

# LentiMorpho: A Lens Array Based Display with Switchable View-Dependent and View-Independent Modes by Varying Liquid Volume

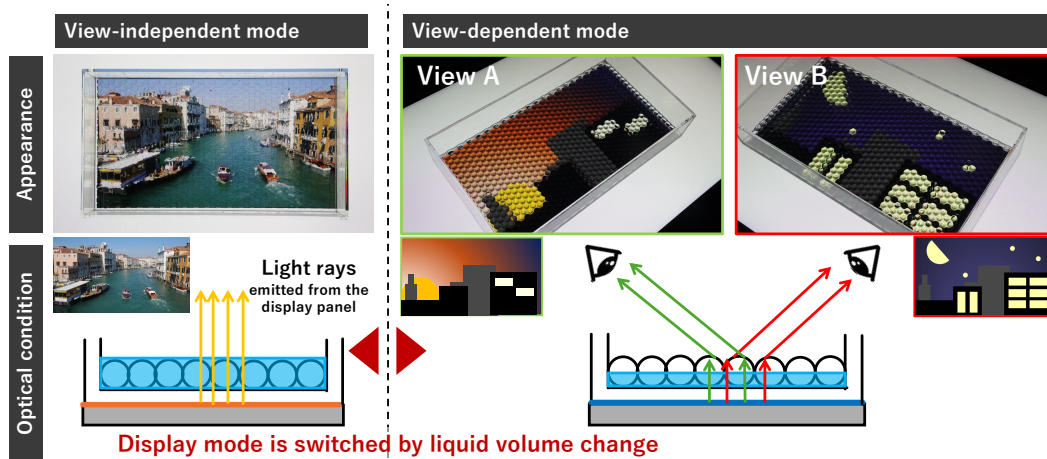
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**Figure 1: Overview of LentiMorpho.** LentiMorpho switches its display mode by changing the optical state of the lens array via liquid volume change. In the view-dependent mode, a precomputed pattern is displayed on the panel to realize ray separation.

## Abstract

View-dependent displays can present different visual information depending on the viewing position. These displays have been studied for applications including stereoscopic imagery and personalized presentation. However, placing optical elements such as lenses in front of the display inevitably introduces trade-offs with respect to the original display’s resolution, brightness, and effective display area. These limitations remain even when a view-independent presentation is required, making it difficult to flexibly adapt a single display device to different usage scenarios. We present LentiMorpho,

a lens-array-based display that can dynamically switch between view-dependent and view-independent presentation by varying liquid volume. By immersing glass beads arranged in a honeycomb structure into a liquid with a matched refractive index, the optical function of the lens array can be physically enabled or disabled. This approach allows a single display to alternate between high-quality shared presentation and viewpoint-specific content delivery without permanent optical trade-offs. To evaluate our method, we captured images using a stereo camera within the designed viewing zone during view-dependent display. The results showed that the similarity between the images corresponding to the left and right eyes exceeded 90 %, indicating stable binocular consistency. The leakage of image components intended for other viewpoints, referred to as crosstalk between view-specific images, was approximately 15 % on average, showing that view-dependent content was predominantly separated by viewing position. These results



demonstrate that LentiMorpho enables a single display to switch its images flexibly between shared and individualized visual presentation, providing a new interaction capability for multi-user display environments.

## CCS Concepts

• **Hardware** → **Emerging interfaces**; • **Human-centered computing** → **Displays and imagers**.

## Keywords

view-dependent displays, lens array based display, lens arrays, light-fields, optics

### ACM Reference Format:

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## 1 Introduction

Visual display systems are used in a wide range of situations such as signage and advertising, and methods for presenting different content to multiple users have attracted increasing attention. Among them, view-dependent displays, which can present different information depending on the observer’s viewpoint position, have been widely studied as a representative approach for realizing such multi-user information presentation. For example, a view-dependent display has been presented for use in public spaces such as airports and train stations, where different seat information or languages can be presented to each observer [8]. In addition, view-dependent displays have been investigated to support co-located collaboration and protect privacy [12, 19, 20].

Many of these view-dependent displays employ optical elements such as lenticular lenses or microlens arrays placed in front of the display, which separate light rays according to viewing direction. This structure allows different information to be presented to different observers. However, since such optical configurations are designed on the premise of always performing view-dependent presentation, they impose constraints due to light-ray separation even in situations where the displayed content should be shared by all users, resulting in degraded image quality. Specifically, trade-offs arise with respect to the original display performance, such as resolution, brightness, and display area. In other words, existing view-dependent displays are optimized for presenting separated information, but they are not designed for scenarios in which information is presented without separation.

