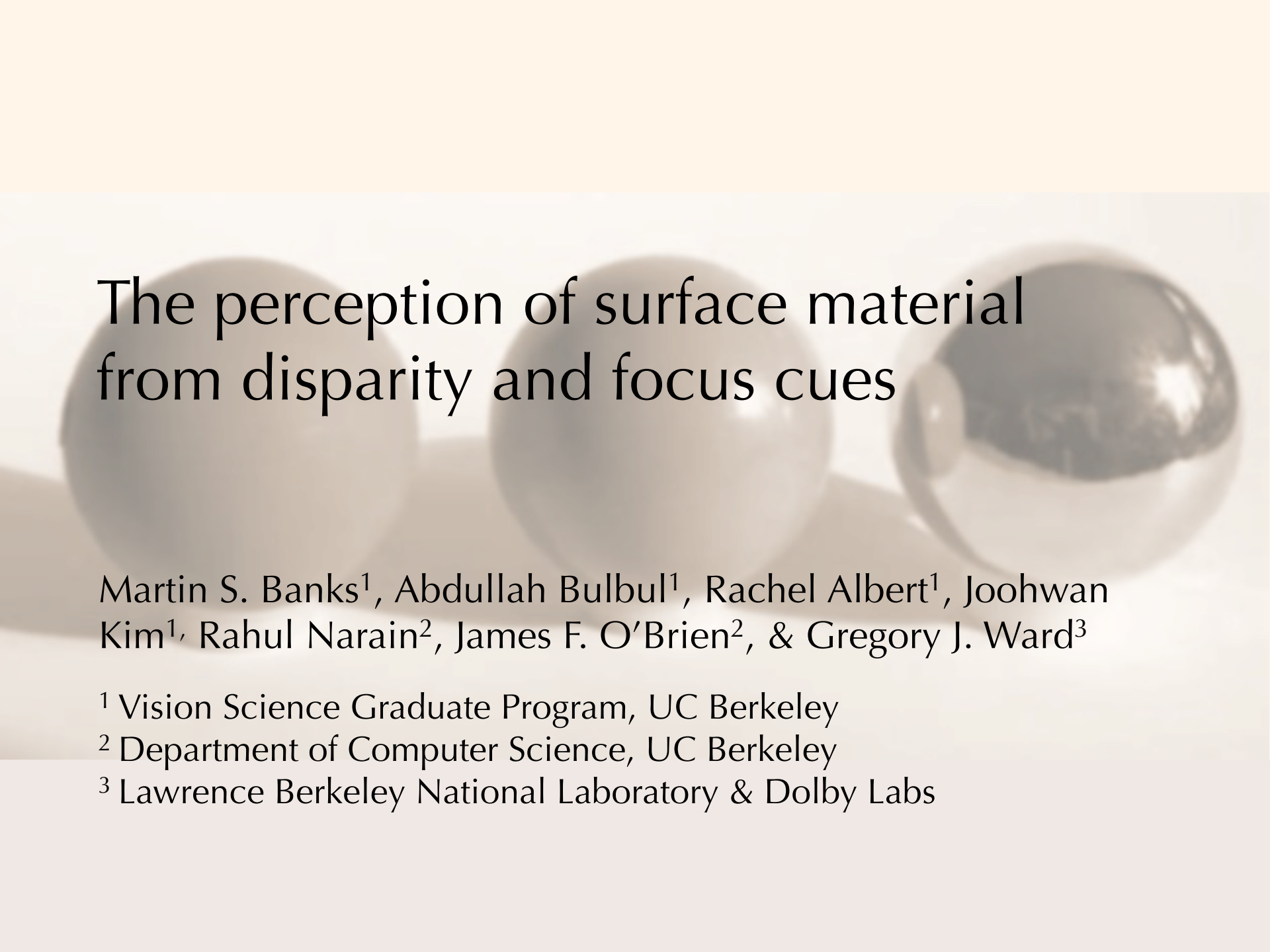


The background of the slide features three spheres of varying sizes and materials. The sphere on the left is the largest and has a matte, off-white finish. The middle sphere is slightly smaller and has a semi-gloss, light gray finish. The sphere on the right is the smallest and has a highly reflective, metallic silver finish. They are arranged in a row, slightly overlapping, against a light beige background.

The perception of surface material from disparity and focus cues

Martin S. Banks¹, Abdullah Bulbul¹, Rachel Albert¹, Joohwan Kim¹, Rahul Narain², James F. O'Brien², & Gregory J. Ward³

¹ Vision Science Graduate Program, UC Berkeley

² Department of Computer Science, UC Berkeley

³ Lawrence Berkeley National Laboratory & Dolby Labs

Inferring Material Properties

- Retinal image determined by:
 - properties of surrounding environment
 - surface geometry
 - viewer's position
 - surface reflectance properties
- Determining surface material greatly under-constrained



Inferring Material Properties

Image statistics

- highlights are bright & desaturated
- skew of luminance histogram (Motoyoshi et al., 2007)
- curvature flow (Fleming, 2014)



Inferring Material Properties

Image statistics

- highlights are bright & desaturated
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- curvature flow (Fleming, 2014)

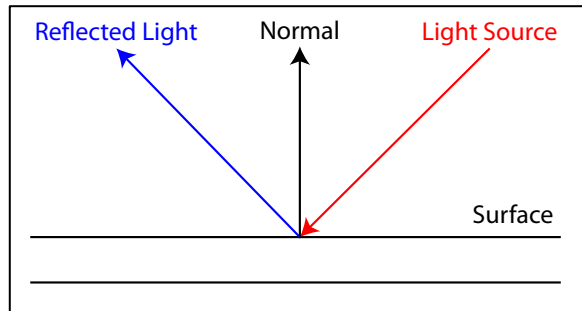
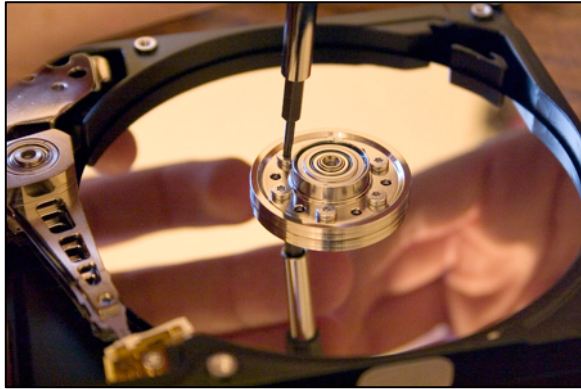
Natural viewing

- binocular
- motion
- accommodation & blur

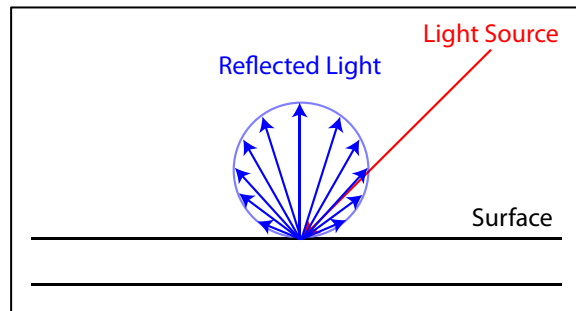
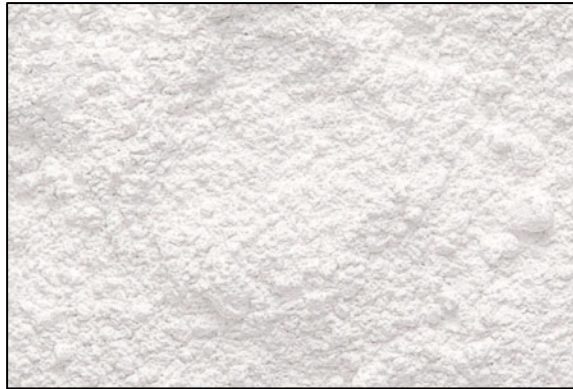


Reflections from Different Materials

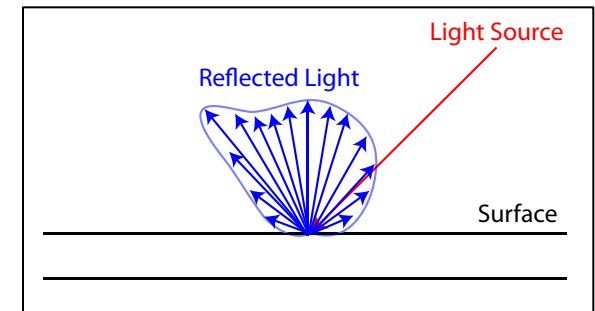
specular



Lambertian

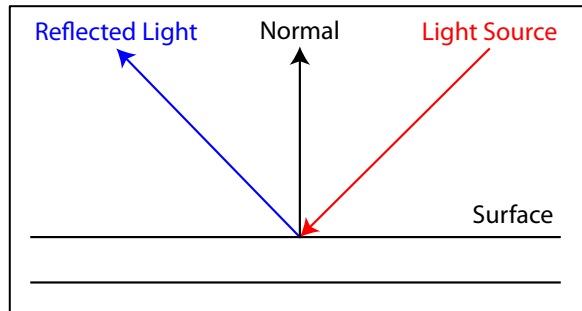
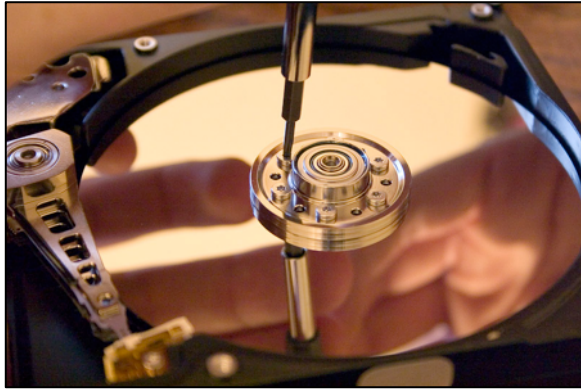


complex

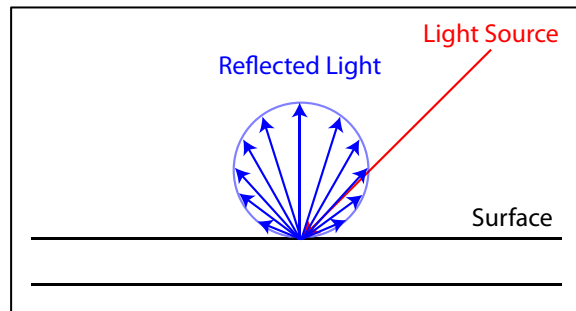
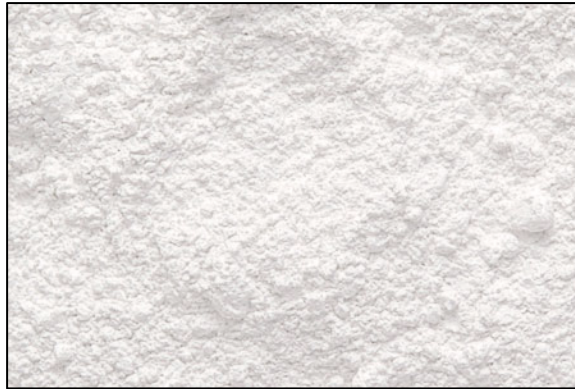


Reflections from Different Materials

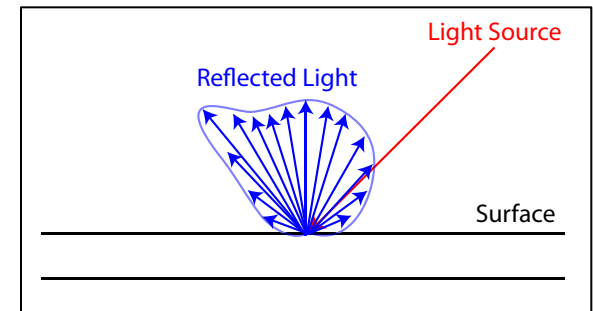
specular



Lambertian

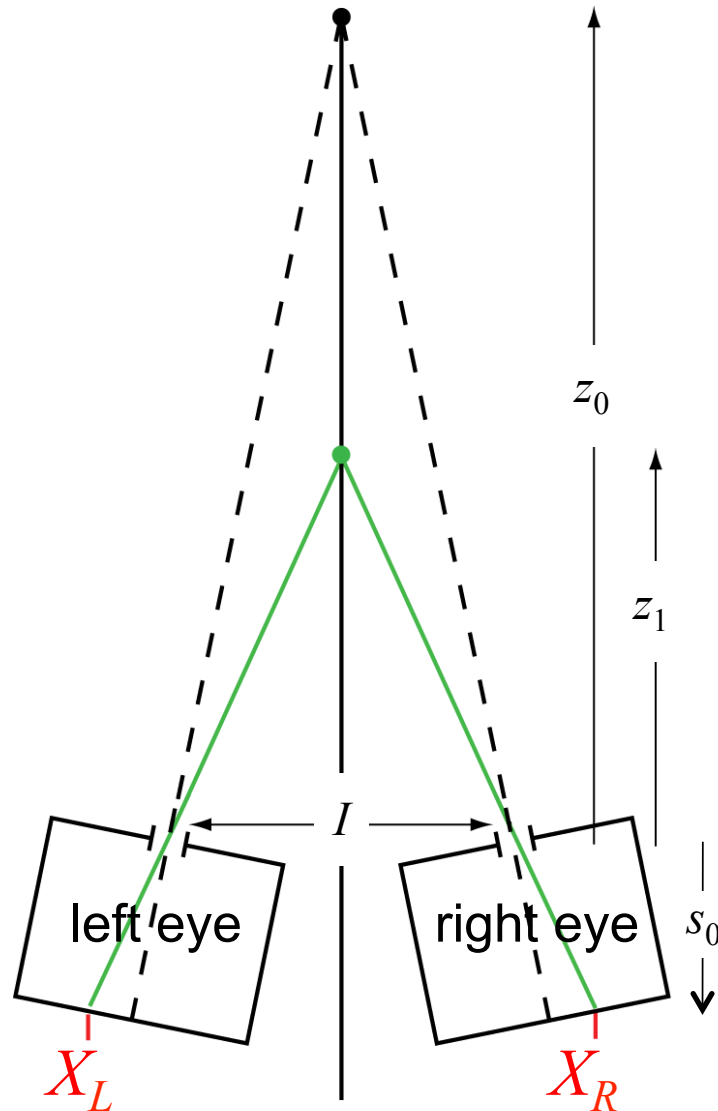


complex



Bidirectional Reflectance Distribution Function (BRDF)

Binocular Disparity



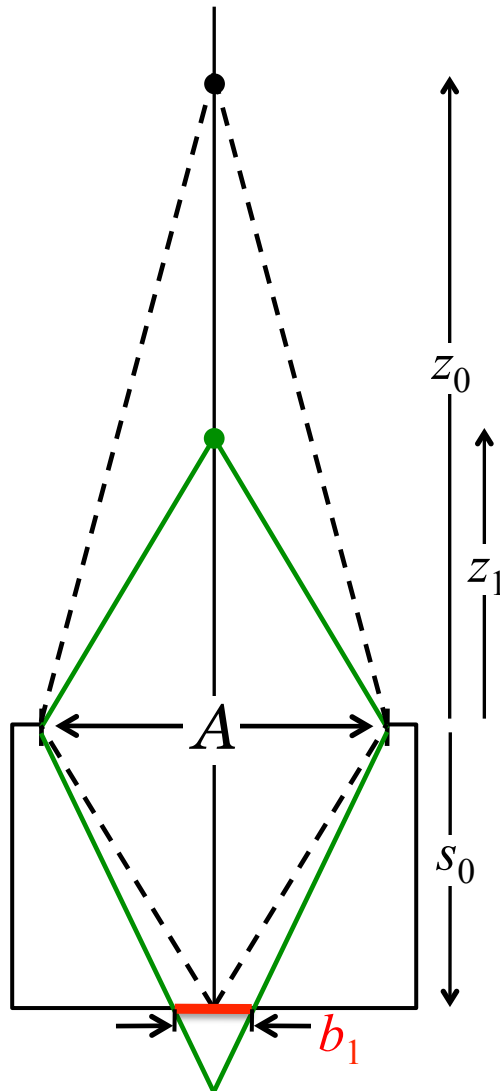
$$d_1 = X_R - X_L = \frac{Is_0}{z_0} \left[1 - \frac{z_0}{z_1} \right]$$

