Observation method of photon flow using virtual reality headsets -Application to architectural light environment design-

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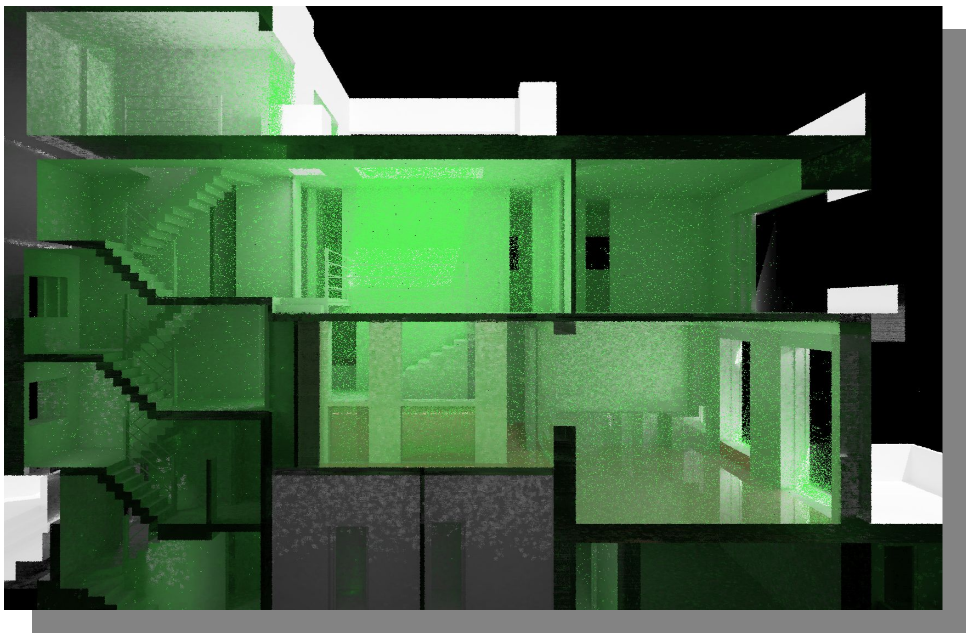
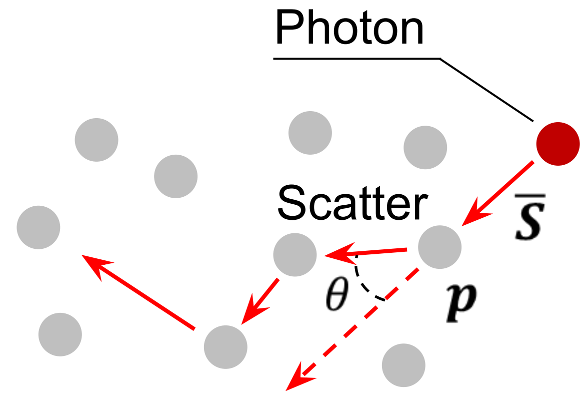
Radiance Workshop 2023 in Innsbruck

1. Motivation and purposes

<u>Photon Flow: Volume Photon</u>





Mean free distance : $\overline{s}$

$$\overline{s} = -\frac{\log \xi}{\sigma_t}, \qquad \xi \in [0,1]$$

Absorption : p

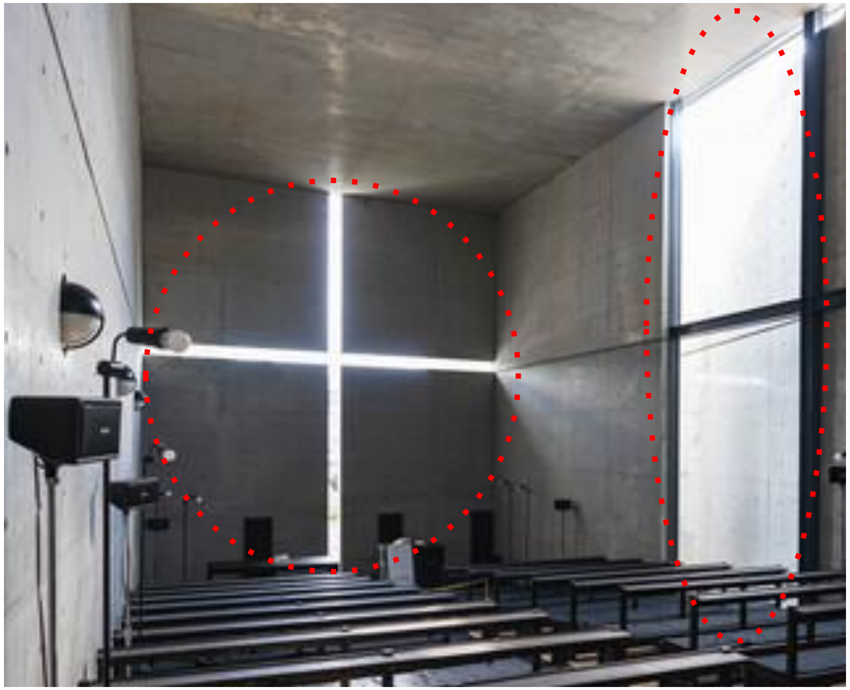
$$p = 1 - \sigma_\alpha, \qquad \sigma_\alpha \in [0,1]$$

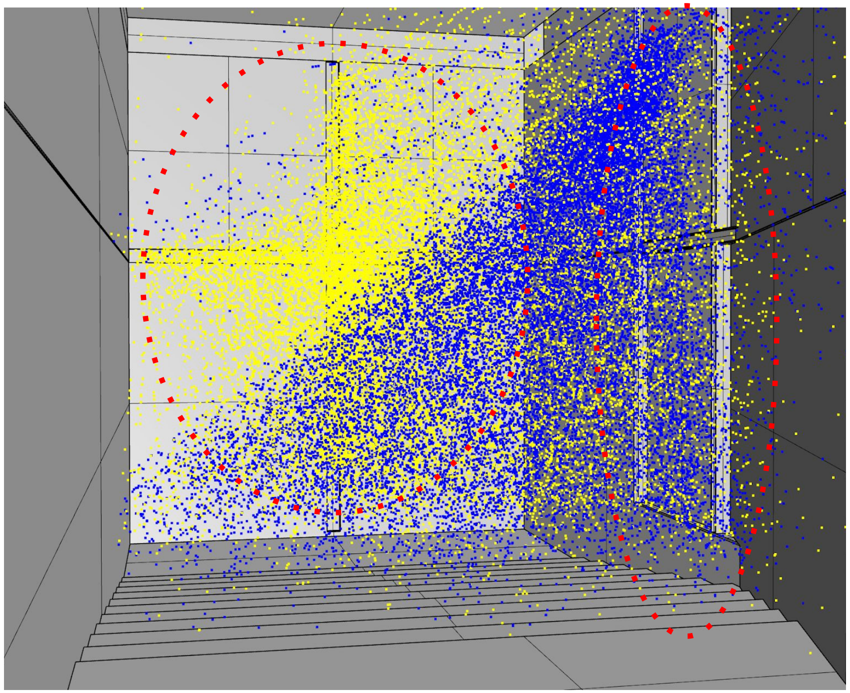
- Volume photons deposited in <u>nonabsorbing / nonscattering</u> mist
- Directional light distribution as particles (photons) in volume
- Photons carry RGB flux, direction
- Estimate illuminance on arbitrary surface (≙ photon density)

1. Motivation and purposes

Photon Flow: The Church of the Light

Designed by Tadao Ando, built 1989 in Osaka, Japan

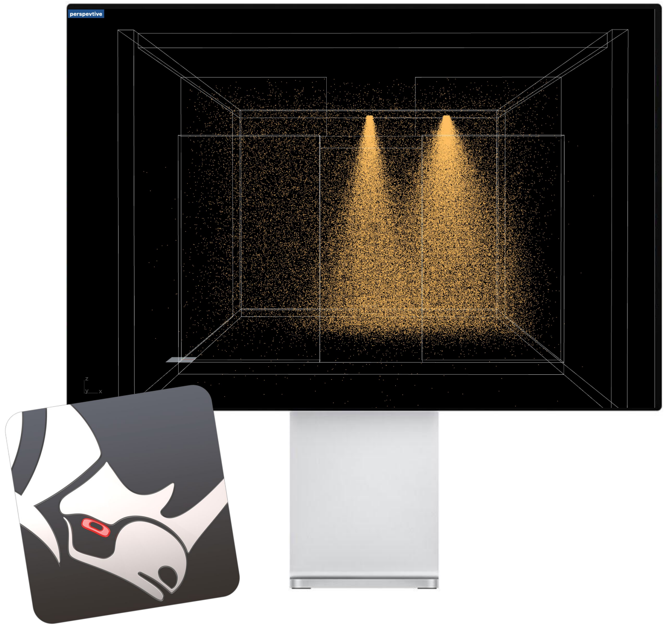




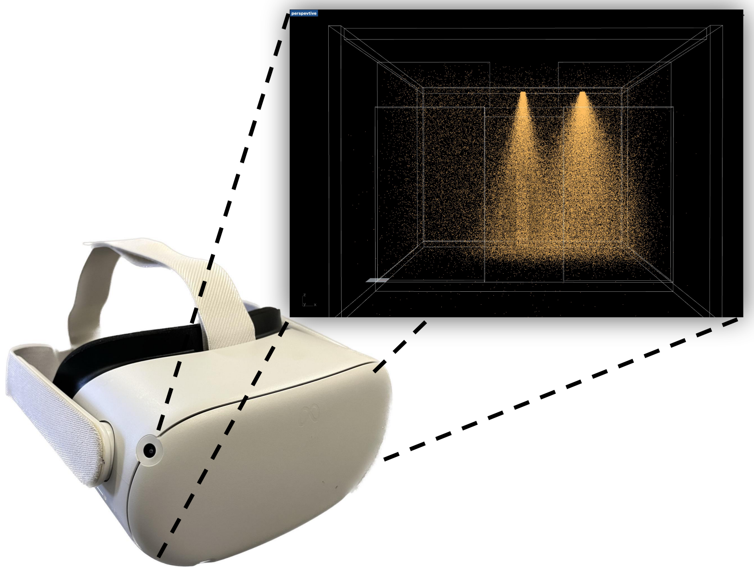
The light distribution from the front and side openings is well visualised by the photons.

1. Motivation and purposes

Observation method



Observation in 2D displays



Observation in HMDs

We propose a new observation method of photon flow, in which photons are displayed on HMDs and observed in stereoscopic view.

