Directionally guided photon flow in VR

-An ongoing subjective experiment on the perception of physical light field-

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Radiance Workshop 2024 in Salt lake city

0. Outline

■Subjective experiment on the perception of physical light field -Directionally-guided photon flow-

1. Motivation and purposes
2. Observation method of conical photon flow using HMDs
3. Estimation of light field
4. Results

■Practitioner survey on the photon flow

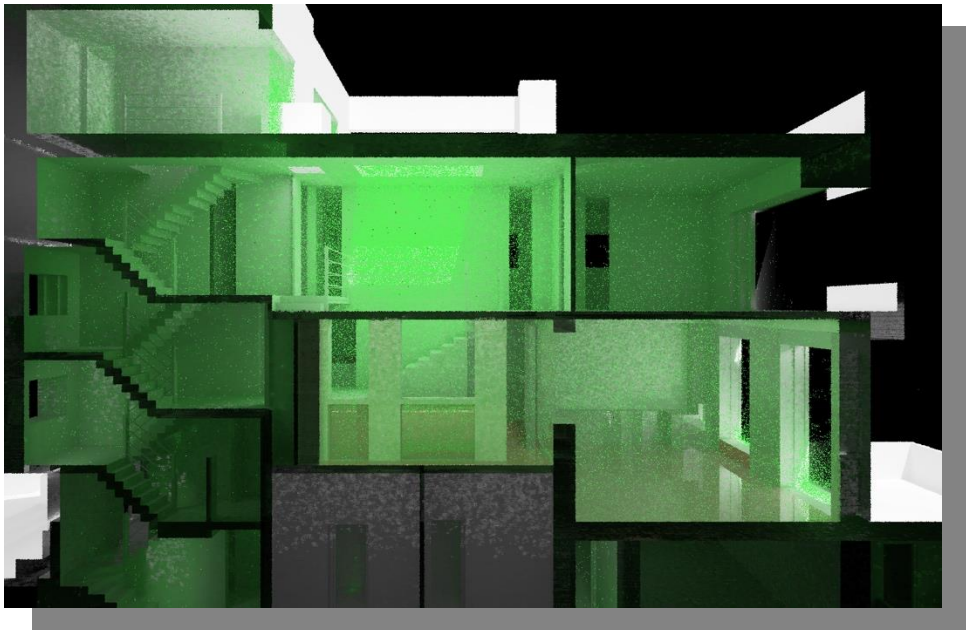
5. Interviews with designers and engineers
6. Conclusion and future works

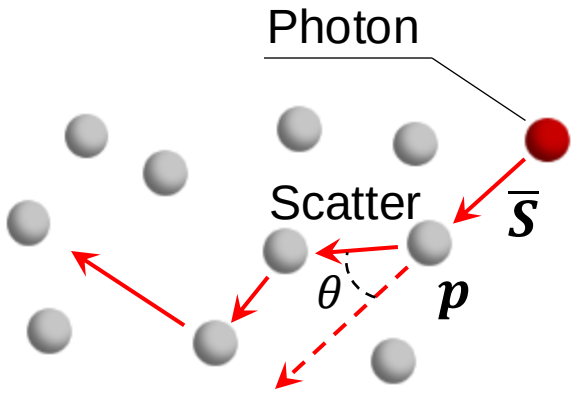
Subjective experiment on the perception of physical light field

-Directionally-guided photon flow-

1. Motivation and purposes

Photon Flow: Volume Photon





Mean free distance : $\overline{S}$

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

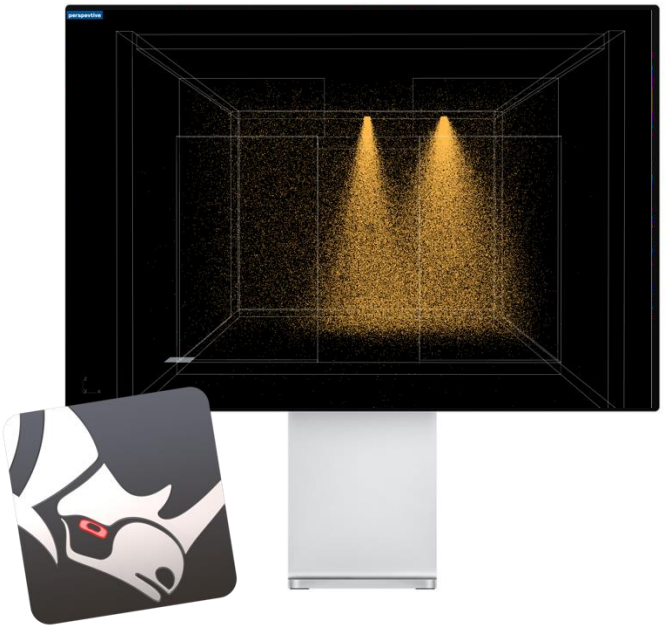
Absorption : p

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

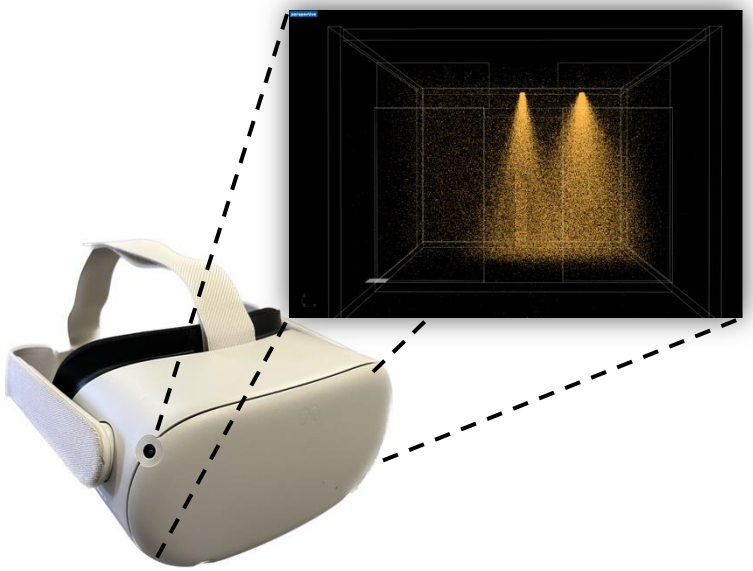
- Volume photons deposited in nonabsorbing / nonscattering mist
- Directional light distribution as particles (photons) in volume
- Photons carry RGB flux, direction
- Estimate illuminance at arbitrary location in space

1. Motivation and purposes

Observation method (Last year)



Observation in 2D displays



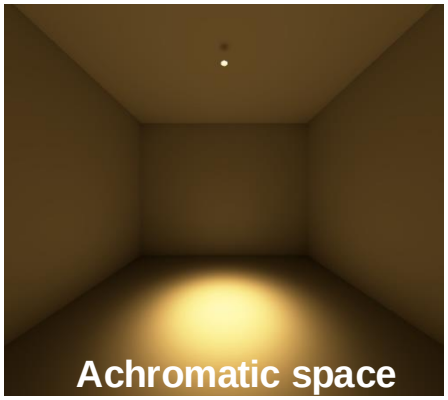
Observation in HMDs

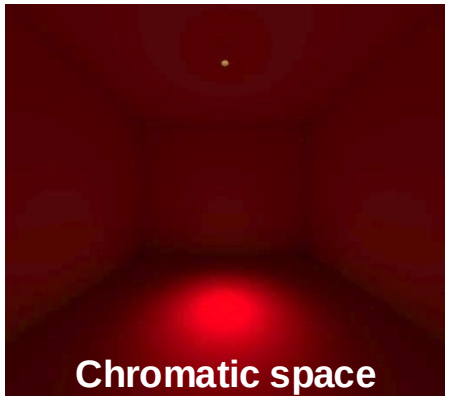
We observed photon flow in three dimensions using HMDs, however, the problem remained under certain conditions.

1. Motivation and purposes

Summary of the results (Last year)

A space with a single directional light source

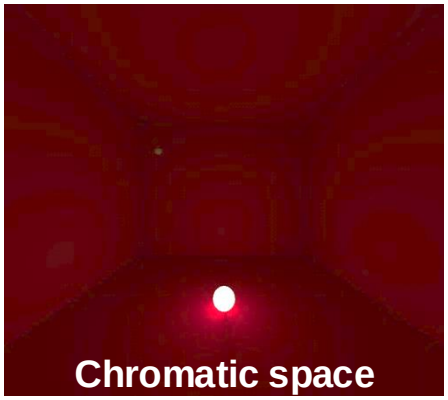




The prediction accuracy of physically correct light field improved when observing the photon flow in a VR space.

In the chromatic space, the accuracy was lower than in the achromatic space.

A space with a single diffuse light source

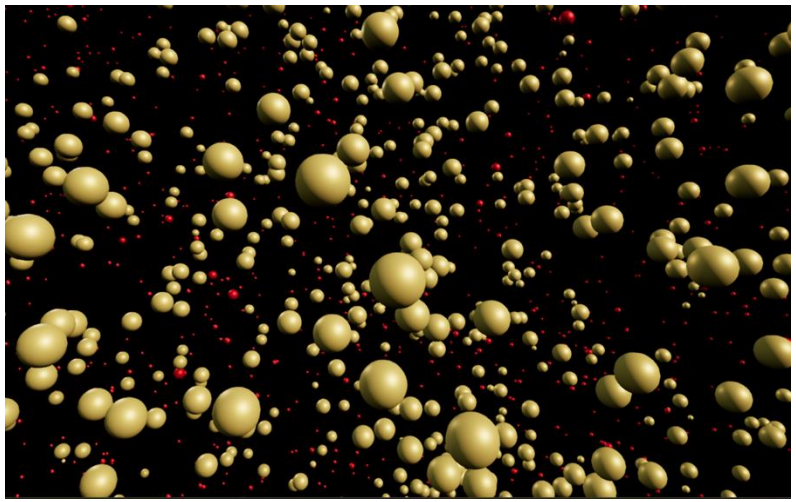


In both achromatic and chromatic spaces, it was difficult to predict the directionality of physically correct light field by observing the photon flow in a VR space.

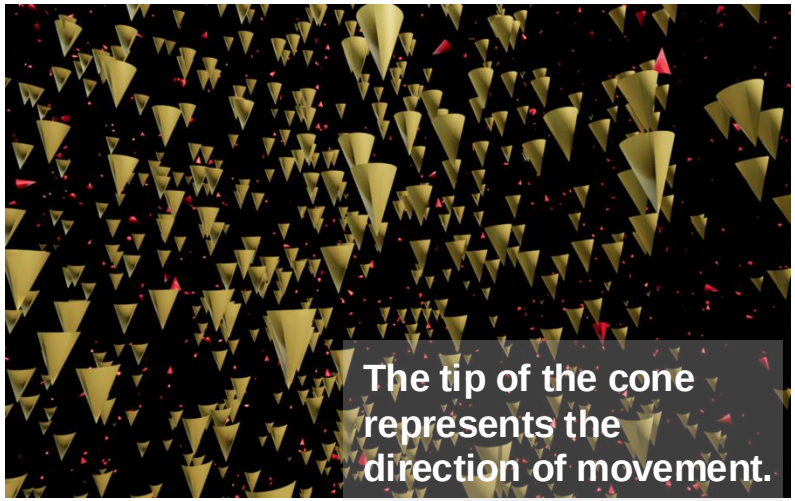
1. Motivation and purposes

We'll propose the Directionally guided photon flow !

Spherical photon



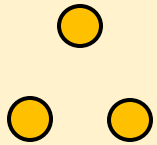
Conical photon



Directionally guided photon flow would improve the prediction accuracy of the physical light field (=physically correct light environment).

2. Observation method of conical photon flow using HMDs

Spherical Photon Flow



Making photon flow

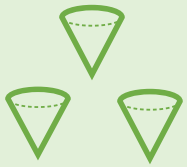
mkpmap -apV ***.vpm ***k -me .001 .001 .001 ***.oct

density of photons along a ray

Output photon's information

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

New ! Conical Photon Flow



Making photon flow

mkpmap -apV ***.vpm ***k -me .001 .001 .001 ***.oct

Output photon's information

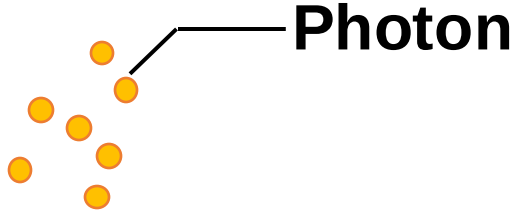
pmapdump –a **-N+** -n ***k ***.vpm > ***.xyz**

-N option : Output xyz vector information in the direction of movement for each Photon

2. Observation method of conical photon flow using HMDs

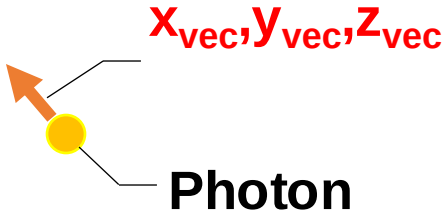
Output of Photon Flow

xyz coordinates and RGB



+

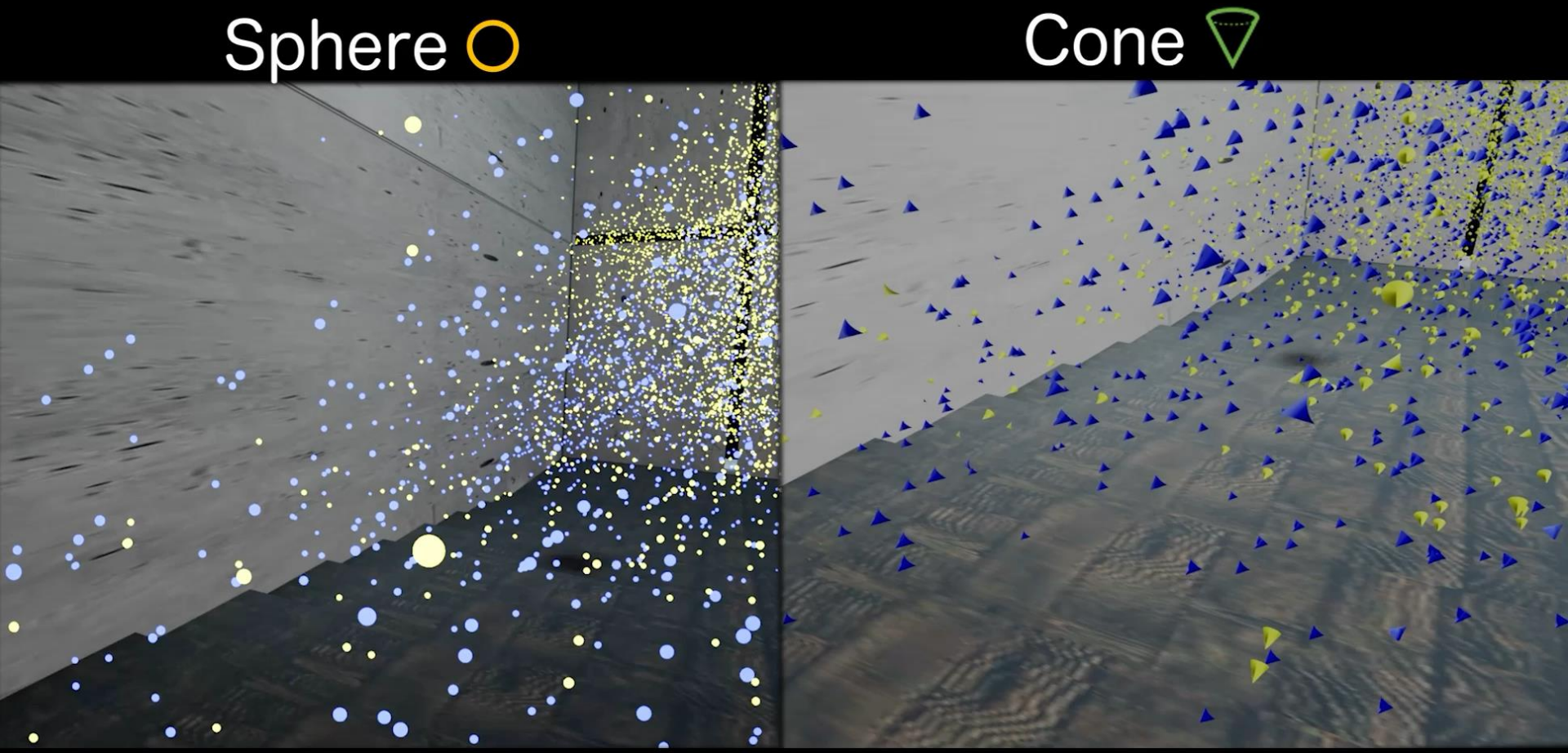
Vector of movement direction



UNREAL ENGINE

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

2. Observation method of conical photon flow using HMDs



Blue photons ：Entered from side openings
Yellow photons ：Entered from front openings

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 adding directionality to the Photon Flow would improve the accuracy of predictions for physical light fields.