$$\text{where } \frac{1}{s_0} = \frac{1}{f} - \frac{1}{z_0}$$

$$\delta \approx I \left(\frac{1}{z_0} - \frac{1}{z_1} \right) = I(\Delta D)$$

δ in radians

Focus & Blur

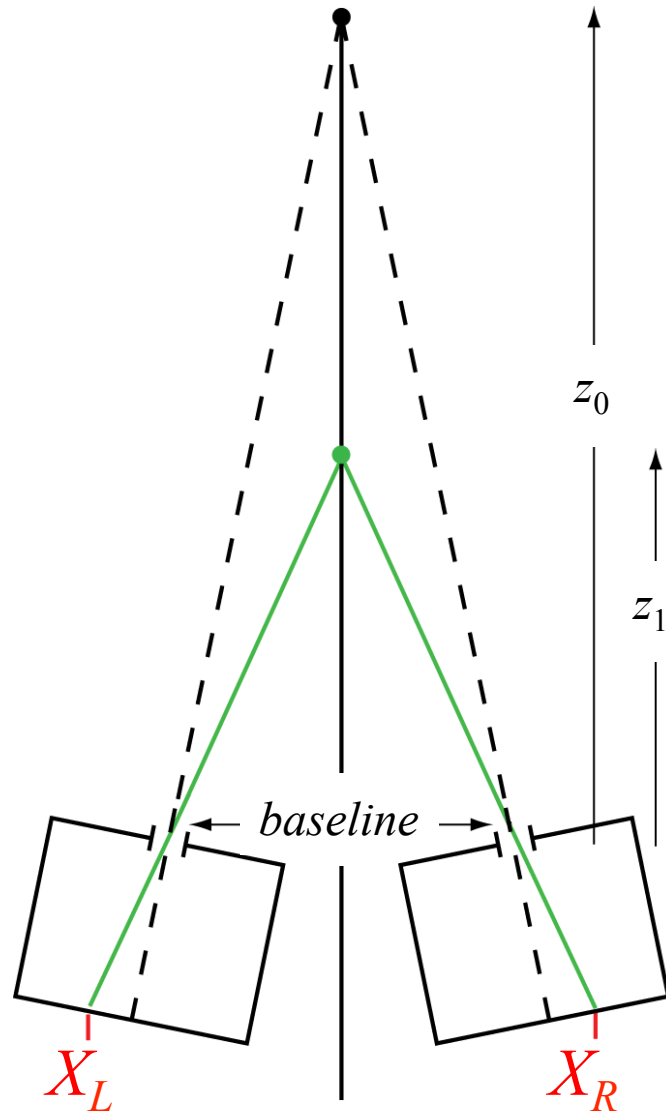


$$b_1 = \frac{As_0}{z_0} \left| 1 - \frac{z_0}{z_1} \right|$$

$$\beta \approx A \left| \frac{1}{z_0} - \frac{1}{z_1} \right| = A |\Delta D|$$

β in radians

Triangulation Cues to Depth



binocular disparity

$$\delta \approx I \left(\frac{1}{z_0} - \frac{1}{z_1} \right) = I(\Delta D)$$

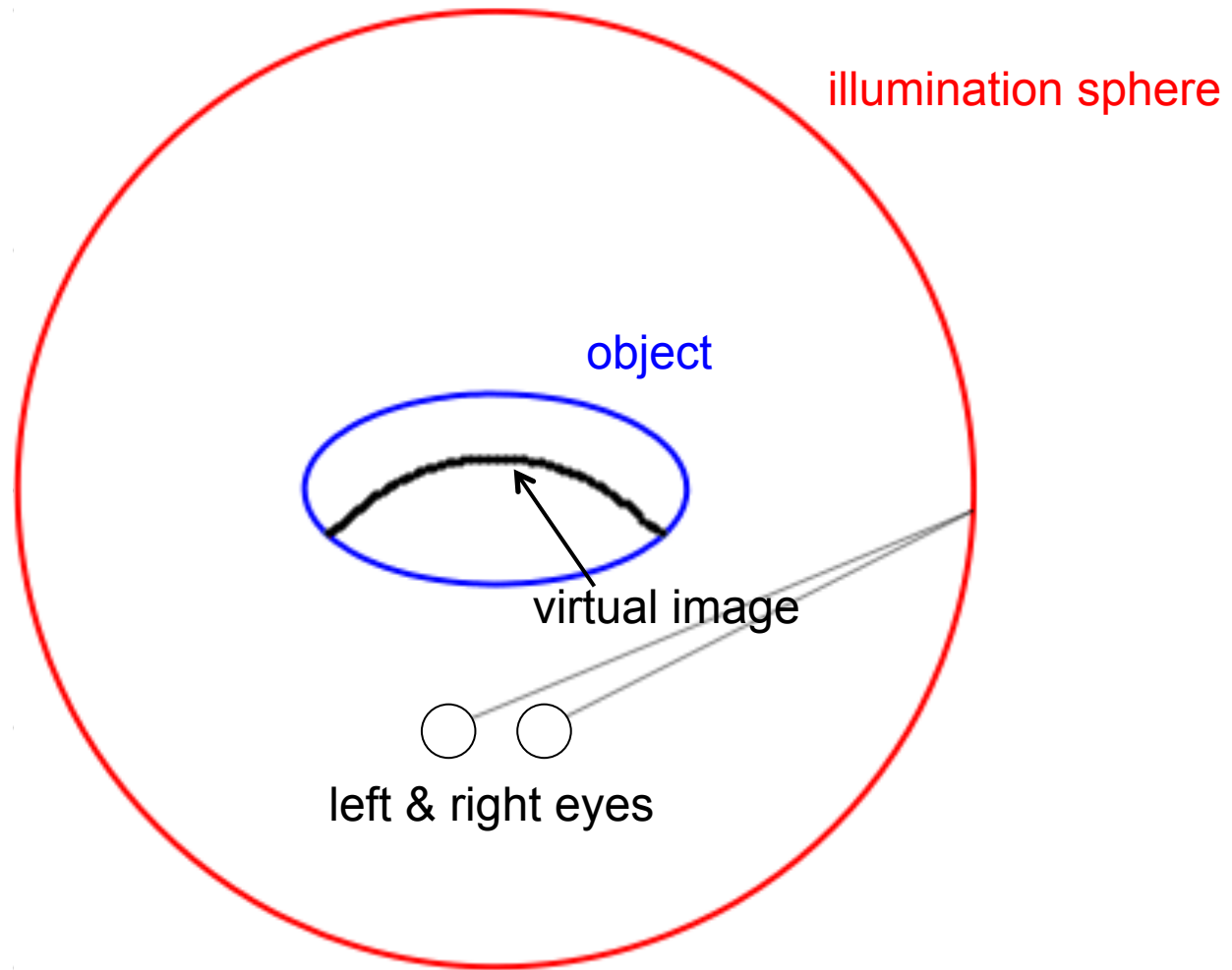
motion parallax

$$\mu \approx M \left(\frac{1}{z_0} - \frac{1}{z_1} \right) = M(\Delta D)$$

blur

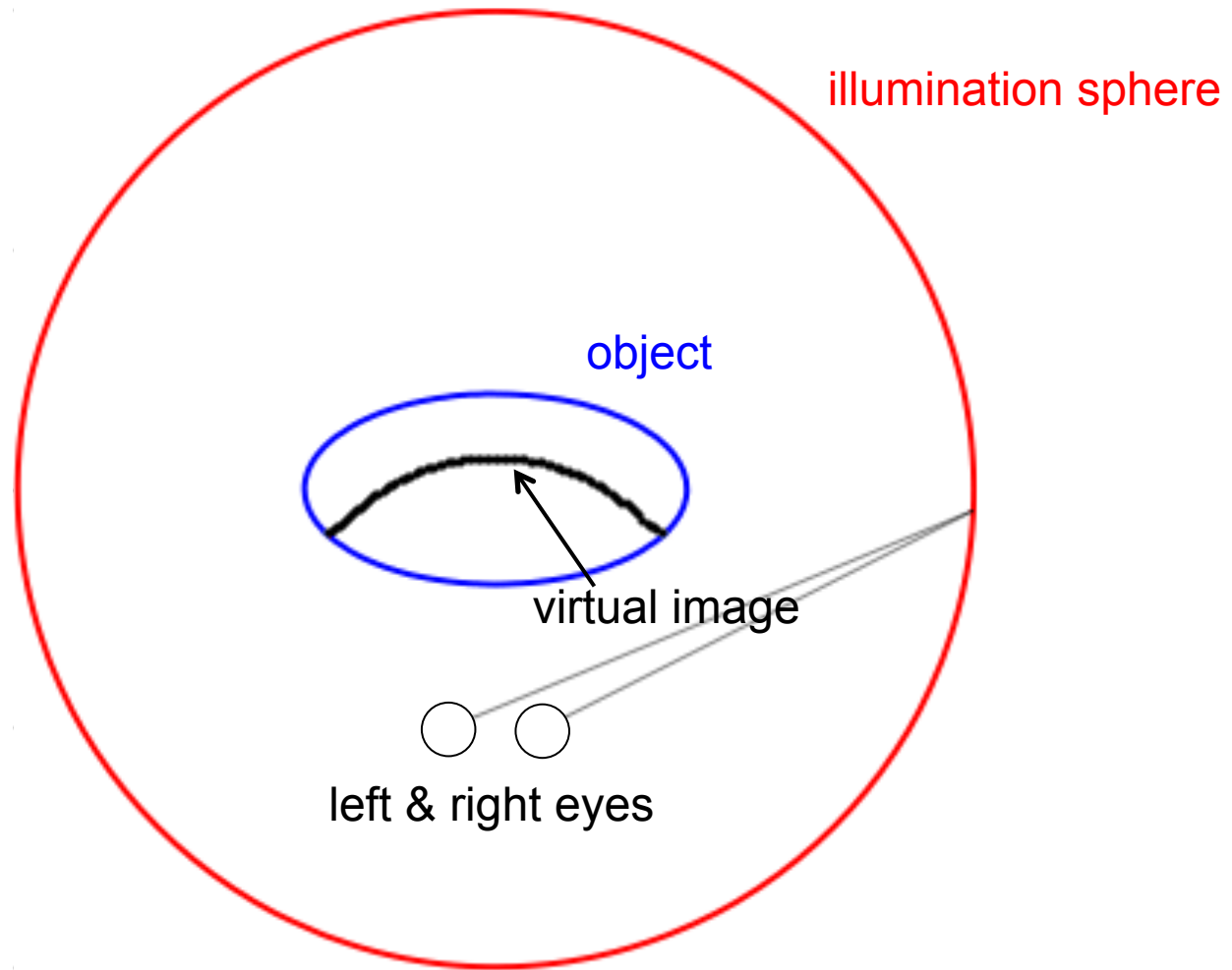
$$\beta \approx A \left| \frac{1}{z_0} - \frac{1}{z_1} \right| = A|\Delta D|$$

Reflection Geometry: Disparity



Kirschmann (1895)
Blake & Bülthoff (1990)
Murphy, Fleming, & Welchman (2013)

Reflection Geometry: Disparity



Kirschmann (1895)
Blake & Bülthoff (1990)
Murphy, Fleming, & Welchman (2013)

Reflections & Disparity

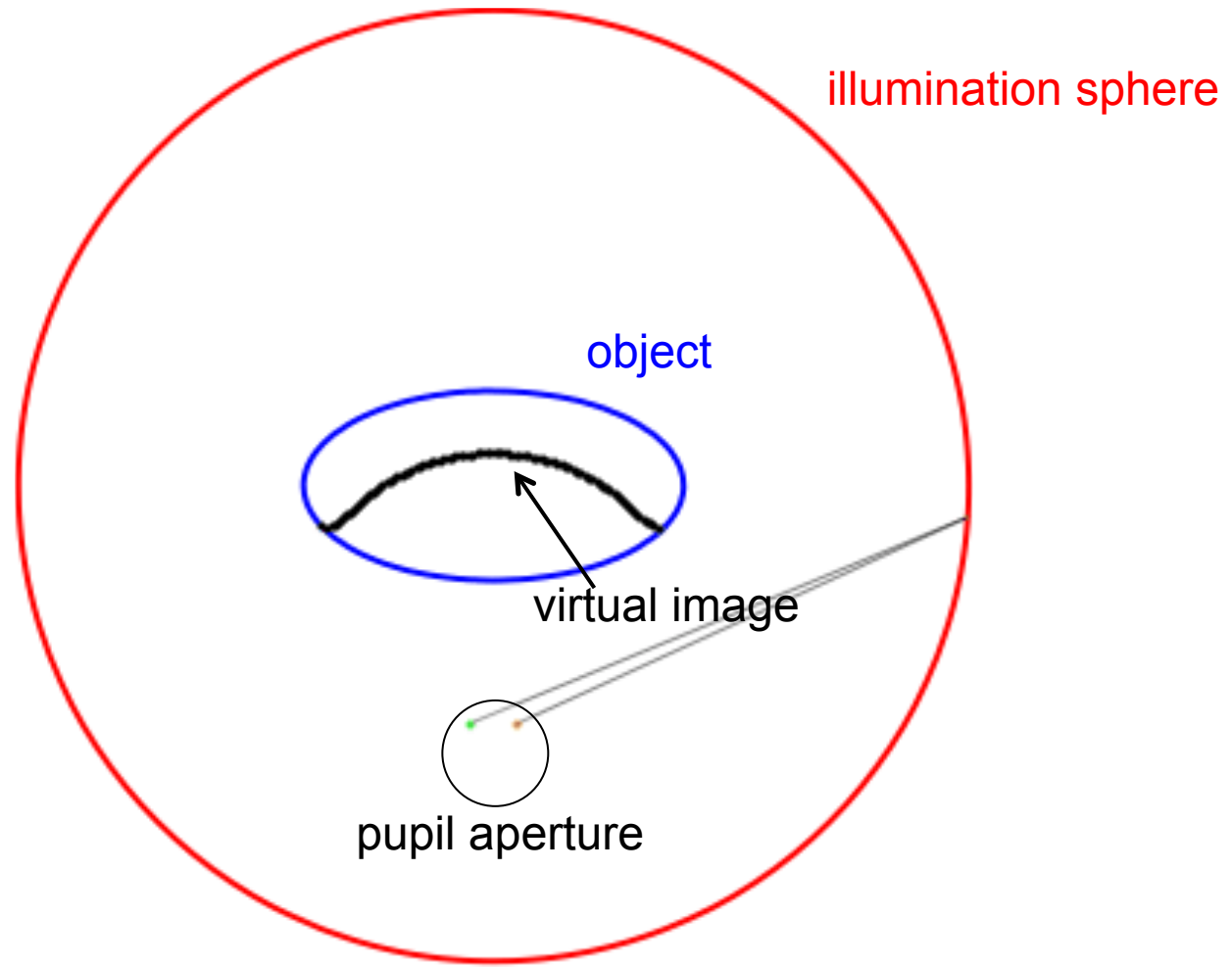


Reflection:
virtual image
with uncrossed
disparity

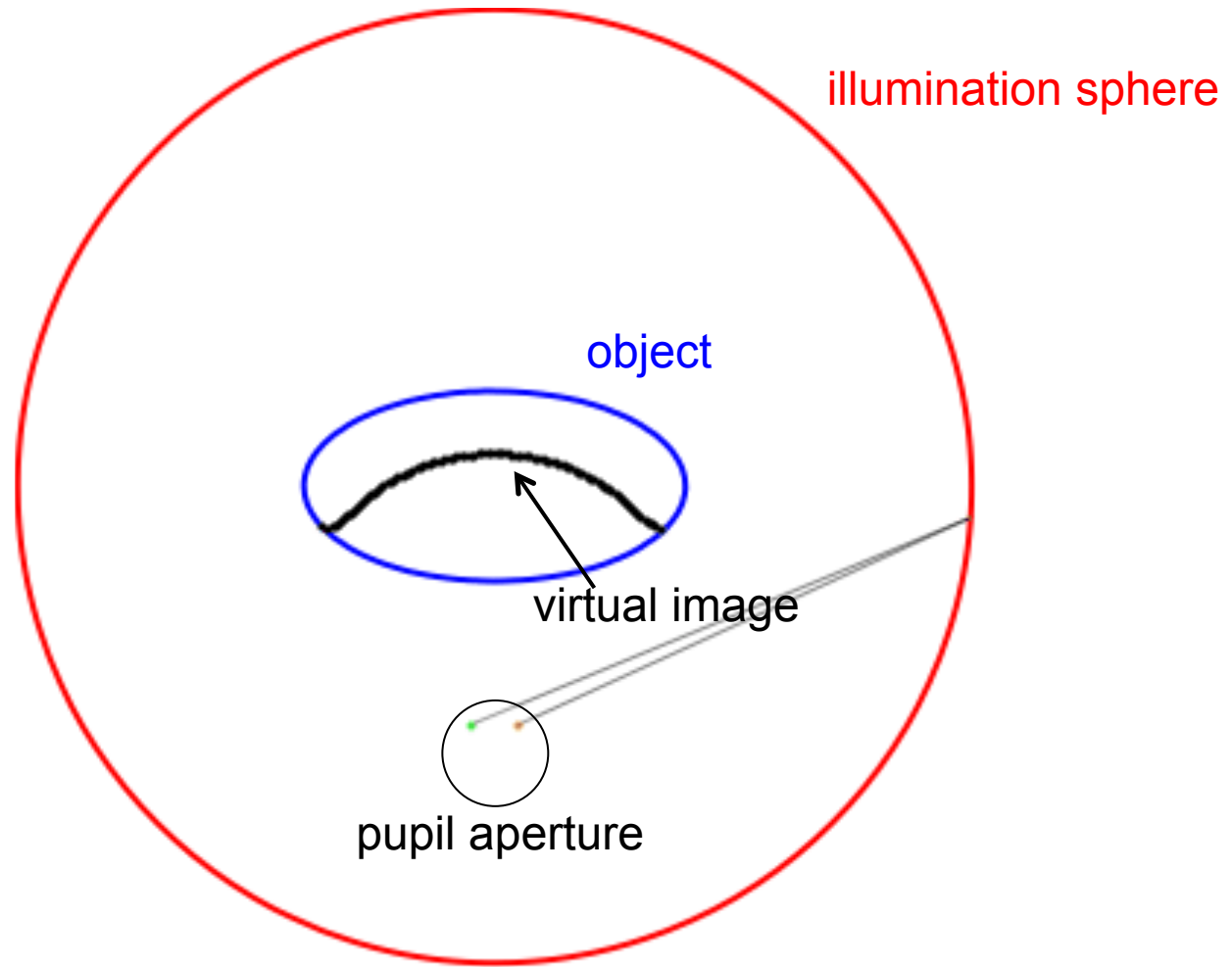


Paint: same
highlight with
zero disparity

Reflection Geometry: Blur



Reflection Geometry: Blur



Reflections & Blur



focus on surface



focus on reflection

Reflections & Blur

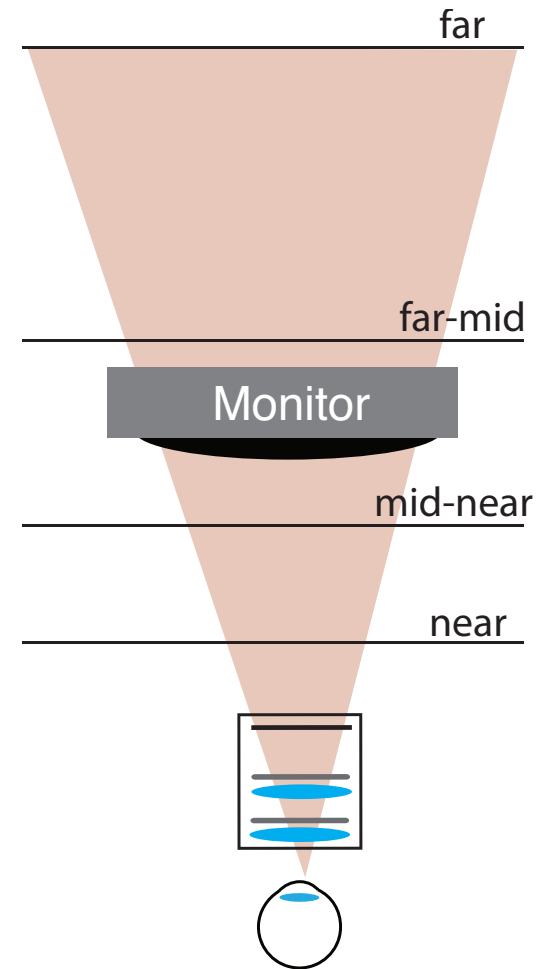
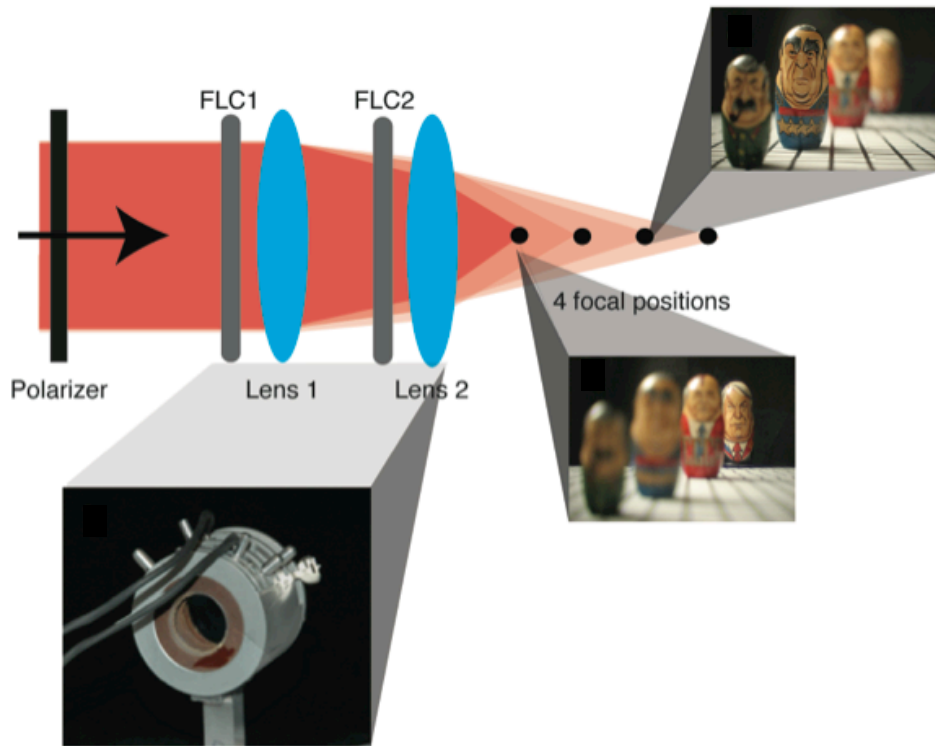


focus on surface

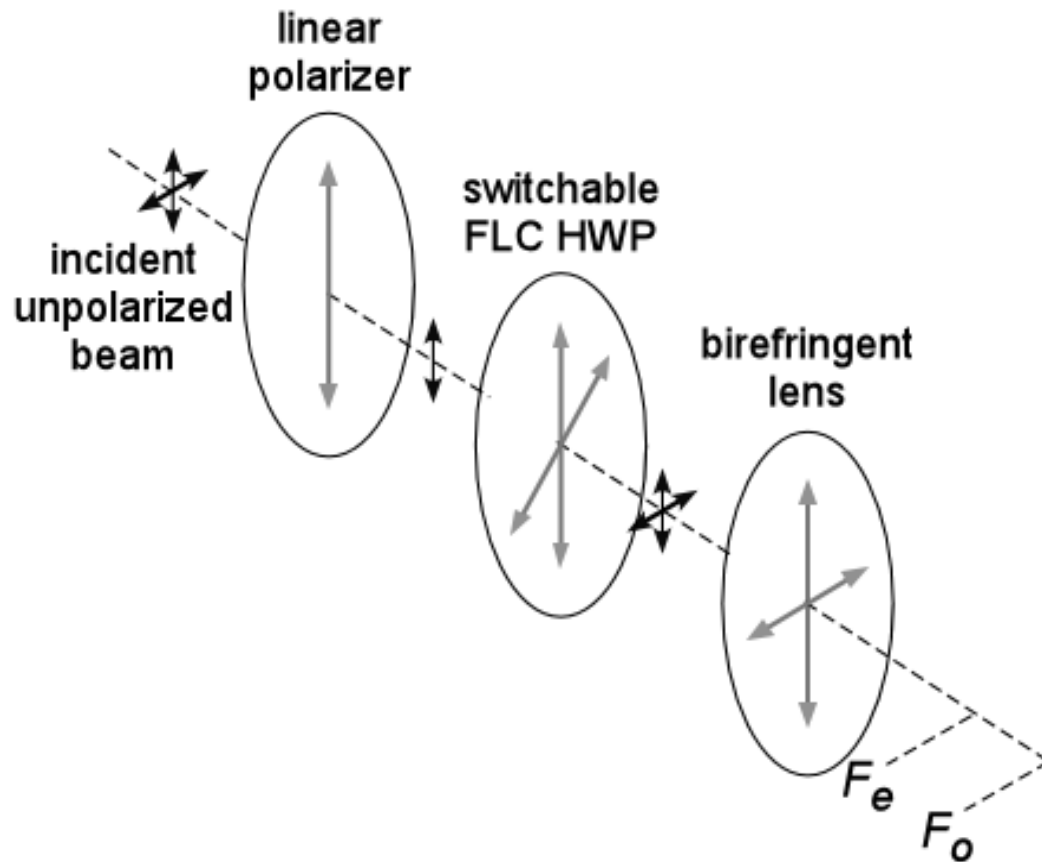


focus on reflection

Multi-plane Display



Switchable Lens



Birefringent material (e.g., calcite) has ordinary & extraordinary refractive indices depending on polarization