Allowing a view-dependent display to also function as a view-independent display effectively adds the capability of view-dependent presentation to conventional view-independent displays. This extension has the potential to broaden the usage of view-dependent displays from specialized applications to more general-purpose display devices. For example, in exhibitions or digital signage, it would become possible to switch between a mode in which the same content is shared in high quality and a mode in which different information is presented depending on the viewer’s position,

thereby expanding the applicability of view-dependent presentation to more versatile scenarios.

In this study, we implement a reconfigurable lens array using glass beads and liquid, and propose a view-dependent display, “LentiMorpho”, which enables switching between view-dependent and view-independent presentation on a single display. In the proposed method, by using a liquid that has the same refractive index as glass, the refractive state of the lens array can be switched by changing the amount of liquid, allowing the presence or absence of the lenses to be controlled at the physical-structure level. This makes it possible to achieve high-quality view-independent presentation without being constrained by optical elements in situations where view-dependent presentation is not required. Figure 1 shows the implemented LentiMorpho. The example on the left shows view-independent presentation, while the two examples on the right illustrate view-dependent presentation, where the color pattern for realizing view-dependent presentation is visualized.

Many existing view-dependent displays are optically designed under the assumption of a specific display size and resolution. As a result, the design of the optical elements is strongly coupled with the size of the display surface, and redesign of the optical configuration is required when the display size is changed. Consequently, it is difficult to flexibly select the display size according to the usage environment, which has limited the range of applicable scenarios.

The proposed method adopts a structure that combines a general-purpose liquid crystal display with a lens array, and the lens array can be constructed as an assembly of simple structural elements without requiring specialized microfabrication equipment. Therefore, our approach has the potential to mitigate the design cost issues inherent in existing view-dependent displays, where optical elements must be redesigned for each display size.

The main contributions of this study are as follows:

- We introduce a physically reconfigurable lens array whose optical behavior can be switched between lens and non-lens states by changing liquid volume, enabling dynamic modulation of light-ray separation.
- We demonstrate a display configuration that supports view-dependent presentation while maintaining binocularly matched images, avoiding unintended stereoscopic disparity.
- We present a reconfigurable display interface that enables seamless switching between view-dependent and view-independent presentation within a single device, expanding the applicability of multi-user displays across diverse interaction scenarios.

## 2 Related Work

### 2.1 Light Field Displays

A view-dependent display presents different images depending on the observer’s viewpoint, enabling viewpoint-specific information presentation. Such displays are often realized based on the principle of light field displays, which reproduce predefined light ray positions and directions using mathematical formulations [4, 16]. Many view-dependent displays adopt configurations in which the displayed content primarily changes when the viewpoint moves in a single direction. In approaches using lenticular lenses or parallax barriers, different images can be presented mainly in response

to horizontal viewpoint movement [17, 21, 24]. Such approaches correspond, in the classification of light field displays, to configurations that control the emission direction of light rays in only one direction. As a result, in situations where multiple observers view the display from different heights or distances, unintended mixing of images and degradation of the intended view-dependent presentation performance are likely to occur.

In contrast, approaches represented by Integral Photography using a lens array [18] can realize image changes in response to viewpoint movement in both horizontal and vertical directions. Such configurations are positioned as light field displays that control the emission direction of light rays in two dimensions, namely horizontal and vertical. Since these approaches have mainly been studied with the objective of allowing observers to perceive three dimensional shapes while freely moving their viewpoints [1–3, 7], designs that assume multi-user displays presenting different information content depending on the point of view, or switching between view-dependent and view-independent displays, have not been treated as primary topics.

LentiMorpho, which is proposed in this study, is classified as a light field display that reproduces four dimensional light ray information (two-dimensional spatial position and two-dimensional angular direction), in that it controls the emission direction of light rays using a lens array with two degrees of freedom in the horizontal and vertical directions. Although many conventional view-dependent displays have been based on configurations assuming viewpoint movement in a single direction, the proposed method realizes view-dependent presentation that supports viewpoint movement in both horizontal and vertical directions. The main focus of this method is not the two-dimensional viewpoint variation itself, but the use of light ray control to switch between view-dependent and view-independent displays. This enables a new usage scenario in which shared content can be presented without degrading display quality when view-dependent presentation is unnecessary, and view-dependent presentation is activated only when required.

## 2.2 View-Dependent Display

In situations where multiple users share the same display, there is a demand to present different information content simultaneously depending on the viewpoint. For example, in studies that assume a tabletop environment, some approaches achieve directional presentation of information, such as text and images, for each user by placing an optical film on the display [12]. In addition, many methods have been proposed for presenting different aerial images depending on viewpoint position [13, 25], as well as methods for presenting stereoscopic images with viewpoint dependent parallax [5, 14, 15, 28, 29].

As described above, view-dependent displays have been proposed using various optical elements. However, most of these approaches require placing optical components such as lens arrays, barriers, or films in front of the display. As a result, trade-offs with resolution, brightness, and effective display area cannot be avoided even in situations where view-dependent presentation is unnecessary. LentiMorpho enables switching between view-dependent

and view-independent presentation on a single display device by switching the optical function of the lens array.