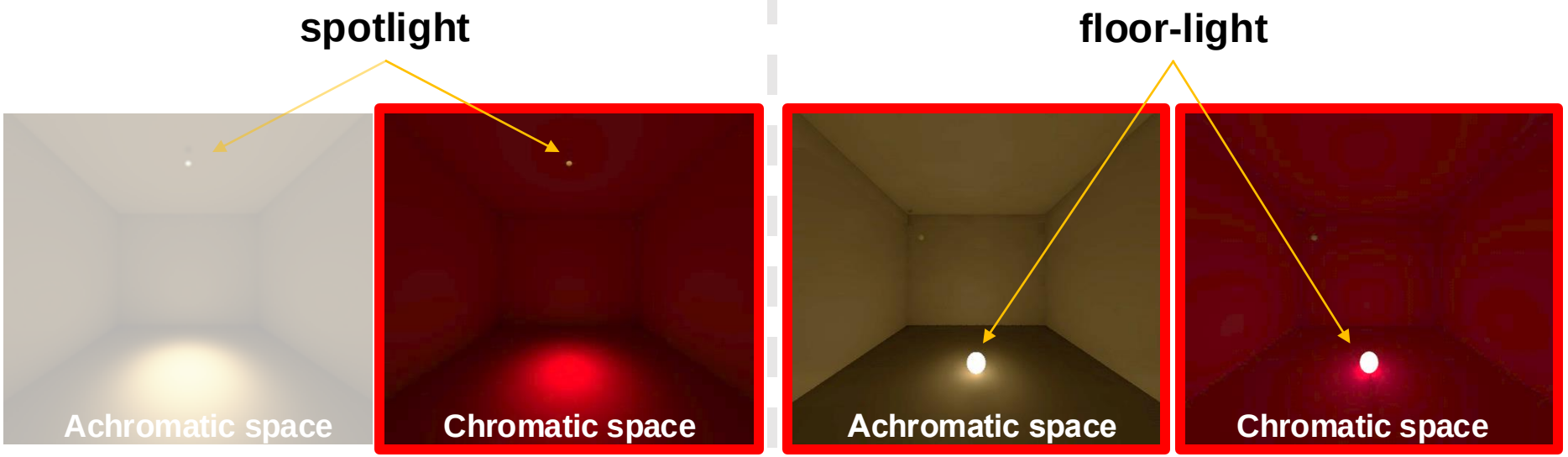
Koenderink JJ, Pont SC, van Doorn AJ, Kappers AML and Todd JT 2007 The visual light field *Percept.* **36** pp 1595–1610

3. Estimation of Light Field

Experimental space

A space with a single **directional light** source

A space with a single **diffuse light** source

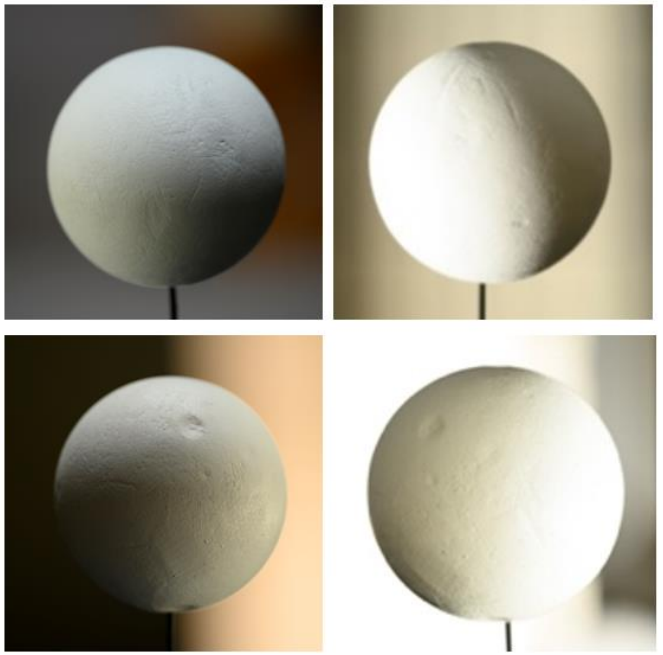


3 spaces were provided

3. Estimation of Light Field

The white sphere method

The white sphere method (same as last year), proposed by Kartashova, was employed in this experiment to capture the light field.
Participants predicted the shade on a hypothetical (= not physically existing) white sphere.



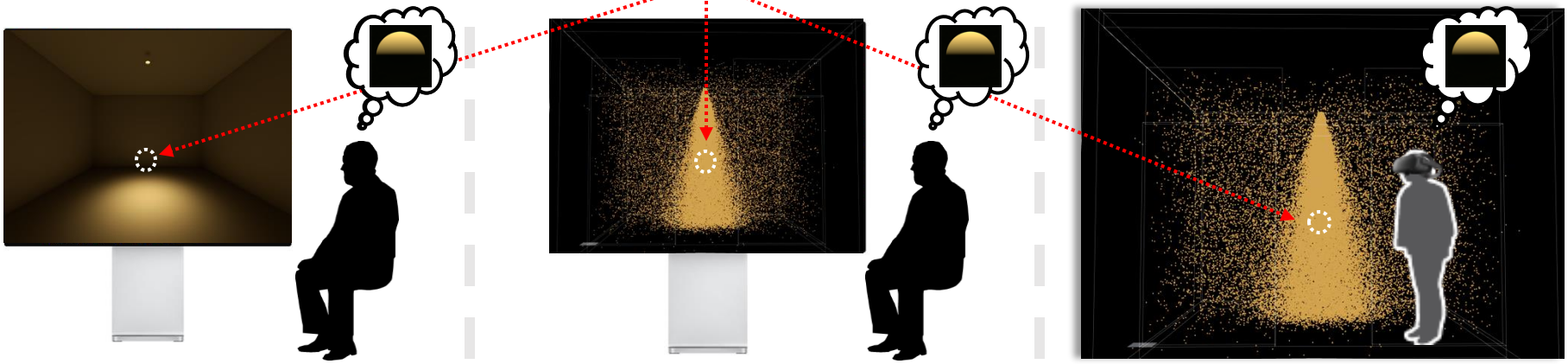
Not actually installed in the presented space

KARTASHOVA, T. 2016. The Global Structure of the Visual Light Field and Its Relation to the Physical Light Field, Journal of Vision August 2016, Vol.16, 9.

3. Estimation of Light Field

Three methods for presenting the experimental space

Hypothetical white sphere
(Evaluation target position)



Participants observed rendered images that reproduce real space. (=Visual light field)

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

Participants observed the (spherical & conical) photon flow on HMDs in a VR space.

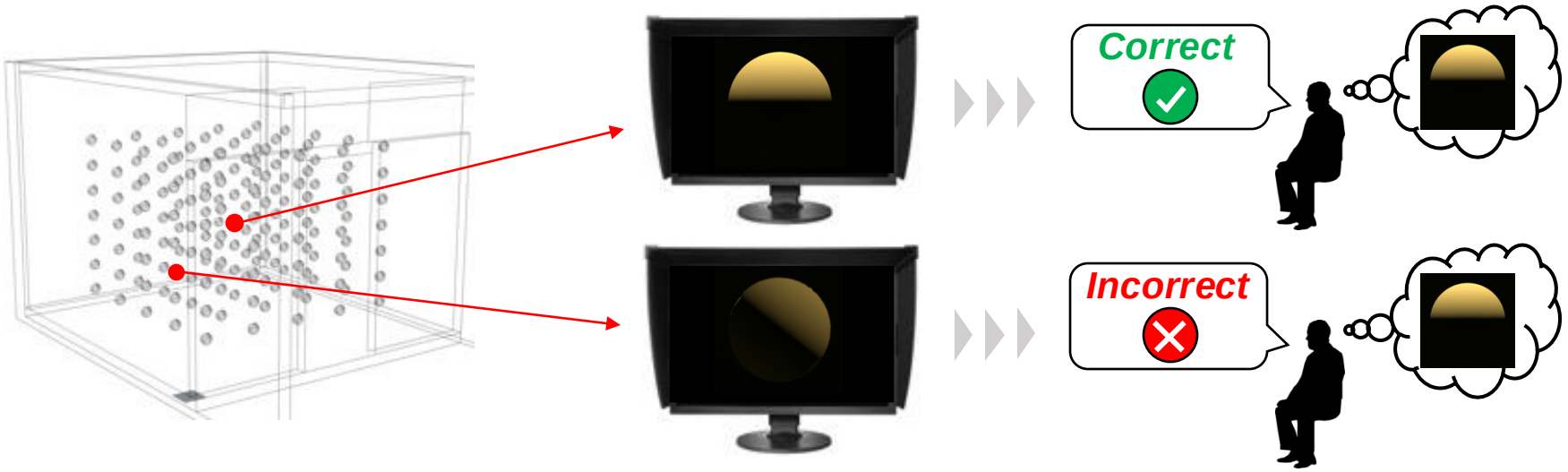
Participants infered the shades on the hypothetical white sphere which was supposed to be at the position indicated by the experimenter.

Not actually displayed on the monitor or in the VR space.

3. Estimation of Light Field

Evaluation Method

Grid points for the white spheres in the space ▶ ***Present white spheres on the monitor*** ▶ ***Participants judged correct / undecided / incorrect***



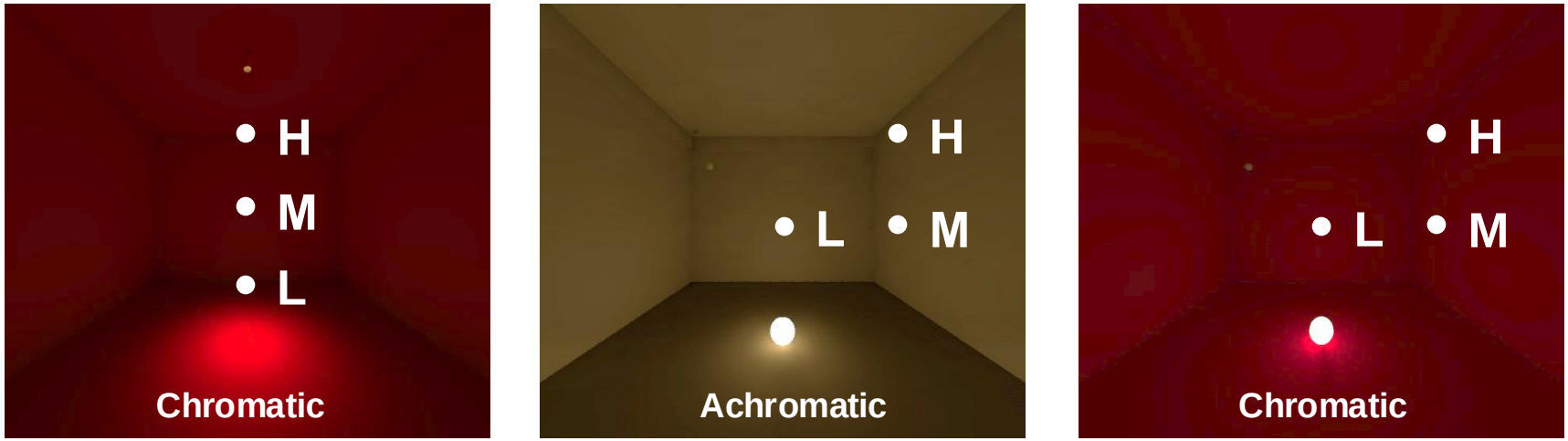
- White sphere images, rendered from a horizontal direction, represented the light field at different locations in the space.
- Participants compared the shades on white sphere images on a monitor with their estimation of the shade on a hypothetical white sphere.
- Participants judged whether the shade presented on the monitor was *correct* / *undecided* / *incorrect* as the one on the hypothetical white sphere.

3. Estimation of Light Field

Evaluation Method

Evaluation target position (Hypothetical white sphere)

spotlight **floor-light**



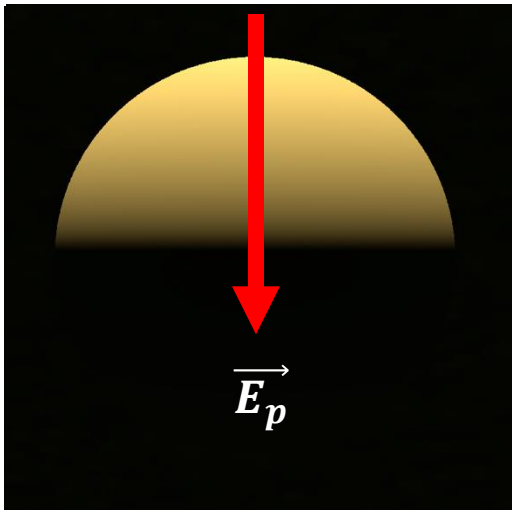
participants predicted the shade of the white sphere when they observed these evaluation target positions ● from the horizontal direction.

3. Estimation of Light Field

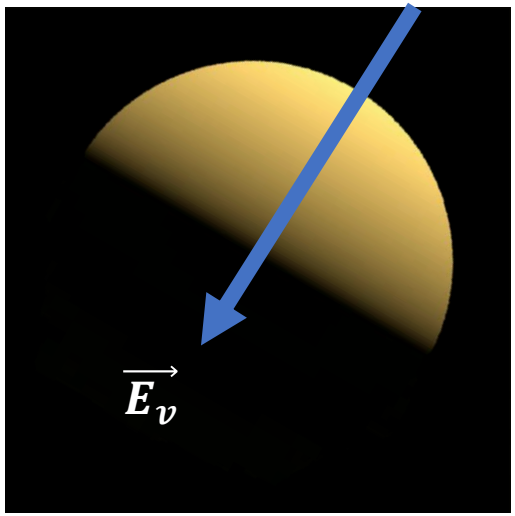
Three metrics (direction/intensity/diffuseness) were used to confirm how well participants could perceive the physical light field.