Calcite lens has two focal lengths F_o & F_e

Variation in power effected by polarization modulator (FLC)

Can stack lenses; 2^N states

Changing Focal Distance

lens in near state



lens in near-mid state



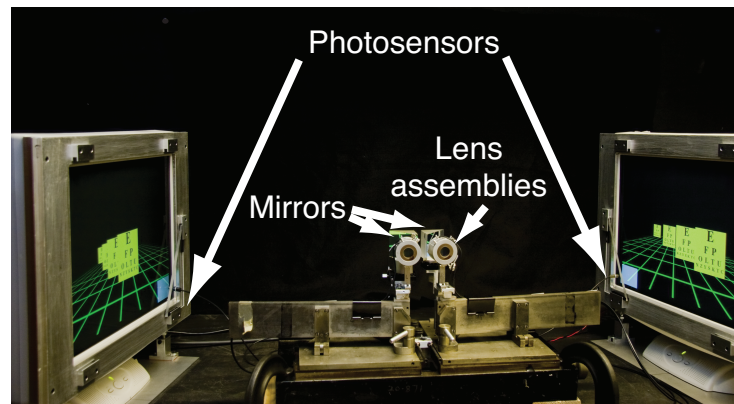
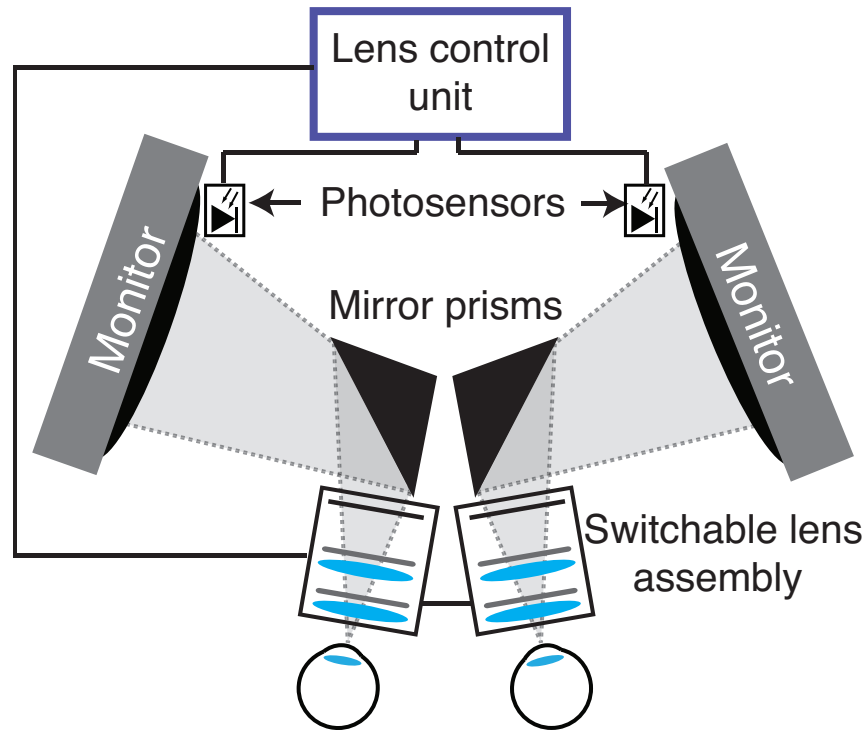
lens in mid-far state



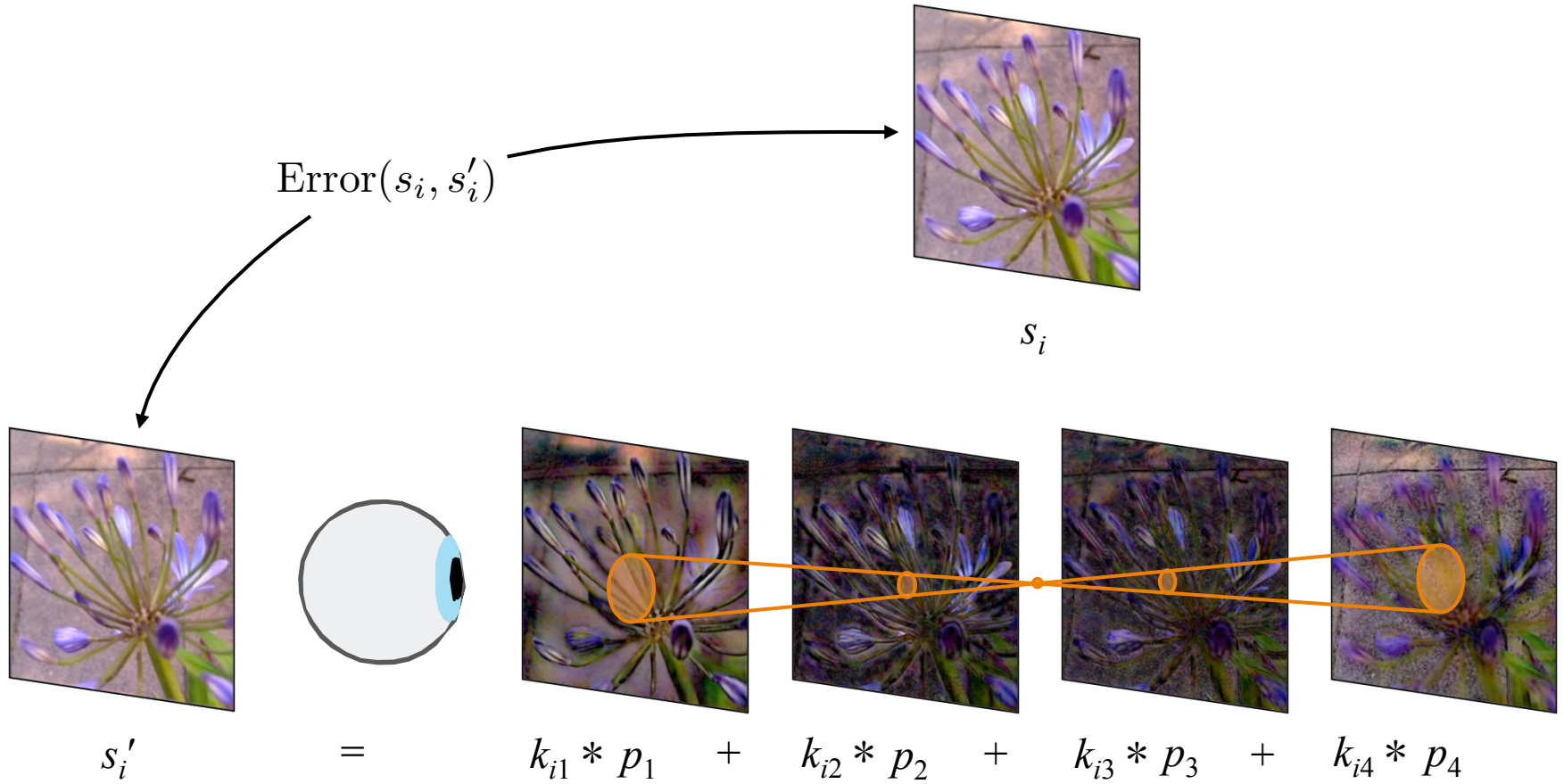
lens in far state



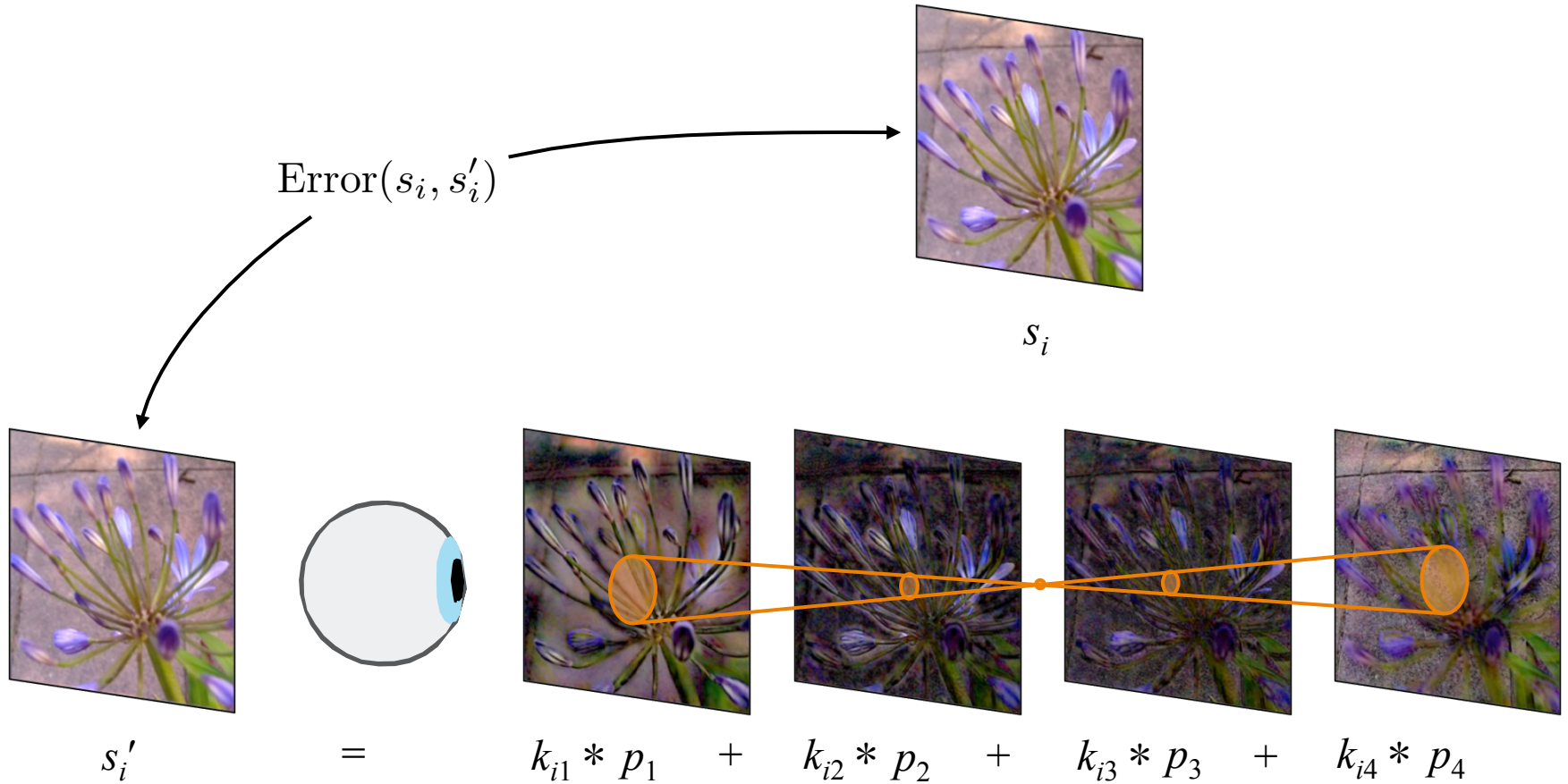
Multi-plane Display



Optimized Blending



Optimized Blending



$$\begin{aligned} & \text{minimize} \quad \sum_{i=1}^n \text{Error}(s_i, s'_i) \\ & \text{subject to} \quad 0 \leq p_1, p_2, p_3, p_4 \leq 1 \end{aligned}$$

Stimulus Conditions

Stereo

	No cues	Stereo alone, paint	Stereo alone, reflection	All cues
Stereo	Monocular	Consistent with paint	Consistent with reflection	Consistent with reflection
Motion	No motion	No motion	No motion	Consistent with reflection
Blur	Single plane	Single plane	Single plane	Consistent with reflection

Motion

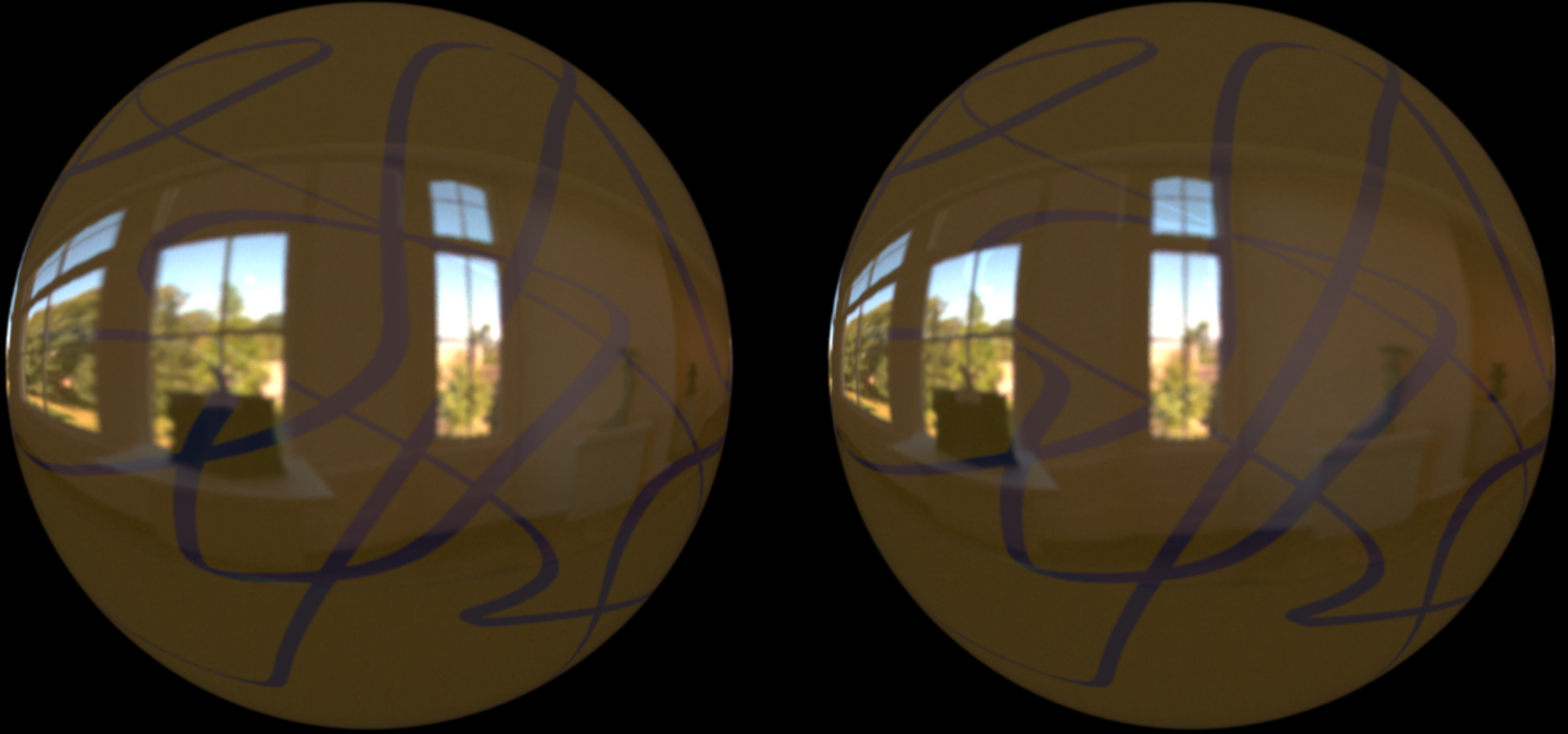
	No cues	Motion alone, paint	Motion alone, reflection	All cues
Stereo	Monocular	Monocular	Monocular	Consistent with reflection
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Blur	Single plane	Single plane	Single plane	Consistent with reflection

Blur

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Stereo	Monocular	Monocular	Monocular	Consistent with reflection
Motion	No motion	No motion	No motion	Consistent with reflection
Blur	Single plane	Consistent with paint	Consistent with reflection	Consistent with reflection