2. Observation method of photon flow using HMDs.

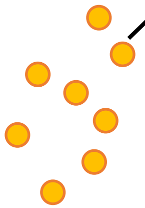
Making photon flow

mkpmap -apV ***.vpm ***k -me .001 .001 .001 -ma 1 1 1 -mg 1 ***.oct

-me .001 .001 .001: density of photons along a ray

-ma 1 1 1: nonabsorbing / -mg 1: nonscattering

pmapdump -a -n ***k ***.vpm > ***.xyz



Photon

xyz coordinates and RGB

UNREAL

ENGINE

Meta Quest2

Unreal Engine is used to display the photon flow on the HMD.

3. Estimation of Light Field

Physical Light Field

▸ No consideration of psychological effects, simply the physically correct light field.

Visual Light Field

▸ Light field perceived by people.

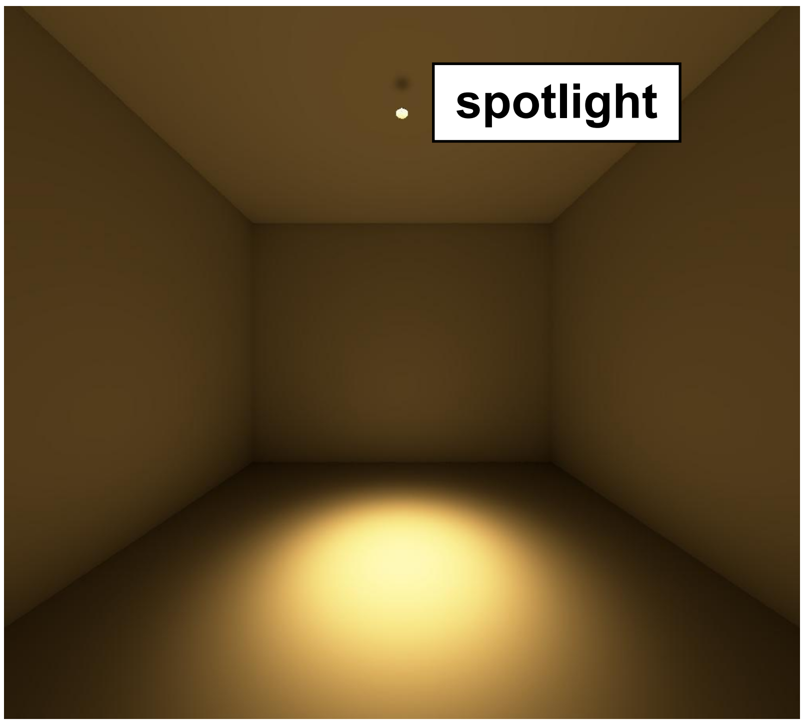
By understanding the physical light field, it is possible to predict how light will hit an object and how it will ultimately appear.

We examined whether people could predict the physical light field when they observed photon flow in VR space.

3. Estimation of Light Field

Experimental space

A single **directional light source** at the center of the ceiling

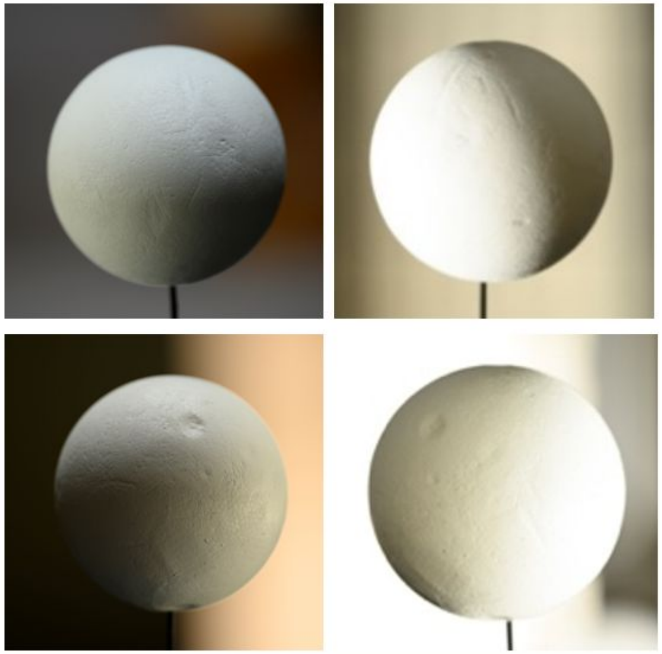


A single **diffuse light source** on the center of the floor

3. Estimation of Light Field

The white sphere method

The **white sphere method,** proposed by Kartashova, was employed in this experiment to capture the light field, in which participants **predicted the shade on a virtual (= not physically existing) white sphere**.

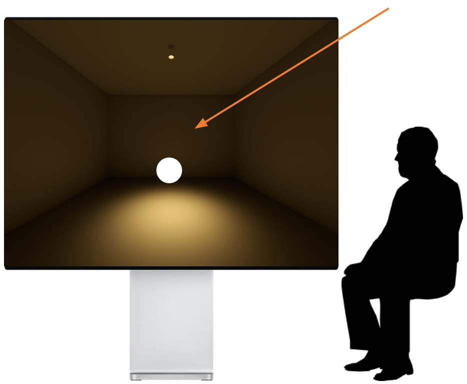


Not actually installed in the presented space

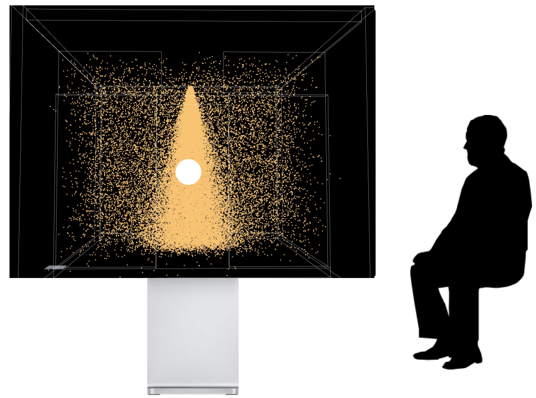
3. Estimation of Light Field

Three methods for presenting the experimental space

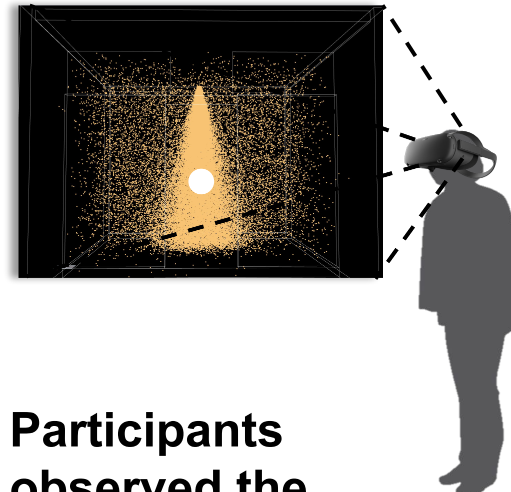
virtual white sphere
(evaluation position)



Participants observed rendered images that reproduce real space.



Participants observed the photon flow presented on the 2D displays.

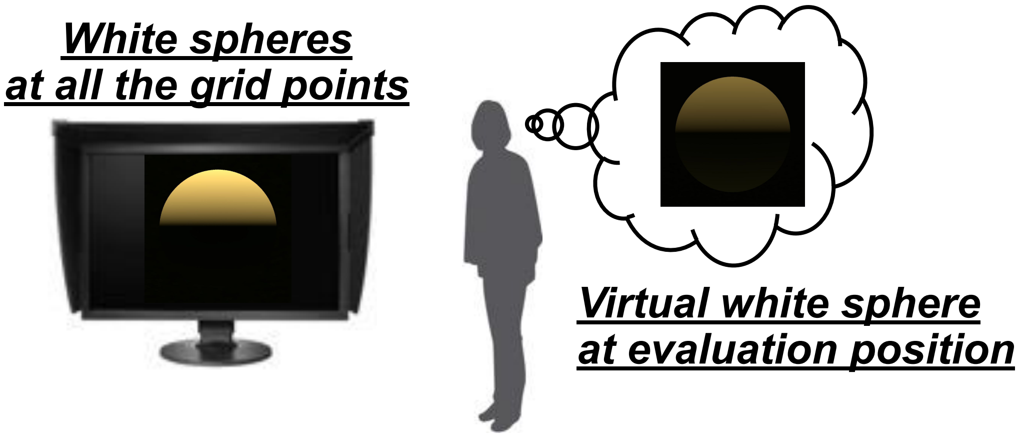


Participants observed the photon flow on HMDs (VR space).

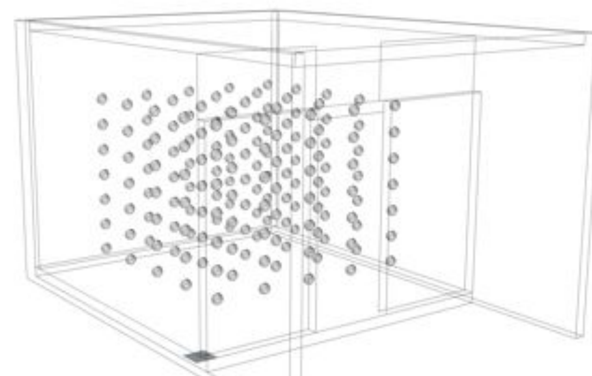
Participants infered the shades on the virtual (i.e. physically not existing) white sphere which was supposed to be at the position indicated by the experimenter.

3. Estimation of Light Field

Evaluation Method



Participants judged whether the shades on the white spheres at all the grid points were correct/undecided/incorrect.