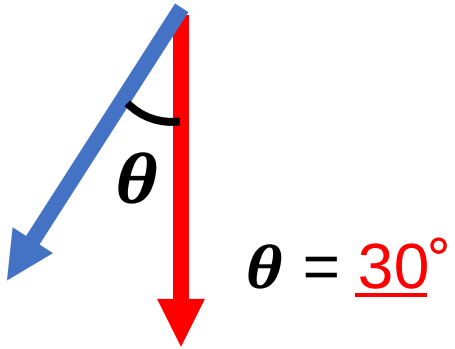
Directionality : $\theta = cos^{-1} \frac{\overrightarrow{E_v} \cdot \overrightarrow{E_p}}{|\overrightarrow{E_v}||\overrightarrow{E_p}|}$

Physically correct shade



Estimated shade





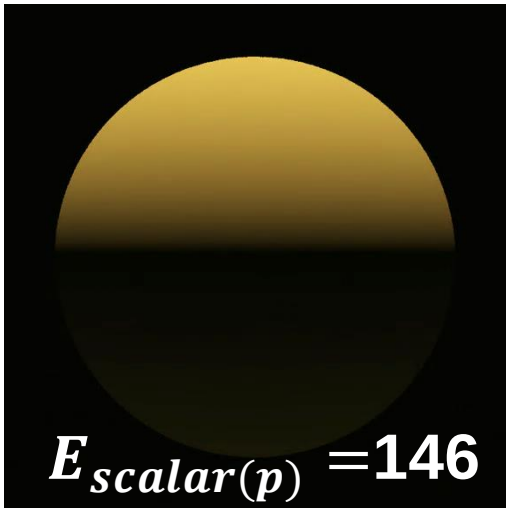
The closer *θ value* is to 0, the closer the light field is to the physical light field.

3. Estimation of Light Field

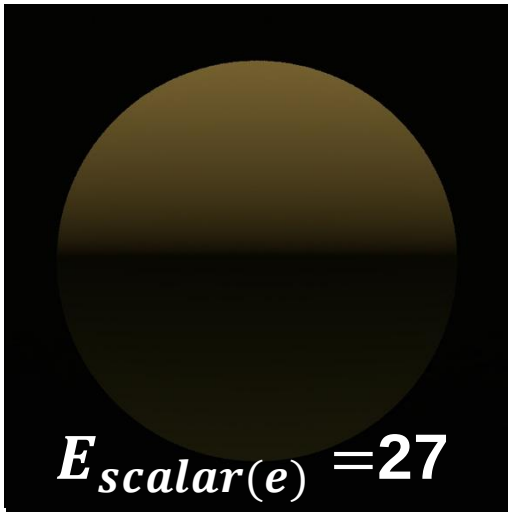
Three metrics (direction/intensity/diffuseness) were used to confirm how well participants could perceive the physical light field.

Intensity：E_{scalar} (=Scalar illuminance according to Cuttle)

Physically correct shade



Estimated shade



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

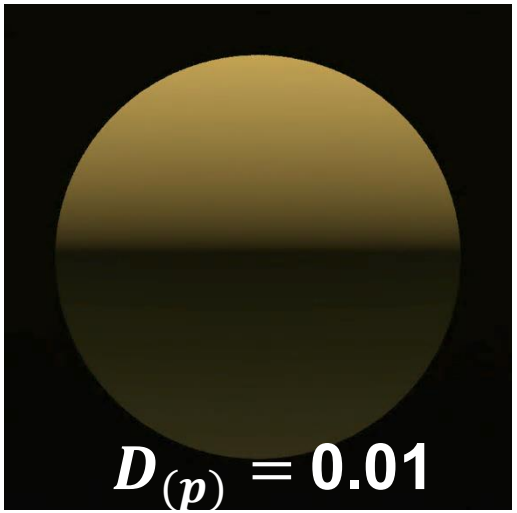
$$I = |log(E_{scalar(p)}) - log(E_{scalar(e)})| = 0.7$$

3. Estimation of Light Field

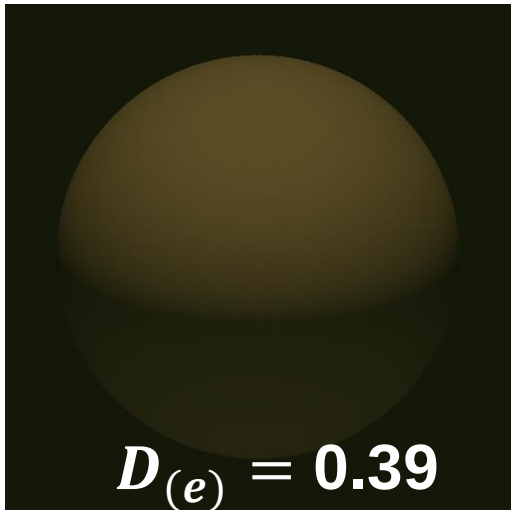
Three metrics (direction/intensity/diffuseness) were used to confirm how well participants could perceive the physical light field.

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

Physically correct shade



Estimated shade

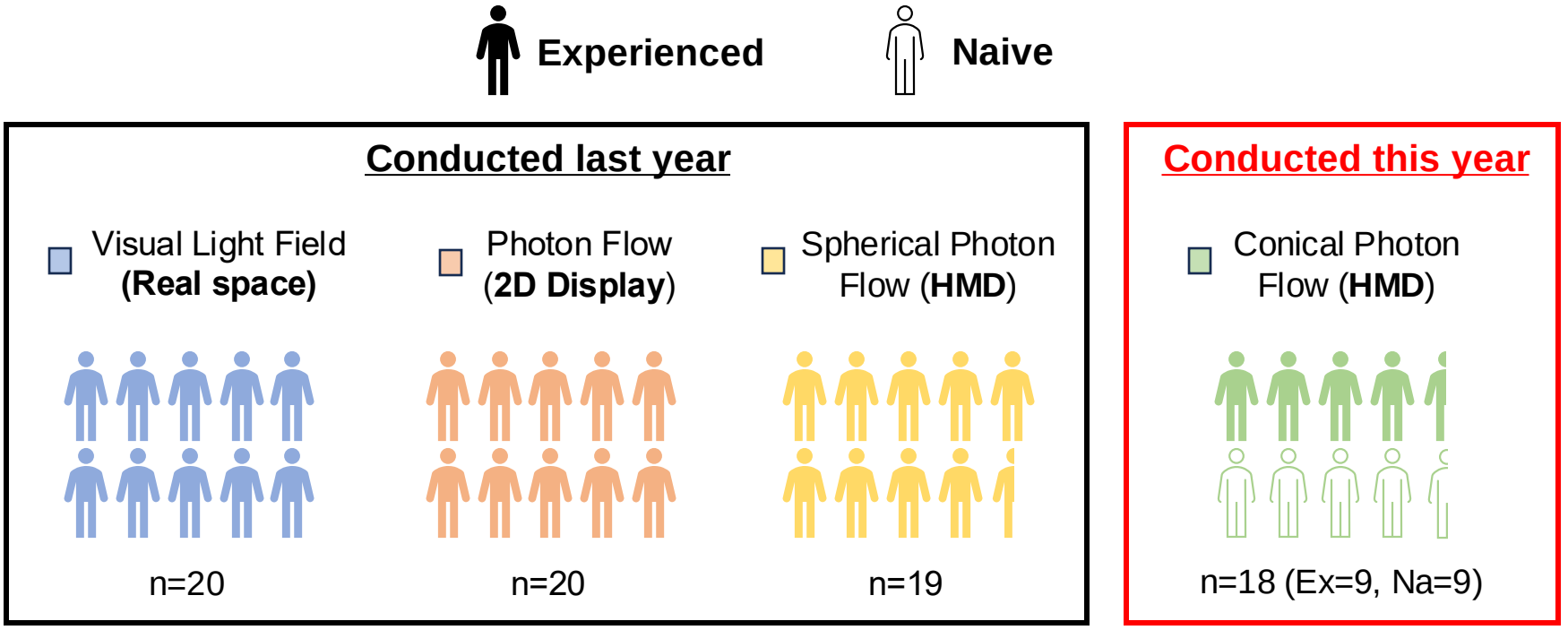


The closer the *D value* is to 0, the closer the light field is to the physical light field.

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

4. Experimental results

Participants



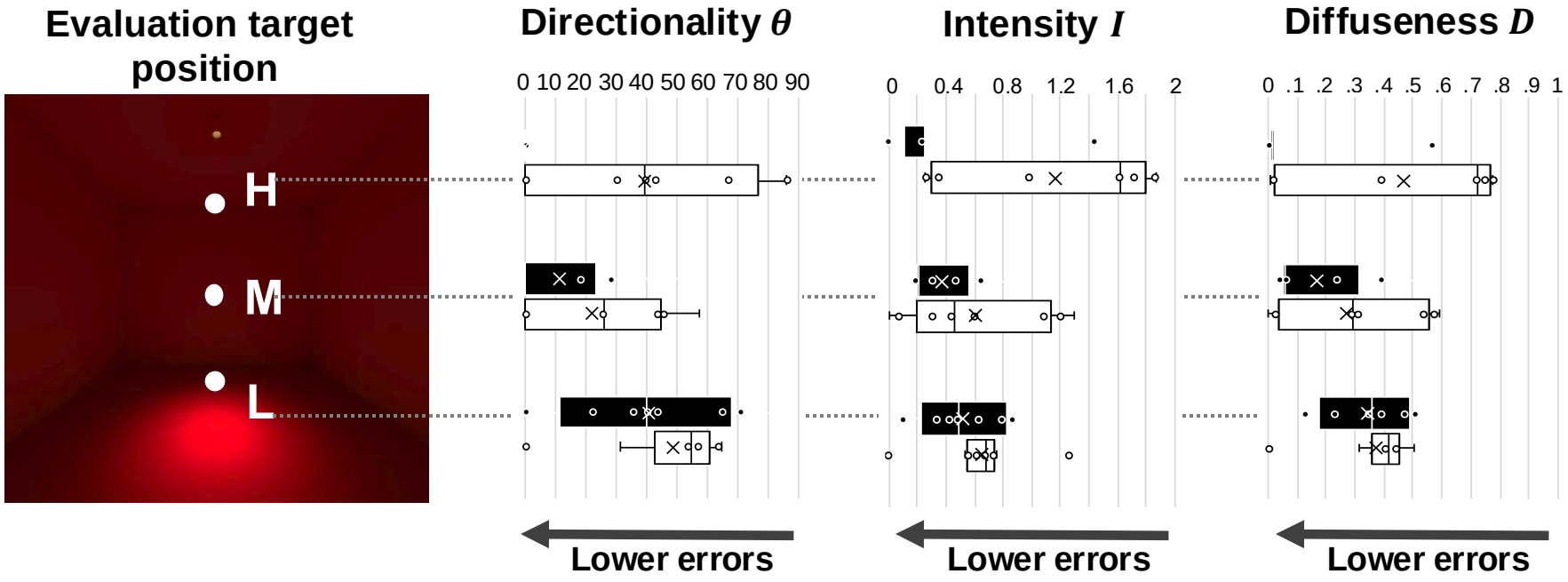
In the experiment conducted last year, all participants had already had multiple experiences of predicting shading by observing photon flow.

On the other hand, in this year, half of the participants were naive and saw the photon flow for the first time.

4. Experimental results

Participants

Comparison of the results (this year's experiment) between experienced participants and naïve ones in observing the photon flow.



The experience had a significant impact on the errors.

Since all of the participants were experienced in last year's experiments, only the data from experienced participants (n=9) of this year's experiment were extracted for the following comparative analysis.

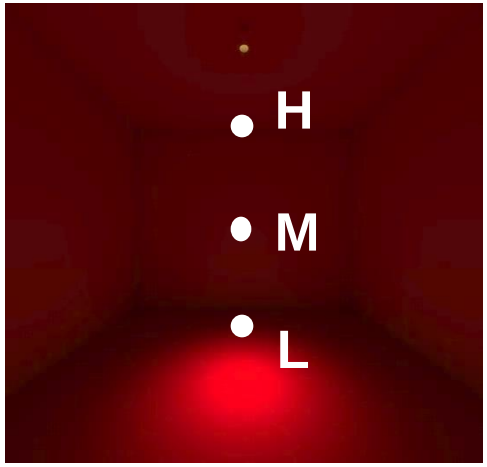
4. Experimental results

Directional light source condition (Chromatic)

Multiple Comparison Procedure

One-way ANOVA → Tukey's honestly significant difference test

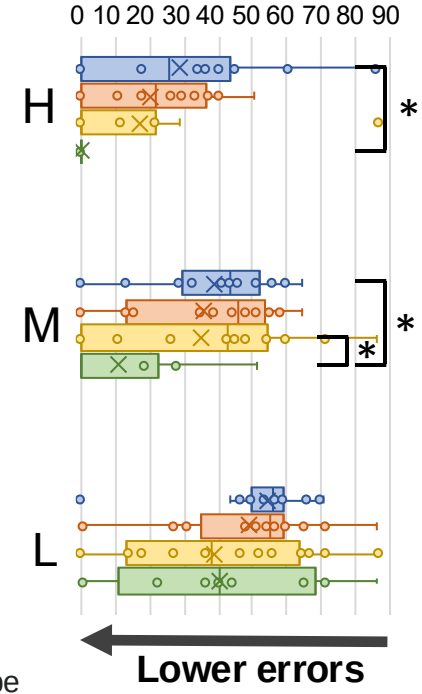
Evaluation target position



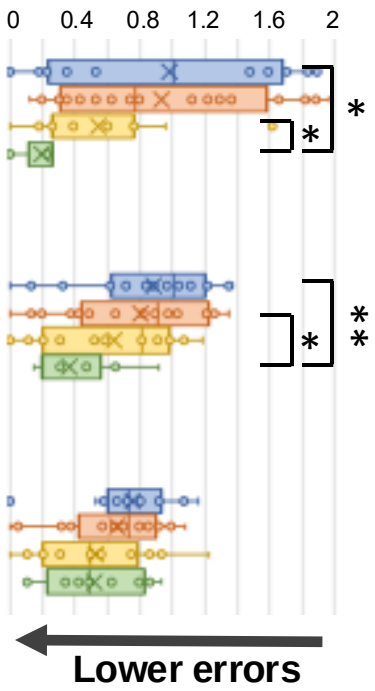
* (p-value < 0.05)
** (p-value < 0.01)

A very small *p*-value means that such an extreme observed outcome would be very unlikely under the null hypothesis.

