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Depth sensitivity of stereoscopic displays

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Depth sensitivity is considered one of the factors influencing 3D displays the most. In this paper, the perceptual 3D depth was quantitatively measured to compare the depth difference among the display devices. No difference was found in the typical display performance among the devices, but the subjective evaluation of the depth sensitivity where the disparity was varied showed that the organic light emitting diode (OLED) had the highest performance, mainly due to its almost 0% crosstalk, one of the features of OLED. Crosstalk is a form of image superposition that greatly affects the depth sensitivity. The experiment results showed that the quantitative depth sensitivity varies due to geometric factors such as disparity, viewing distance, and subjective sensitivity, depending on the display image characteristics, such as crosstalk and contrast.

Keywords: depth sensitivity; 3D depth; virtual image; disparity; quantitative depth; subjective depth

1. Introduction

In 3D displays, the key factor perceived is depth. The components of perceived depth are variable, and the basic theory of perceived depth in 3D displays is that the left and right images generally fall on the retinas due to eye disparity (65 mm) when the human eyes view the images. The two images are transmitted to the brain through the retinas, and the images converge in the brain. Thus, the depth and reality sensitivity of original 3D images are reproduced [1]. In other words, the theory of 3D display is that images separated into left and right images are viewed separately by each eye. 3D types can be divided into two groups – the so-called *stereoscopic* and *autostereoscopic* types – via image separation. The stereoscopic type, where the images are separated by 3D glasses, is spatially divided again into the shutter-type glasses and the separated timely and polarizer-type glasses. The autostereoscopic-type display device separates images based on the viewer's position, using lens, a barrier, and a liquid crystal shutter. The factors affecting the human eyes' perception of depth are physiological and psychological cues. The physiological cues are organized with binocular disparity, convergence, accommodation, and motion parallax, while the psychological cues are organized with a linear perspective, aerial perspective, retinal-image size, visual-field size, overlapping or occlusion, shading and shadow, texture gradient, advancing color, and receding color [2,3].

Binocular disparity has been reported to be the most effective cue to depth perception in a 10 m viewing distance, according to the effectiveness of the depth cues as a function of distance (Figure 1) [4]. Therefore, binocular disparity is the most influential cue for depth sensitivity for TV devices.

2. Theoretical background

2.1. Depth sensitivity principle by binocular disparity

The kinds of perceived depth by binocular disparity in 3D displays are the front and rear depths with the left–right image disposition [4]. Figure 2(a) shows the negative disparity, where the left image shifts to the right direction and the right image shifts to the left direction on the display surface ($Z = 0$). The right image on the left side is seen in the right eye. Conversely, the left image is seen in the left eye. This phenomenon creates virtual images in front of the display surface, called *front depth*. Likewise, virtual images are created behind the display surface by positive disparity, called the *rear depth* [5–8].

2.2. Depth distance calculation

The perceived depth is the distance between the display surface and the virtual images, and it is calculated, using Equations 1 and 2 (Figure 3).

W_0: $W \times (1/2)$;
W_p: shifted pixel distance from the display center point;
W_{0p}: $W_0 - W_p$;
d_0: distance between the display surface ($Z = 0$) and the eyes;
$d_{f(cal)}$: calculated front depth distance between the display surface ($Z = 0$) and the virtual image; and
$d_{r(cal)}$: calculated rear depth distance between the display surface ($Z = 0$) and the virtual image.

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Equations for depth calculation are as follows:

(a) front depth calculation $d_{\mathrm{f(cal)}}$

$$d_{\mathrm{f(cal)}} = \frac{W_{\mathrm{p}} \times d_0}{W_0 + W_{\mathrm{p}}} \tag{1}$$

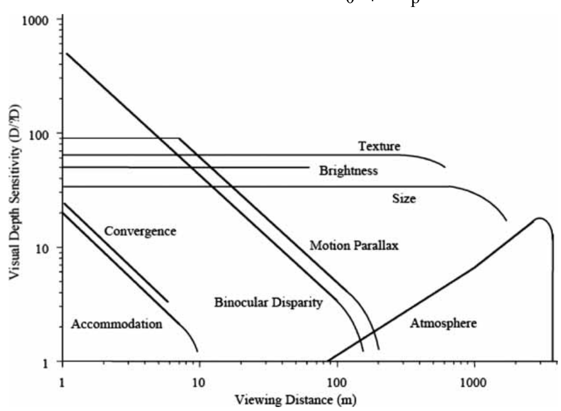

Figure 1. Effectiveness of depth cues as a function of distance.