Grid points for the white spheres in the room

- **The participant compared the shades on white sphere images on all the grid points in the room presented on a monitor with their own estimation of the shade on the virtual white sphere.**
- **These white sphere images, which were prepared in advance and representing the light field at various locations in the space, were always rendered from the horizontal direction.**
- **The participant judged whether the shade presented on the monitor was correct/undecided/incorrect as the one on the virtual white sphere.**

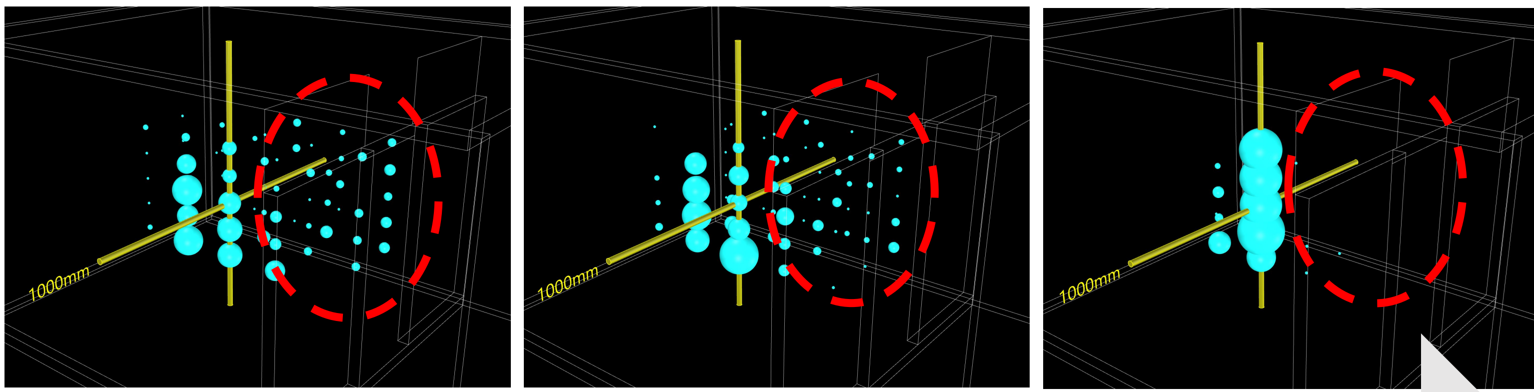
3. Estimation of Light Field

Results

The larger the sphere size is, the more participants answered ”correct”.

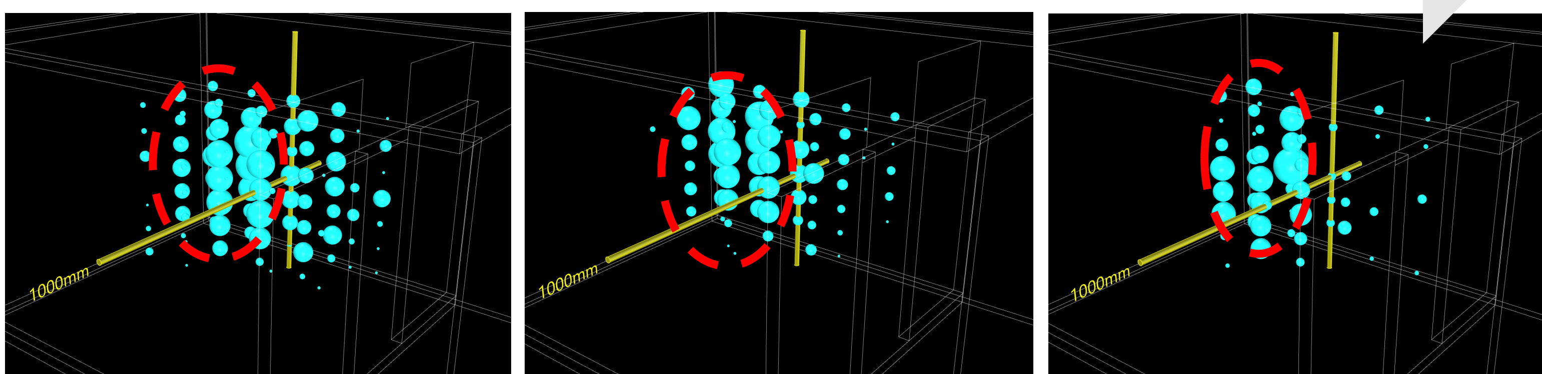
Visual Light Field | **Photon flow on 2D Displays** | **Photon flow (HMD)**

The directional light condition



The number of participants who answered "correct" to the shades of the white spheres at the incorrect position was decreased.

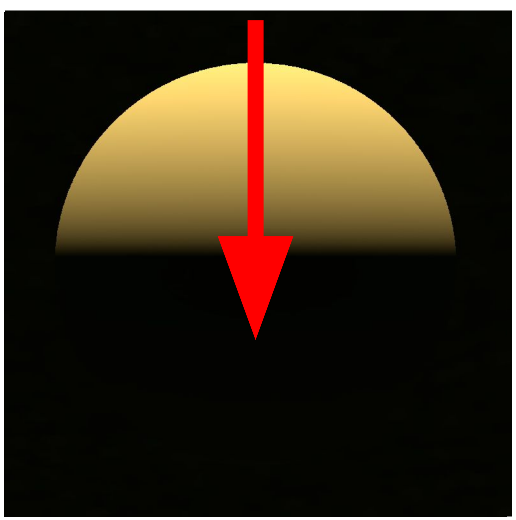
The diffuse light condition



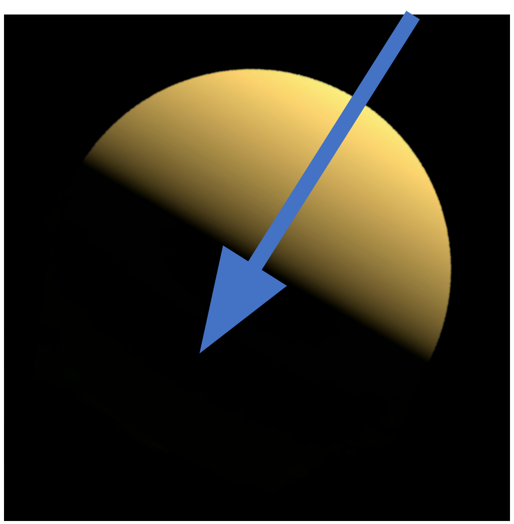
3. Estimation of Light Field

<u>Three metrics (direction/intensity/diffuseness)</u> were used to confirm how well participants could perceive the physical light field.

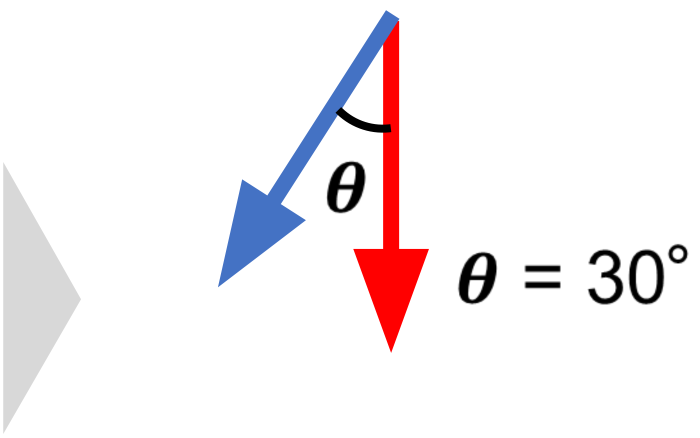
Directionality : $\theta = cos^{-1} \frac{\overrightarrow{E_v} \cdot \overrightarrow{E_p}}{|\overrightarrow{E_v}||\overrightarrow{E_p}|}$



Physically correct shade



Estimated shade

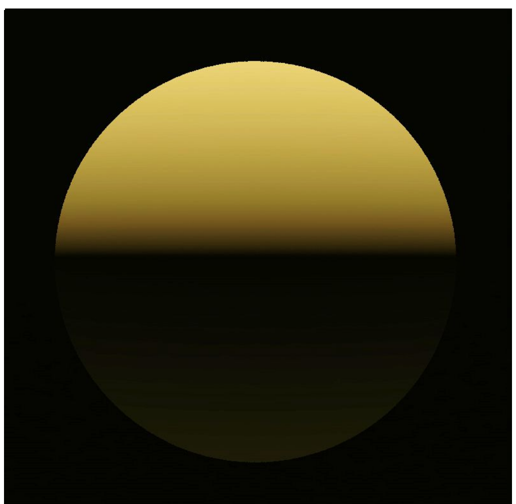


The closer θ is to 0, the closer the light field is to the physical light field.

3. Estimation of Light Field

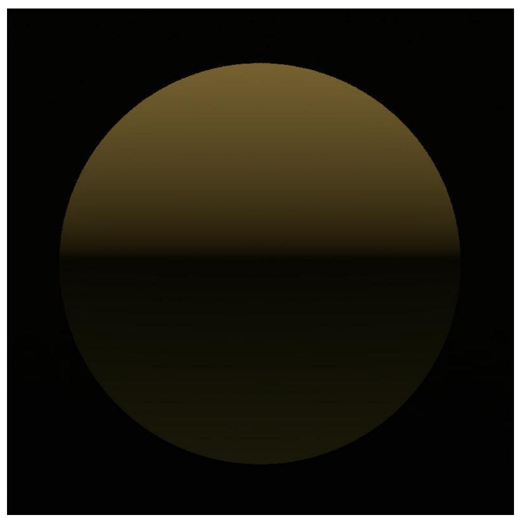
<u>Three metrics (direction/intensity/diffuseness)</u> were used to confirm how well participants could perceive the physical light field.

Intensity: $E_{scalar} = \frac{\left|\overrightarrow{E_v}\right|}{4} + \sim E$



Physically correct shade

$E_{scalar(p)}$ =**146**



Estimated shade

$E_{scalar(e)}$ =**27**

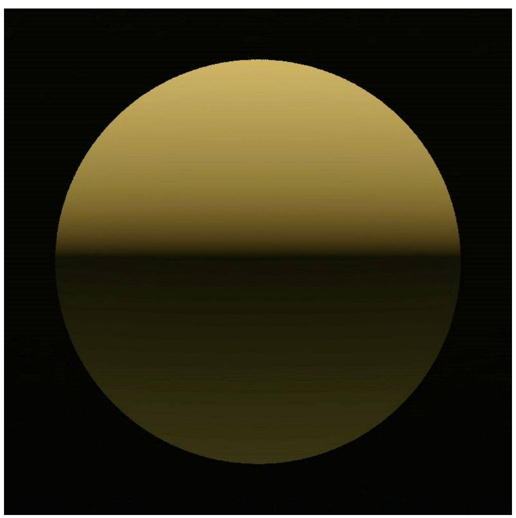
$$|log(E_{scalar(p)}) - log(E_{scalar(e)})| = 0.7$$

The closer the value is to 0, the closer the light field is to the physical light field.