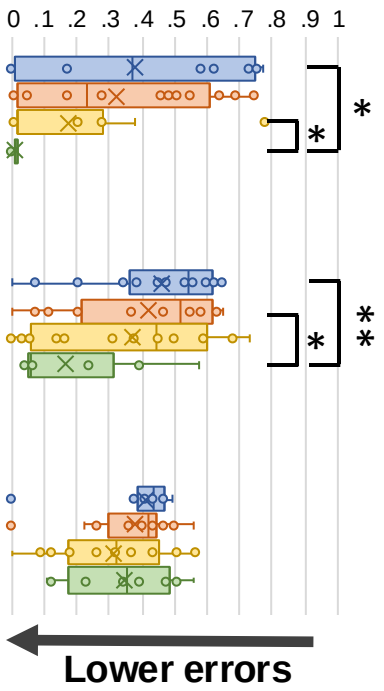
Directionality θ



Intensity I



Diffuseness D

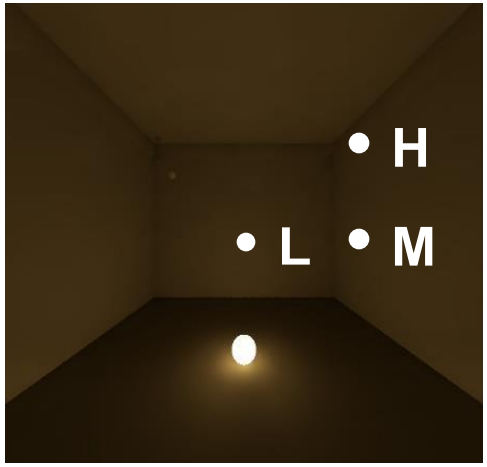


Visual Light Field | Photon (**2D Display**) | Spherical Photon (**HMD**) | Conical Photon (**HMD**)

4. Experimental results

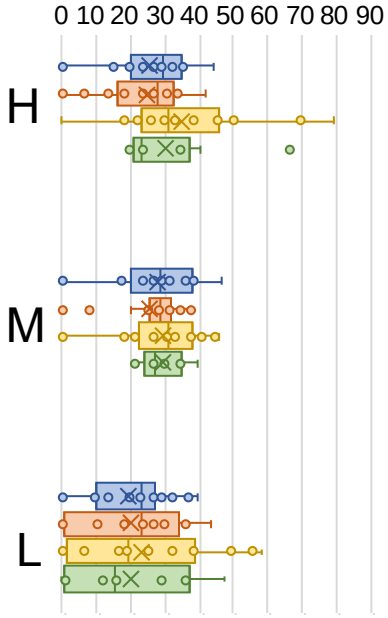
Diffuse light source condition (Chromatic)

Evaluation target position



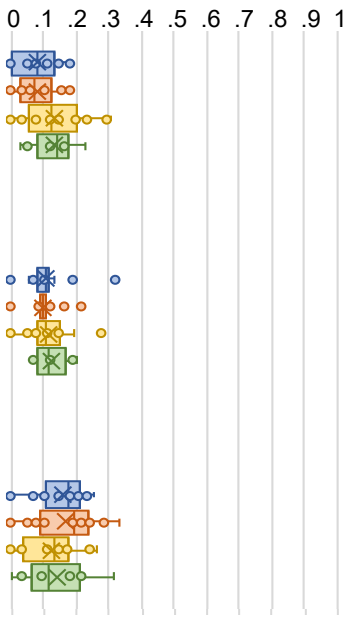
* (p-value < 0.05)
** (p-value < 0.01)

Directionality θ



Intensity I

Diffuseness D

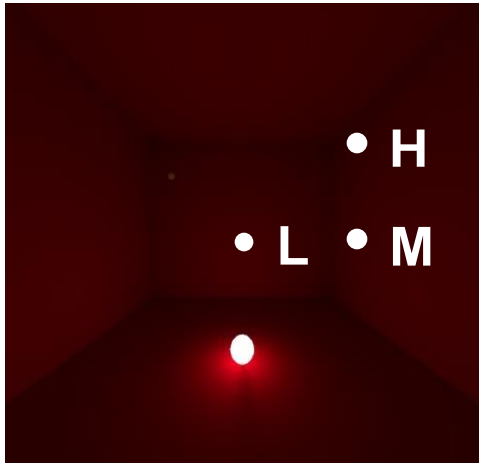


Visual Light Field | Photon (**2D Display**) | Spherical Photon (**HMD**) | Conical Photon (**HMD**)

4. Experimental results

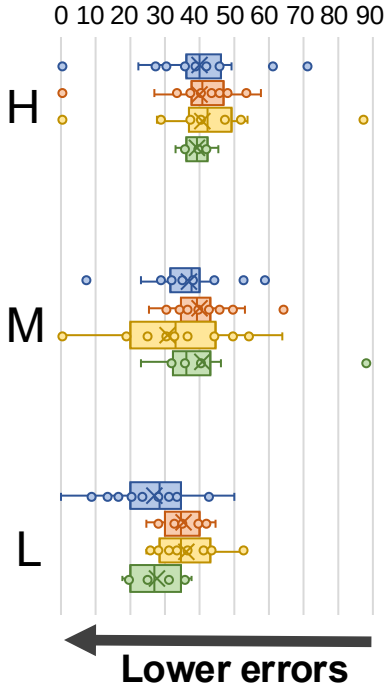
Diffuse light source condition (Achromatic)

Evaluation target position

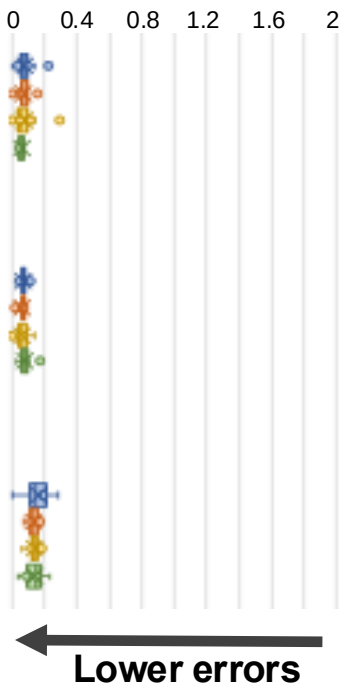


* (p-value < 0.05)
** (p-value < 0.01)

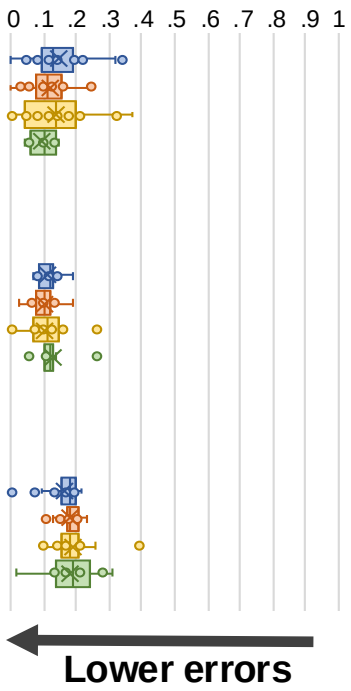
Directionality θ



Intensity I



Diffuseness D

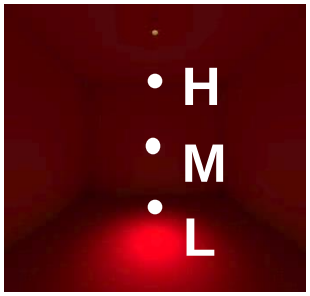


Visual Light Field | Photon (**2D Display**) | Spherical Photon (**HMD**) | Conical Photon (**HMD**)

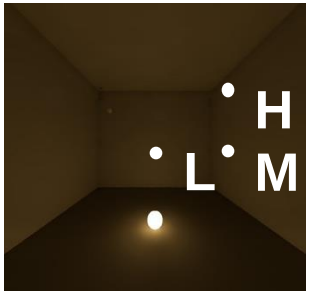
4. Experimental results

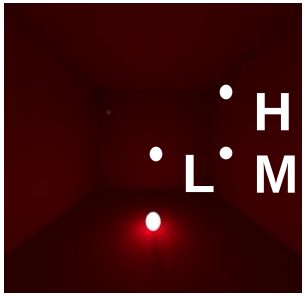
Evaluation target position

spotlight



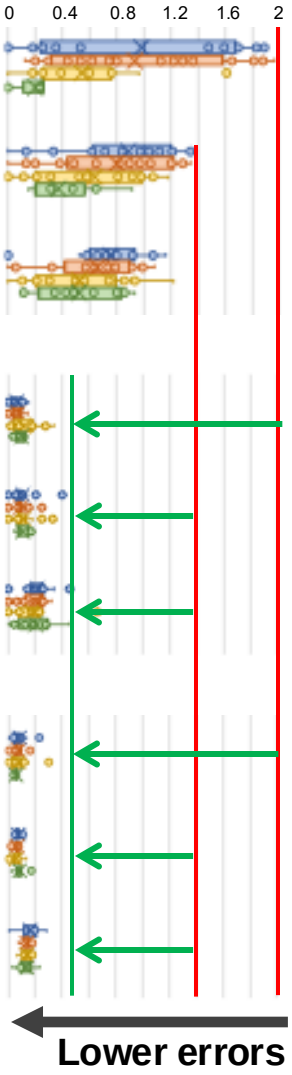
floor-light



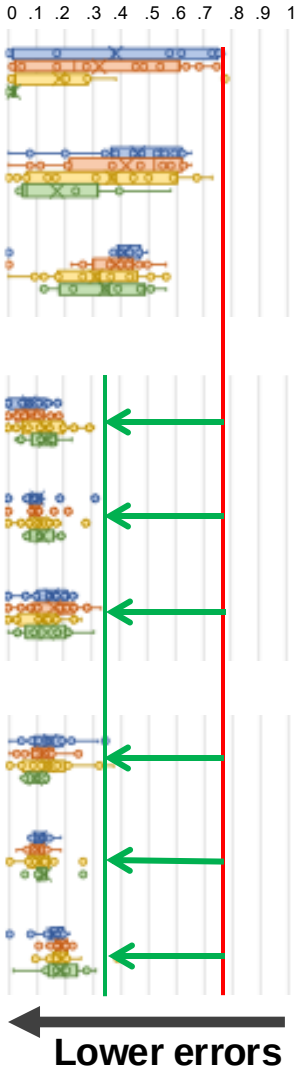


The absolute values of the errors in the floor light conditions are much lower than those in the spotlight condition, regardless of which observation method is used.

Intensity I



Diffuseness D

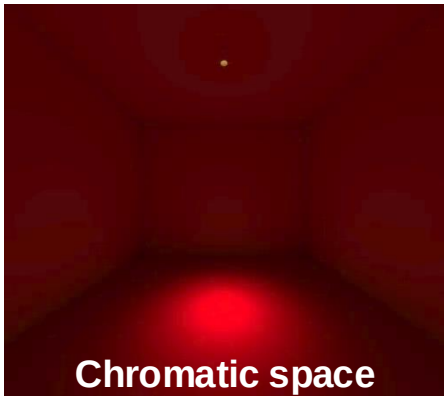


Visual Light Field | Photon (**2D Display**) | Spherical Photon (**HMD**) | Conical Photon (**HMD**)

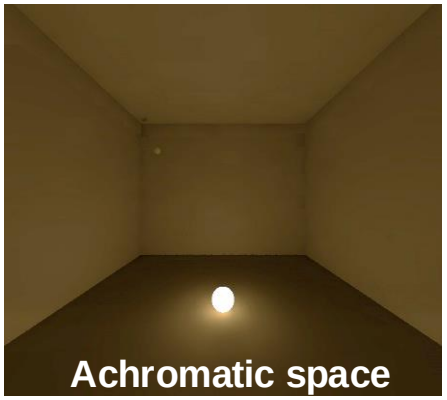
4. Experimental results

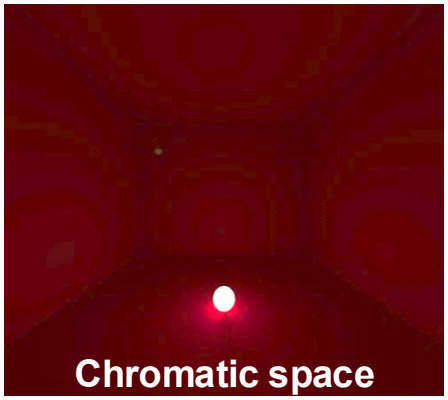
Summary

A space with a single **directional light** source



A space with a single **diffuse light** source





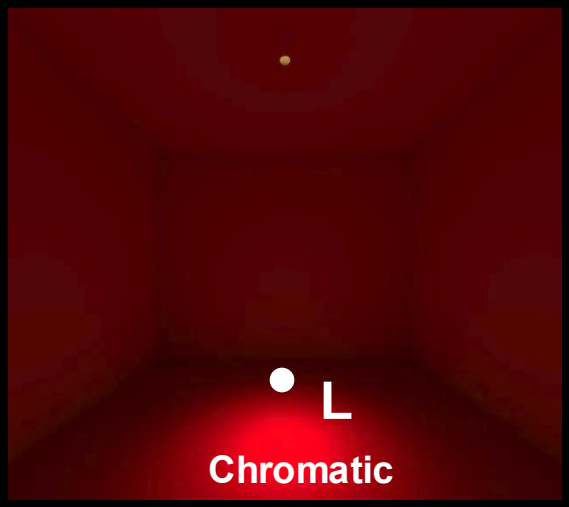
Excluding positions with a high proportion of indirect light, observing the conical photon flow in a VR space improved the accuracy of predictions for physical light fields.

In both achromatic and chromatic spaces, it was still difficult to predict the directionality of physical light fields even by observing the conical photon flow in VR space.

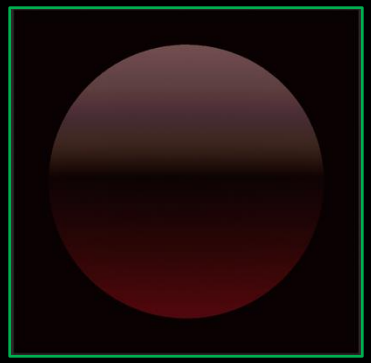
4. Experimental results

Directional light source condition

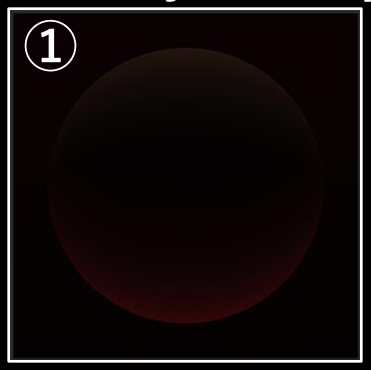
Evaluation target position



Physically correct shade



Estimated shade by lots of participants

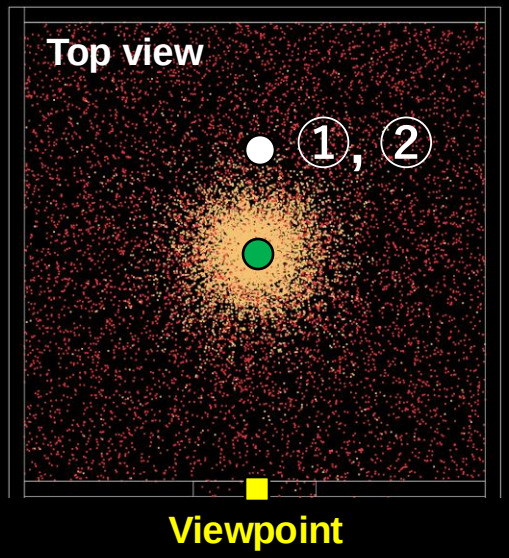


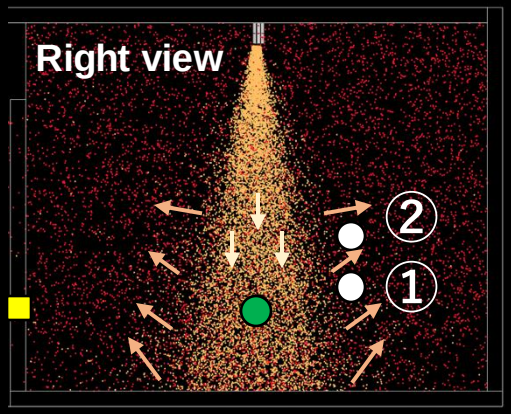
Percentage of the participants who judged it correct.	33%	33%
Errors of Directionality	56	86
Errors of Intensity	0.56	0.93
Errors of Diffuseness	0.40	0.56