## 2.3 Manufacturing Optical Elements

The lens array proposed in this method is characterized by the fact that it does not require specialized fabrication equipment for shaping the lenses. One common manufacturing method for lenticular lenses and lens arrays is to shape glass by polishing processes such as etching. However, such glass-based fabrication is costly and unsuitable for large-scale or mass production.

To address this issue, several alternative fabrication approaches have been proposed. These include methods that fabricate lenses by stacking ink using an inkjet printer [22], as well as approaches that shape lenses by layering resin using a 3D printer or a UV printer [26, 31]. Another approach forms a jelly with a lens array shape by pouring a solution containing dissolved gellan gum into a mold fabricated with a 3D printer [30]. While these methods reduce fabrication cost, the size of the resulting lens arrays is inherently constrained by the size and precision of the fabrication equipment.

Due to these constraints, it is difficult to fabricate lens arrays that can be applied to large displays such as signage. The proposed method has the potential to relax constraints on the size of the target display.

## 2.4 Liquid-Based Interface

Many visual information presentation methods based on the properties of liquids have been proposed. Sahoo et al. proposed a visual display that uses liquid gallium as pixels by exploiting the property that gallium suspended in sodium hydroxide can be controlled to move, vibrate, merge, and split under an electric field [23]. Other examples include a display that uses individual soap bubbles as pixels by exploiting the property of soap solution that expands when air is injected [10], and a display that uses bubbles generated by electrolysis as pixels [11]. In addition, as a study that utilizes the refractive index of liquids, Fade-in Pixel is a device that blurs real world objects and changes their appearance depending on the presence or absence of paraffin oil [9]. As shown in prior work, various visual information presentation methods using liquids have been proposed. However, in the context of view-dependent display design, no method has been investigated that switches between view-dependent and view-independent displays by using the amount of liquid.

# 3 LentiMorpho

## 3.1 Principle

In this study, we present a lens array display called LentiMorpho, which uses glass beads and a liquid with a refractive index close to that of glass to enable switching between view-dependent and view-independent presentation. By increasing or decreasing the amount of liquid, the refractive behavior at the surface of the glass beads changes. This makes it possible to switch between a state in which a lens effect occurs and a state in which no lens effect occurs optically.

The configuration of the lens array proposed in this study is shown in Fig. 2 (a). A lens array is placed on top of a flat panel display such as an LCD or an OLED. The lens array consists of an

acrylic case and glass beads and liquid inside it. By arranging the glass beads in a honeycomb pattern, the structure functions as a fly-eye lens.

Liquid paraffin is used as a liquid with a refractive index close to that of the glass beads. The refractive index of the liquid paraffin used in this study is approximately 1.47, which is close to the refractive index of common soda lime glass, approximately 1.52. Therefore, when the glass beads are immersed in the liquid, the difference in refractive index at the interface between the glass beads and the liquid becomes small, and light refraction at this interface almost disappears.

Fig. 2 (b) shows a schematic illustration of the state in which the glass beads are half immersed in liquid paraffin. In this state, only the upper half of each glass bead, which is in contact with air, functions as a refractive boundary, while the lower half, which is in contact with the liquid, becomes effectively flat. As a result, each bead behaves as a plano convex lens. As a result, light rays emitted from the flat panel display are separated according to their emission directions, and different images are presented depending on the observer's viewpoint position. This enables view-dependent presentation. In this paper, this state is referred to as the view-dependent presentation mode.

Fig. 2 (c) shows a schematic illustration of the state in which the amount of liquid paraffin is increased and the glass beads are fully immersed. Since light rays are no longer refracted at the surface of the glass beads, the lens function is effectively disabled. This state enables view-independent presentation. In this paper, this state is referred to as the view-independent presentation mode.

In this study, in order to avoid real image formation by the lenses and to control only the emission directions of light rays, the distance between the lens array and the flat panel display is set within the focal length  $f$  of the lenses. Here, the glass beads are approximated as plano convex lenses, and the focal length is calculated using the lens maker's formula. The focal length  $f$  of the lens array is expressed by Eq. 1 using the refractive index  $n$  and the radius of curvature  $r$  of the lenses.