3. Estimation of Light Field

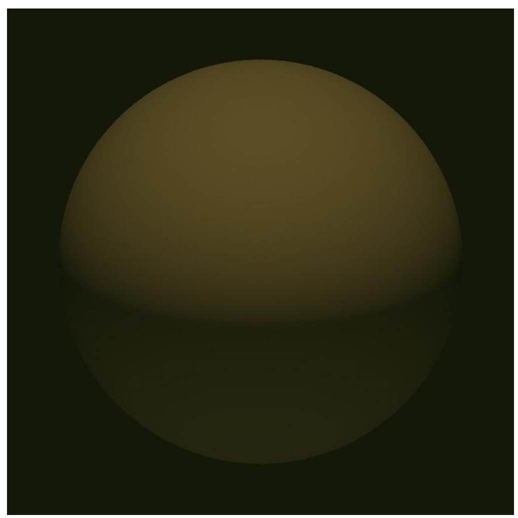
<u>Three metrics (direction/intensity/diffuseness)</u> were used to confirm how well participants could perceive the physical light field.

Diffuseness：$D = 1 - \frac{|\overrightarrow{E_v}|}{4E_{scalor}}$



Physically correct shade

$D_{(p)} = 0.01$



Estimated shade

$D_{(e)} = 0.39$

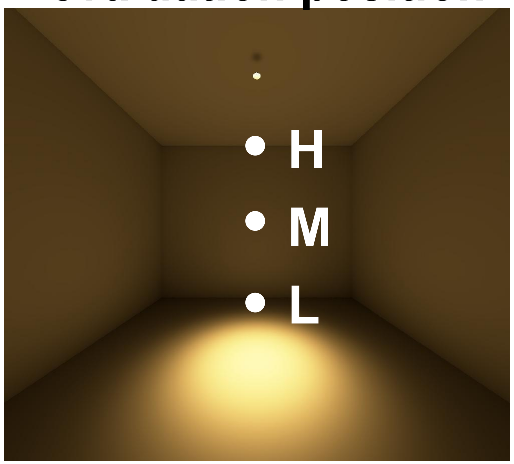
$$|D_{(p)} - D_{(e)}| = 0.38$$

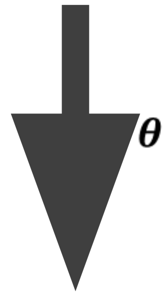
The closer the value is to 0, the closer the light field is to the physical light field.

3. Estimation of Light Field

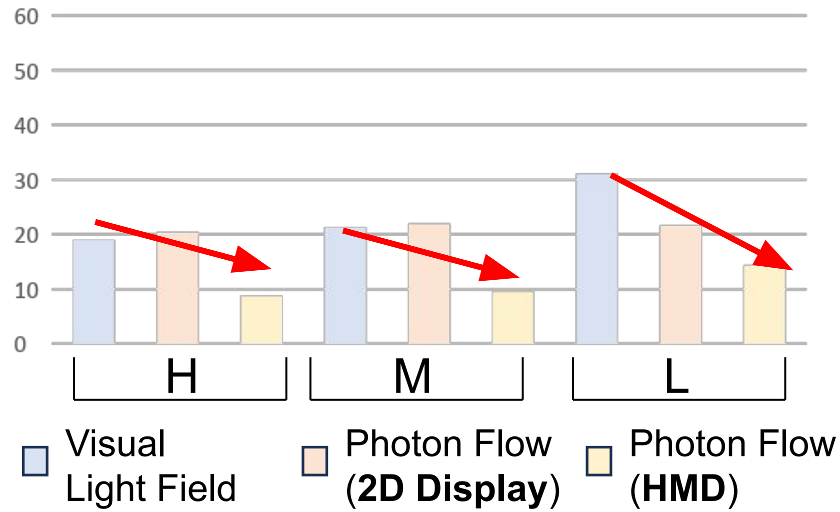
Directional light source condition: Directionality

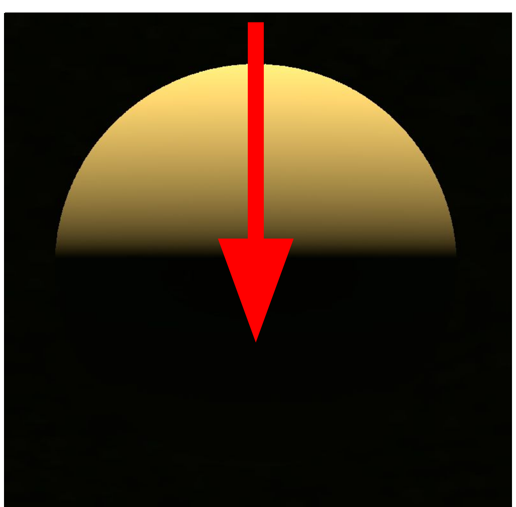
evaluation position



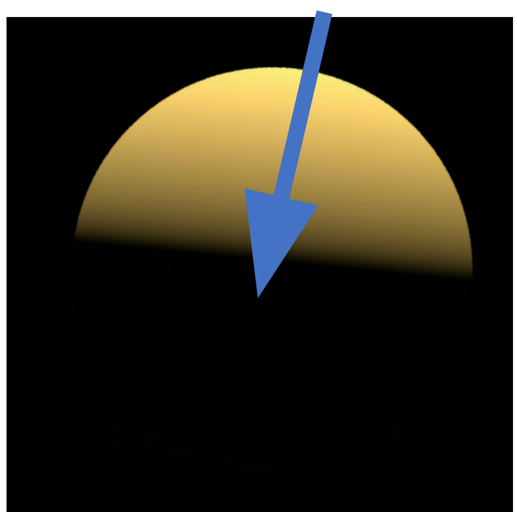


Approaching to the physical light field value

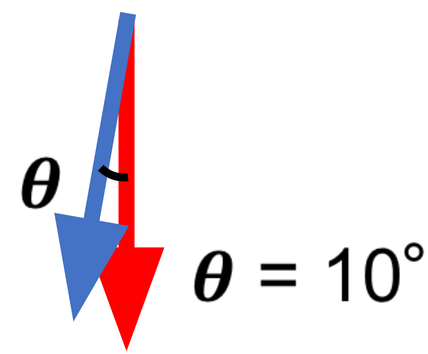




Physically correct shade



Estimated shade

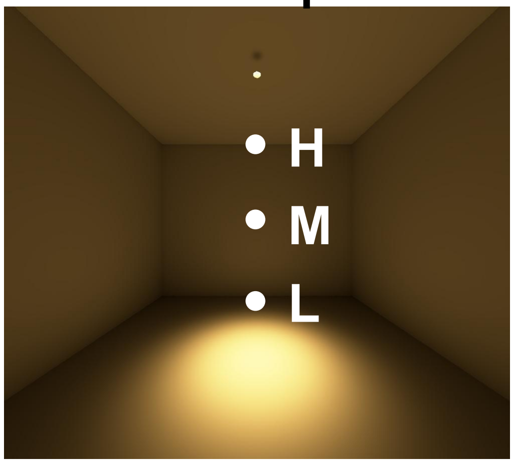


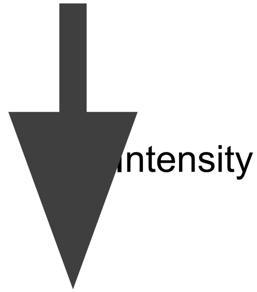
When Photon Flow was observed in the VR space, the directionality is close to the value of physical light field.

3. Estimation of Light Field

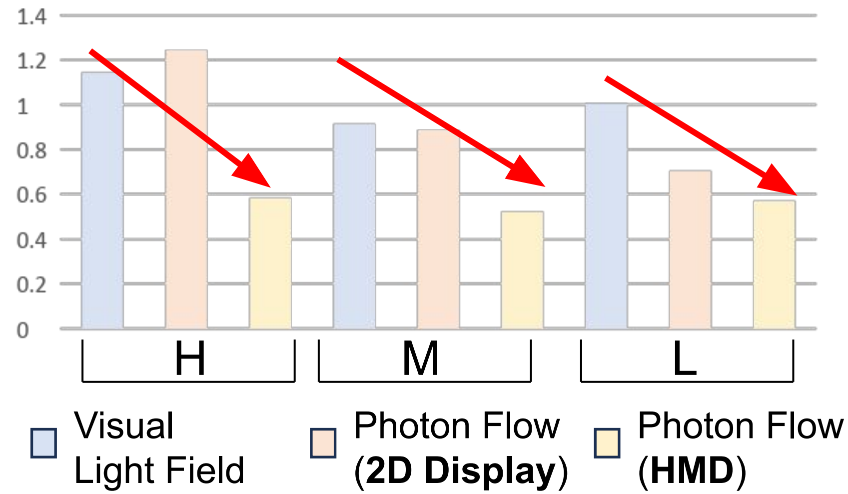
Directional light source condition: Intensity

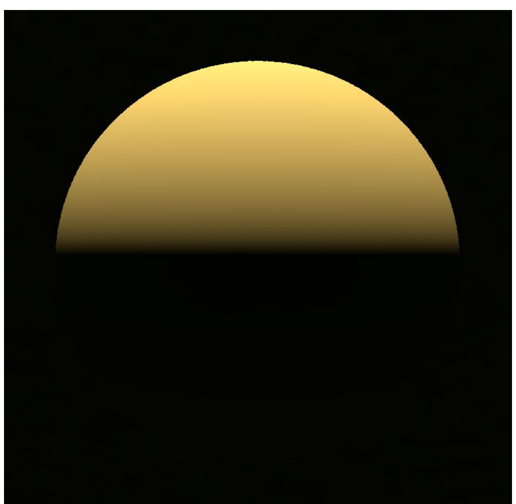
evaluation position





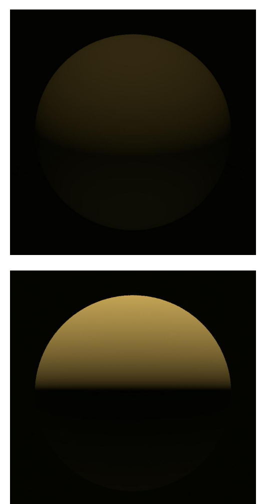
Approaching to the physical light field value





Photon Flow(2D)

Photon Flow(VR)



$= 1.1$

$= 0.5$

The closer the value is to 0, the closer the light field is to the physical light field.