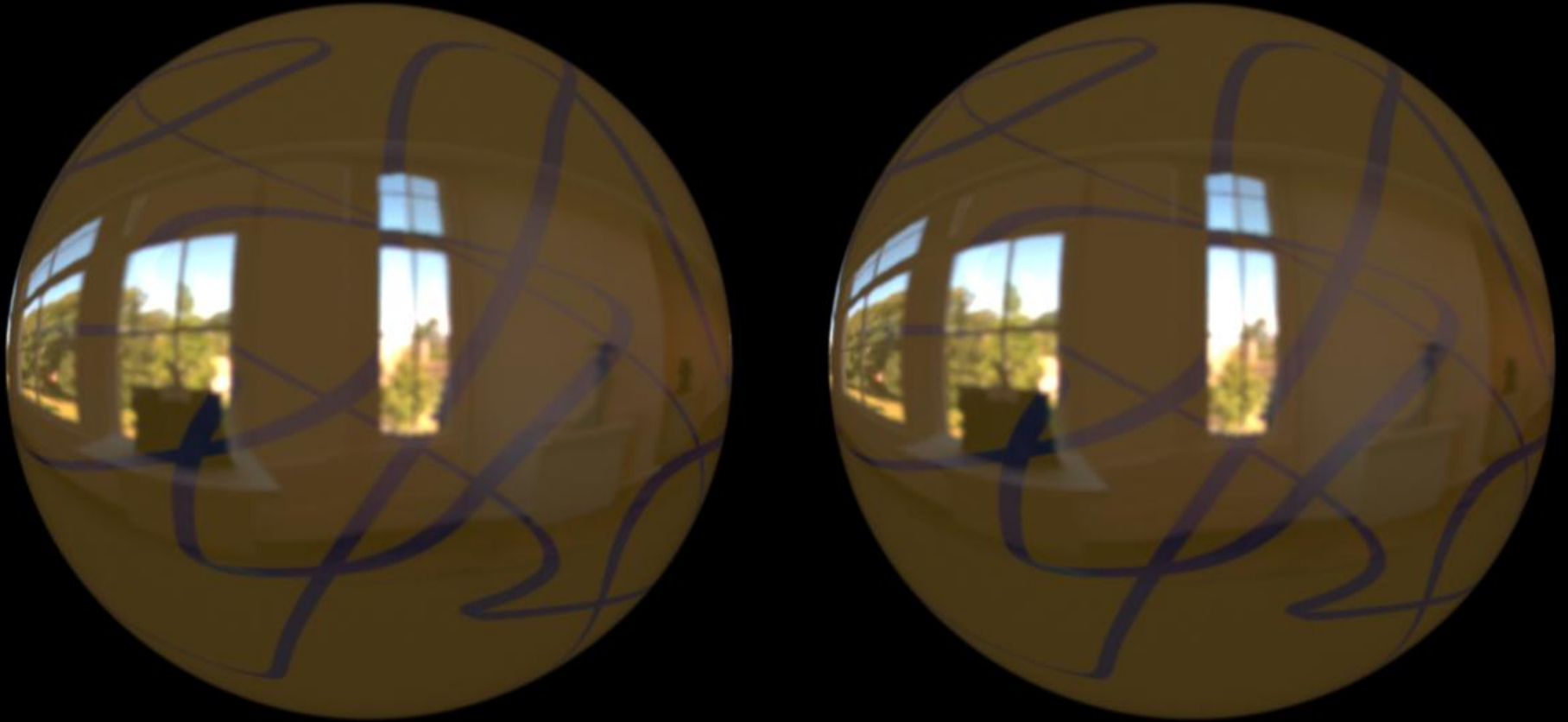
Experimental Stimulus: Stereo

reflection



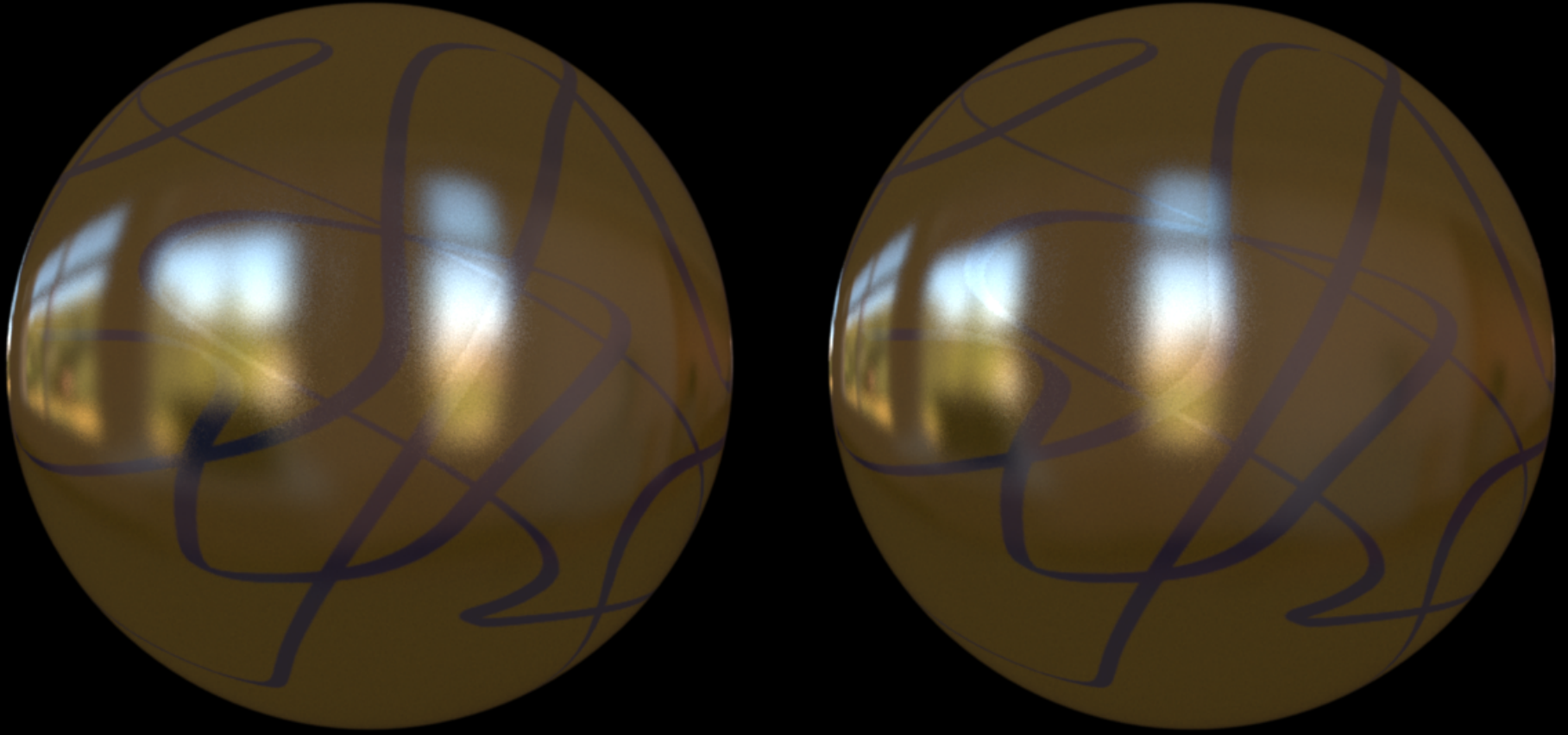
Experimental Stimulus: Stereo

paint



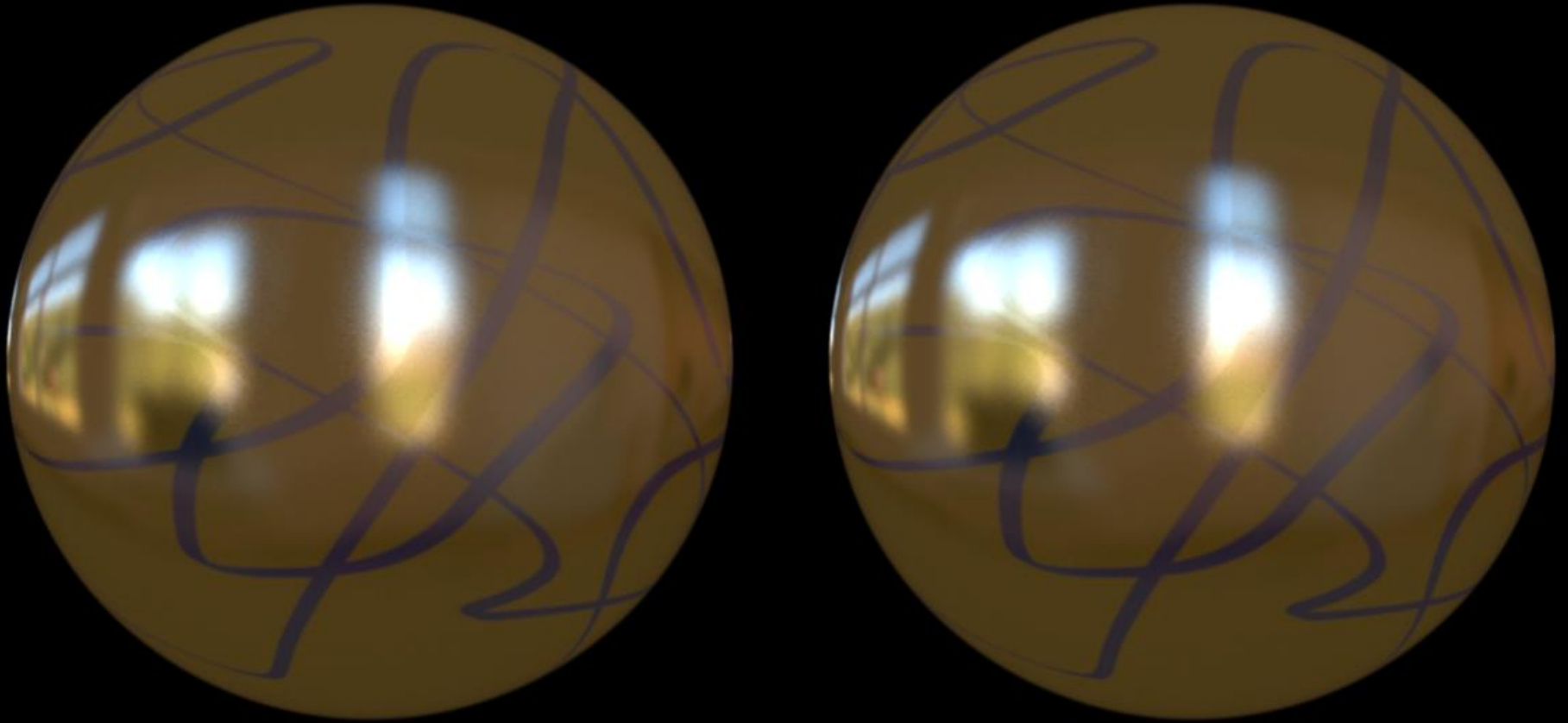
Experimental Stimulus: Stereo

reflection



Experimental Stimulus: Stereo

paint



Stimulus Conditions

Stereo

	No cues	Stereo alone, paint	Stereo alone, reflection	All cues
Stereo	Monocular	Consistent with paint	Consistent with reflection	Consistent with reflection
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Motion	No motion	Consistent with paint	Consistent with reflection	Consistent with reflection
Blur	Single plane	Single plane	Single plane	Consistent with reflection

Blur

	No cues	Blur alone, paint	Blur alone, reflection	All cues
Stereo	Monocular	Monocular	Monocular	Consistent with reflection
Motion	No motion	No motion	No motion	Consistent with reflection
Blur	Single plane	Consistent with paint	Consistent with reflection	Consistent with reflection

Experimental Stimulus: Motion Parallax

reflection



Experimental Stimulus: Motion Parallax

paint



Stimulus Conditions

Stereo

	No cues	Stereo alone, paint	Stereo alone, reflection	All cues
Stereo	Monocular	Consistent with paint	Consistent with reflection	Consistent with reflection
Motion	No motion	No motion	No motion	Consistent with reflection
Blur	Single plane	Single plane	Single plane	Consistent with reflection

Motion

	No cues	Motion alone, paint	Motion alone, reflection	All cues
Stereo	Monocular	Monocular	Monocular	Consistent with reflection
Motion	No motion	Consistent with paint	Consistent with reflection	Consistent with reflection
Blur	Single plane	Single plane	Single plane	Consistent with reflection

Blur

	No cues	Blur alone, paint	Blur alone, reflection	All cues
Stereo	Monocular	Monocular	Monocular	Consistent with reflection
Motion	No motion	No motion	No motion	Consistent with reflection
Blur	Single plane	Consistent with paint	Consistent with reflection	Consistent with reflection

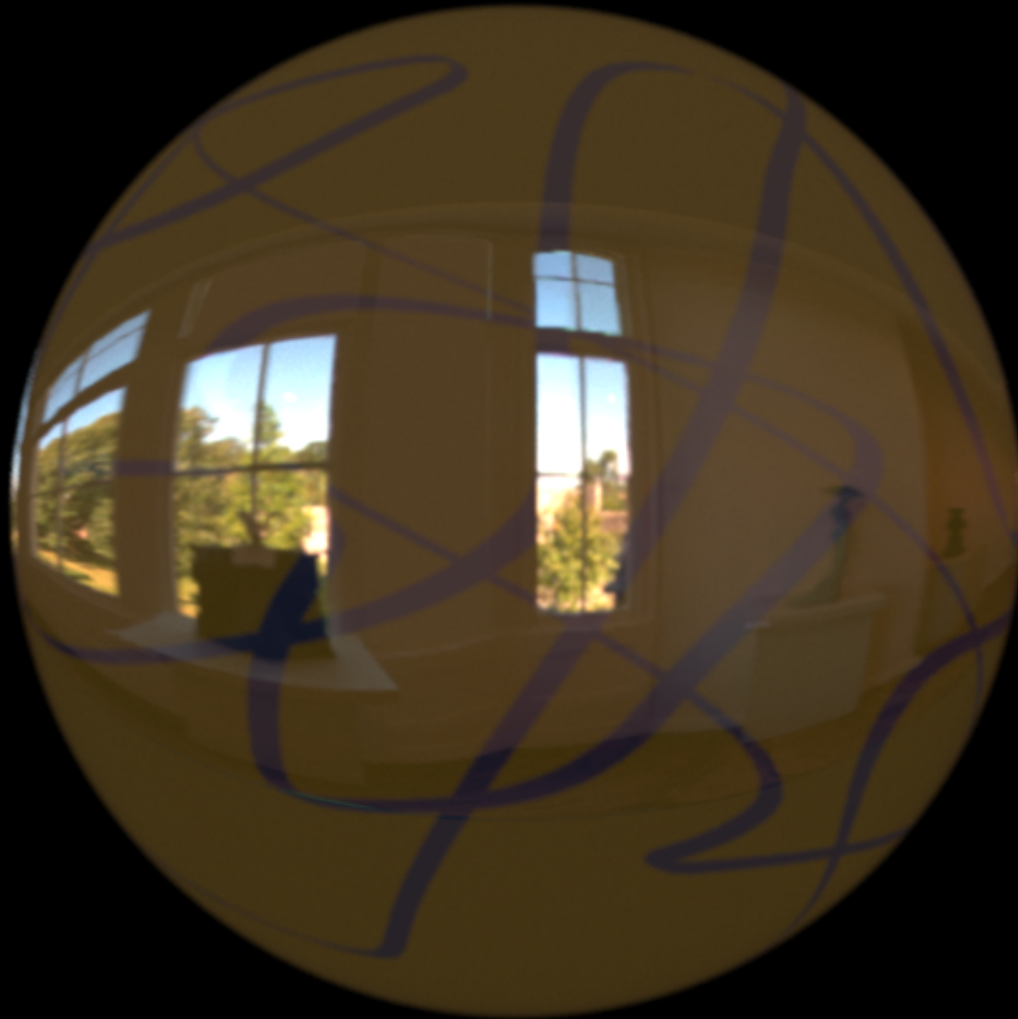
Experimental Stimulus: Volumetric

camera focused on surface



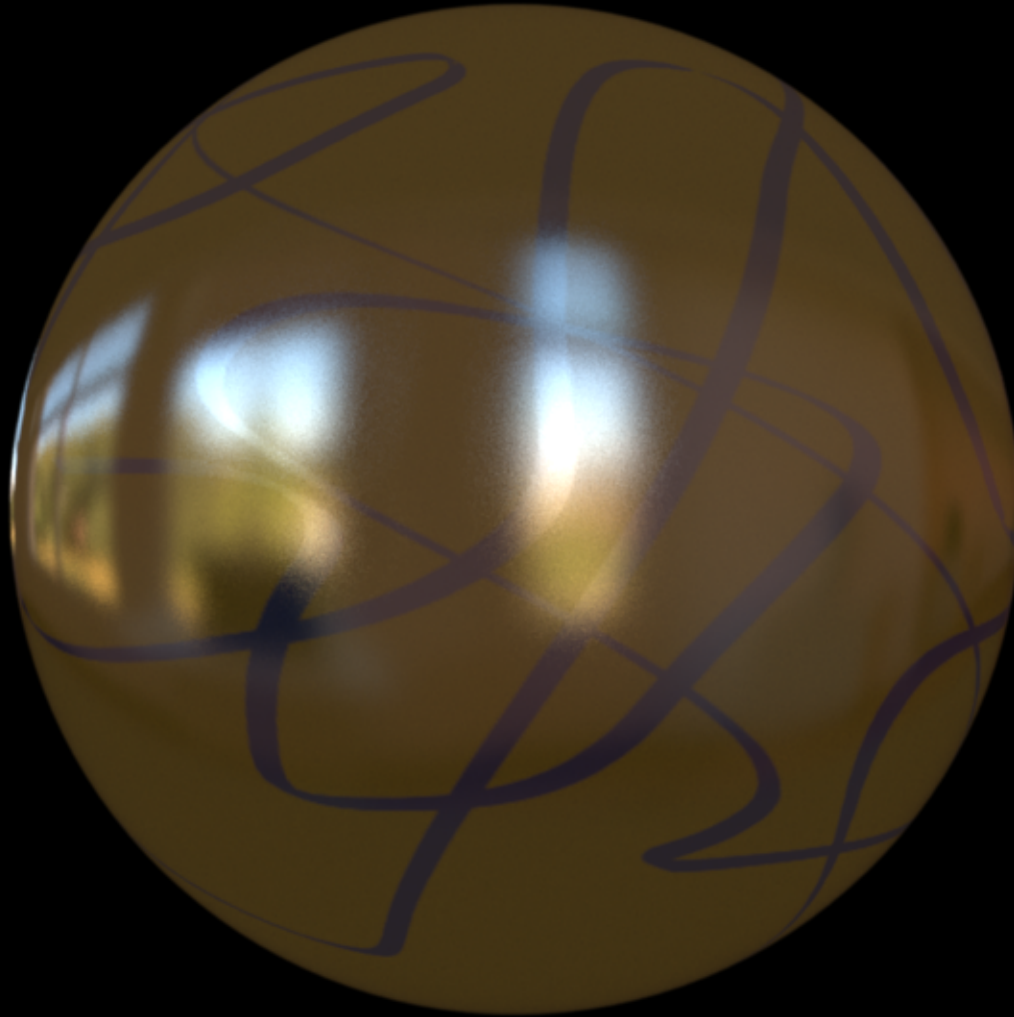
Experimental Stimulus: Volumetric

camera focused on reflection



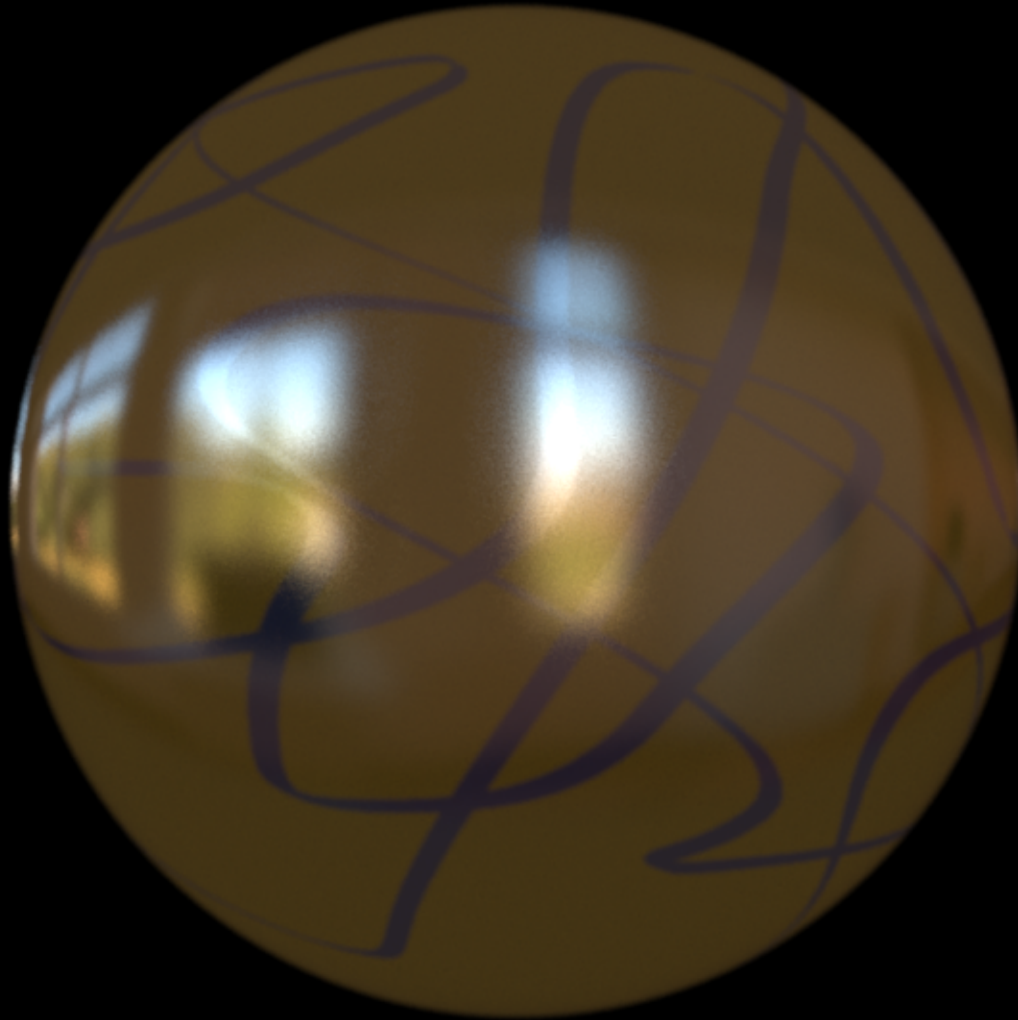
Experimental Stimulus: Volumetric

camera focused on surface



Experimental Stimulus: Volumetric

camera focused on reflection



Experimental Procedure

Stimuli

- textured flattened ovoids; four different textures
- material rendered according to Ward's isotropic BRDF model
specular reflection or slightly rough specular
Lambertian analog to both
- distant environment map for illumination
- duration = 4 sec