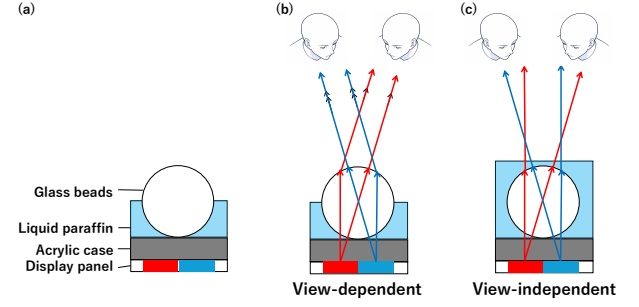
$$f(n, r) = \frac{r}{(n - 1)} \quad (1)$$

When the display is placed outside the focal length, light rays emitted from the display converge after passing through the lenses and form a real image. In contrast, when the display is placed within the focal length, the light rays do not converge, and only their emission directions are controlled. In this study, we adopt a configuration that satisfies this condition.

In the view-dependent presentation mode, a precomputed color pattern, as described in section 3.2, is displayed on the flat panel display, whereas in the view-independent presentation mode, a normal 2D image is displayed.

### 3.2 Color Pattern Design

To enable viewpoint-dependent presentation while presenting identical images to both eyes in the proposed system, we design the color patterns displayed on the LCD beneath the lens array using ray tracing based on a geometrical optics model. In this process, the



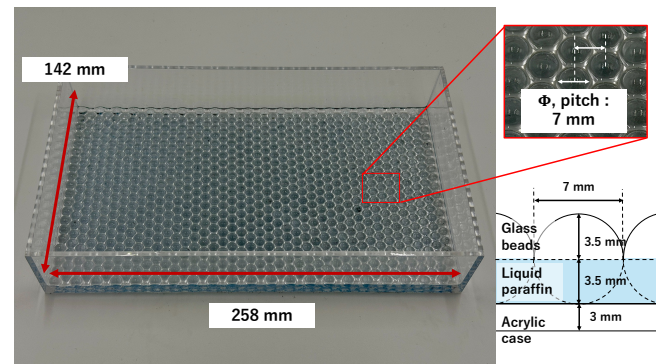
**Figure 2: Structural configuration (a) and schematic light ray paths in LentiMorpho for view-dependent (b) and view-independent presentation mode(c).**

lens array is modeled as a set of spherical lenses arranged in a honeycomb pattern with a constant pitch, and ray tracing is performed assuming a known geometrical configuration.

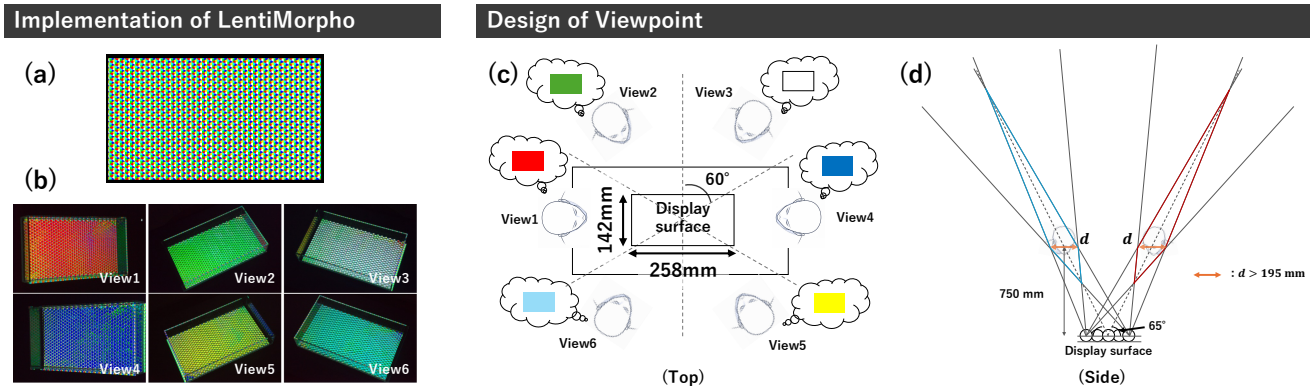
First, the viewpoint positions for observation are defined. Here, we adopt the concept of the cyclopean eye, in which the midpoint between the left and right eyes is regarded as a virtual observation position. The center of each viewing zone is set to the cyclopean eye, and the width of each viewing zone is set to approximately three times the interpupillary distance (IPD), 195 mm, so that both eyes are reliably included within the same viewing zone. In this study, we assume binocularly matched presentation, in which both eyes perceive the same viewpoint image, and design the color patterns to satisfy this condition.

Light rays are emitted from each viewpoint toward the display panel, and the lens through which each ray passes and the pixel that each ray reaches are calculated. At this stage, refraction of the light rays at the lens surface is computed based on Snell's law. This process determines the pixels that reach the observer for each viewpoint.

Based on the ray tracing results, image spots formed beneath the lenses are calculated. An image spot represents a set of pixels



**Figure 3: Designed lens array.**



**Figure 4: Implemented LentiMorpho and designed viewpoint positions. (a) Color pattern displayed on the flat panel display. (b) Appearance of the lens array placed on the display showing (a). (c, d) Schematic diagrams of the designed viewpoint positions. (c) Top view. (d) Side view.**

that are visible through a lens when observed from a specific viewpoint. The color pattern is generated by integrating the image spots corresponding to all viewpoints across all lenses.