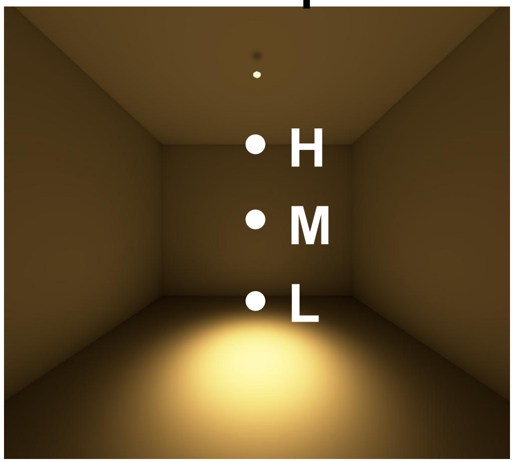
Physically correct shade

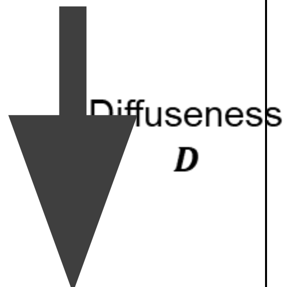
Estimated shade

3. Estimation of Light Field

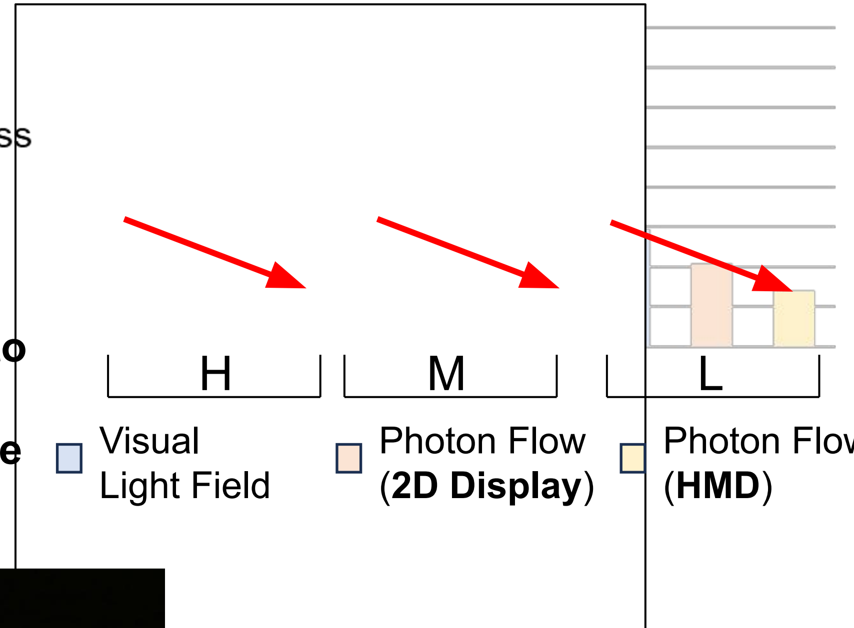
Directional light source condition : Diffuseness

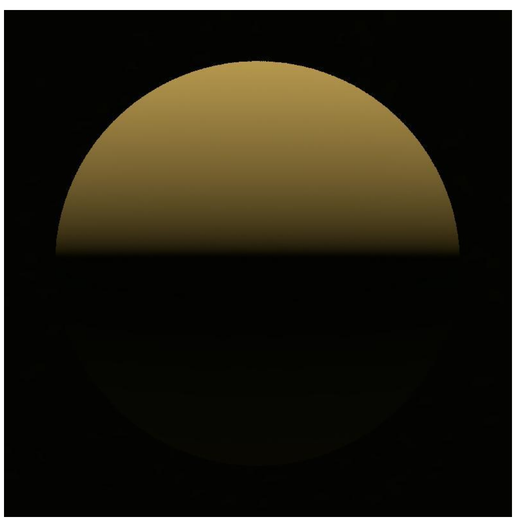
evaluation position



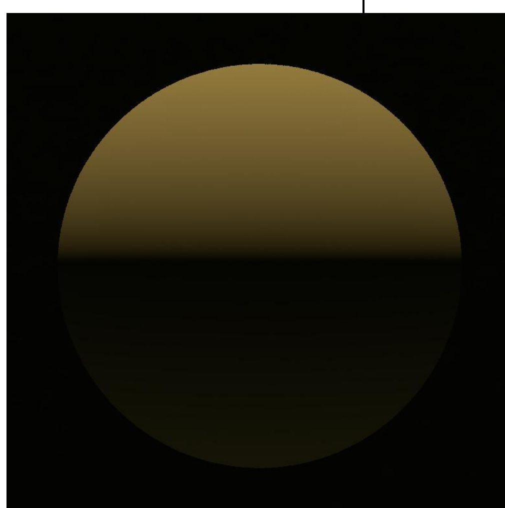


Approaching to the physical light field value





Physically correct shade



Estimated shade

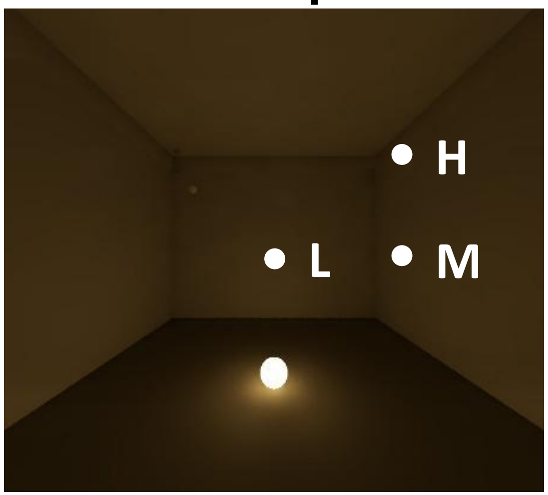
$$|D_{(c)} - D_{(s)}| = 0.11$$

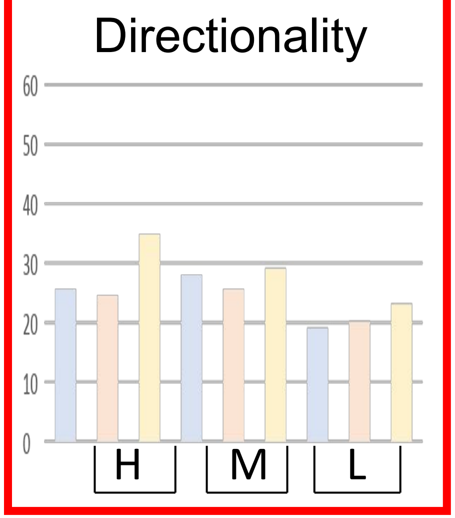
There is almost no difference.