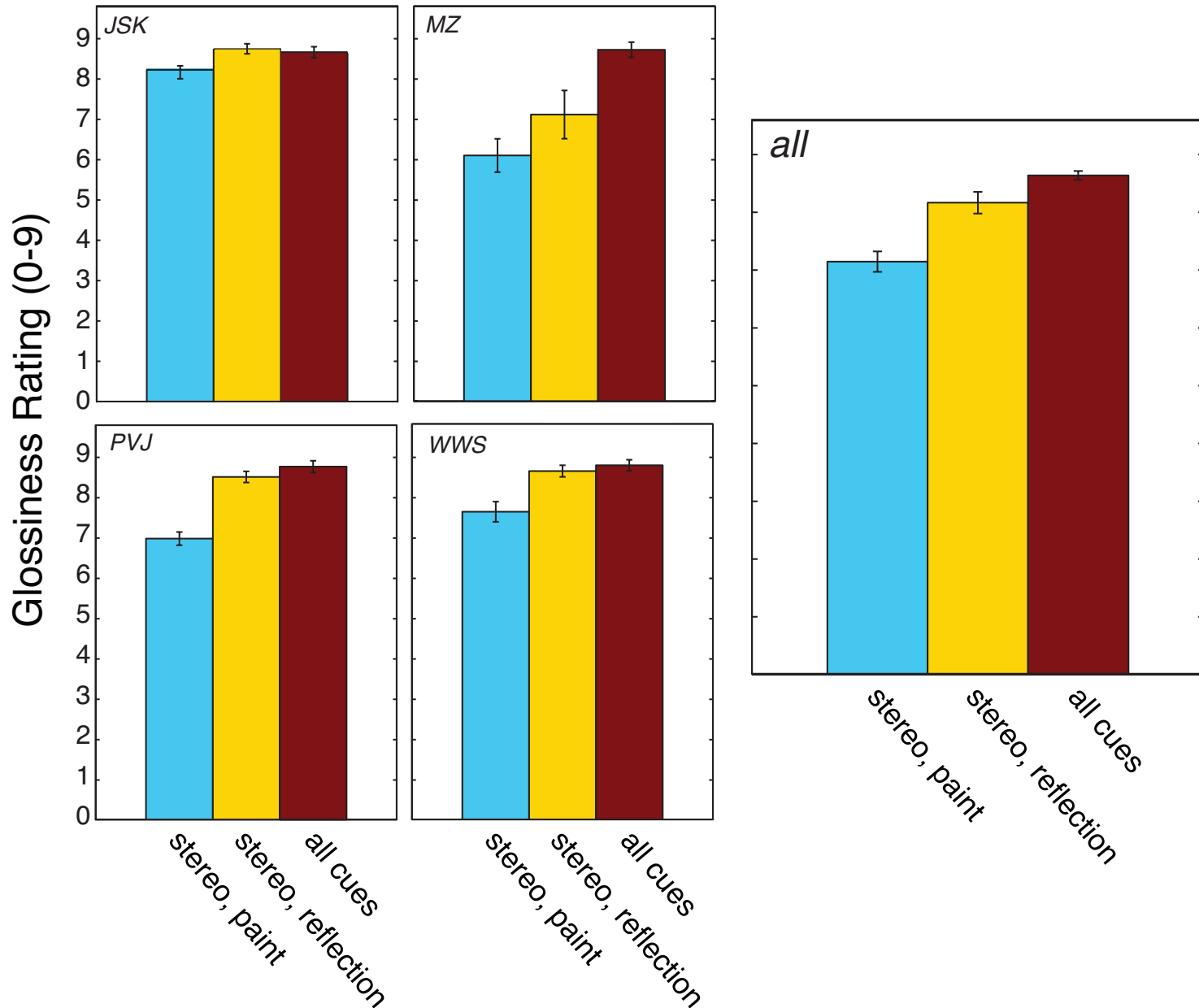
Response measure

- subjects indicate perceived glossiness of each stimulus on 0-9 scale
- 15-min training session with no feedback to anchor scale

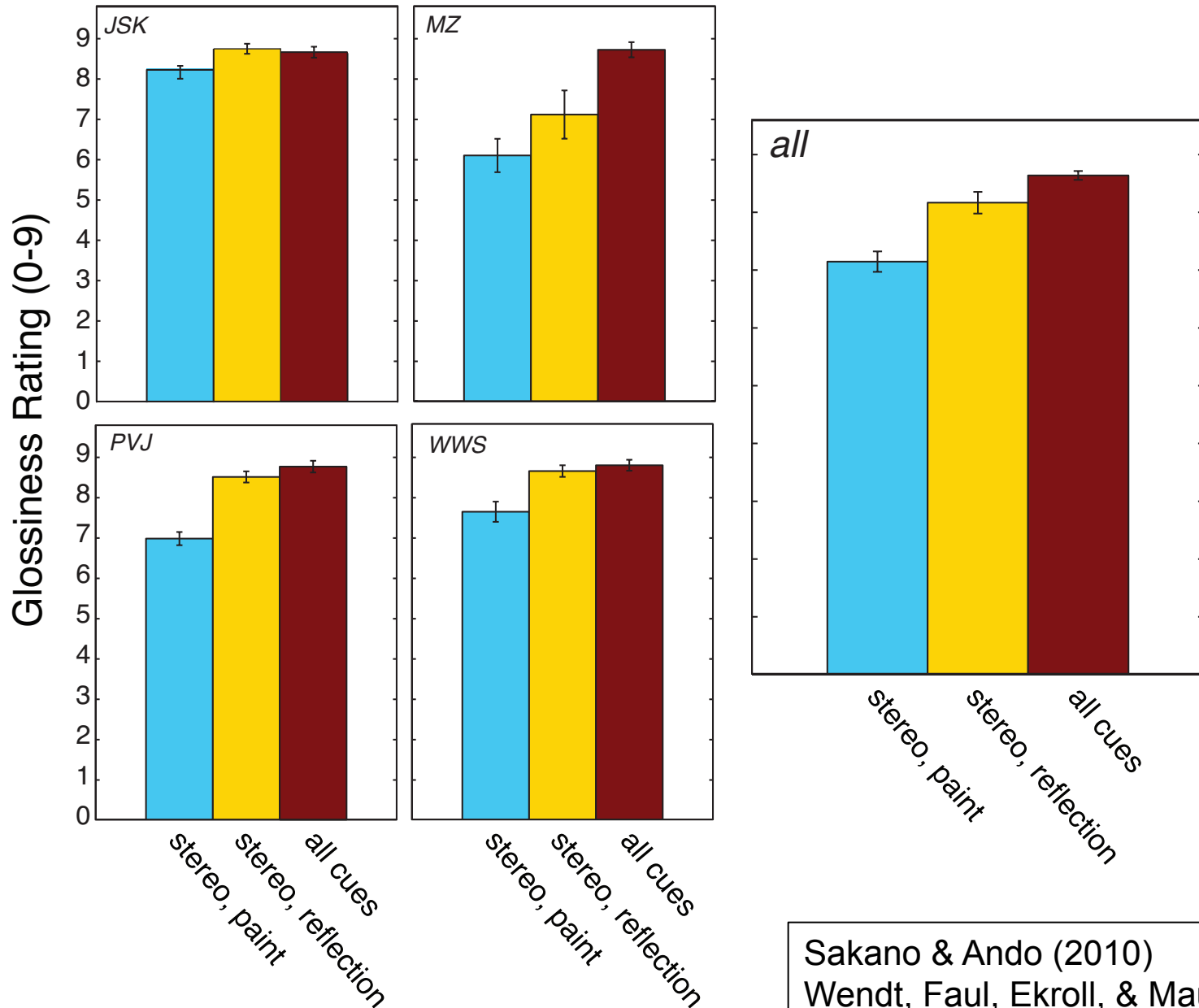
Subjects

- four young adults with corrected-to-normal acuity (three naïve)
- 264 observations per subject (12 presentations of 22 conditions)

Results: Disparity

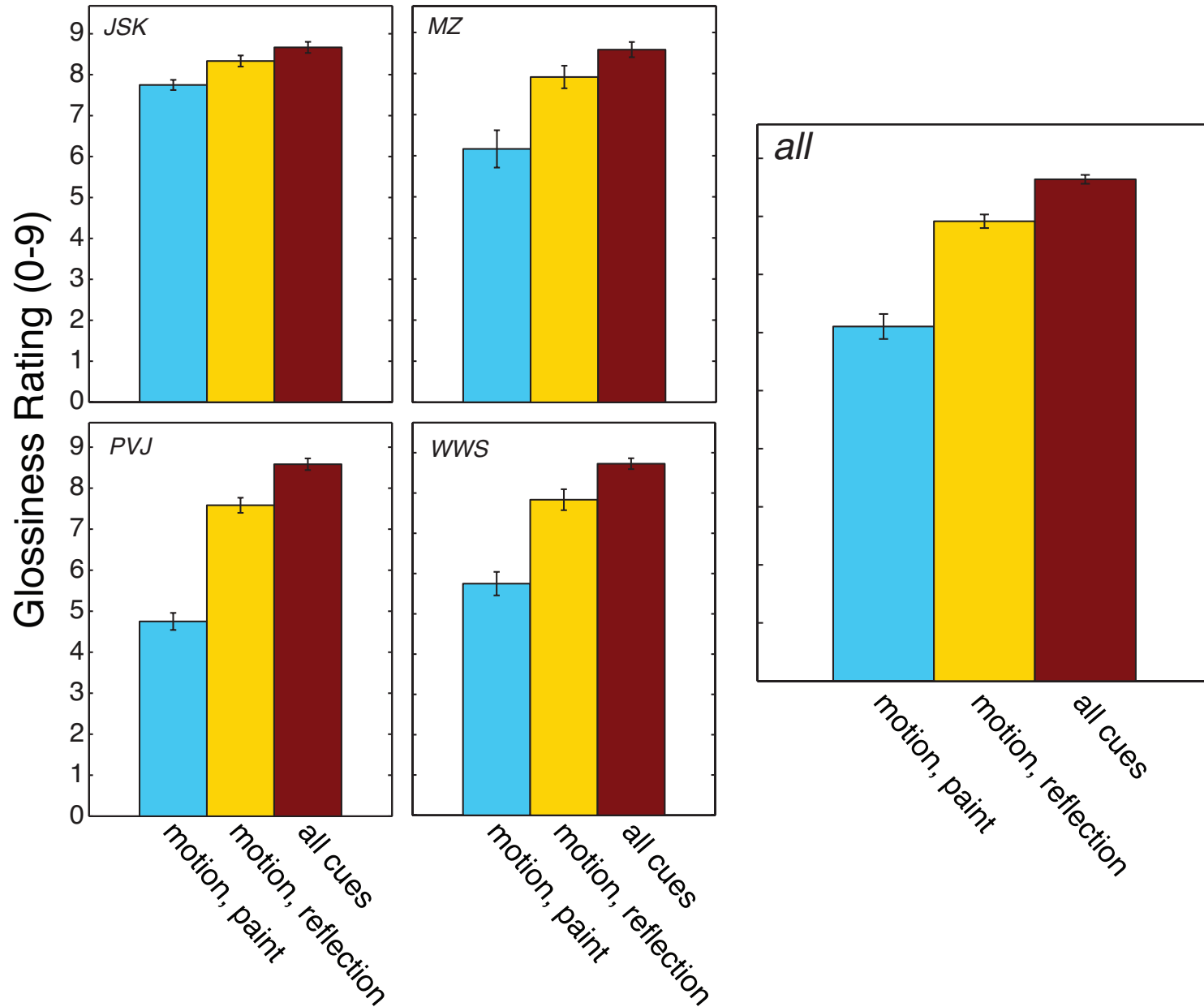


Results: Disparity

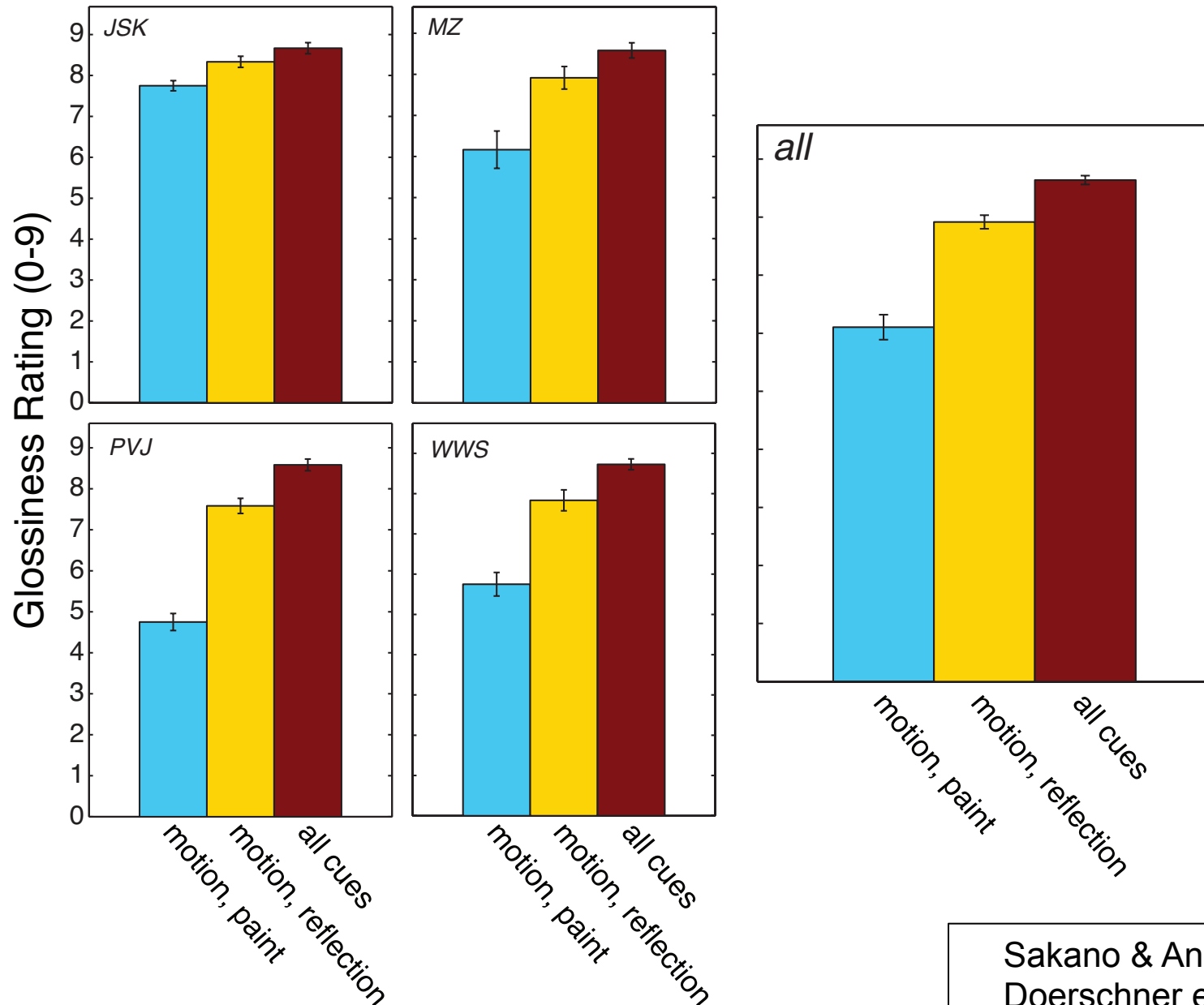


Sakano & Ando (2010)
Wendt, Faul, Ekroll, & Mausfeld (2010)