An example of the designed color pattern is shown in Fig. 4(a). Depending on the viewpoint positions surrounding the display, the colors switch among red, green, white, blue, yellow, and cyan. In this image, the area beneath each lens is filled with pixels corresponding to the colors observed from each viewpoint. In the view-dependent display mode, the pixels magnified by the lenses vary depending on the viewing position.

### 3.3 Prototyping

Fig. 3 shows the designed lens array. The acrylic case used in this study has inner dimensions of 142 mm in height and 258 mm in width, and a thickness of 3 mm. The acrylic case is filled with glass beads (Y-7, Bright Beads) and is half immersed in liquid paraffin (Hayashi Pure Chemical Ind., Ltd.). The diameter of the glass beads is 7 mm. The lens array is placed on top of a 23 inch flat panel display (ZenScreen MB249C, ASUS Inc., resolution  $1920 \times 1080$  px, display area  $527.04 \times 296.46$  mm).

Fig. 4(b) shows the appearance of the display with the lens array placed on it, where the color pattern designed in Section 3.2 (Fig. 4(a)) is displayed. These images were captured from a position 750 mm from the center of the screen with an elevation angle of 65 degrees. The viewpoint positions are designed as shown in Fig. 4(c, d). The observer is positioned at the cyclopean eye corresponding to the center of each viewing zone, with a viewing distance of 750 mm from the display and an elevation angle of 65°. The six viewing directions illustrated in Fig. 4(c) are defined as View1 through View6. As shown in Fig. 4(d), the width of each viewing zone was set to 195 mm, which is three times the interpupillary distance (IPD) of 65 mm. When observed from the designed viewpoint positions, the colors displayed on the screen appear to switch depending on the viewpoint.

## 4 Evaluation

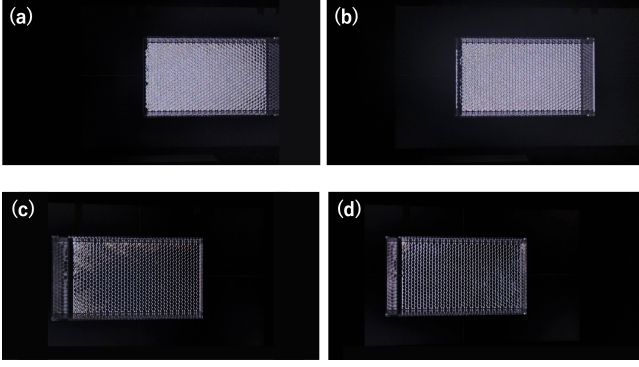
### 4.1 Similarity Evaluation of Left and Right Images Captured by a Stereo Camera

**4.1.1 Objective.** The objective of this evaluation is to quantitatively verify whether LentiMorpho functions correctly as an optical system that presents identical visual information to the left and right eyes in the view-dependent presentation mode. In other words, this evaluation examines whether unintended luminance differences or disparities occur between the two eyes. Binocular consistency in view-dependent presentation can be defined as the consistency of the light ray distributions reaching the two eyes. Therefore, image similarity is evaluated based on luminance distributions that reflect differences in the light ray distributions reaching the eyes.

At the viewpoint defined for evaluation, images are captured from two viewpoints placed at positions corresponding to the human left and right eyes. The degree of similarity between the luminance distributions of the left and right images is used as an index to quantitatively evaluate the consistency of the visual information presented to both eyes. In the view-independent presentation mode, the lens effect is disabled and a display equivalent to a conventional flat panel display is obtained. For this reason, our work explores only the view-dependent presentation mode in the evaluation.

**4.1.2 Experimental Setup.** A stereo camera (SpatialLabs Eyes, Acer) is used for the evaluation. The distance between the lenses of the stereo camera used in this study is 65 mm, which corresponds to the IPD. Therefore, the left and right cameras of the stereo camera are used as imaging positions corresponding to the human left and right eyes. The camera is fixed on a motorized stage shown in Fig. 6, and the camera position can be controlled in the horizontal direction with a resolution of 1 mm from a stage control PC. Control of the angular direction is performed by rotating the display and adjusting it using a digital protractor.

The camera is placed at the centers of the six viewing zones designed in Fig. 4(c, d), and images are captured once at each position. Image acquisition is performed under exposure conditions that avoid saturation and flare, with a shutter speed of 1/40 s, F2.0,



**Figure 5:** (a, b) Left view image (a) and right view image (b) captured by the stereo camera from the target viewpoint position used for evaluation. (c, d) Left view image (c) and right view image (d) captured from a different viewpoint position.

ISO 500, and a white balance of 6000 K. Images are captured at a resolution of  $7680 \times 2160$  pixels.