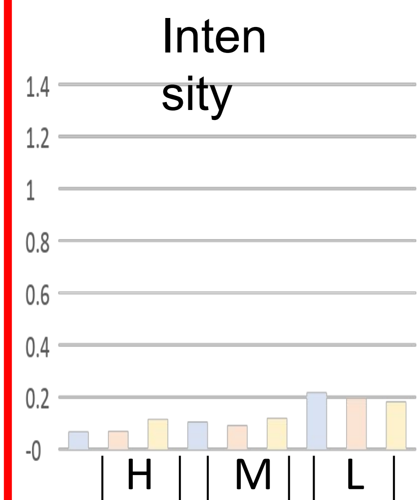
3. Estimation of Light Field

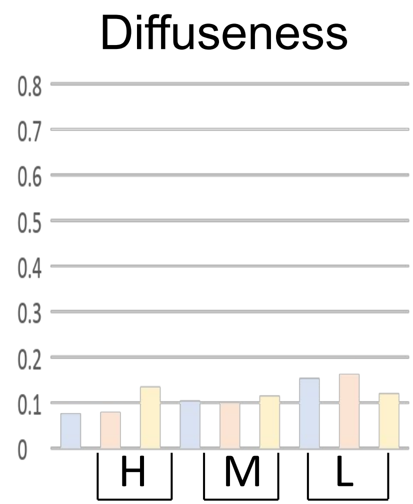
Diffuse light source condition

Evaluation position





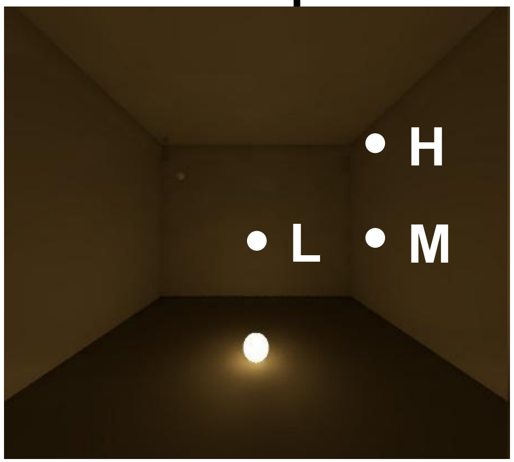




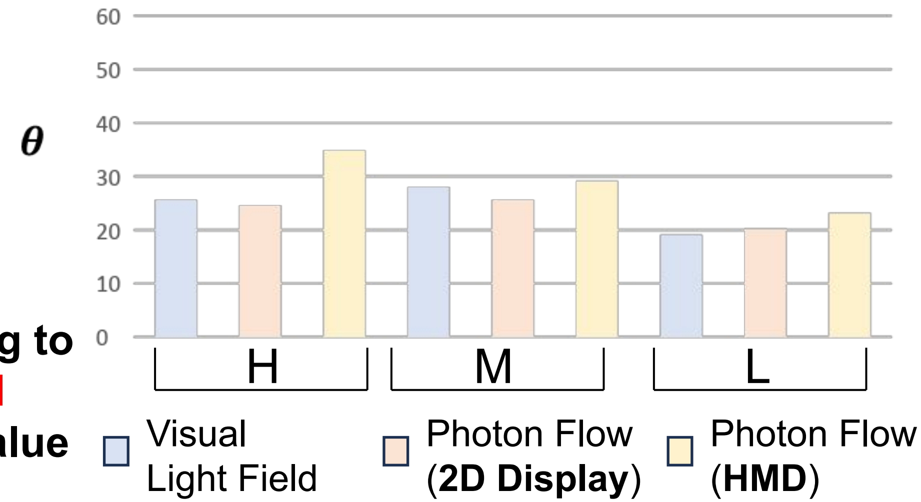
3. Estimation of Light Field

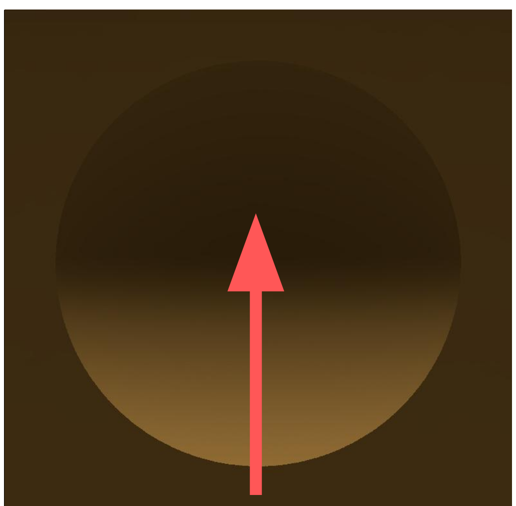
Diffuse light source condition

evaluation position

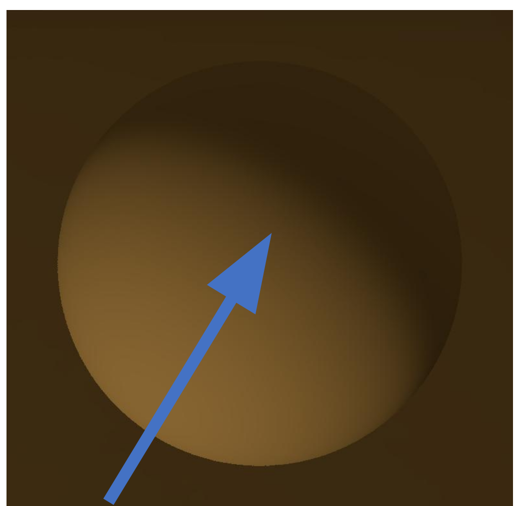


Approaching to the physical light field value

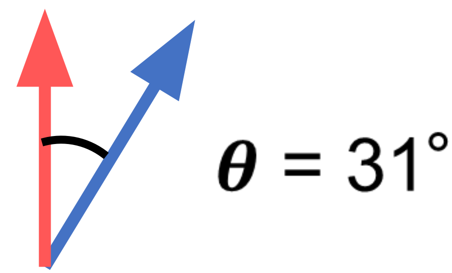




Physically correct shade



Estimated shade

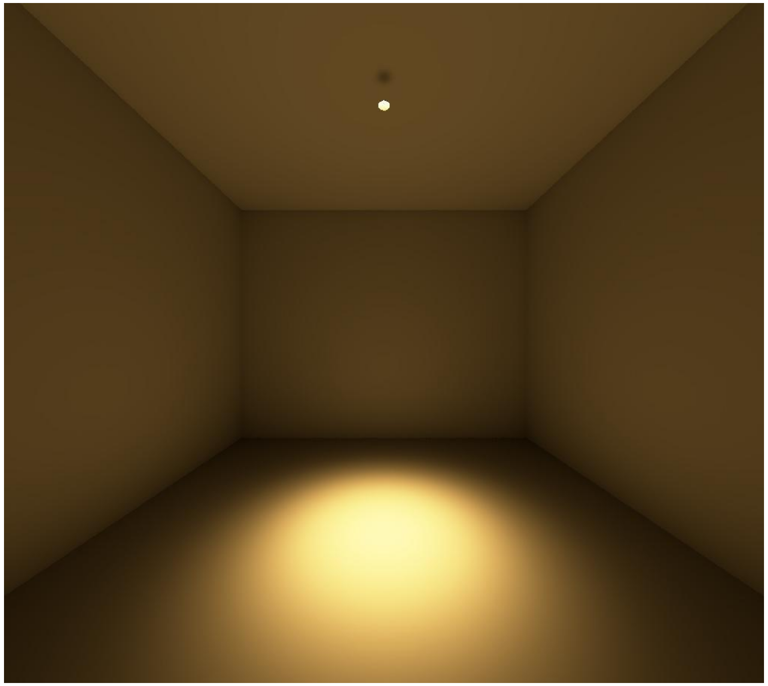


The participants greatly misperceived the directionality.

3. Estimation of Light Field

Summary of the results

A space with a single directional light source



The prediction accuracy of the physical light field improved when observing photon flow in the VR space.

A space with a single diffuse light source

The physical light field was difficult to predict even when observing photon flow in the VR space.

4. Interview Survey with architects and lighting designers

Purpose of the Survey

- Clarify the advantages of observing the photon flow using the VR.
- Figure out how the photon flow can be used in practice.
- Identify the points for improvements and inconveniences on the photon flow.

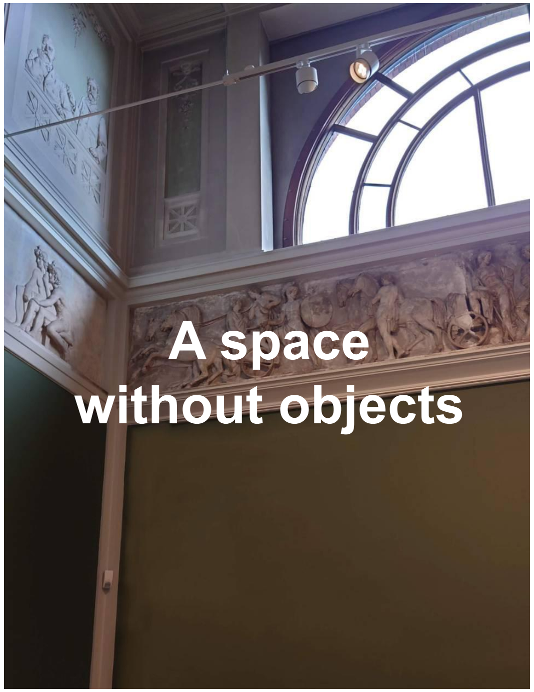
【 Interview Survey】

Q1. In which situations do you plan to use photon flow ?

Q2. Please tell us about any improvements or inconveniences on the photon flow.

4. Interview Survey with architects and lighting designers

Q1. In what situations do you plan to use photon flow?

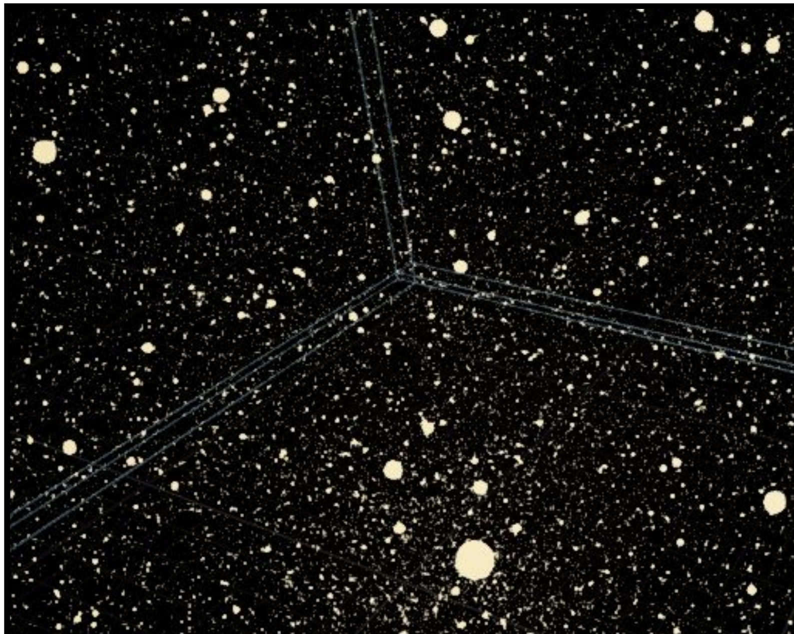


A1. ・We would like to predict the visibility of objects, i.e., where the light comes from, how it hits the object, and what it looks like when the object is placed in the space.

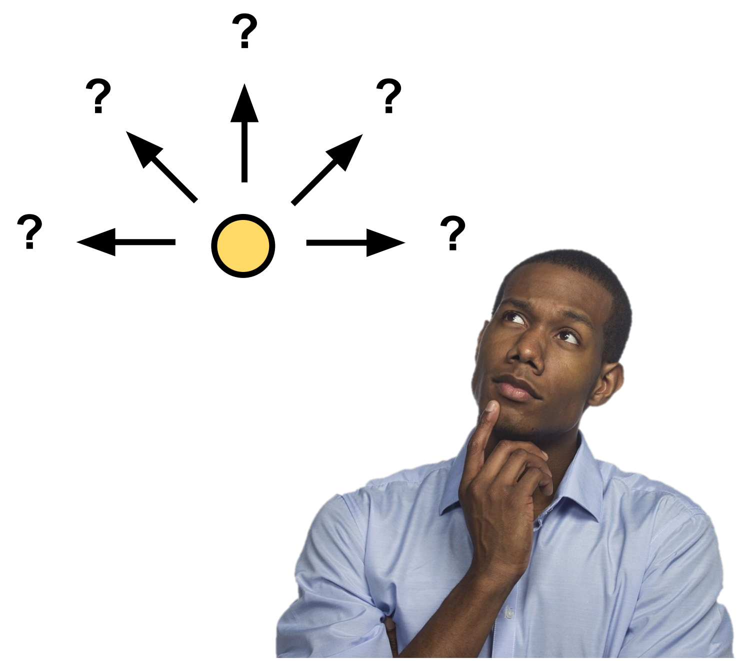
・It was easy to intuitively understand that the area with high density of photons was bright, so we can easily use this when communicating with non-specialists (clients).

4. Interview Survey with architects and lighting designers

Q2. Please tell us about any improvements or inconveniences on the photon flow.

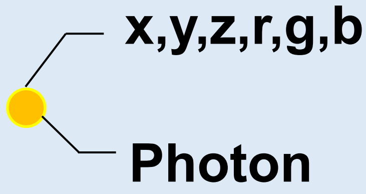


Photon flow in the space with a diffuse light source



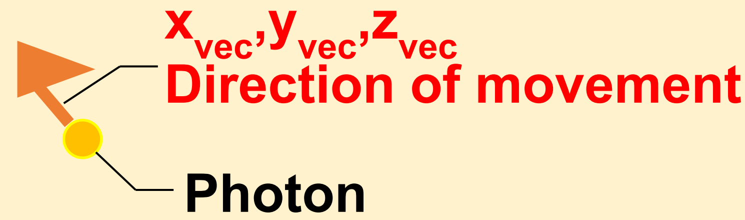
A2. For diffuse or indirect light, it was difficult to judge the direction of the photons without vector information.

5. Future works



The XYZ coordinates and colour RGB of each photon is outputted.

+



(New) Extract the direction of movement of each photon.