Results: Motion Parallax

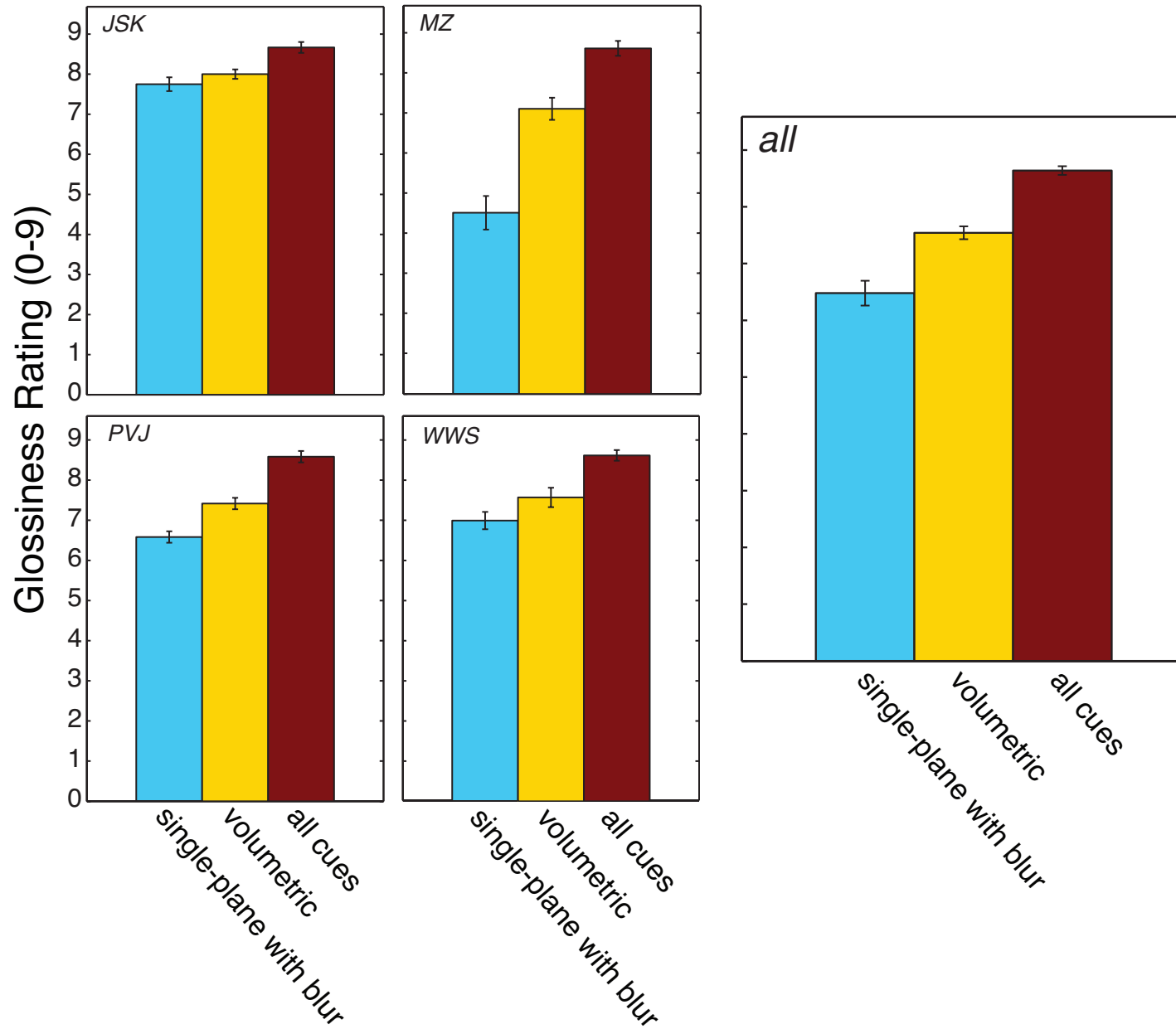


Results: Motion Parallax

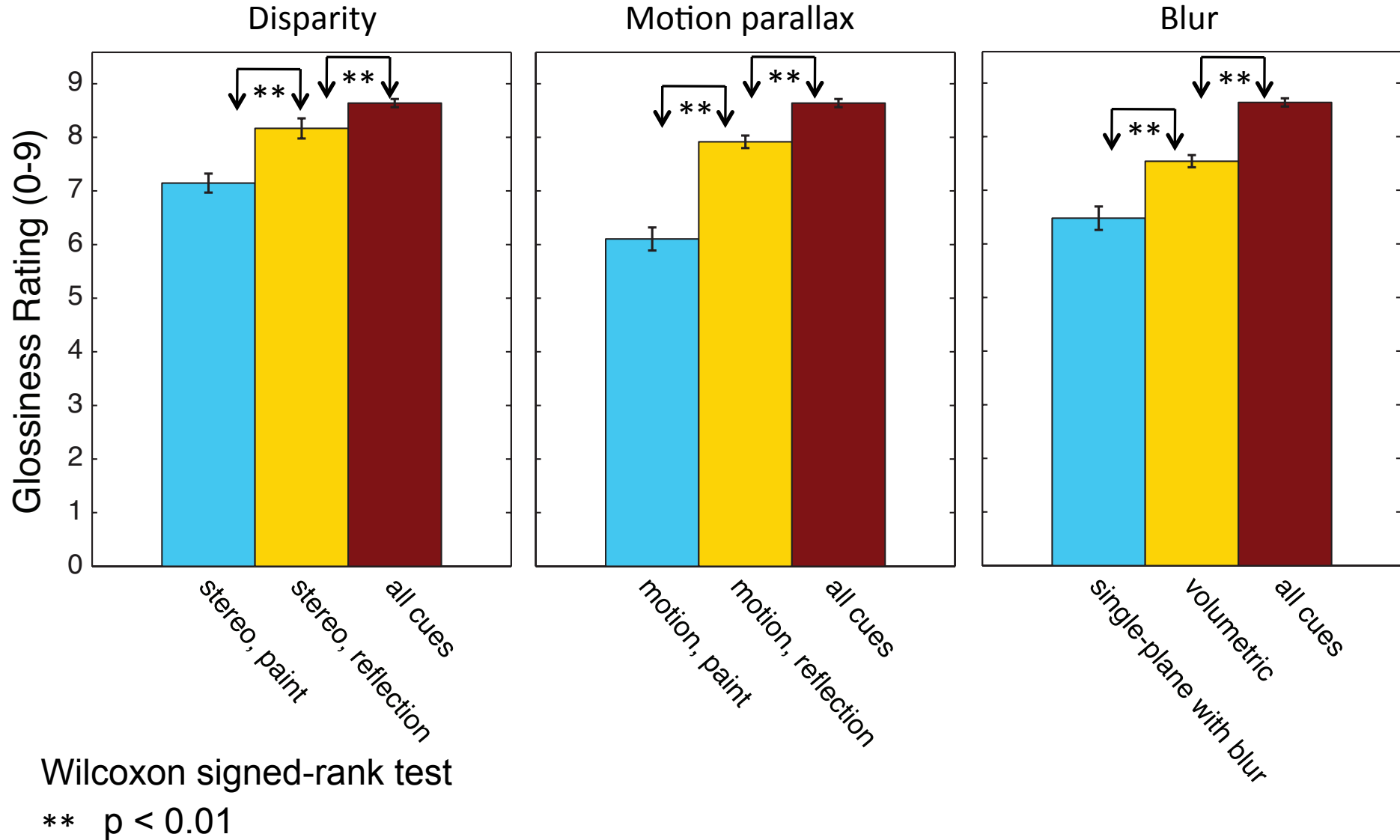


Sakano & Ando (2010)
Doerschner et al. (2011)

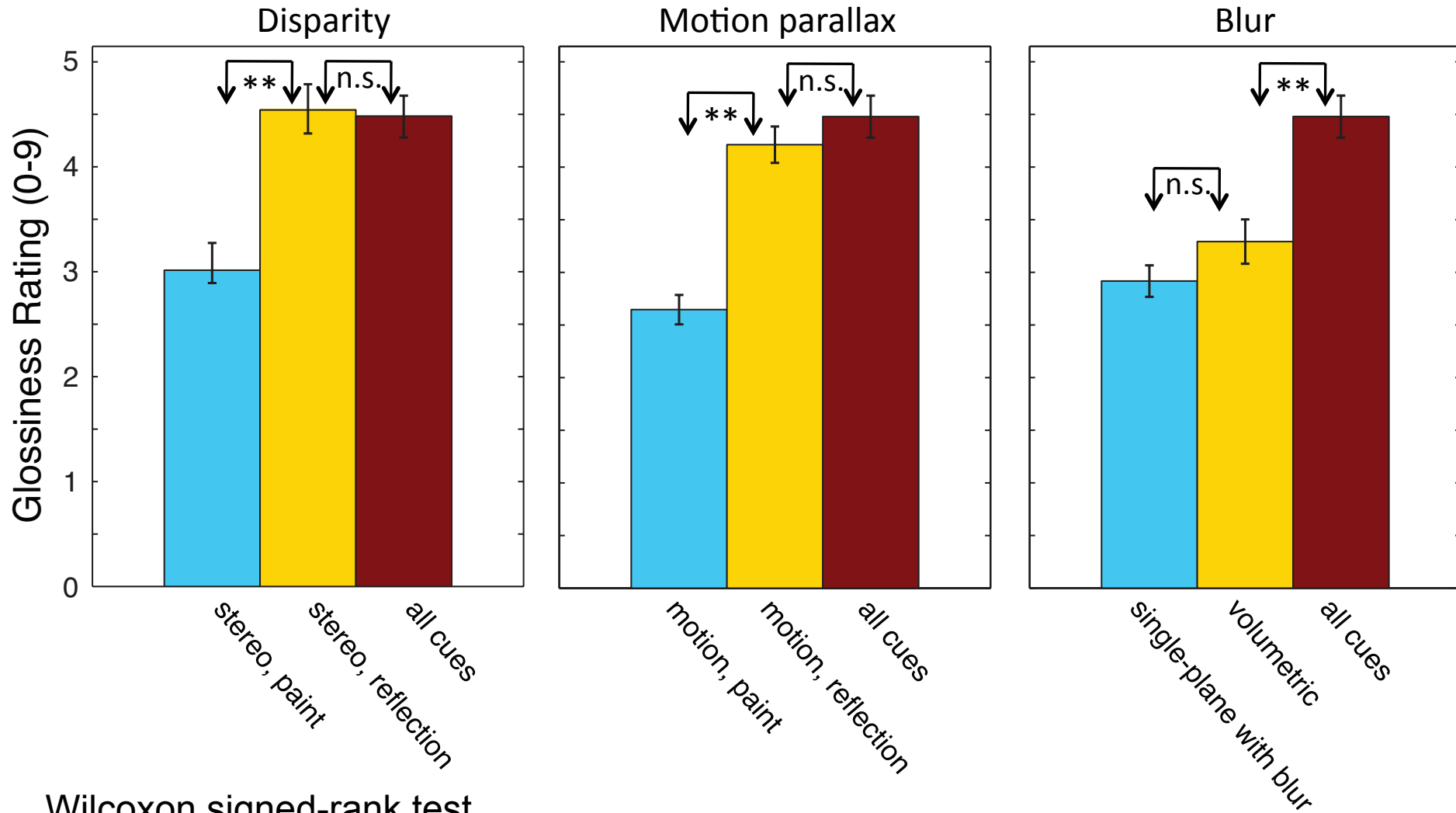
Results: Blur



Average Results: Roughness = 0



Average Results: Roughness = 0.01



Wilcoxon signed-rank test

** $p < 0.01$

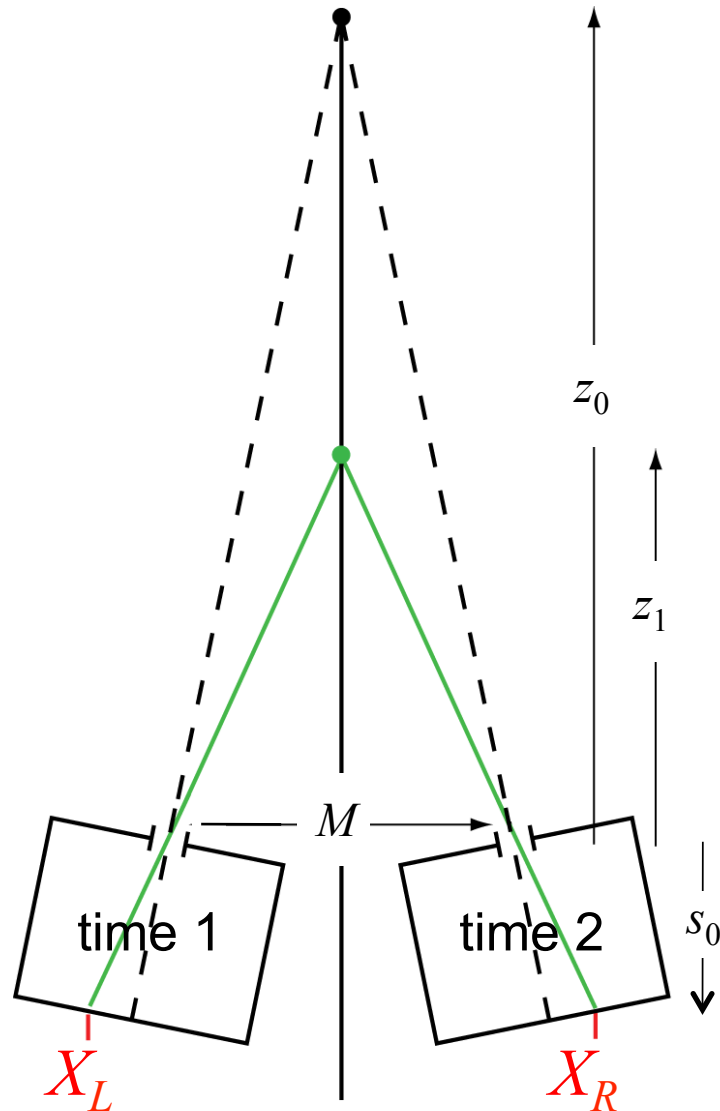
n.s. not significant

Conclusions

- Reflections from specular surfaces with smooth geometry create virtual reflection images distinguishable from the surface by disparity, motion parallax, & blur.
- Humans use each of those reflection cues—in isolation and in combination—to estimate surface gloss. The novel observation is that blur is used.
- When surface material is rough, virtual reflection images become less distinct.
- Pinhole rendering of reflections, which is commonplace, is inappropriate because humans use focus cues to estimate gloss.

Funding from NSF & NIH

Motion Parallax



$$m_1 = X_R - X_L = \frac{Ms_0}{z_0} \left[1 - \frac{z_0}{z_1} \right]$$

$$\mu \approx M \left(\frac{1}{z_0} - \frac{1}{z_1} \right) = M(\Delta D)$$

μ in radians

Motion Parallax



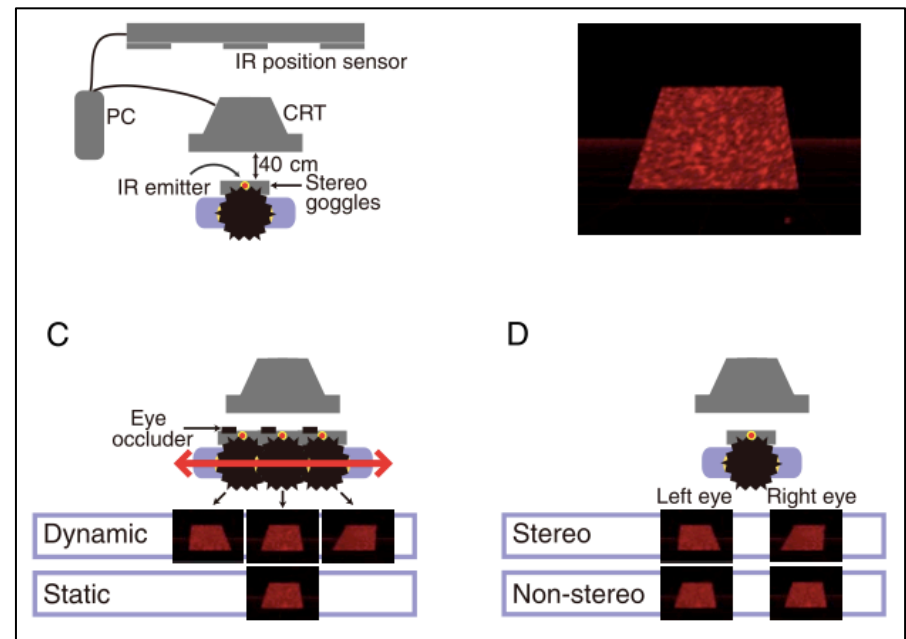
Previous work on triangulation cues and material perception

Perception of gloss is enhanced by

- Changes in illumination with observer motion
- Differences between the two eyes in the luminance of an area

No previous work on blur and material perception

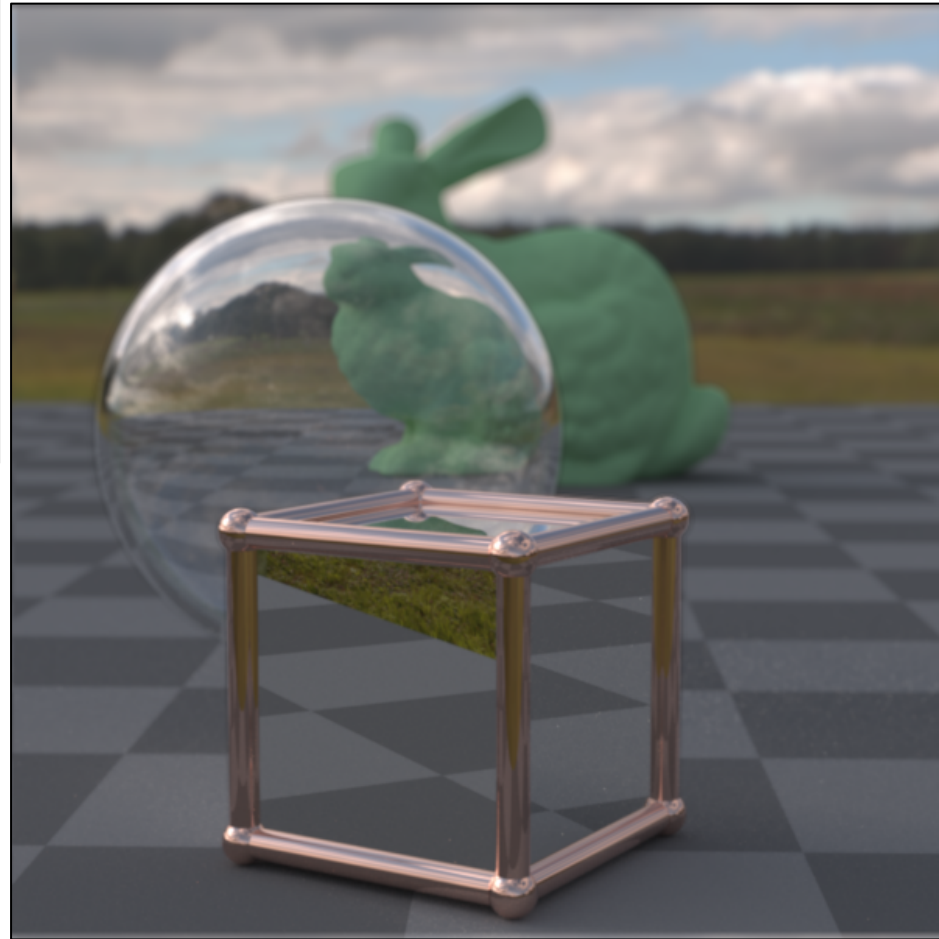
Sakano & Ando
(JOV, 2010)



Example layers (optimized blending)

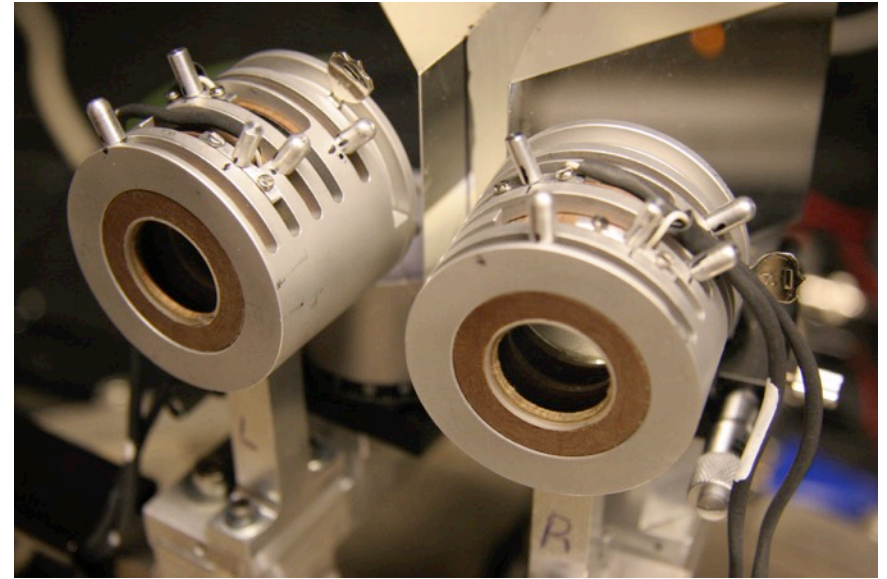
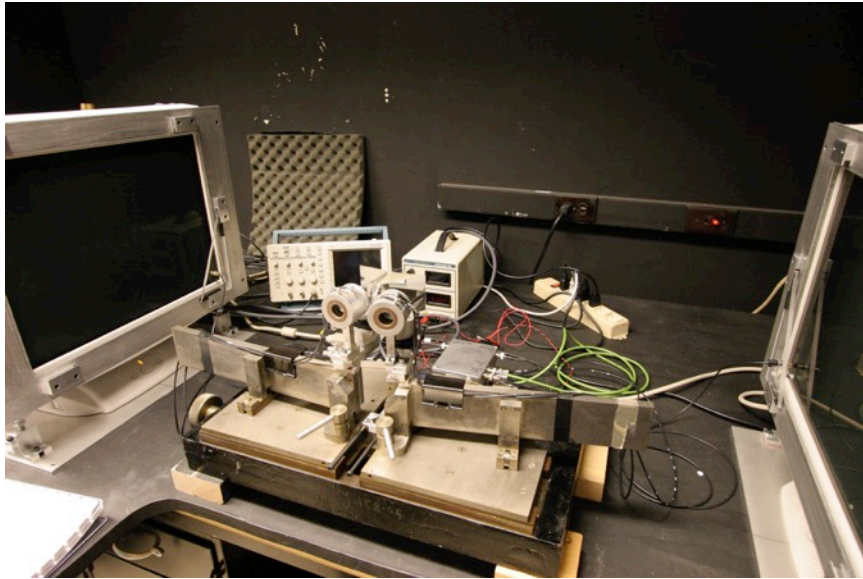
Layers

Original scene



Courtesy of Rahul Narain

Two-monitor Configuration



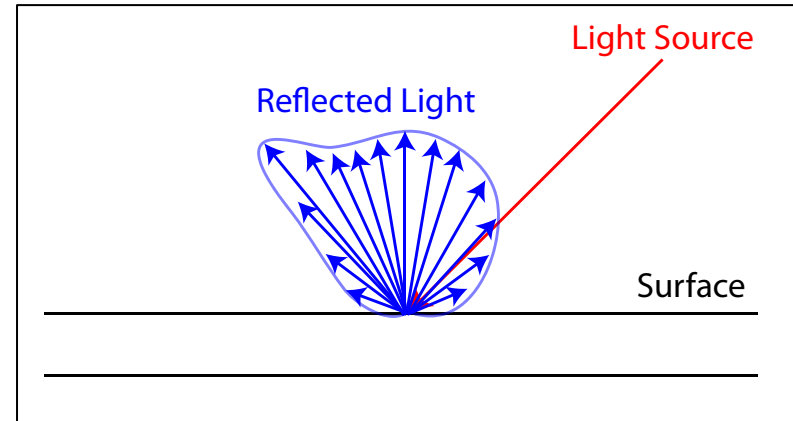
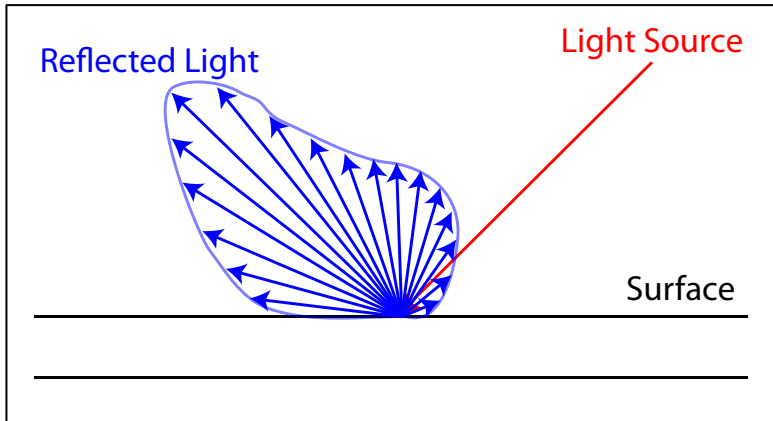
- 4 focal powers separated by 0.6 diopters
- workspace of 1.8 diopters; insertion of ophthalmic lenses allows adjustment
- monitor & lens refresh of 180 Hz, so 45 Hz per eye per lens state
- field of view of $\sim 15^\circ$