For the capture environment, we used a room equipped with blackout curtains. During image acquisition, the room lights and the monitor of the stage control PC are turned off. This setup minimizes the influence of external and ambient light, so that only light emitted from the display is included in the captured images. In addition, the brightness and contrast settings of the display are fixed.

The experimental setup used in the evaluation is shown in Fig. 5. As shown in Fig. 5(a, b), only white is visible at the target viewpoint positions. As shown in Fig. 5(c, d), only black is visible at the other viewpoint positions.

**4.1.3 Procedure.** At each viewpoint position, left and right images are captured using the stereo camera. For the captured images, a projective transformation is applied so that the corresponding regions are aligned, and the images are normalized to rectangular images of the same size,  $710 \times 1290$  pixels. The projective transformation is performed based on a homography matrix computed using the four corners of the lens array as corresponding points.

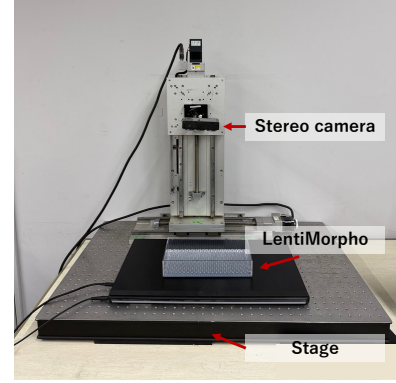
Each RGB image after the projective transformation is converted into a luminance image. Let the pixel values be  $R(x, y)$ ,  $G(x, y)$ , and  $B(x, y)$ . The luminance  $Y(x, y)$  is defined by Eq. 2 based on ITU-R BT.709.

$$Y(x, y) = 0.2126R(x, y) + 0.7152G(x, y) + 0.0722B(x, y) \quad (2)$$

Next, the luminance image is divided into a grid of  $N_x \times N_y$  blocks. Let  $\Omega_{u,v}$  denote the set of pixels contained in block  $(u, v)$ . The block average luminance  $m_1(u, v)$  for the left image is expressed by Eq. 3.

$$m_1(u, v) = \frac{1}{|\Omega_{u,v}|} \sum_{(x,y) \in \Omega_{u,v}} Y_1(x, y) \quad (3)$$

Similarly,  $m_2(u, v)$  is defined for the right image, and vectors  $\mathbf{m}_1, \mathbf{m}_2 \in \mathbb{R}^{N_x N_y}$  are generated by arranging these values. The



**Figure 6:** Evaluation environment for binocular similarity assessment (Section 4.1)

**Table 1:** Cosine similarity of captured images at each viewpoint position.

Viewpoint	Cosine similarity
View1	0.940
View2	0.931
View3	0.919
View4	0.922
View5	0.928
View6	0.930

block resolution and all processing parameters are kept identical for all viewpoint positions.

**4.1.4 Evaluation Metrics.** The degree of similarity between the left and right images is defined as the cosine similarity  $s$  between the block average vectors  $\mathbf{m}_1$  and  $\mathbf{m}_2$ , as expressed in Eq. 4.

$$s = \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{\|\mathbf{m}_1\| \|\mathbf{m}_2\|} \quad (4)$$

The value of  $s$  ranges from  $-1$  to  $1$ , and values closer to  $s = 1$  indicate higher similarity between the luminance distributions of the left and right images. In this study, this similarity is used as a quantitative index representing how similar the luminance distributions of the visual information presented to both eyes are.

**4.1.5 Results.** The cosine similarity values computed from the captured images are shown in Table 1. For all viewpoint positions, the binocular similarity  $s$  shows high values above 0.9. Since cosine similarity is interpreted as indicating higher similarity as its value approaches 1 [6], it is confirmed that the luminance distributions of the left and right images exhibit very high similarity. These results suggest that, at the designed viewpoint positions, the visual information reaching the left and right eyes is presented with high consistency.

From these results, we confirm that the proposed lens array functions as an optical system capable of presenting visual information with high consistency to both eyes in the view-dependent presentation mode.

## 4.2 Image Separation Performance at Each Viewpoint

**4.2.1 Objective.** The objective of this evaluation is to quantitatively assess, in the view-dependent presentation mode of LentiMorpho, the extent to which light rays observed at a given viewing position include components from viewpoints other than the intended one. In this paper, this phenomenon, in which components from other viewpoints are observed, is referred to as crosstalk, and the ratio of such unintended components is defined as the crosstalk rate  $\rho_t$ .

**4.2.2 Experimental Setup.** The designed viewpoint positions are denoted as View  $n$  ( $n = 1, 2, \dots, 6$ ), as shown in Fig. 4(c), and one of them is selected as the target viewpoint View  $t$  for evaluation. When the camera is placed at the target viewpoint View  $t$ , the extent to which components corresponding to other viewpoints are observed is measured.