4. Experimental results

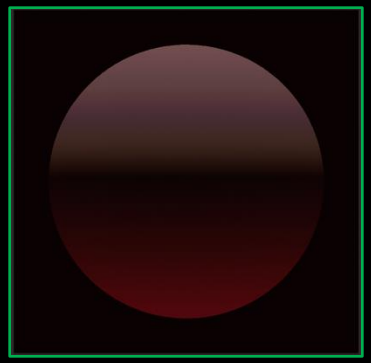
Directional light source condition

Photon Flow

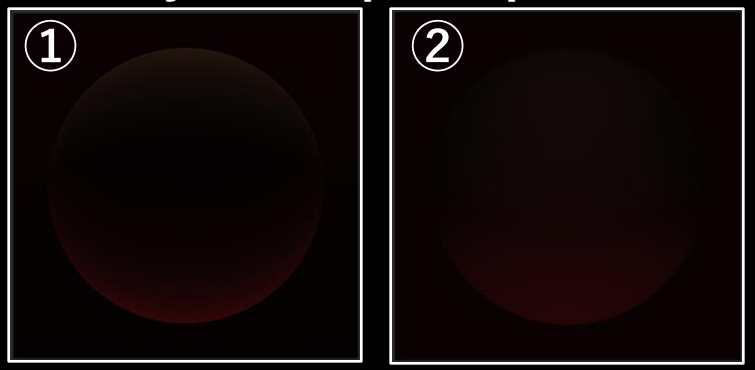




Physically correct shade



Estimated shade by lots of participants



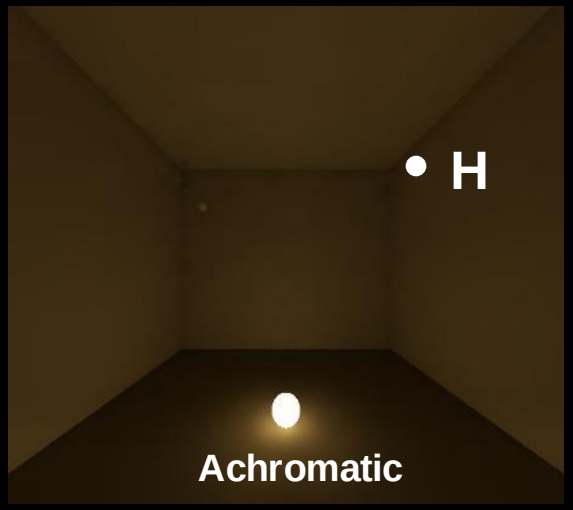
When the evaluation target position was far from the light source, distribution of photons became low density and participants more likely underestimated the direct and indirect light reaching the target position.

In case that an image outside the light distribution angle (①, ②) is selected, the effect of reflected light from the floor becomes relatively stronger, resulting in a large directional error.

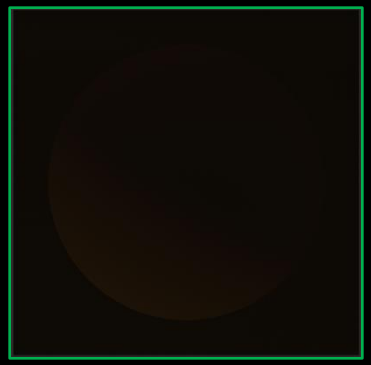
4. Experimental results

Diffuse light source condition

Evaluation target position



Physically correct shade



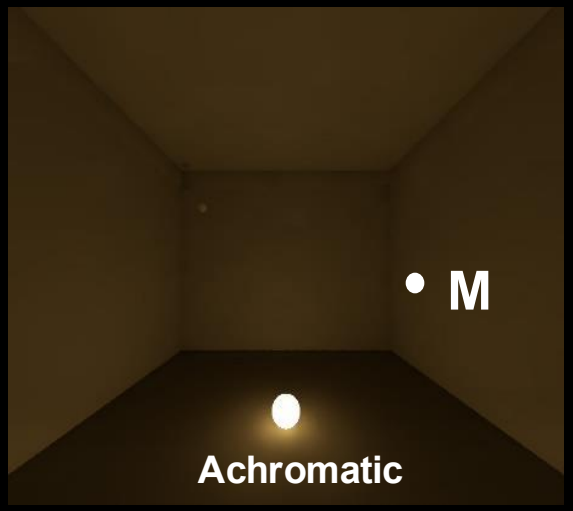
Estimated shade by lots of participants

Percentage of the participants who judged it correct.	44%	44%
Errors of Directionality	21	35
Errors of Intensity	0.041	0.031
Errors of Diffuseness	0.018	0.041

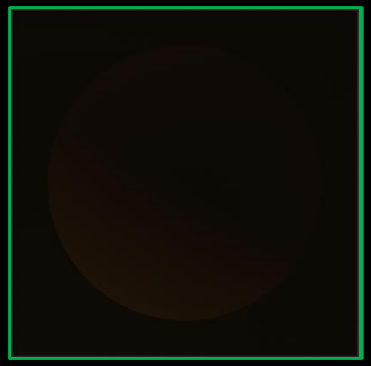
4. Experimental results

Diffuse light source in an achromatic space condition

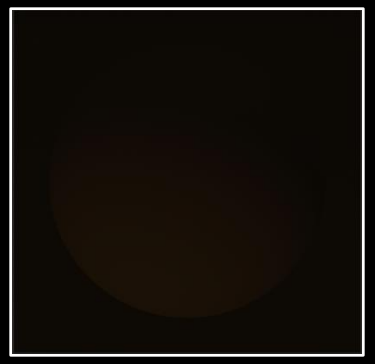
Evaluation target position



Physically correct shade



Estimated shade by lots of participants

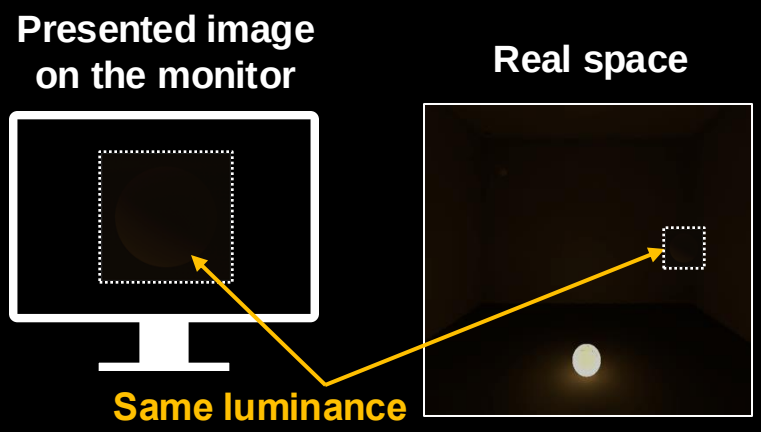


Percentage of the participants who judged it correct.	44%	44%
Errors of Directionality	36	31
Errors of Intensity	0.24	0.18
Errors of Diffuseness	0.26	0.20

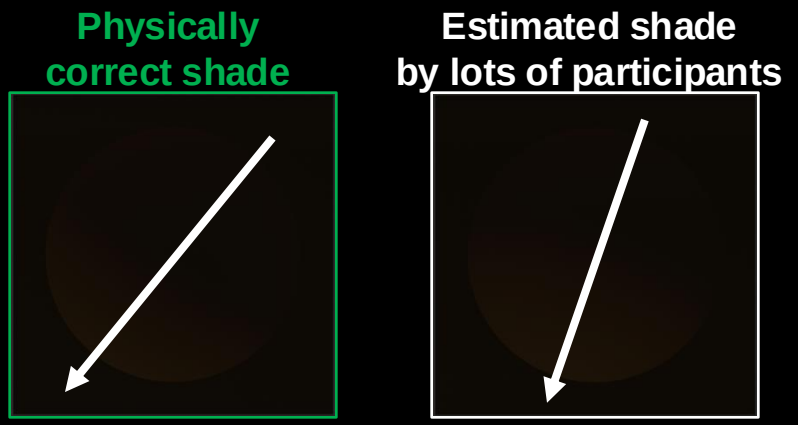
4. Experimental results

Diffuse light source condition

The presented images on the monitor were tone-mapped to have the same luminance as in the real space.
However, those images were too dark, and it was difficult for participants to distinguish between correct and incorrect images.



The misjudgment may have been due to misinterpreting the directionality of the presented images rather than incorrect predictions based on observing photon flow.



There is a high possibility that there was an issue with the presented images, therefore, we would like to revisit this matter in our future experiments.

Practitioner survey on the photon flow

-Directionally-guided photon flow-

5. Interviews with practitioners

Purpose of Survey

- ***Figure out whether the directionally-guided photon flow could be used in architectural and lighting design.***
- ***Identify the areas of improvement of the photon flow.***

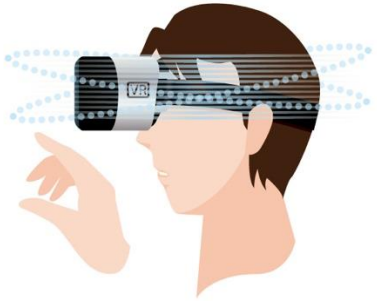
A total of 21 practitioners

4 architects, 9 lighting designers, 2 facility designers, and 6 light environment engineers.

5. Interviews with practitioners

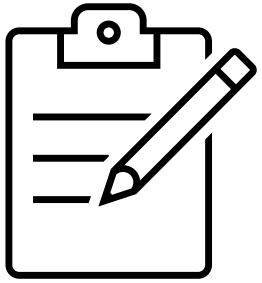
Procedure of Survey

1. ***Receive an explanation on the photon flow and put on a Head Mounted Display***