×

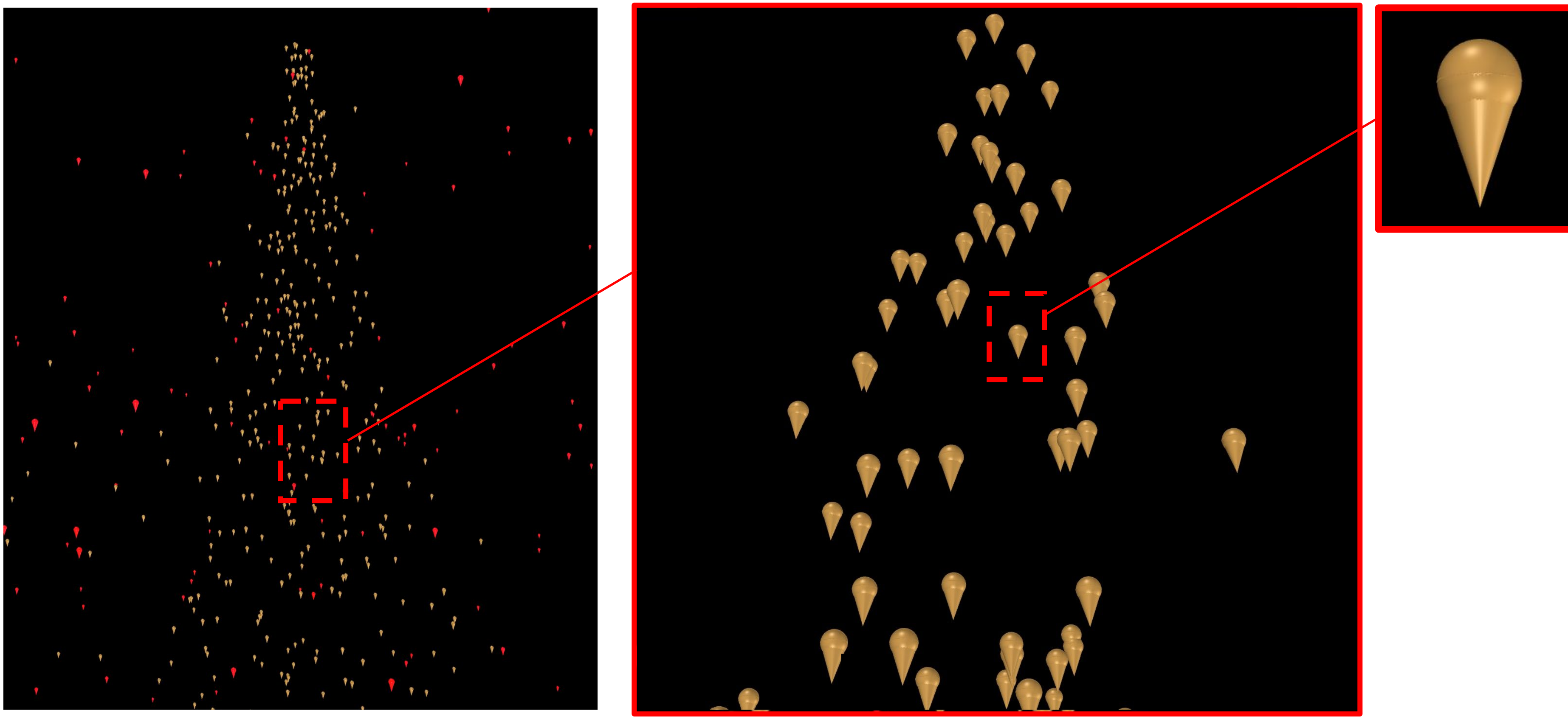
Modelling tool

Grasshopper + Rhinoceros

We can transfer this vector information to modeling tools.

5. Idea (future works)

Photons with vector information



The figure shows the direction of each photon added to the coordinate information obtained when creating the photon map, so that the direction of each photon can be seen at a glance.

6. Conclusion

A method of observing photon flow using a head-mounted display was proposed.

■**Advantages**: It is easy to grasp the three-dimensional light field for non-specialists when directional light sources are used.

■**Problems**: It is still difficult to perceive the directionality of light when diffuse light sources were used.

Adding the directional information to photons will also improve the perception of directionality in a space with a diffuse light source

Photon flow will help architects and lighting designers to comprehend the process of light propagation and to design the space with an appropriate understanding of the light field which affects the appearances of objects.

Another topic

Precomputed Contribution Photon Map

1. Background

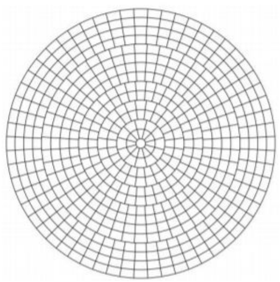
Light pollution caused by reflected light from the building skin has long been a problem in the modern urban built environment.

I would like to use **Precomputed Contribution Photon Map for the annual calculation of reflected glare**, but the matrix calculation cannot be performed due to a different sky division scheme.

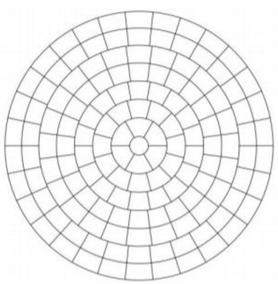
2. Comparison of sky divisions

(Old) Contribution Photon Map: Reinhart subdivisions

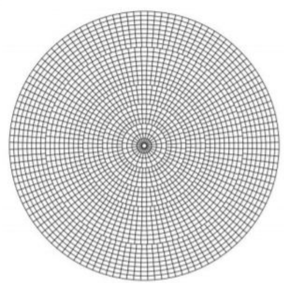
MF=2:580 div



MF=1: 145 div



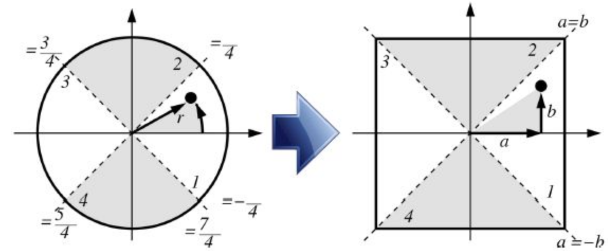
MF=4:2305 div



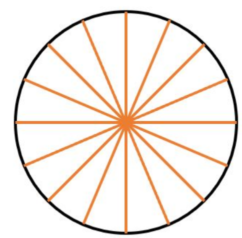
Number of divisions = 144 $(MF)^2$ + 1

(New) Precomputed Contribution Photon Map: Shirley-Chiu subdivisions

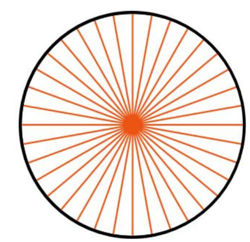
n=2: 4 div



n=4: 16 div



n=6: 36 div



Only n^2 divisions → facilitates 2D wavelet transform

3. Suggested Approach

①Adapt *genskyvec* to also support Shirley-Chiu mapping

②Remapping the sky vector's Reinhart bins to the S-C square by

- chaining *reinhartb.cal* and *disk2square.cal* -OR-
- via Python script

→ suboptimal due to potential aliasing artefacts

4. Parameters and Criteria

①Investigate effect of wavelet compression ratio on reliability of glare prediction
→ at what point to compression artefacts become problematic?

②Reflected Glare criteria:

- Which guidelines to adopt?
- What (objective) thresholds to identify glare (e.g. annual (il)luminance, max sustained (il)luminance)?
- How do these compare to subjective perception of glare?

To what extent does application of precomp. contribution pmap reliably predict glare based on the selected criteria?

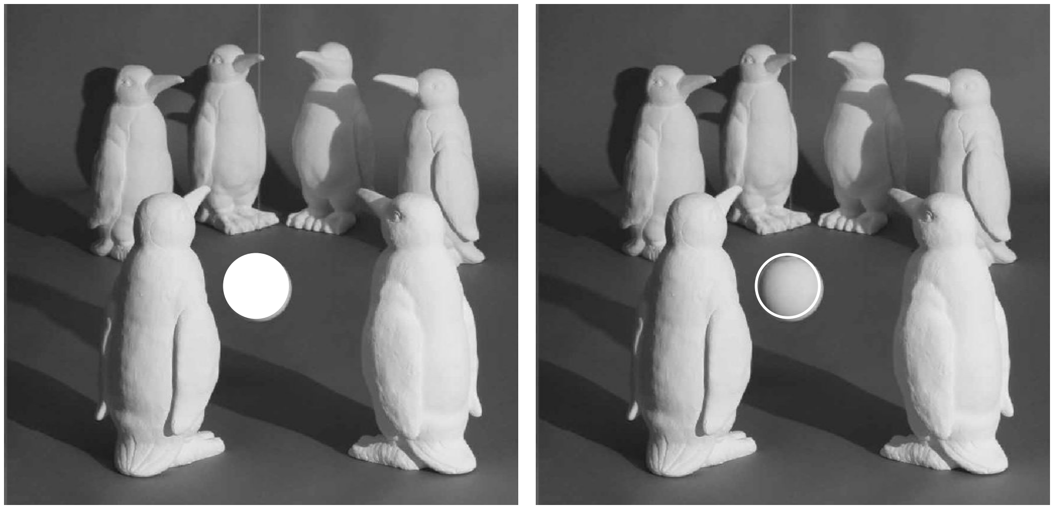
How does the performance measure up to *rcontrib* classic?

Thank you for your attention.

Questions and comments are welcome.

We can demonstrate photon flow in VR!

Is there a problem with the Visual Light Field being obtained by observing a rendered image instead of real space?



Koenderink JJ, et al.: The visual light field (2007)

Visual Light Field was measured by introducing **a picture of a gauge object in a picture of the scene** and let the observer judge its `fit'.

Our research last year also revealed that the Light Field that people perceive when observing a real space and the Light Field that people perceive when observing a rendered image are almost the same.

What is a visual light field?

Physical Light Field

▸ No consideration of psychological effects, simply the physically correct light field.

Visual Light Field

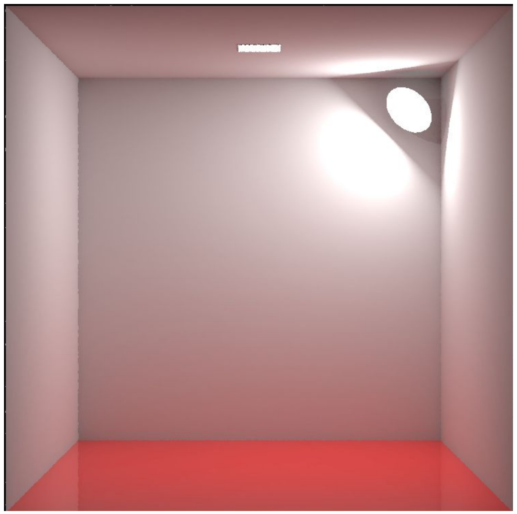
▸ Light field perceived by people.