Complex materials

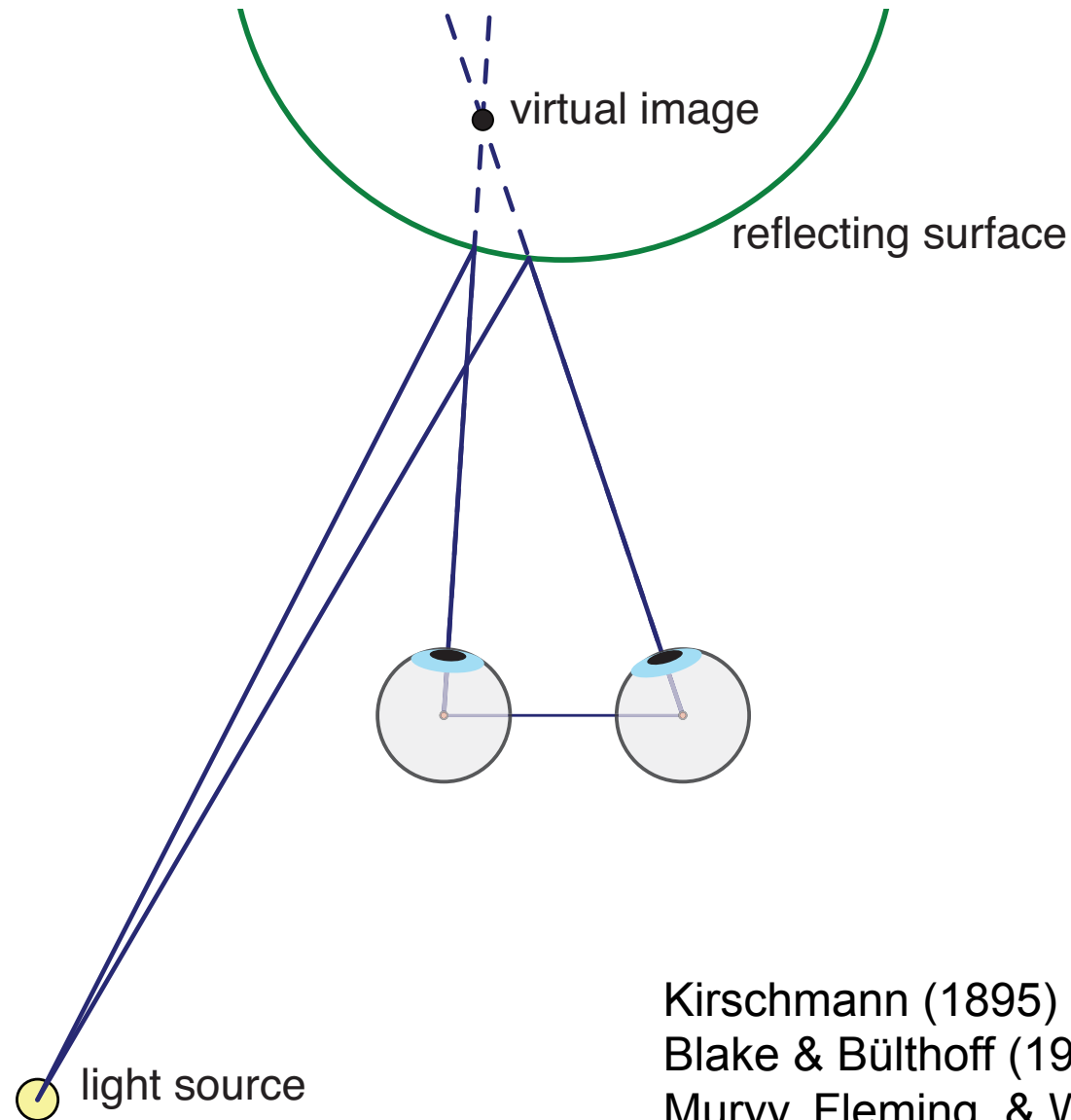
Pearl: Glossy



Rubber: Matte



Reflection Geometry

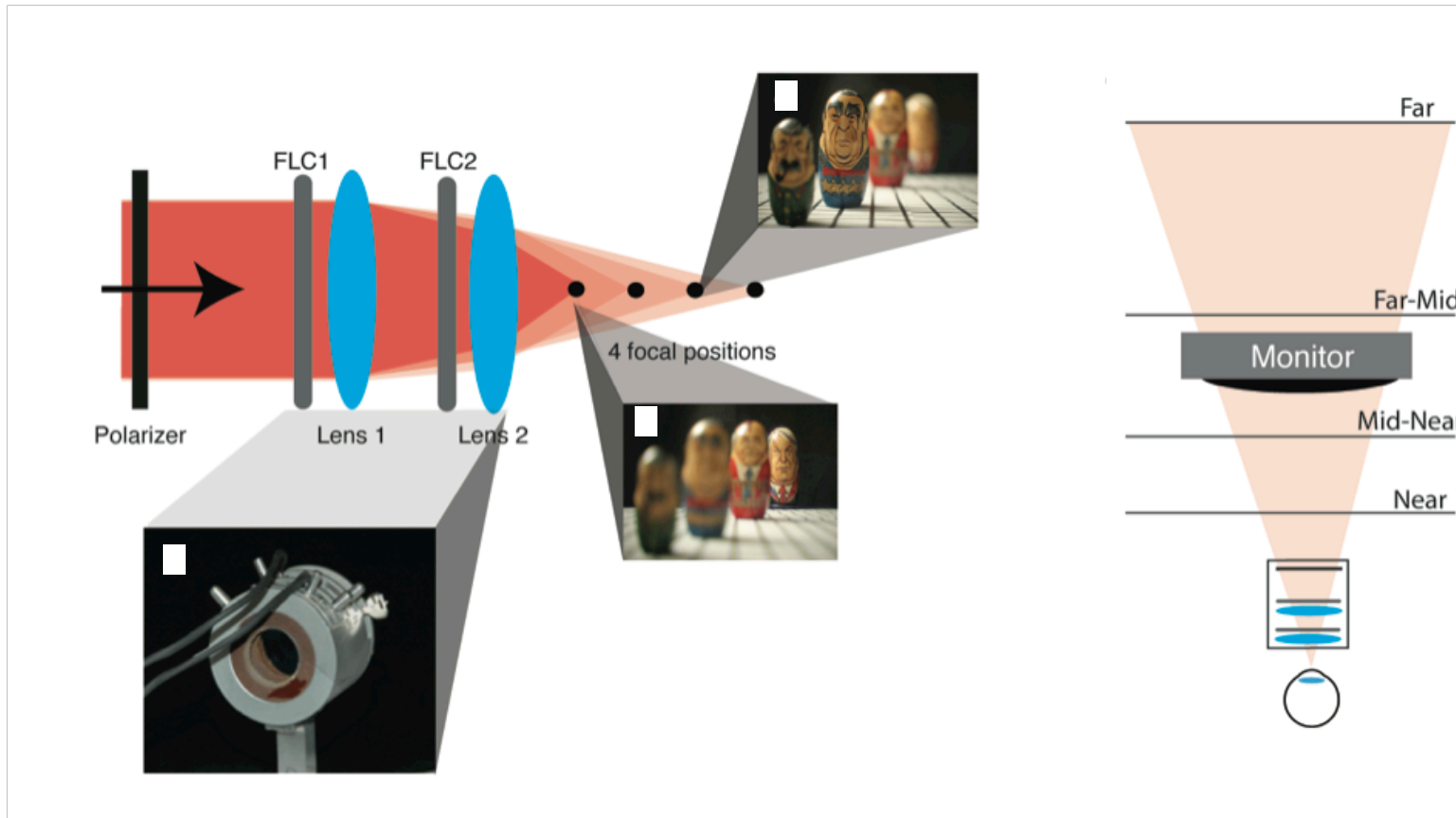


Kirschmann (1895)

Blake & Bülthoff (1990)

Murphy, Fleming, & Welchman (2013)

Schematic of Lens

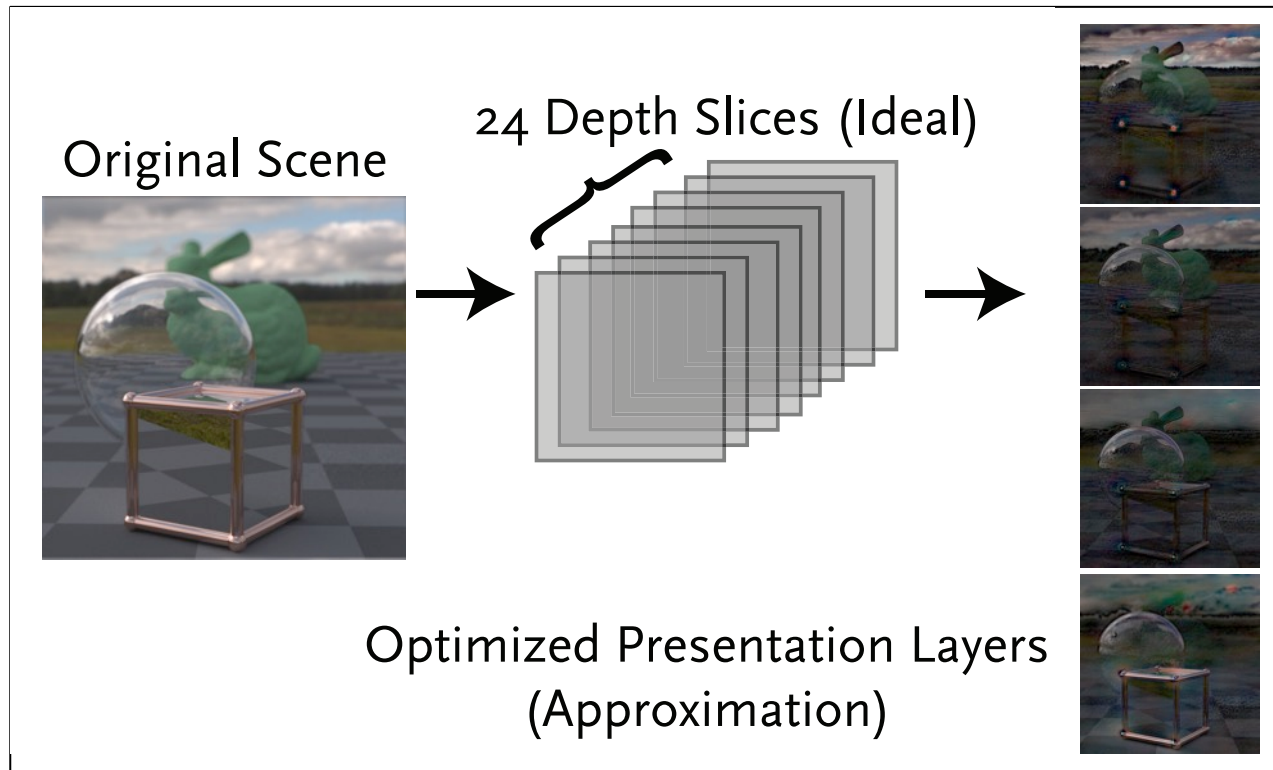


Optimization: in words (for Marty's benefit)

- The input is a set of target images focused at different depths. The unknowns are the images to display on the presentation planes such that the result matches these target images.
- Consider one of the target images, focused at a known depth. When the viewer focuses on that depth in the volumetric display, the image on each presentation plane is blurred by a known PSF. The resulting image seen by the viewer is the sum of these blurred images. We want this image to be the same as the target image.
- We can compute a measure of error between the target image and the viewed image. We seek to minimize the total squared error across all target focus depths, as long as the presentation images remain within the displayable range.

Optimized blending technique

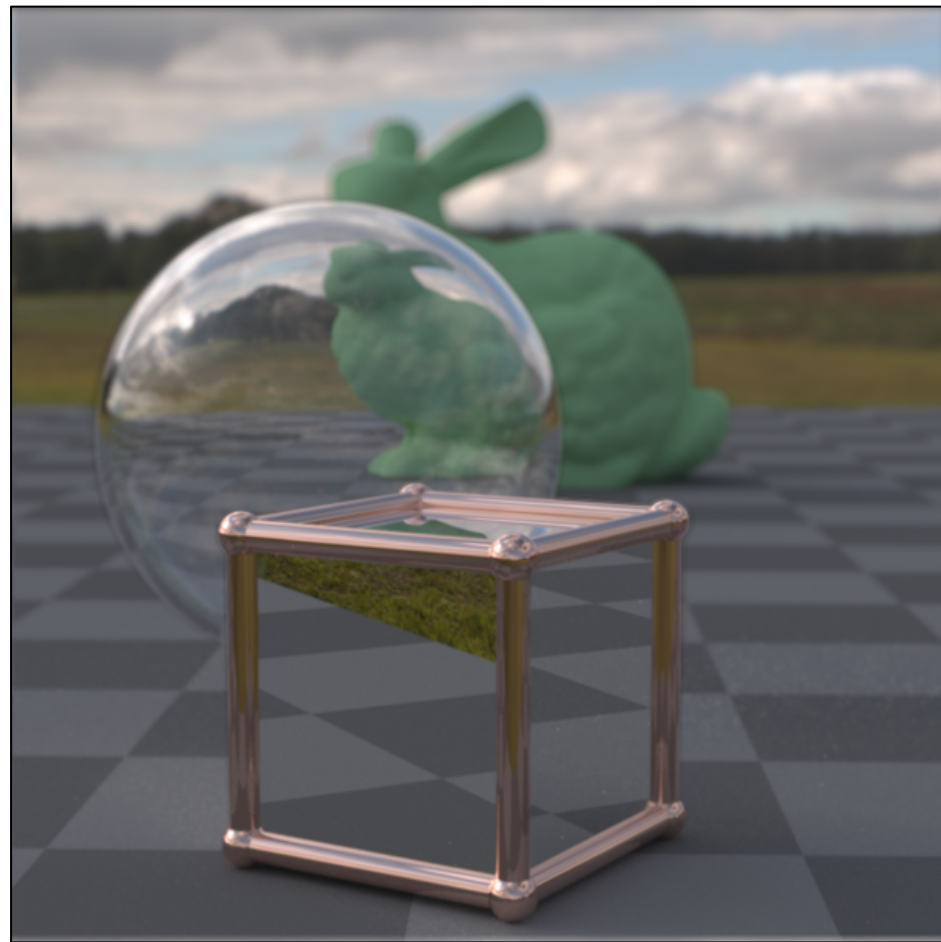
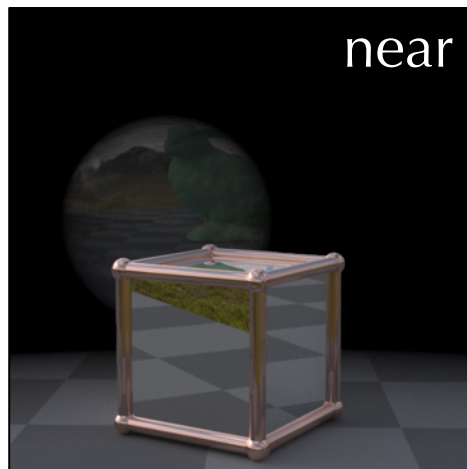
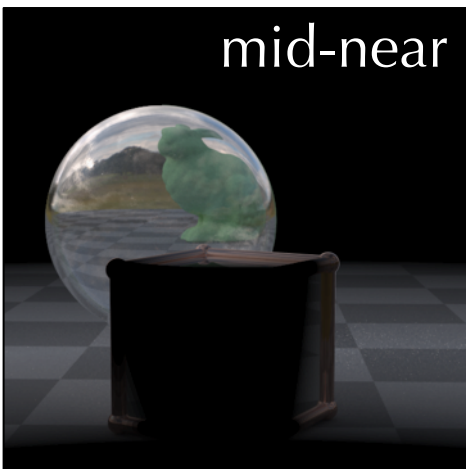
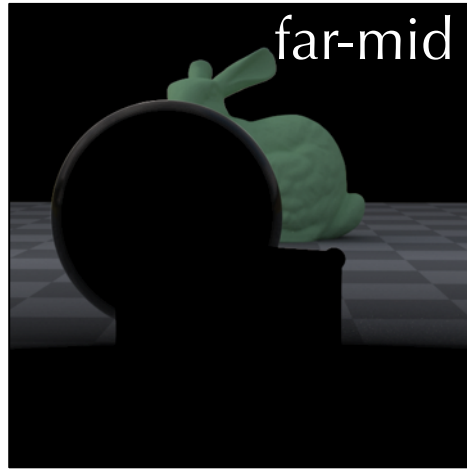
The layers are calculated such that their sum approximates the original scene



Example layers (linear blending)

