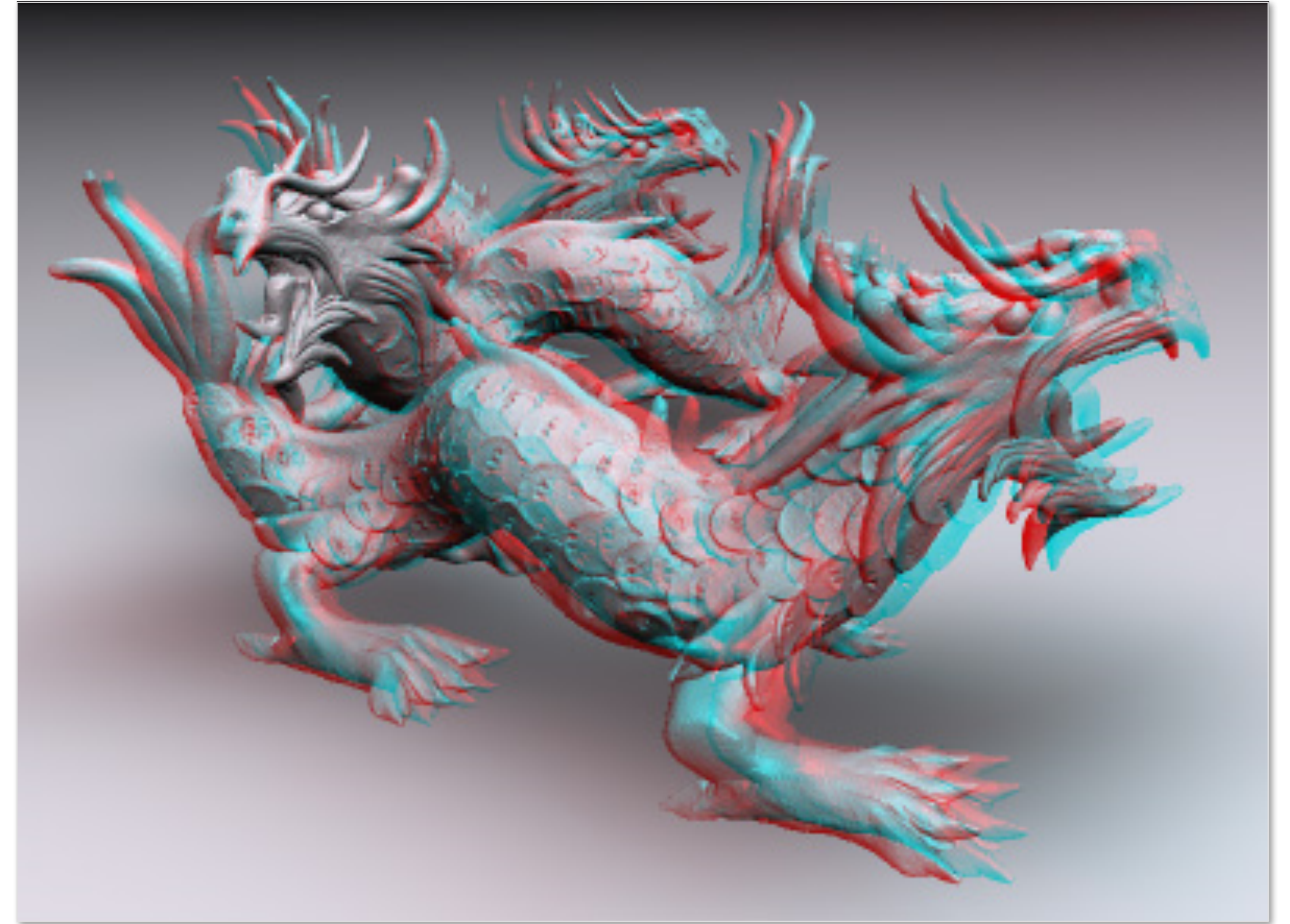


+8 JND



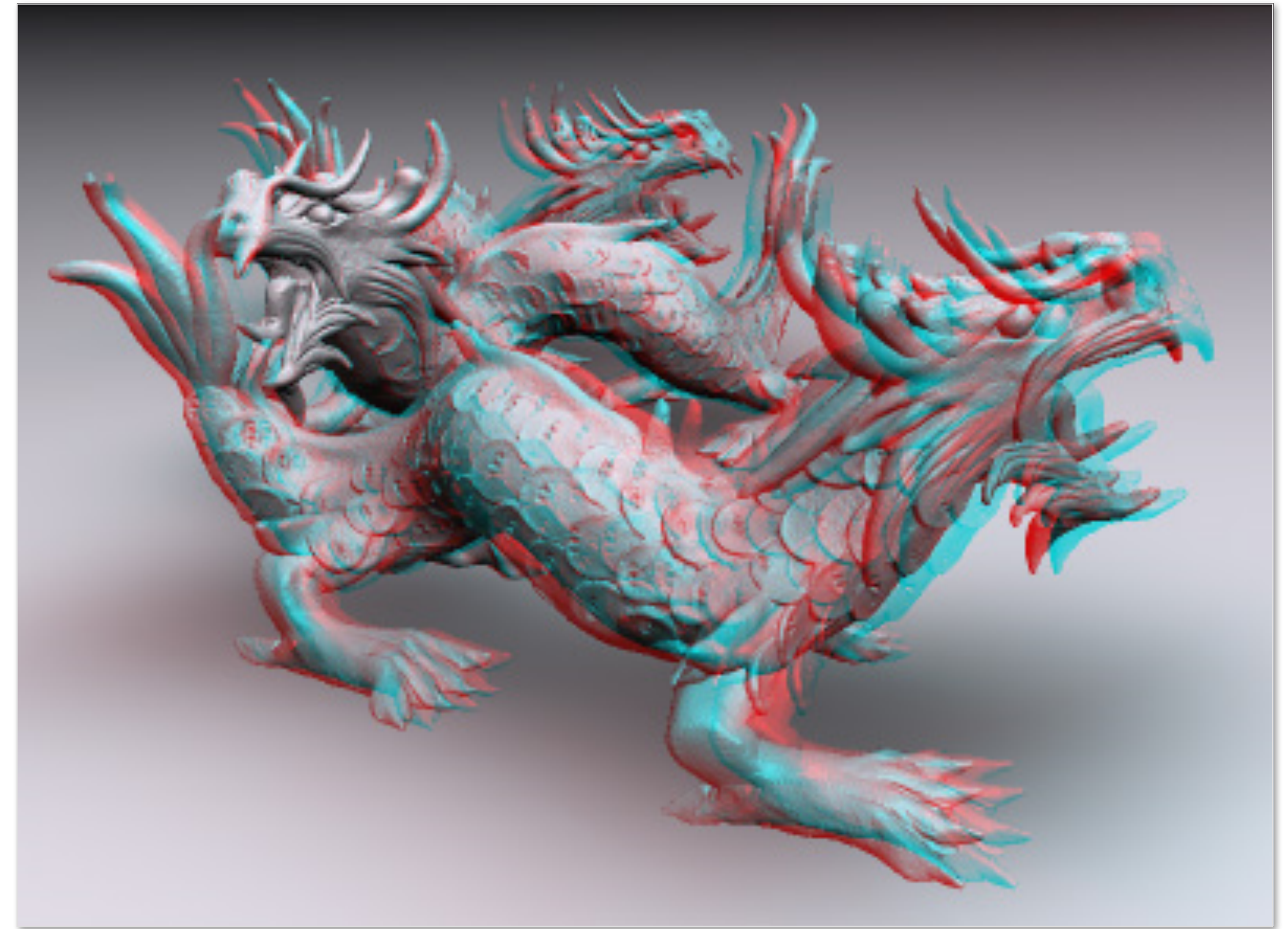
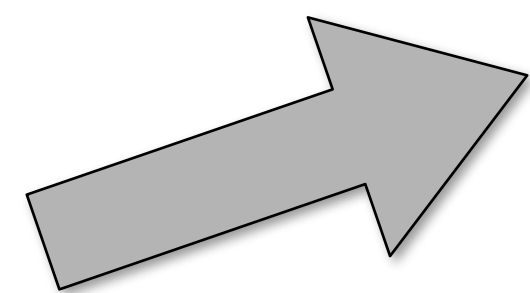
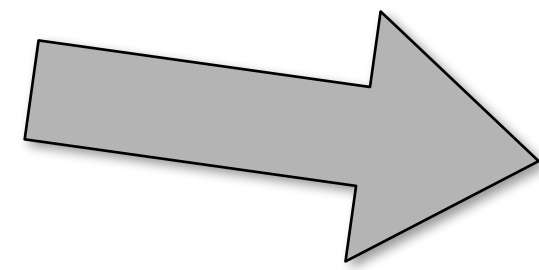
Backward-compatible stereo