For image acquisition, images captured using a digital single-lens reflex camera ( $\alpha 7R$  ILCE-7R, SONY) are used. Image acquisition is performed under exposure conditions set to avoid saturation and flare, with a shutter speed of 1/40 s, F10, ISO 1000, white balance 6000 K, and a resolution of 7680  $\times$  2160 pixels. The capture environment is the same as that described in Section 4.1.2. A room equipped with blackout curtains is used to eliminate the influence of external and ambient light, and the setup is controlled so that only light emitted from the display is included in the captured images. In addition, the brightness and contrast settings of the display are fixed.

Two types of color patterns are displayed on the display, and images are captured for both conditions:

- (i) A color pattern in which all viewpoints display black.
- (ii) A color pattern in which only one viewpoint, including the target viewpoint, displays white, while all other viewpoints display black.

Condition (i) is used to compensate for the influence of ambient light and black level offset, and condition (ii) is used to measure the contribution of each viewpoint component.

**4.2.3 Procedure.** From each captured image, the region corresponding to the lens array is cropped as the evaluation region using the same procedure as described in Section 4.1.3. For each pixel in the cropped image, the luminance  $Y$  is computed from the RGB values ( $R, G, B$ ) using Eq. 2 defined earlier.

The average of the computed luminance  $Y$  is used as the component value for each viewpoint, denoted as  $L_{eval}(n | t)$ . The component value obtained from the image captured under condition (i) is denoted as  $L_{dark}(t)$ . In order to compensate for the influence of ambient light and black level offset, the corrected component value is defined by Eq. 5.

$$\hat{L}_{eval}(n | t) = \max(0, L_{eval}(n | t) - L_{dark}(t)) \quad (5)$$

**4.2.4 Evaluation Metrics.** The proportion of each viewpoint component observed at viewpoint View  $t$ , denoted as  $M(n | t)$ , is calculated by Eq. 6. This index directly reflects the distribution of viewpoint components of the light rays reaching the observation viewpoint, and it is used as a quantitative measure to evaluate viewpoint separation performance.

**Table 2: The proportions of each viewpoint component observed at the target viewpoint positions  $M(n | t)$  and crosstalk rate  $\rho_t$  at each viewpoint position.**

	View1	View2	View3	View4	View5	View6
View1	<b>0.824</b>	0.040	0.030	0.012	0.027	0.101
View2	0.054	<b>0.847</b>	0.031	0.021	0.021	0.027
View3	0.022	0.052	<b>0.851</b>	0.032	0.025	0.015
View4	0.018	0.023	0.043	<b>0.885</b>	0.032	0.029
View5	0.059	0.017	0.026	0.031	<b>0.846</b>	0.018
View6	0.023	0.021	0.019	0.018	0.049	<b>0.810</b>
$\rho_t$	0.176	0.153	0.149	0.115	0.154	0.190

$$M(n | t) = \frac{\hat{L}_{eval}(n | t)}{\sum_k \hat{L}_{eval}(k | t)} \quad (6)$$

Here,  $M(n | t)$  represents the proportion of the light rays observed at viewpoint  $t$  that belong to viewpoint component  $n$ . In particular,  $M(t | t)$  represents the proportion of the viewpoint component that is intended to be observed at viewpoint  $t$ . Based on this, the crosstalk rate  $\rho_t$  at the target viewpoint position  $t$  is defined by Eq. 7.

$$\rho_t = 1 - M(t | t) \quad (7)$$

The value of  $\rho_t$  ranges from 0 to 1, and smaller values indicate less contamination from other viewpoint components and higher viewpoint separation performance.

**4.2.5 Results.** The proportions of each viewpoint component observed at the target viewpoint positions,  $M(n | t)$ , and the computed crosstalk rates  $\rho_t$  are shown in Table 2. The values shown in bold indicate the proportion of the color pattern corresponding to the viewpoint position from which the images were captured. For all viewpoint positions, these values show high proportions in the range of 0.81 to 0.89. Since the corresponding viewpoint component exhibits the highest proportion at each viewpoint position, the viewpoint component corresponding to the observation viewpoint is dominantly observed. This result indicates that visual information separation for each viewpoint is largely achieved within the designed viewing zones.

The crosstalk rates  $\rho_t$  at each viewpoint position range from 11.5% to 19.0%. Since the crosstalk is below approximately 20%, the proposed system demonstrates a practical level of viewpoint separation within the designed viewing points.

## 5 Discussion

### 5.1 Discussion of Evaluation Results

LentiMorpho proposed in this study is a display method that can switch between view-dependent and view-independent presentation. In the view-dependent presentation mode, presenting identical visual information to both eyes and appropriately separating images for each viewpoint position are essential requirements for the optical system. Therefore, in this study, we quantitatively verified whether the proposed method satisfies these requirements by evaluating binocular consistency based on similarity evaluation

of left and right images and by evaluating viewpoint-wise image separation performance.