Layers

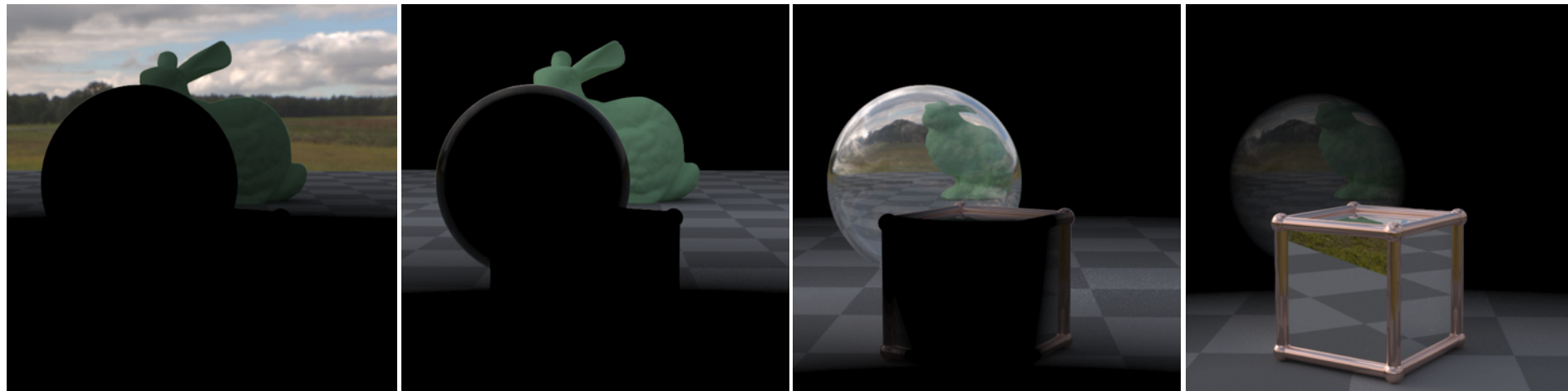
Original scene



Courtesy of Rahul Narain

Comparison of results

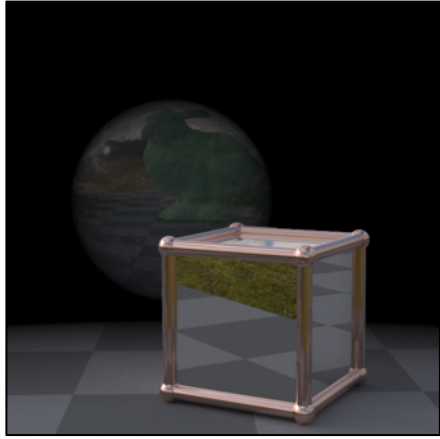
Linear Blending Technique



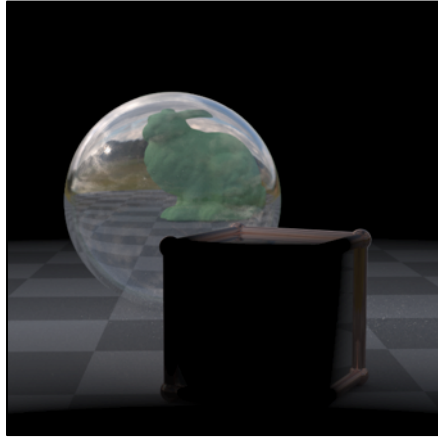
Optimization Technique



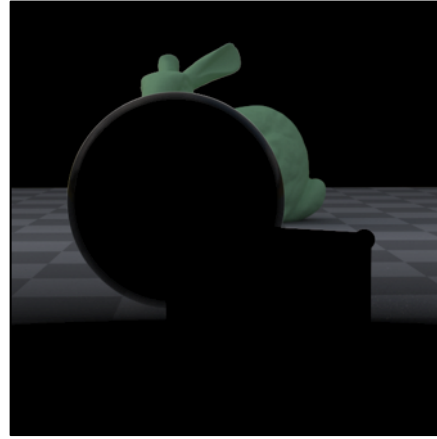
Linear Depth-weighted Blending



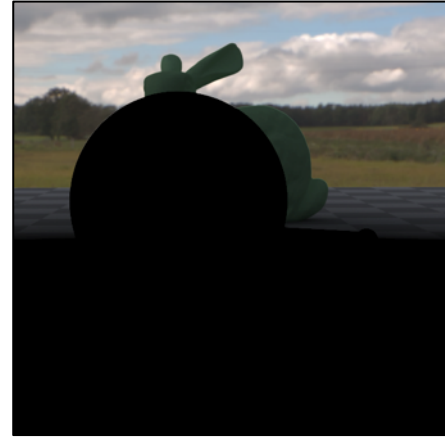
p_1



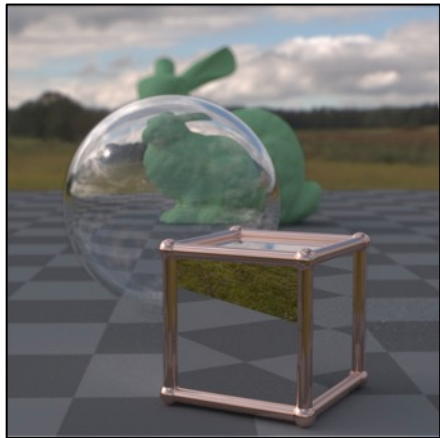
p_2



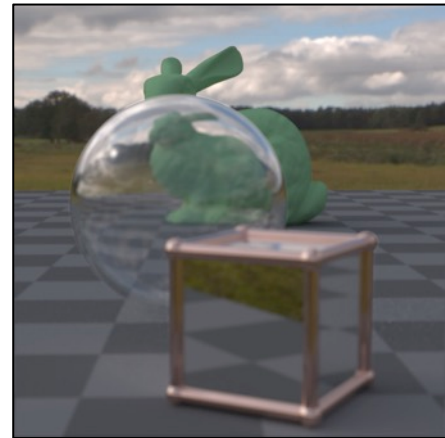
p_3



p_4

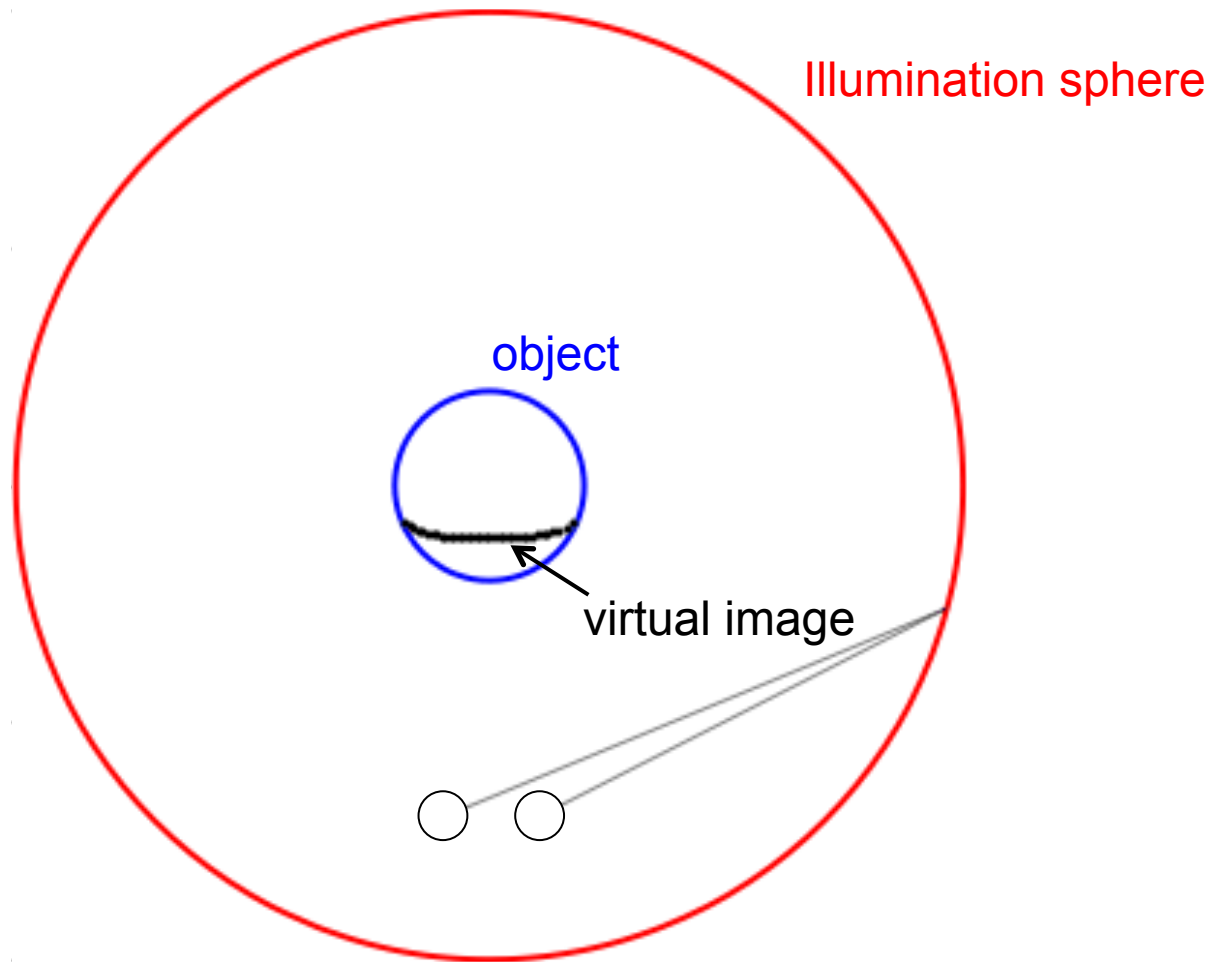


near focus



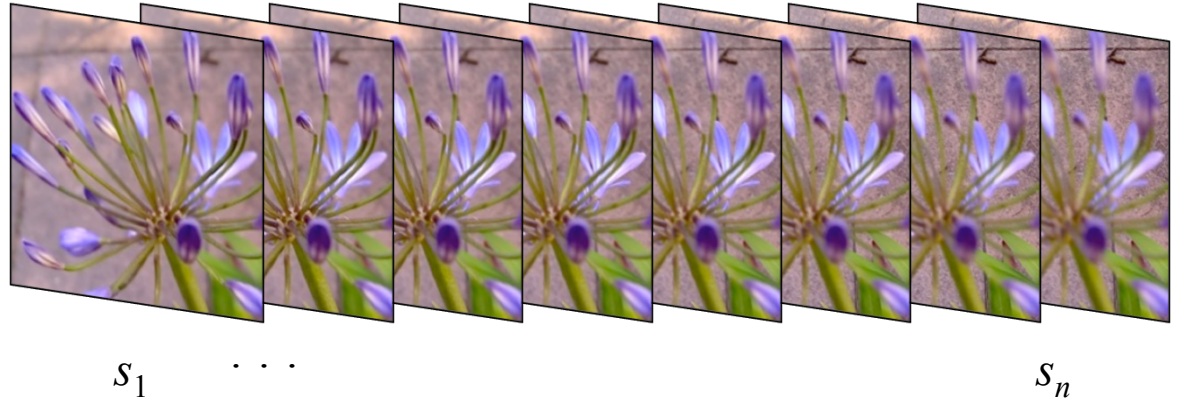
far focus

Reflection Geometry

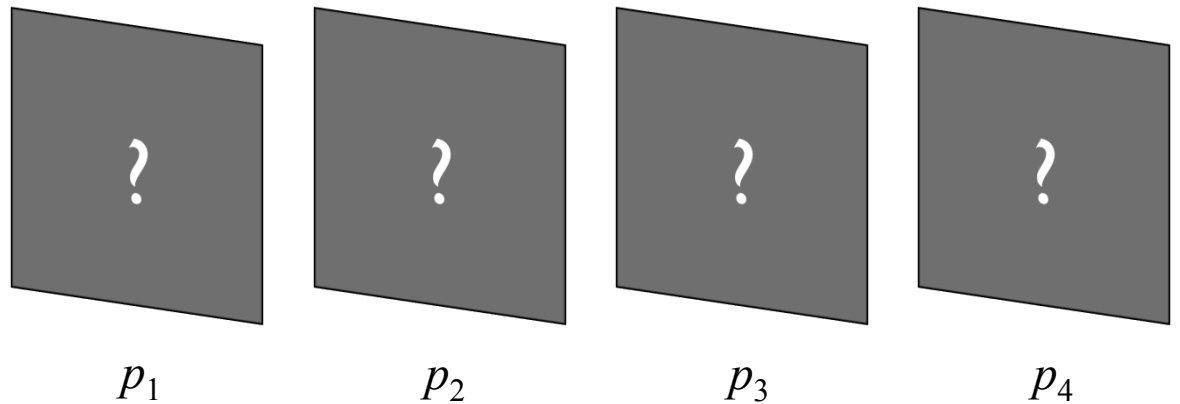


Optimized Blending

Input: target images
with different focus depths

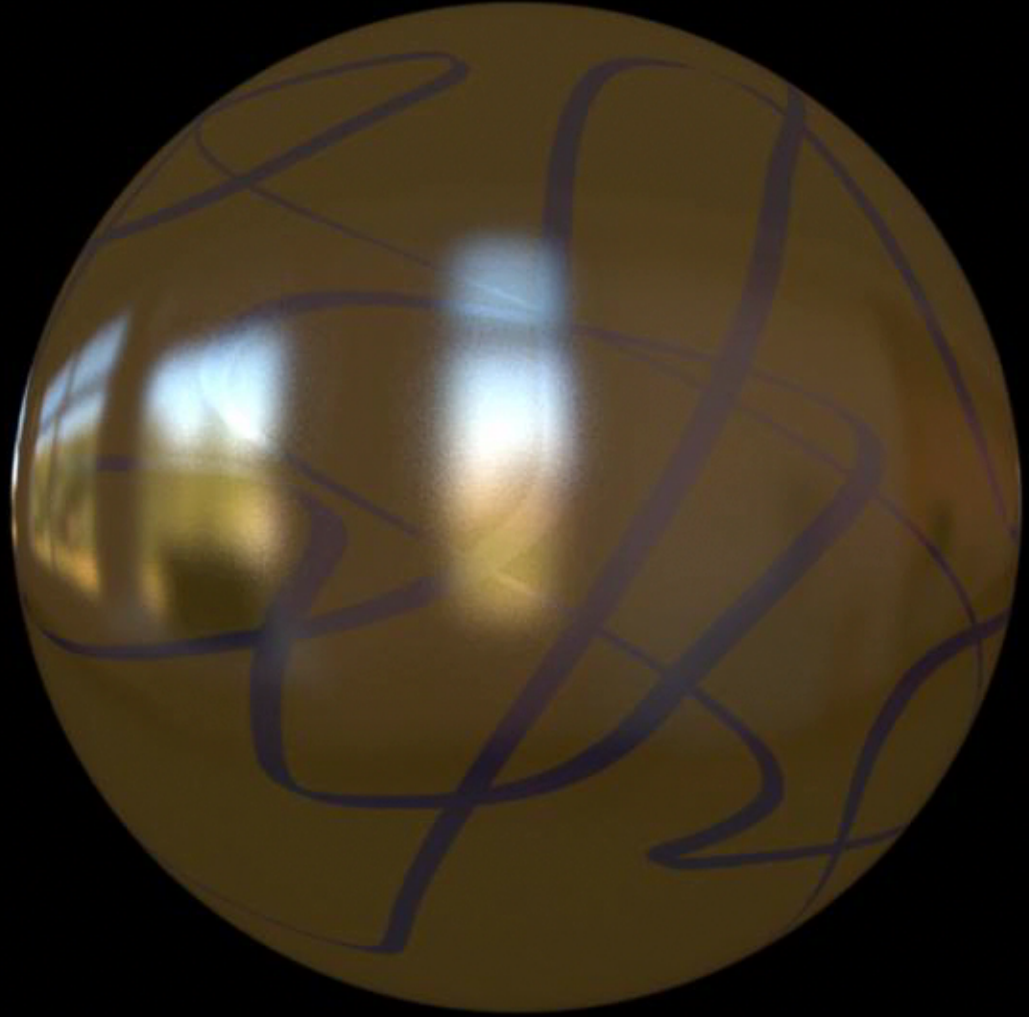


Unknown: images to display
on presentation planes



Experimental Stimulus: Motion Parallax

reflection



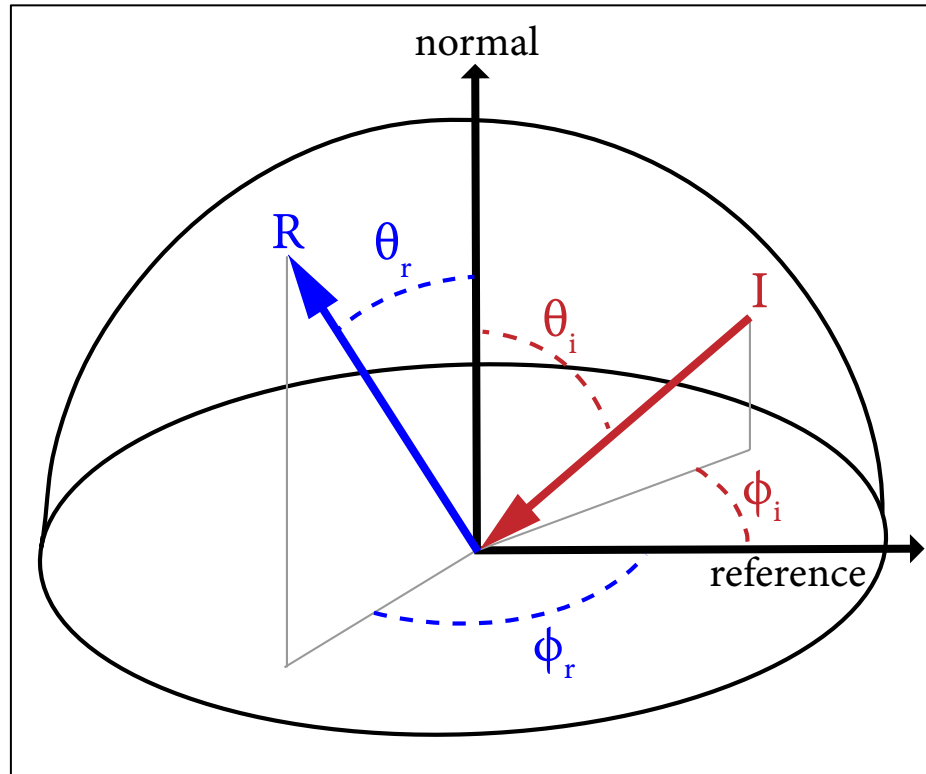
Experimental Stimulus: Motion Parallax

paint



Bidirectional Reflectance Distribution Function

I: incoming light
R: outgoing light



$$\rho_{bd,iso}(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{\rho_d}{\pi} + \rho_s \cdot \frac{1}{\sqrt{\cos \theta_i \cos \theta_r}} \cdot \frac{\exp \left[-\frac{\tan^2 \delta}{\alpha^2} \right]}{4\pi\alpha^2}$$

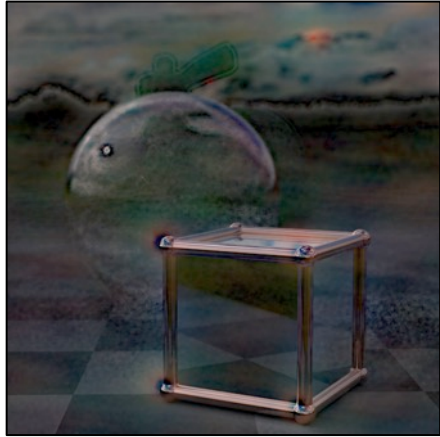
δ angle between normal and half angle between θ_i and θ_r

ρ_d diffuse reflectance

ρ_s specular reflectance

α standard deviation (RMS) of surface slope

Optimized Blending



p_1



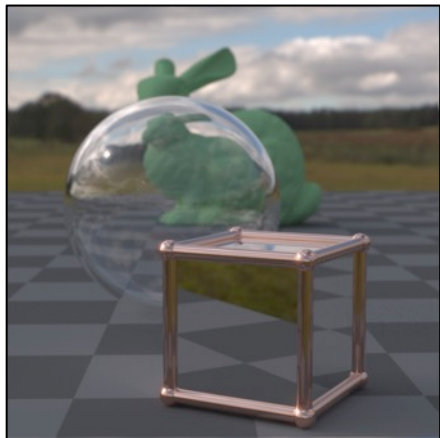
p_2



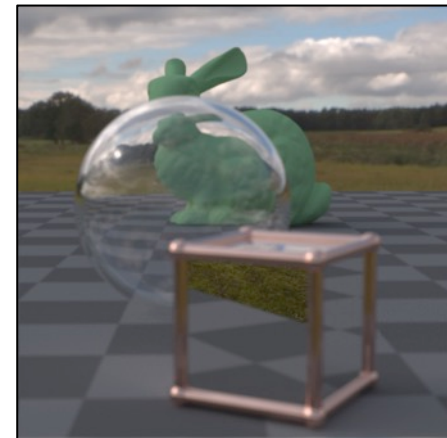
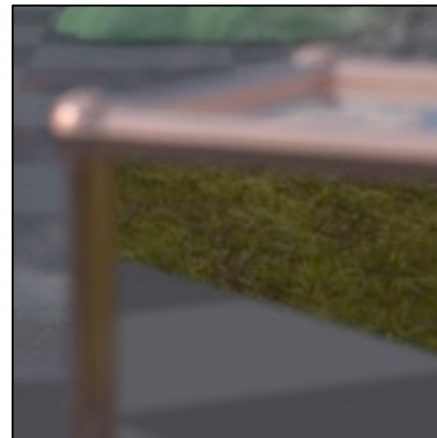
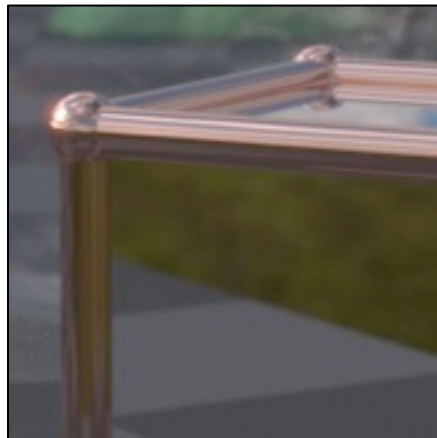
p_3



p_4



near focus



far focus