Backward-compatible stereo



Standard stereo

Backward-compatible stereo



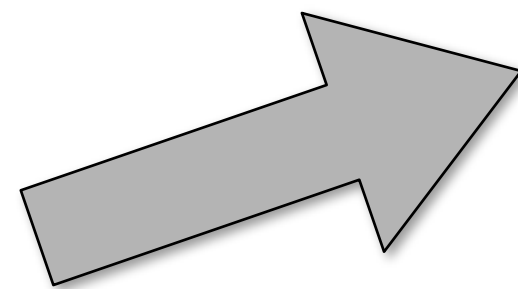
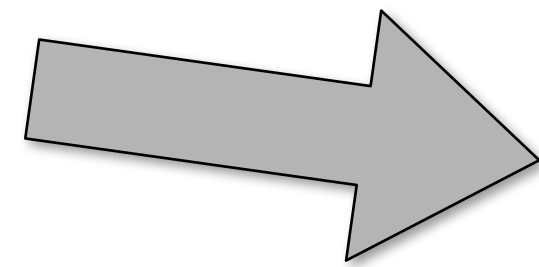
Standard stereo

Backward-compatible stereo



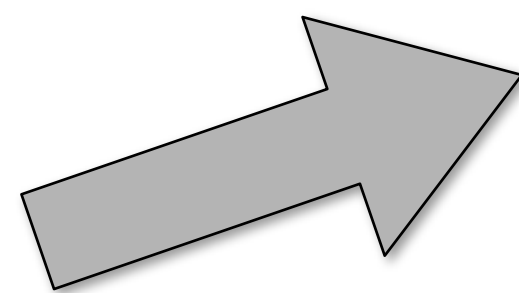
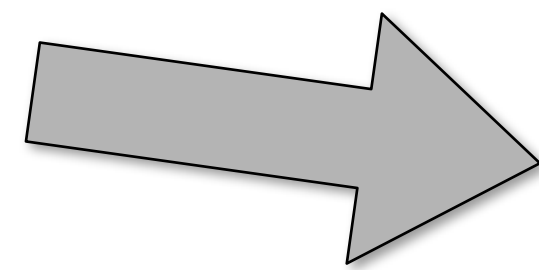
Standard 2D image