2. ***Move freely in the VR space to observe the photon flow***

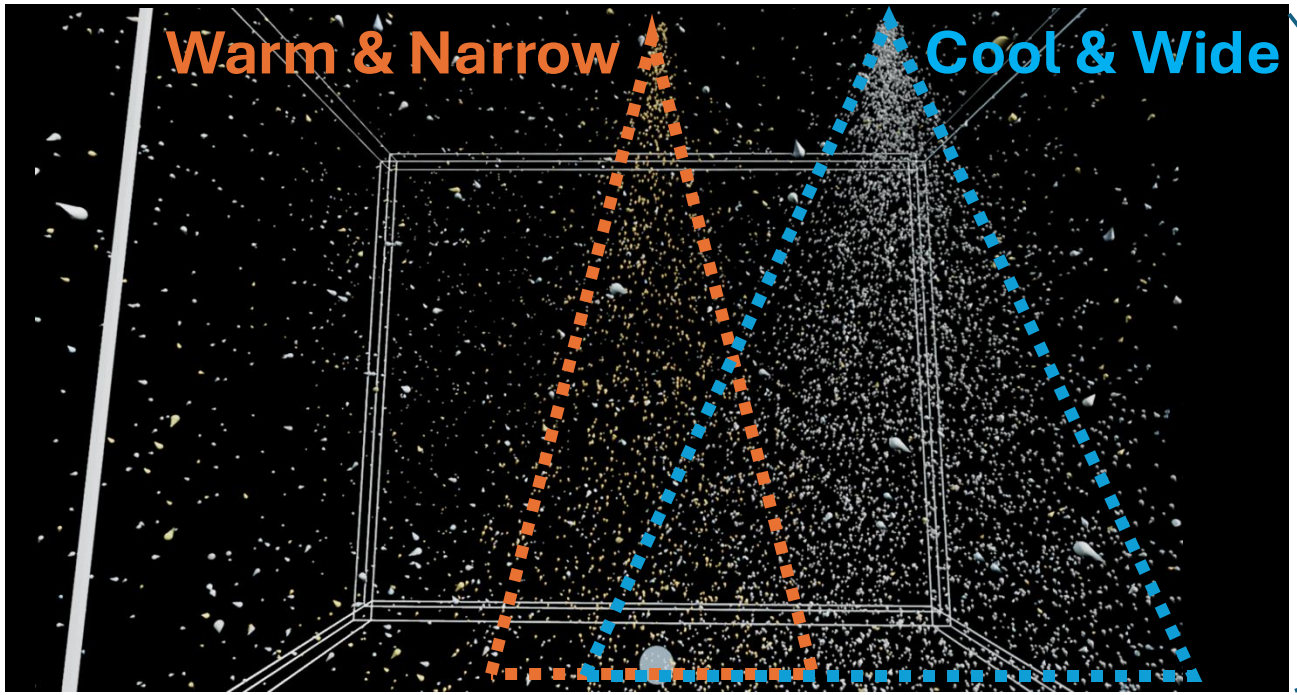
3. ***Answer several questions***

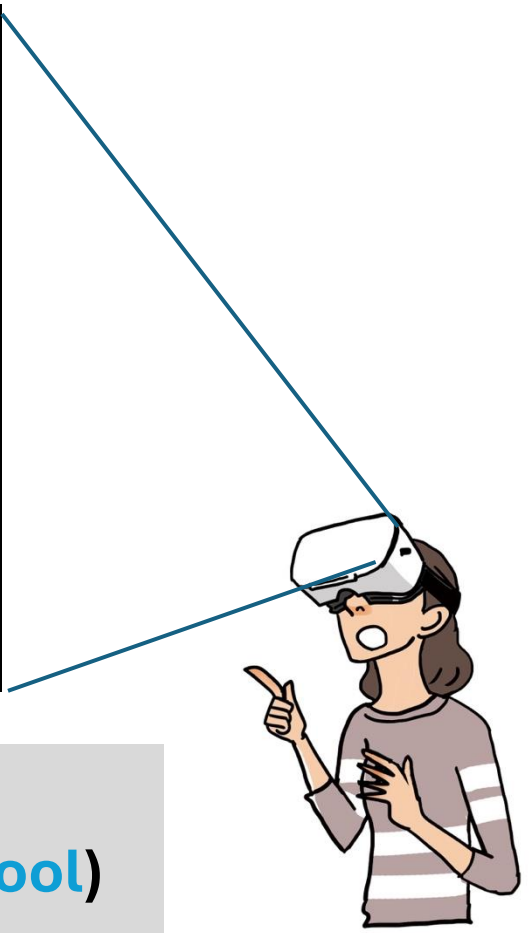


5. Interviews with practitioners

Directionally guided photon flow with two spotlights

Warm	*Cool*
2700 [K]	5000 [K]
Narrow	***Wide***
19 °	34°

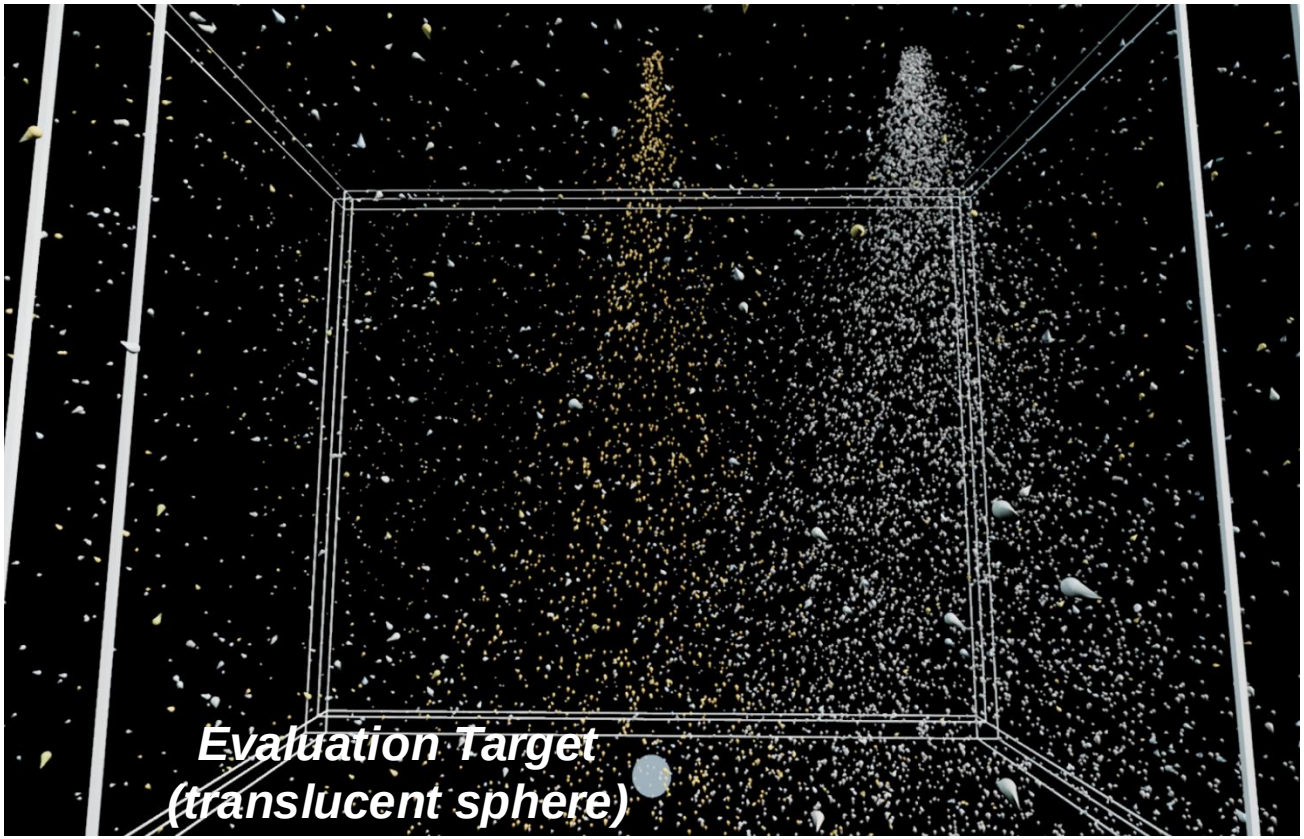




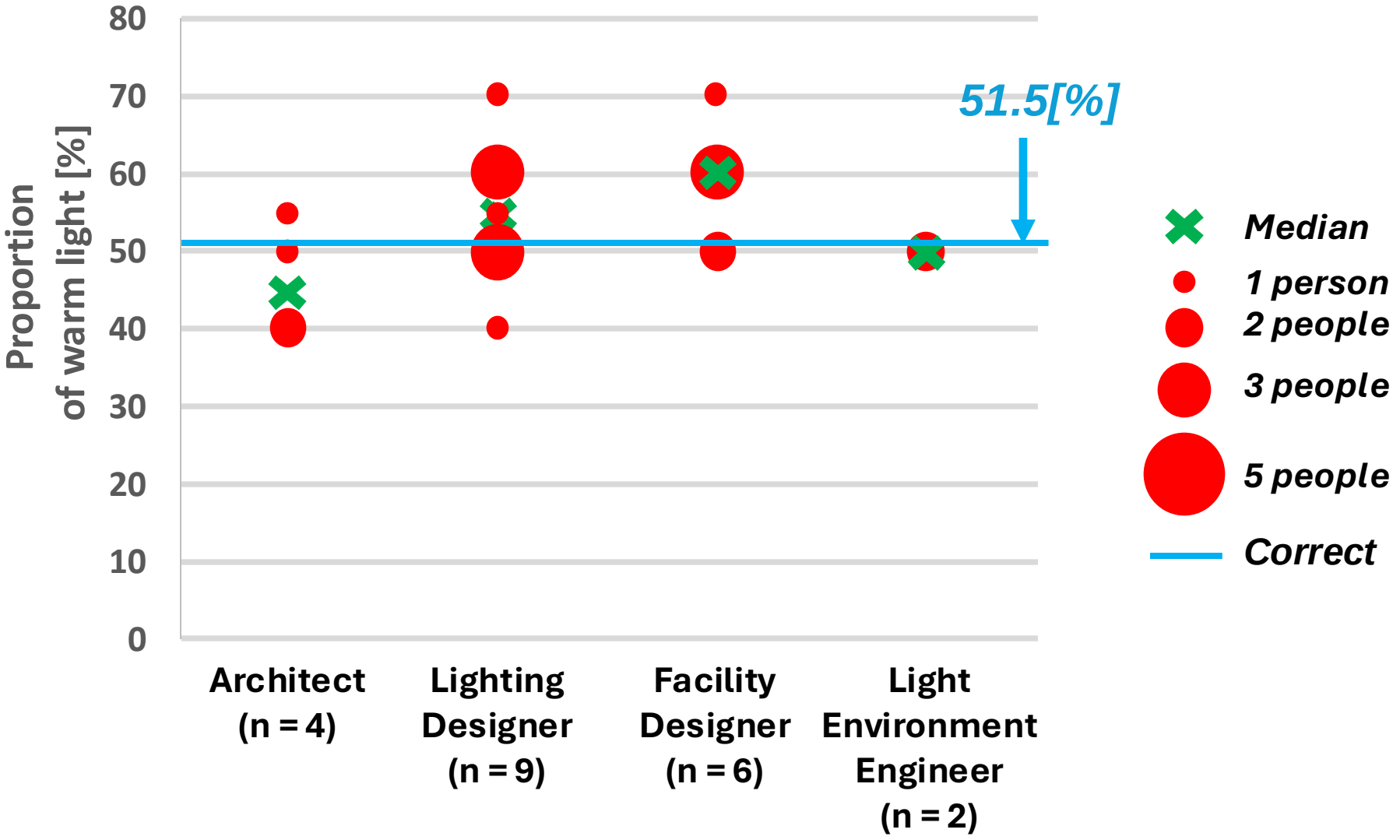
Two spotlights have different color temperatures (Warm and Cool) and beam angles (Narrow and Wide)

Question 1: what is the proportion of warm light to total light incident on the translucent sphere?

Question 2: what is the proportion of indirect light to total light incident on the translucent sphere?

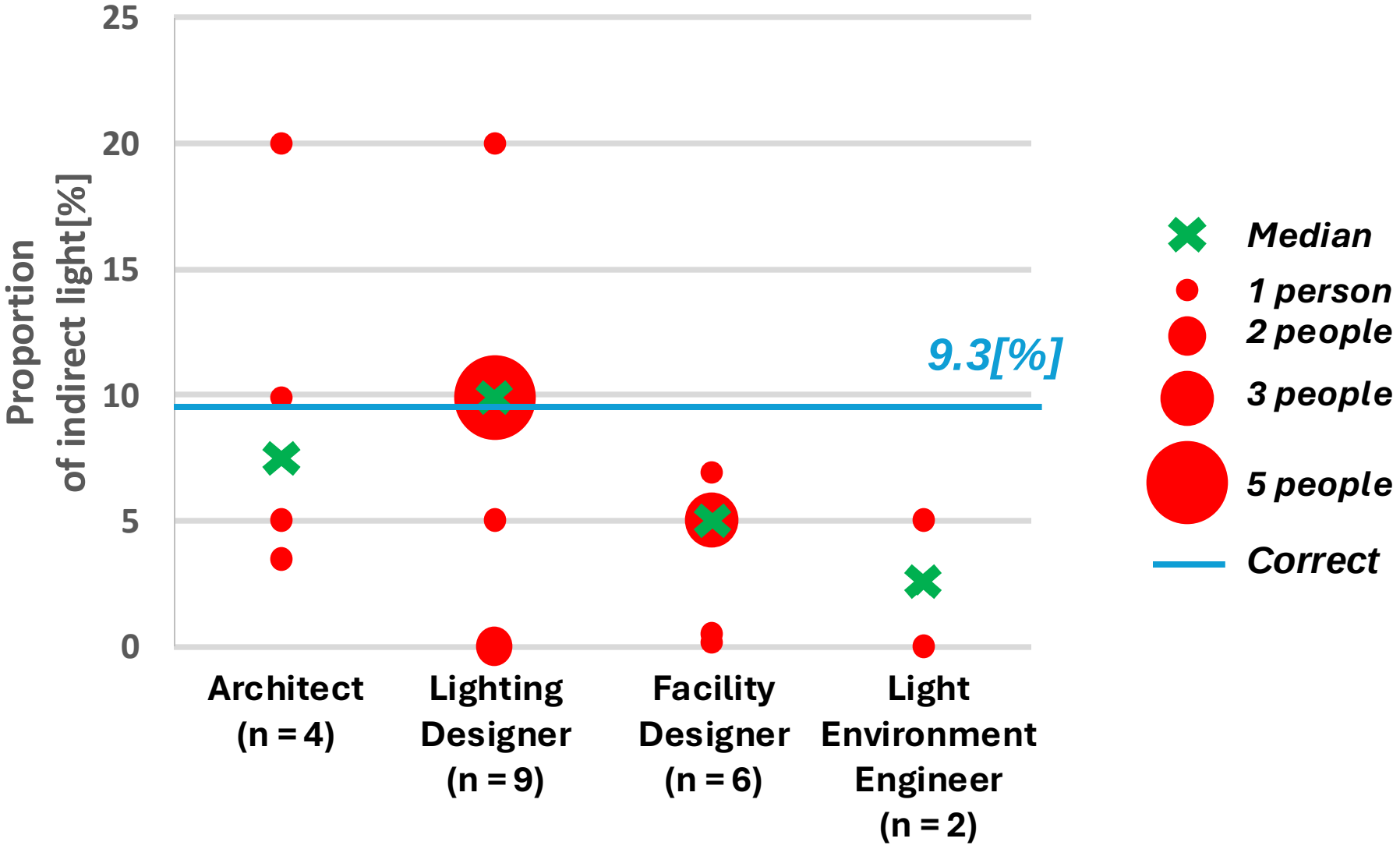


Answer 1. Proportion of warm light



The median values were not so different among profession groups, and they were close to the physically correct values.

Answer 2. Proportion of indirect light



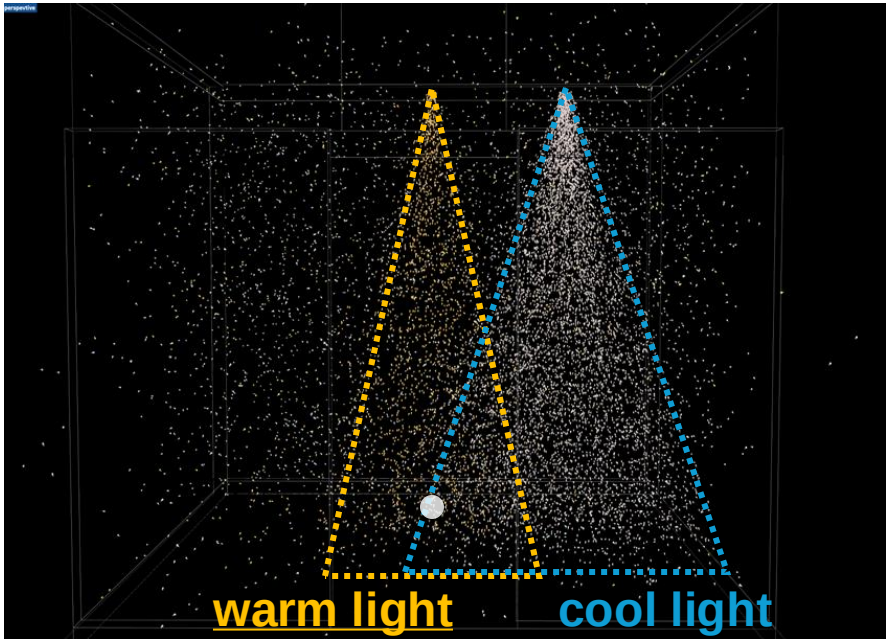
Some lighting designers could answer almost correct value, however, most of them underestimated the proportion of the indirect component.

5. Interview with practitioners

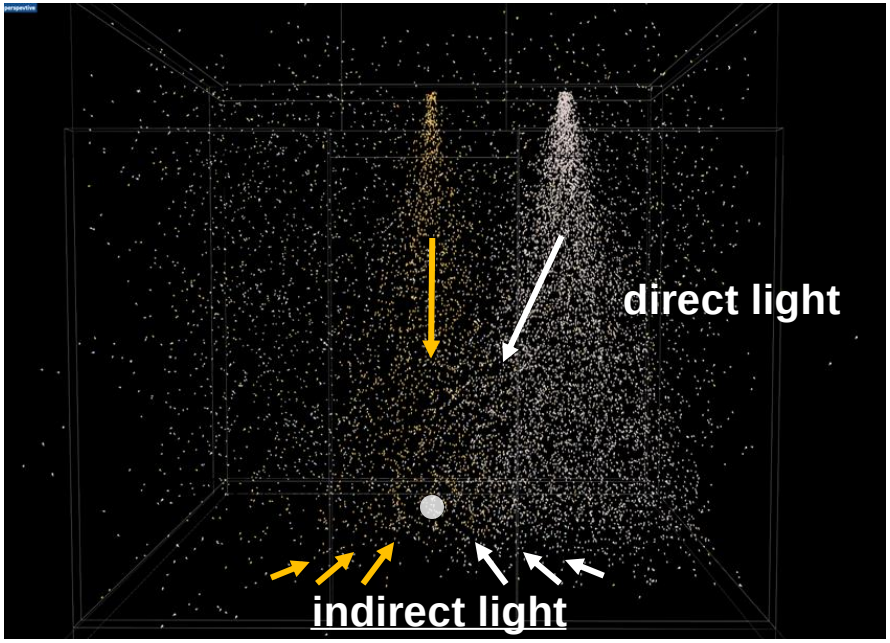
Question 3.

Was it easy for you to judge the proportion of warm light and indirect light by observing the photon flow?
Please also explain the reason for that.

Proportion of warm light



Proportion of indirect light



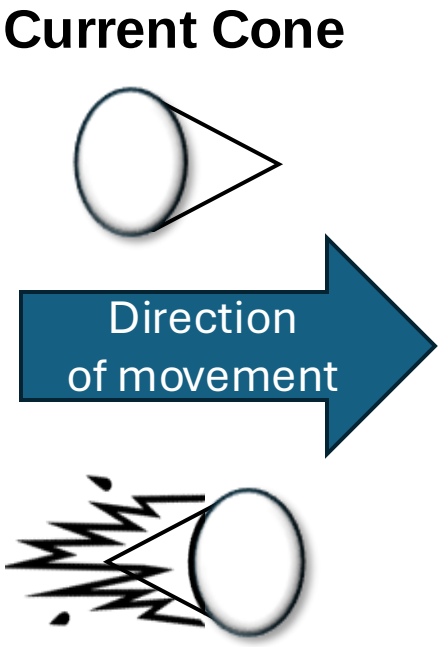
Answer 3.