Visual Light Field is Light Field perceived by people when observing real space.

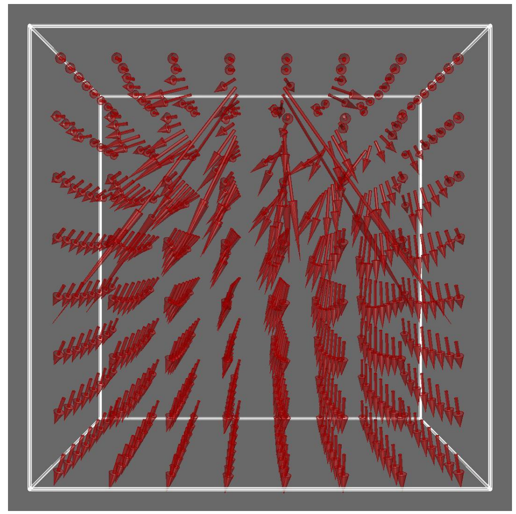
Visual Light Field was also estimated to prove that the Physical Light Field can be perceived by observing the Photon Flow rather than observing real space.

Difference between expression indicators such as illumination vectors and Photon Flow

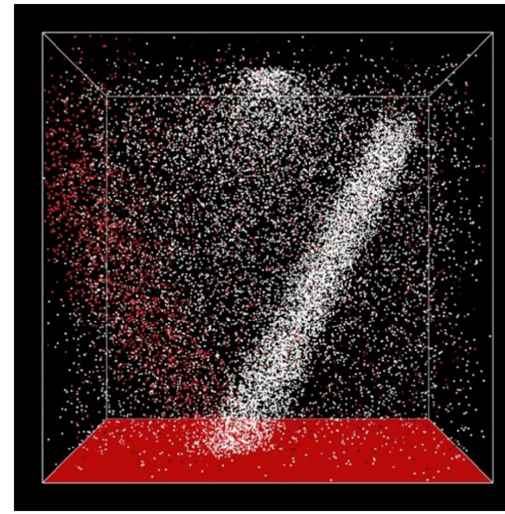
Space with multiple light sources



illumination vector



Photon Flow

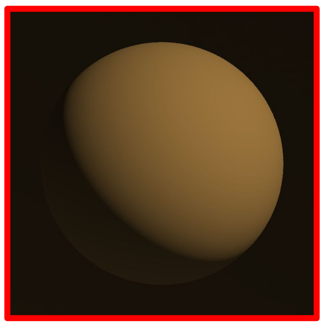


The representation of illumination vectors does not adequately capture the light field, depending on the grid spacing, because the vectors are described on a grid.

Photon Flow is superior in that it is grid-independent and describes the Physical Light Field at any point.

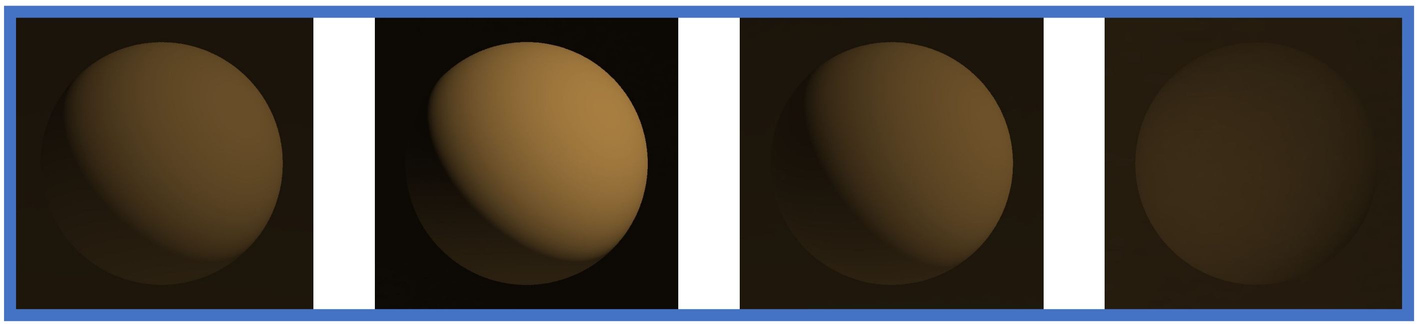
How to obtain each indicator used in the analysis

After observing the Photon Flow, a subject judged one by one whether the white sphere images displayed on the monitor matched their prediction.



The correct shadow of the presented white sphere image

① ② ③ ④



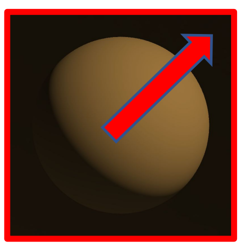
white sphere images selected as "correct" by one subject.

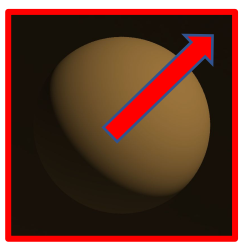
The image surrounded by the red frame on the slide is the correct shadow image, and the image surrounded by the blue frame is the images that one subject answered as "correct".

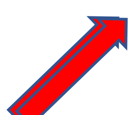
How to obtain each indicator used in the analysis

Physical Light Field

Calculate the illumination vector at the correct shadow position.







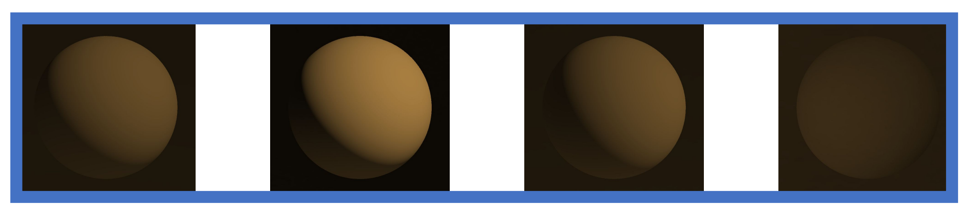
θ=0 degree

Image at the incorrect position

In the same way, calculate the angle from the images ① to④.
Calculate the average of the angle between those images.

①: 10 degrees
②: 5 degrees
③: 16 degrees
④: 25 degrees
→Average : 14 degrees

① ② ③ ④



white sphere images that one subject answered as correct.

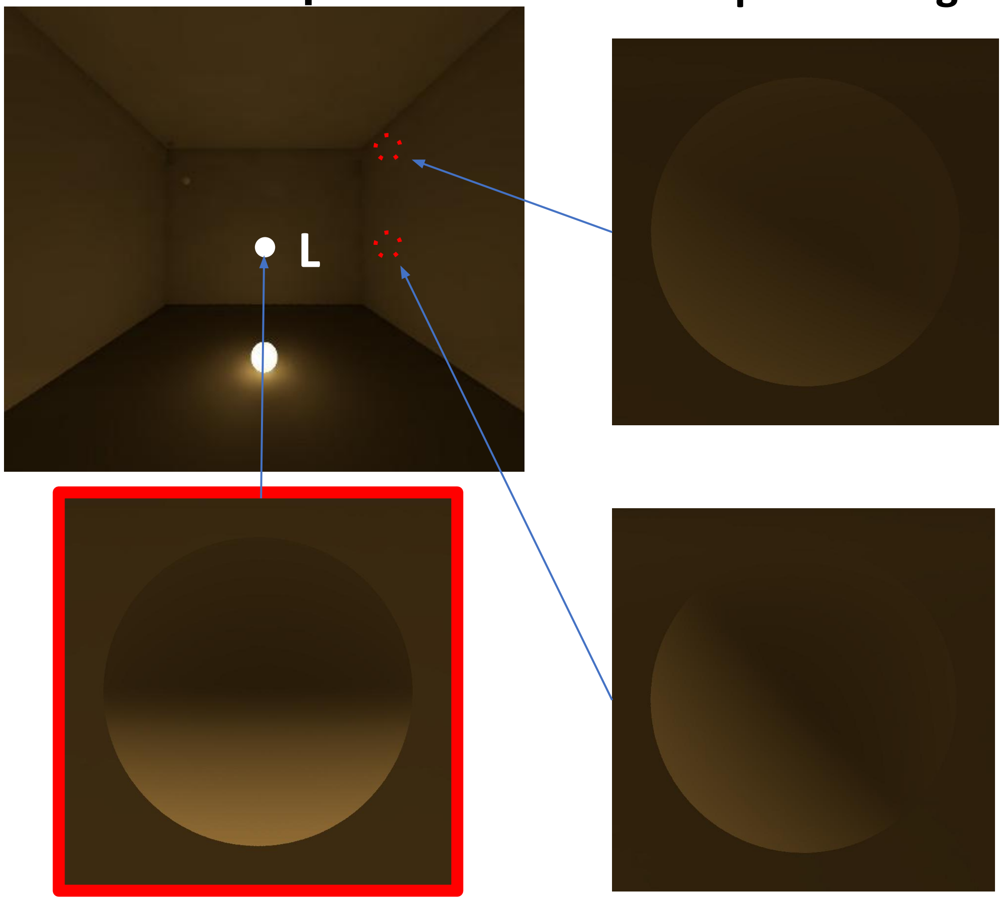
How to obtain each indicator used in the analysis

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	**Average**
Directionality [dgrees]	5.00	29.0	14.0	13.0	40.0	**20.2**

- Directionality was calculated for all subjects and the average value was obtained.
- Similarly, diffuseness, intensity, and RMSE are calculated.

In the experimental conditions for diffuse light sources, why was only directionality dealt with?

evaluation position — **White sphere images presented to the participants**



$$|E_{scalor(c)} - E_{scalor(s)}| = 10.4$$
$$|D_{(c)} - D_{(s)}| = 0.38$$
$$\theta = 39^{\circ}$$

$$|E_{scalor(c)} - E_{scalor(s)}| = 8.2$$
$$|D_{(c)} - D_{(s)}| = 0.23$$
$$\theta = 51^{\circ}$$

Physically correct shade

This is because the space is a uniform light environment filled with diffuse light, so comparing Physically correct shade with the image presented to the subject does not show a large difference except for the directionality.