In the evaluation of binocular image similarity, the cosine similarity between the left and right images exceeds 0.91 at all viewpoint positions, confirming that almost identical luminance distributions are presented to both eyes within the designed viewing zones. This result indicates that the proposed method functions as an optical system that satisfies the binocular matching condition.

In addition, regarding viewpoint-wise image separation performance, the crosstalk rates at each viewpoint position range from 11.5% to 19.0%. Since previous studies have reported that crosstalk levels of approximately 18% to 23% are within an acceptable range for displays [27], the results of this study indicate that the proposed system can sufficiently separate visual information depending on viewpoint position.

## 5.2 Limitations and Future Work

In this study, the result that the crosstalk rate of the proposed method is less than 20% is not a metric whose quality can be intuitively judged from the numerical value alone. In practice, the acceptable range of crosstalk in view-dependent displays varies greatly depending on the displayed content, the number of viewpoints, and the usage scenario. In this study, the crosstalk rate is used solely as a quantitative indicator for assessing whether the viewpoint component corresponding to the observation viewpoint is dominantly presented from the perspective of the optical system. The evaluation in this study mainly investigates the validity of the optical characteristics, and the degree to which crosstalk is perceptually noticeable in actual user experience is not examined. In future work, user studies are required to investigate how perceptually effective viewpoint-wise information separation is, and how crosstalk affects readability and information comprehension. In addition, the evaluation images used in this study are limited to simple patterns with luminance contrast in order to clearly observe the mixing of viewpoint components.

In this context, this study does not address how crosstalk is perceived in natural images or images containing many high frequency components. Evaluating changes in viewpoint separation performance according to the spatial frequency characteristics of images is an important topic for future research. This study also does not evaluate color reproduction or crosstalk in color components. Color components are strongly affected by the characteristics of the display device and the imaging system, and it is difficult to isolate and evaluate only the effects caused by the optical system. Since the liquid paraffin and glass beads used in the proposed method have high transparency, color reproduction is expected to be preserved even in view-dependent presentation. For this reason, our work analyzes luminance distributions for evaluation. However, further investigation is required to assess the practical performance of the display. In addition, although the crosstalk rate is evaluated for six viewpoints and six images in this experiment, it is also necessary to examine how viewpoint separation performance changes when the number of viewpoints and images is increased.

Furthermore, in the prototype used in this study, a mechanism for changing the amount of liquid is not implemented. Therefore,

switching between view-dependent and view-independent presentation requires manual injection and removal of the liquid from the tray. In future work, introducing a mechanism for changing the liquid flow using pumps or solenoid valves will make it possible to extend the system to an interactive display that can support switching between modes, and can be extended to dynamic operation.

## 5.3 Potential Applications

In this study, we focused on view-dependent 2D presentation under the assumption of binocular matching. However, the optical configuration of LentiMorpho itself can be positioned as a light field display that is capable of changing four dimensional light ray information, consisting of two dimensional position and two dimensional direction. Therefore, in principle, it is possible to extend the design to present different disparity images to the left and right eyes and apply the system to a glasses-free stereoscopic display in the future.

In particular, since this method allows dynamic switching of the presence state of the lens array, it has the potential to realize an operation mode in which the system is used as a high resolution 2D display under normal conditions and switched to stereoscopic presentation only when needed.

Another characteristic of the proposed method is that the size of the lens array can be designed without being constrained by fabrication equipment. This feature makes the system applicable to large digital signage used in large commercial facilities and art installations. In addition, since the system employs a lens array, view-dependent presentation can be provided in all directions. This enables, for example, presentation of different visual information for each floor in an open atrium space, in addition to horizontal view-dependent presentation.

## 6 Conclusion

In this study, we presented “LentiMorpho”, a light field display with switchable optical characteristics, by using glass beads and a liquid whose refractive index is similar to that of glass. The proposed method realizes an optical system that presents identical images to both eyes at each viewpoint position, and also enables switching between view-dependent and view-independent presentation on a single display device by changing the amount of liquid.

The quantitative evaluation results confirm that high binocular consistency and high viewpoint separation performance are achieved within the designed viewing zones. This study presents a new design guideline for extending the usage of view-dependent displays from the perspective of dynamically switching the optical characteristics of lens arrays, which have conventionally been fixed. Our method is expected to contribute to future visual information presentation technologies by expanding the interaction design space of shared displays that dynamically balance shared and individualized visual experiences. By treating optical elements as dynamically reconfigurable interface components rather than fixed hardware constraints, LentiMorpho suggests new opportunities for designing adaptive display systems that respond to social context, usage mode, and interaction needs.

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