Easy to understand

"With the addition of directionality to the photons, the overall picture of light has become much clearer."

Difficult to understand

Some participants said that *"the tip of the cone should not point to the direction of movement. The comet-like expression would be more preferable !!!"*



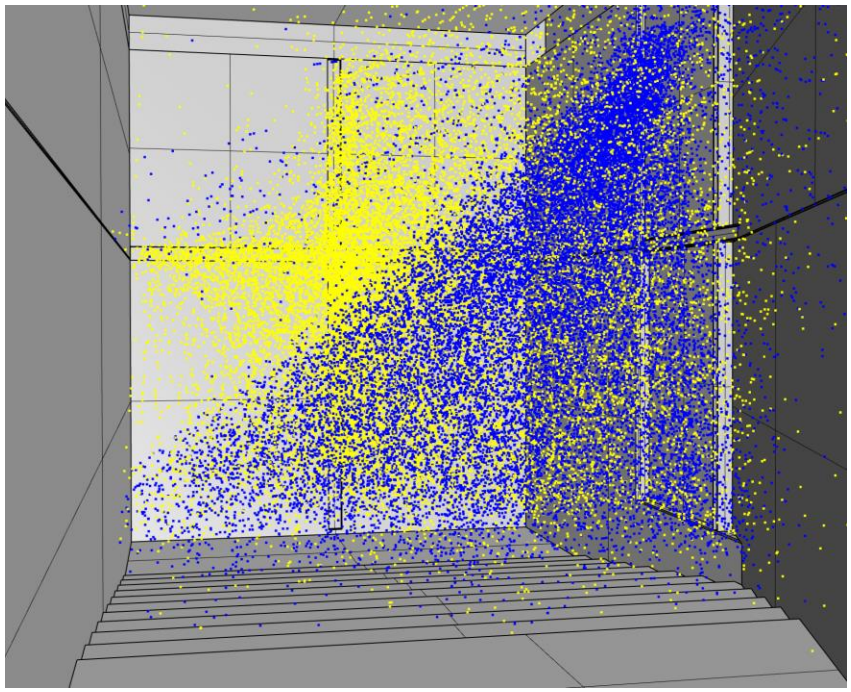
5. Interview with practitioners

Question 4.

In what specific situations could you use the photon flow in actual architectural or lighting design?

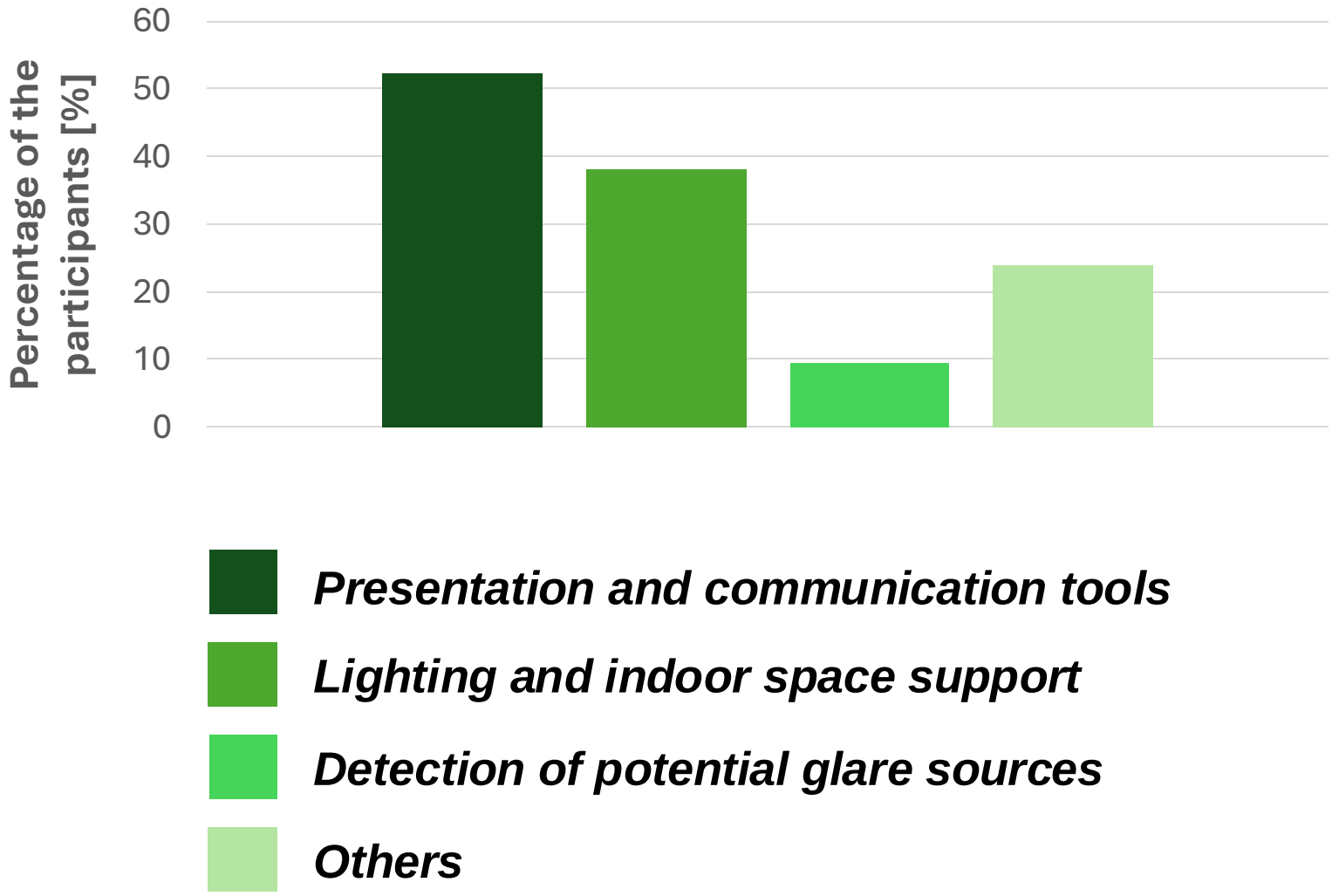
Question 5.

Could you give us any ideas on the areas for improvement of the current photon flow?



Answer 4.

In what specific situations could you use the photon flow in actual architectural or lighting design?

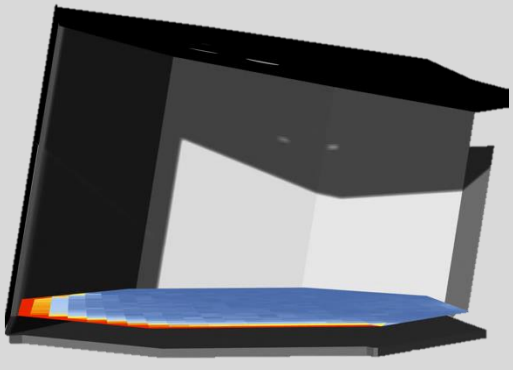


Presentation and communication tools

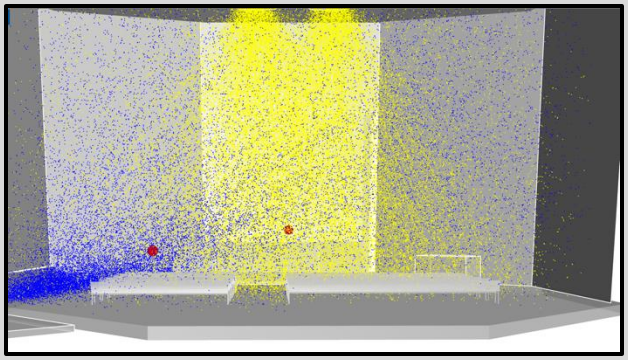
【Architect】

"When explaining the lighting environment, showing the illuminance distribution to clients often cannot make the concept clear to them."

"It seems useful for visually understanding lighting environment and the effect of windows, and for communicating those effects to clients."



Illuminance distribution



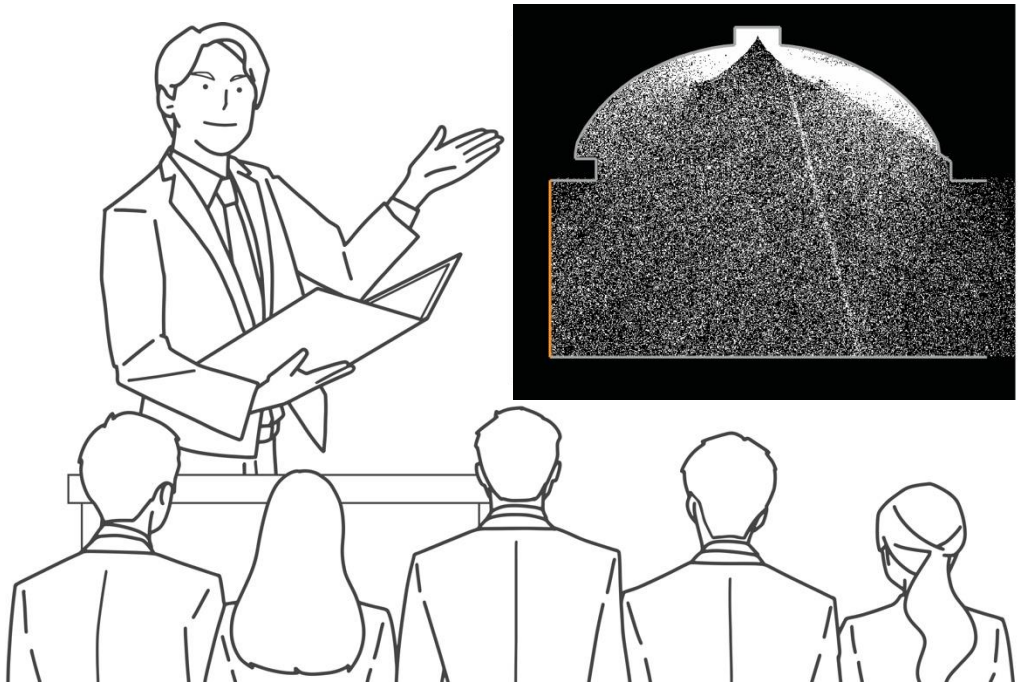
Photon flow

Presentation and communication tools

【Lighting Designers / Facility Designer】

"This tool might be useful for conveying lighting design concepts to architects, who are not specialists of lighting, which include the basic information of dark and bright in the space."

<Communication tools between different profession>

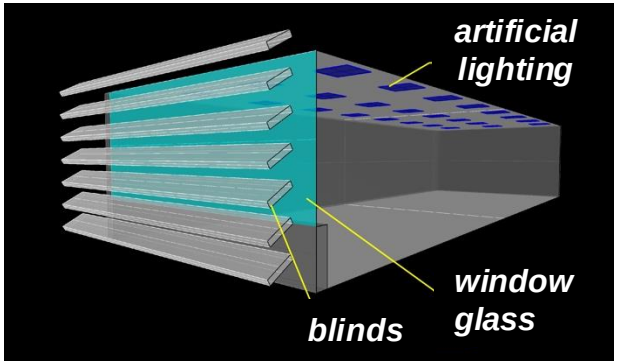


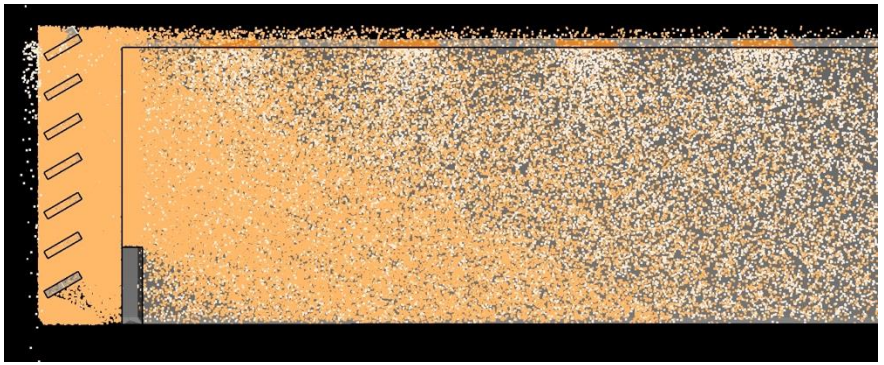
Lighting and indoor space design support

【*Architect*】

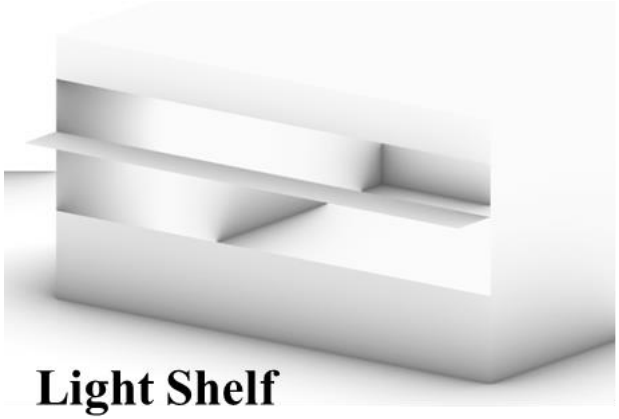
"It could be used to understand how light spreads after passing through blinds with different slat angles or after reflecting on the daylight control system, such as light shelves."