Backward-compatible stereo



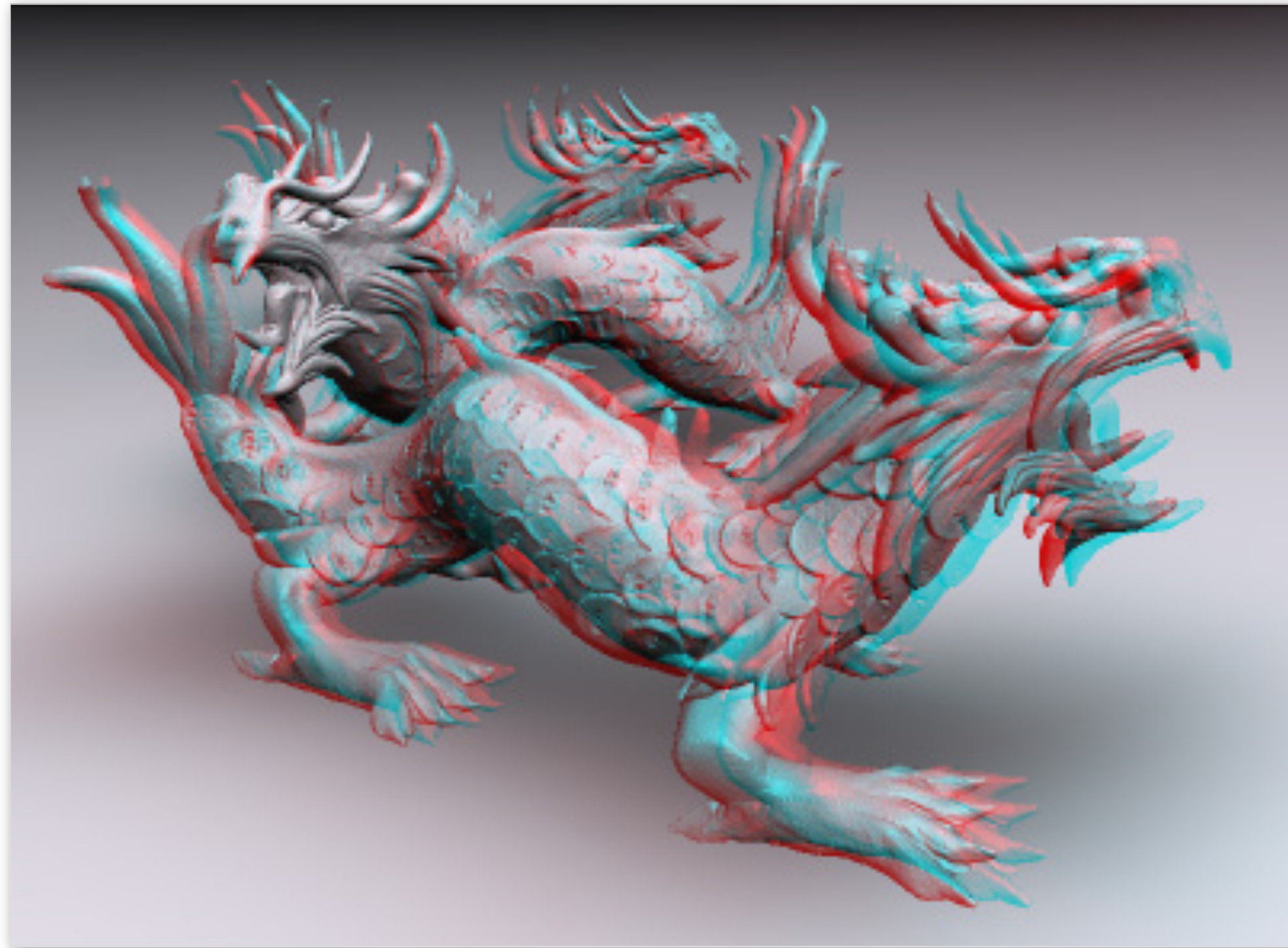
Standard 2D image

Backward-compatible stereo

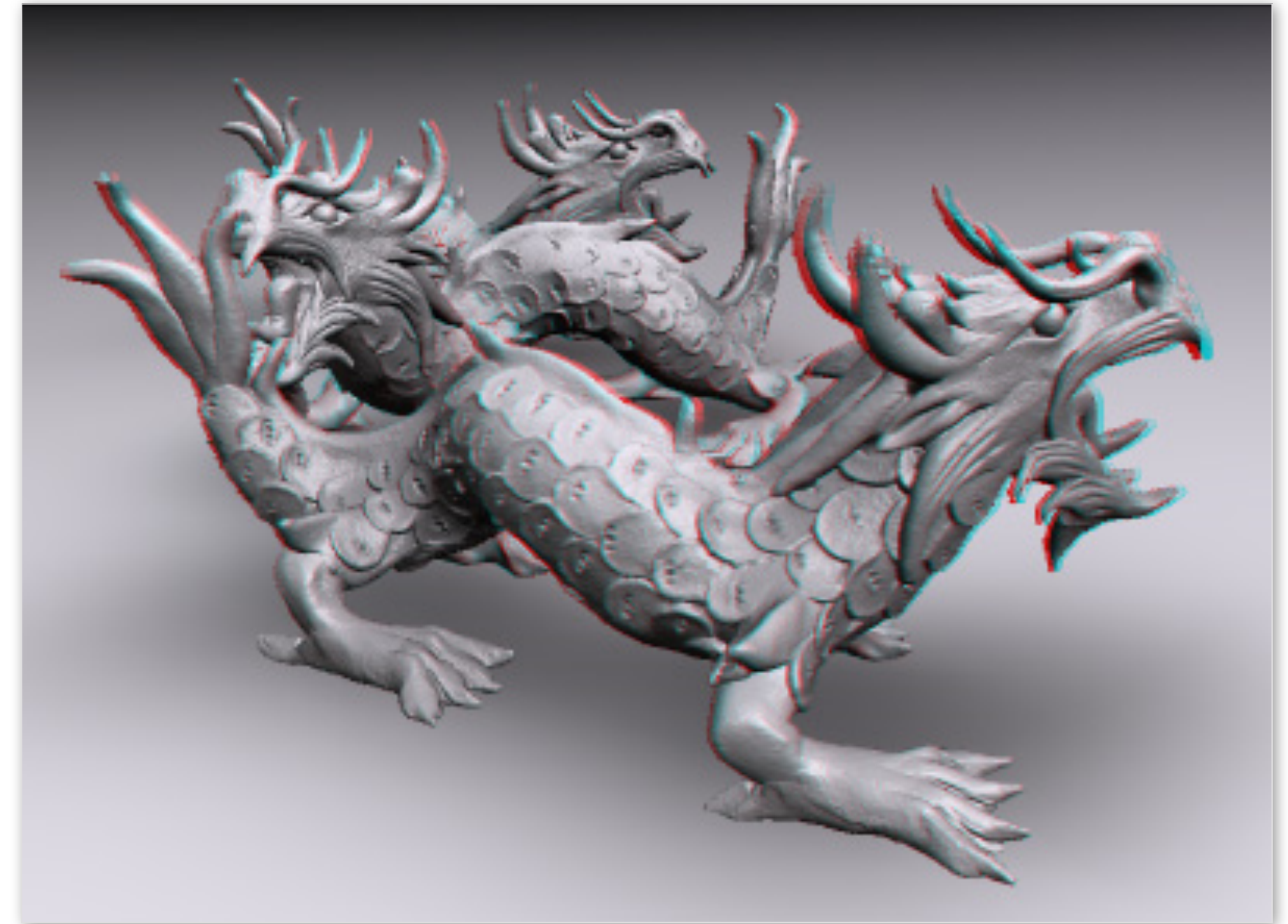


Backward-compatible stereo

Backward-compatible stereo



Standard stereo



Backward-compatible stereo

Use only Cornsweet profiles

Matching experiment

- Small pixel disparity give already good stereo impression



Microstereopsis

“Just enough reality: comfortable 3D viewing via microstereopsis” [Siegel et al. 2000]

Matching experiment

- Small pixel disparity give already good stereo impression



Microstereopsis

Experiment:

- Adjust standard stereo to match percept of depth in backward-compatible



Backward-compatible stereo

“Just enough reality: comfortable 3D viewing via microstereopsis” [Siegel et al. 2000]

Backward-compatible stereo



Microstereopsis



Backward-compatible stereo

“Big Buck Bunny” © by Blender Foundation

Backward-compatible stereo

Backward-compatible stereo

Anaglyph

Microstereopsis



Our



Backward-compatible stereo

Anaglyph

Shutter glasses

Microstereopsis



Our



Backward-compatible stereo

Anaglyph

Shutter glasses

Polarized glasses

Microstereopsis



Our



Hidden stereo



No anaglyph artifacts but similar stereo impression

Beneficial in compression



Left view



Right view

Beneficial in compression



Left view



Right view



Difference

Conclusions

We show:

Conclusions

We show:

- Method for depth impression enhancement

Conclusions

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- The same depth impression can be achieved with smaller disparity range

Conclusions

We show:

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Conclusions

We show:

- Method for depth impression enhancement
- The same depth impression can be achieved with smaller disparity range
- It can be beneficial for stereo content compression

In future:

- How to account for other depth cues, such as shading etc.

Thank you.