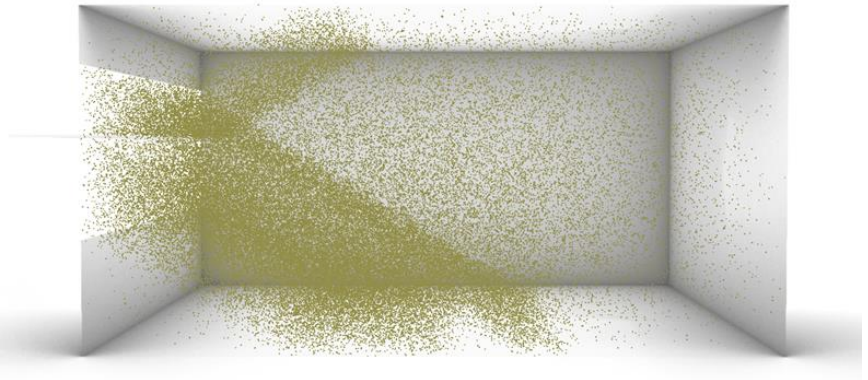
blindsExternal





Light Shelves





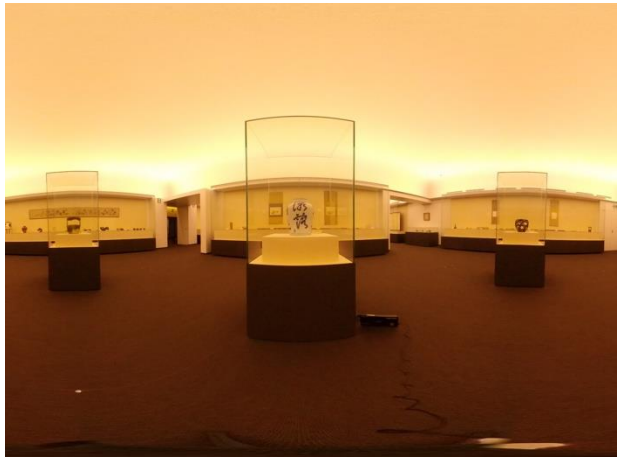
Lighting and indoor space design support

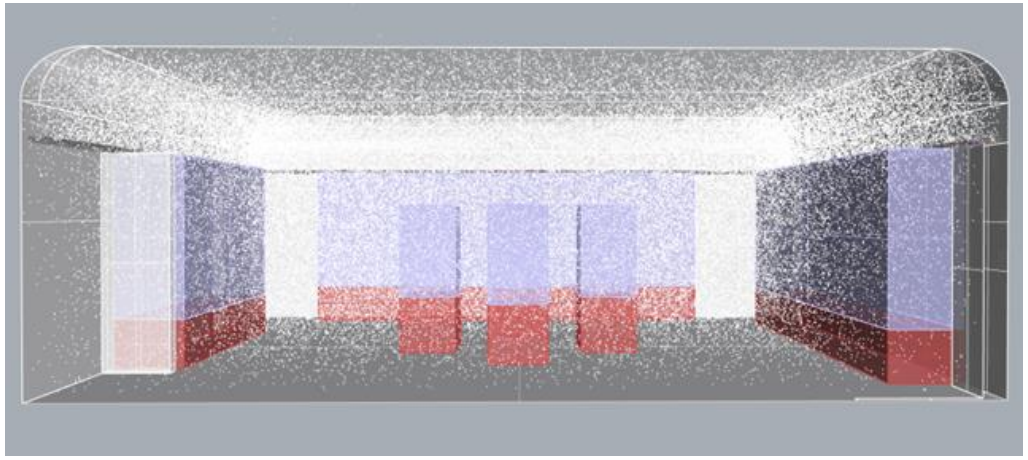
【Lighting Designers / Facility Designer】

"*It seems useful as design assistance tools for spaces where indirect light is crucial, such as museums.*

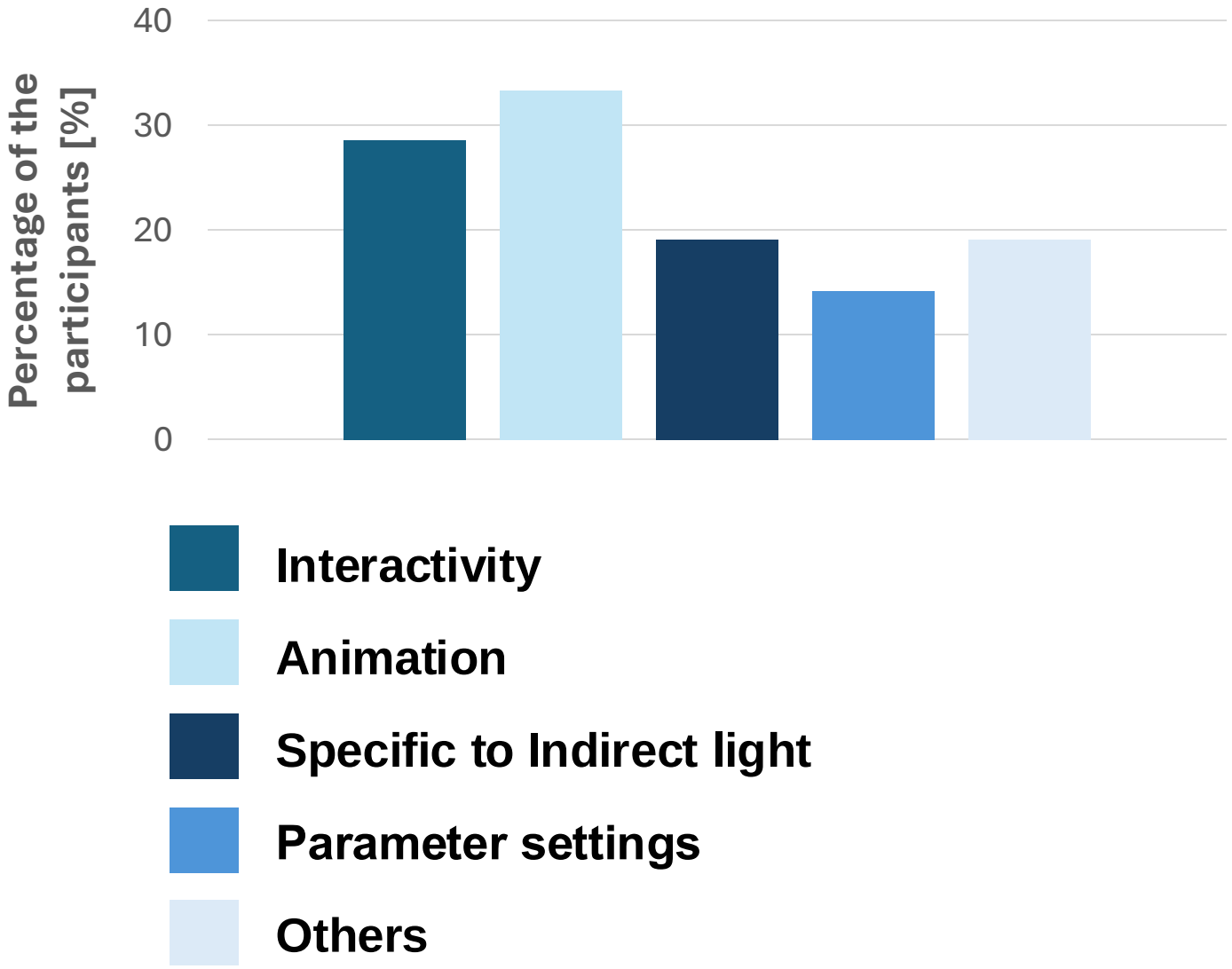
Adachi Museum of Art

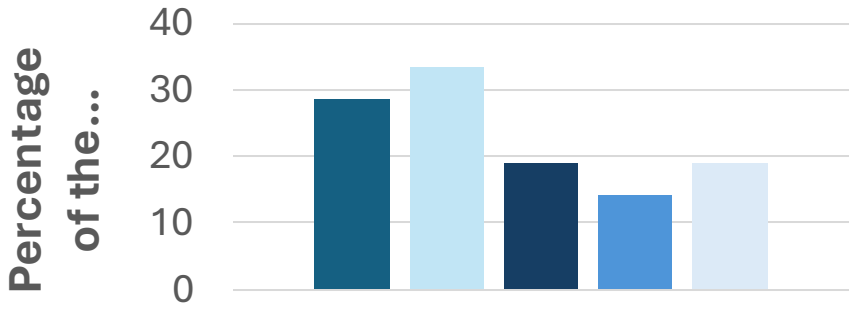
A space with a uniform lighting in which shadows do not fall, and artworks are lit solely by the indirect light.





Answer 5. **Could you give us any ideas on the areas for improvement of the current photon flow?**





Interactivity

"Interactivity, that instantly output photon flow, is necessary."

Animation

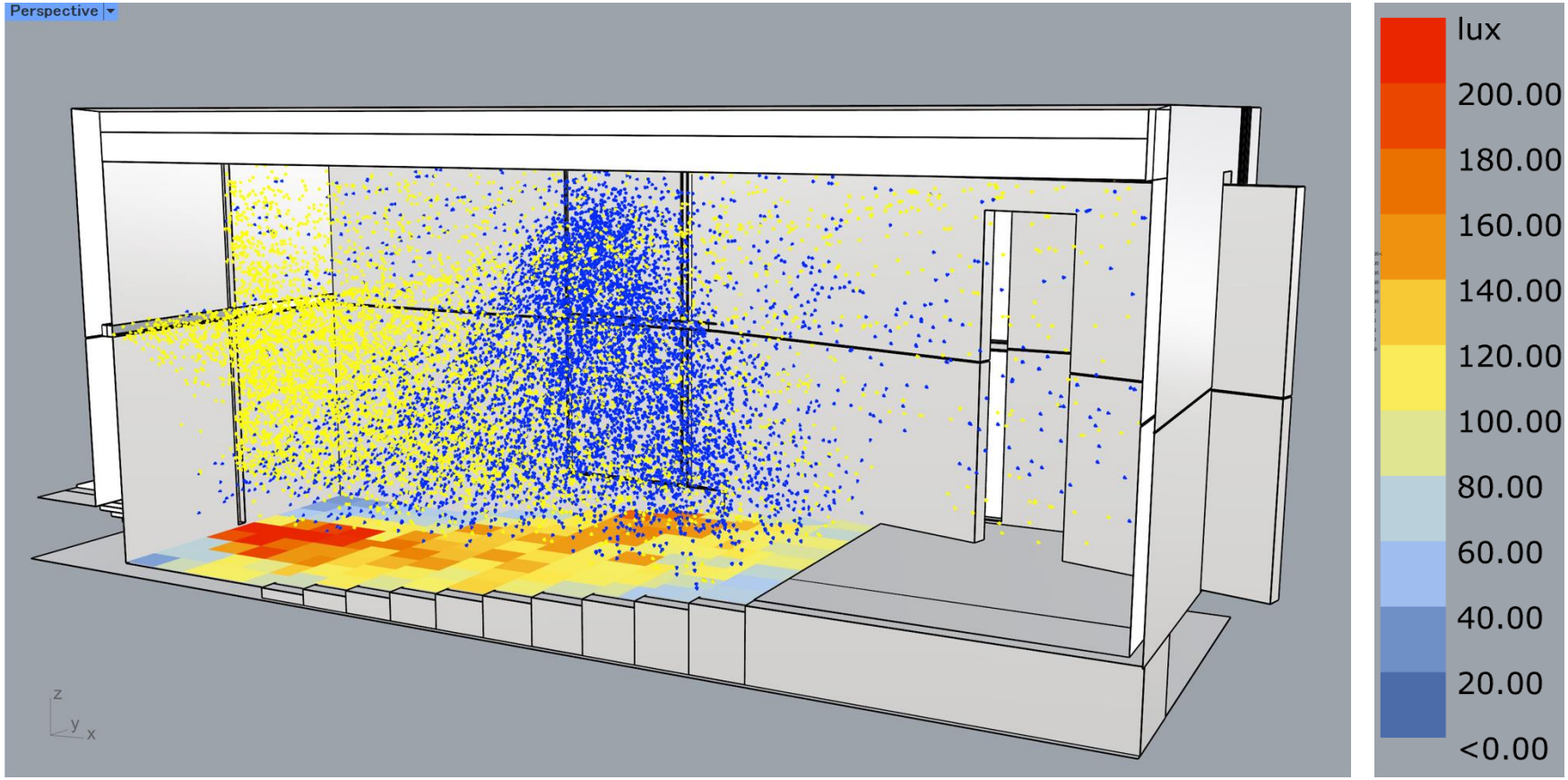
"Move each photon just a little when representing the flow of light. It could make the flow even clearer."

Specific to Indirect light

"The effect of direct light is easy to understand, so I'd like to see the photon flow specific to indirect light."

Others

"Superimpose the photon flow on the horizontal illuminance distribution map."



*Some issues on the photon flow

Some participants pointed out that *"actual brightness was difficult to read from the photon flow alone."*

Judgment criteria / reference points which enable to anchor absolute values of brightness would be necessary.

An architect who does not specialize in lighting told that *"Horizontal illuminance maps and CG images are enough to understand lighting environment."*

That would be controversial...

6. Conclusion and future works

We proposed a method to add the directionality to Photon Flow.

■Advantages:

Using a directionally guided photon flow **improved** the accuracy of prediction when directional light sources are used.

■Problems:

Prediction is difficult at positions under indirect light, and still challenging even when a directional light source is distant. Under the conditions of diffuse light sources, there is a high possibility that there is an issue with the presented image, so it needs to be reconsidered.

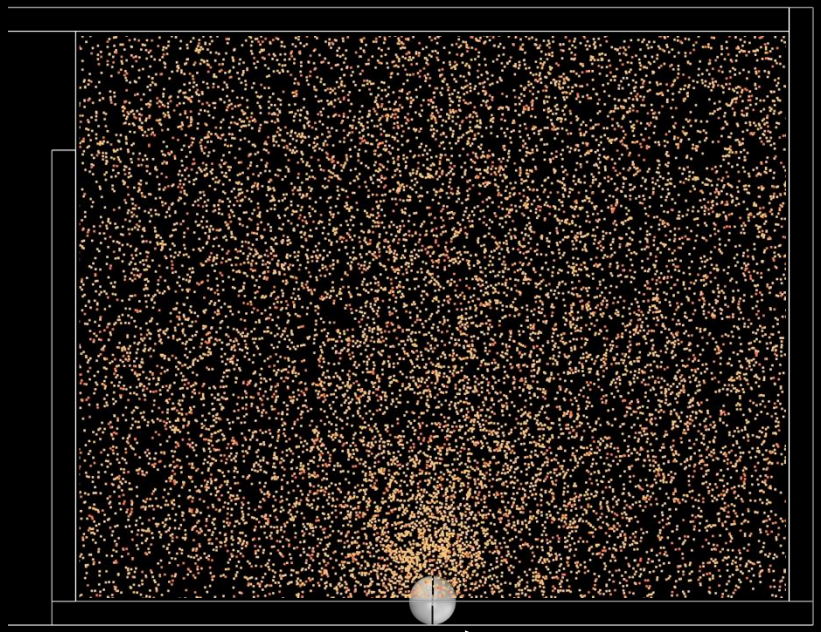
According to subject experiments and interview surveys, it is suggested that having an animation function makes it easier to understand the light environment in locations with a high proportion of indirect light.

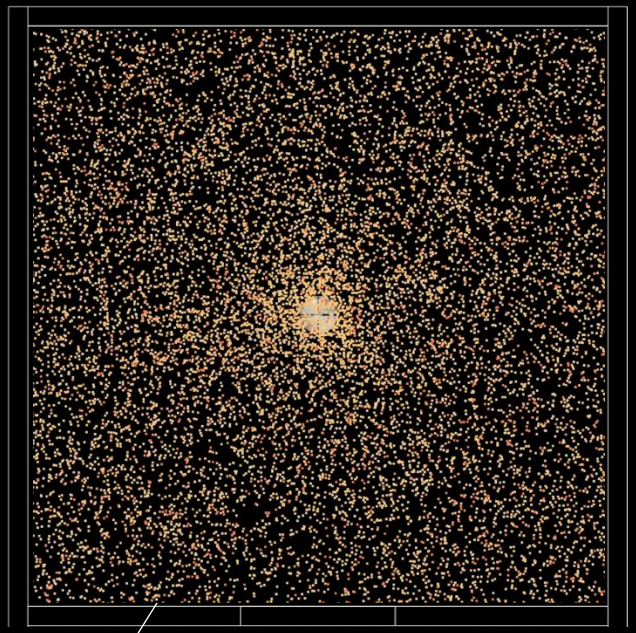
6. Conclusion and future works

Photon Flow Animation (Idea)

This video was created by gradually moving each photon in its direction of movement.

It is easy to intuitively understand in what direction photons around the light source is moving. In the future, we plan to add new features of presenting the direct and indirect components separately, as well as an animation function that can represent reflections on the walls and floor.





Diffuse light source