(b) rear depth calculation $d_{\mathrm{r(cal)}}$

$$d_{\mathrm{r(cal)}} = \frac{d_0 \times W_{\mathrm{p}}}{W_{0\mathrm{p}}} \tag{2}$$

3. Methods

An experiment was conducted to analyze the perceptual-depth change with left- and right-image disparity change, using the quantitative evaluation method. The distance between the virtual image and the display surface was measured by moving the target point to fit it onto the virtual images (Figure 4). The measured distance between the target point and the surface was evaluated as the perceived quantitative depth. Subjective-comparison evaluation was also conducted parallel to quantitative-depth evaluation, and the factors and optical data that influenced the results were analyzed.

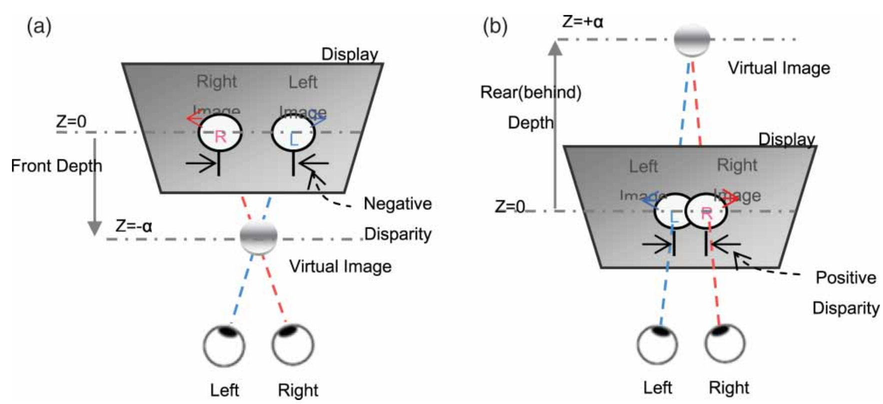

Figure 2. Depth sensitivity diagram: (a) front depth with negative disparity; and (b) rear depth with positive disparity.

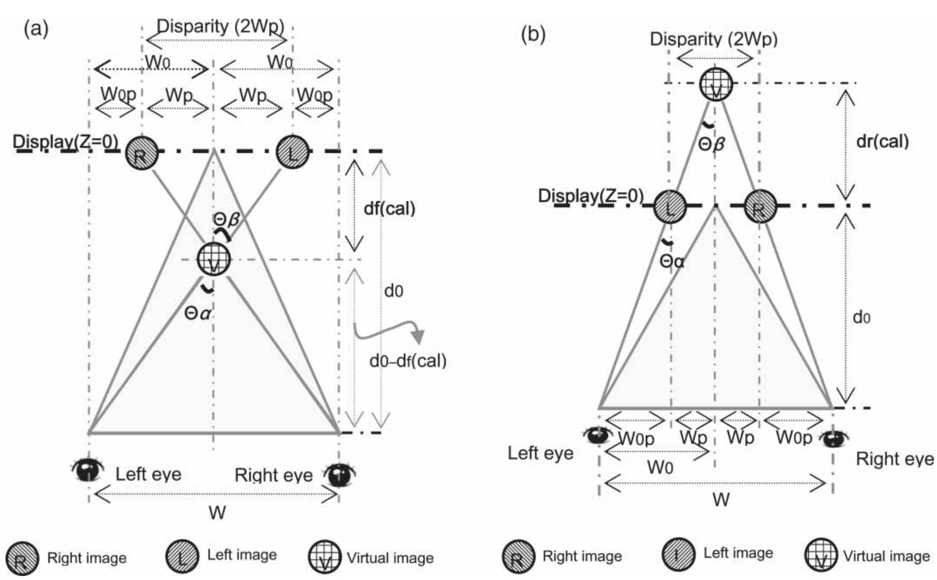

Figure 3. Depth calculation diagram: (a) front depth calculation $d_{\mathrm{f(cal)}}$ diagram and (b) rear depth calculation $d_{\mathrm{r(cal)}}$ diagram.

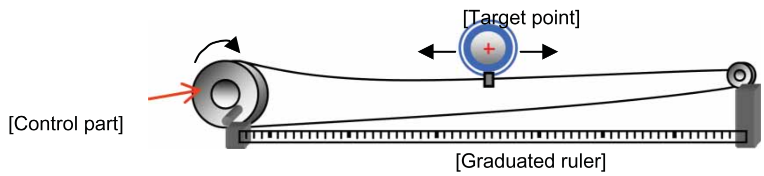

Figure 4. Quantitative-depth measurement system.

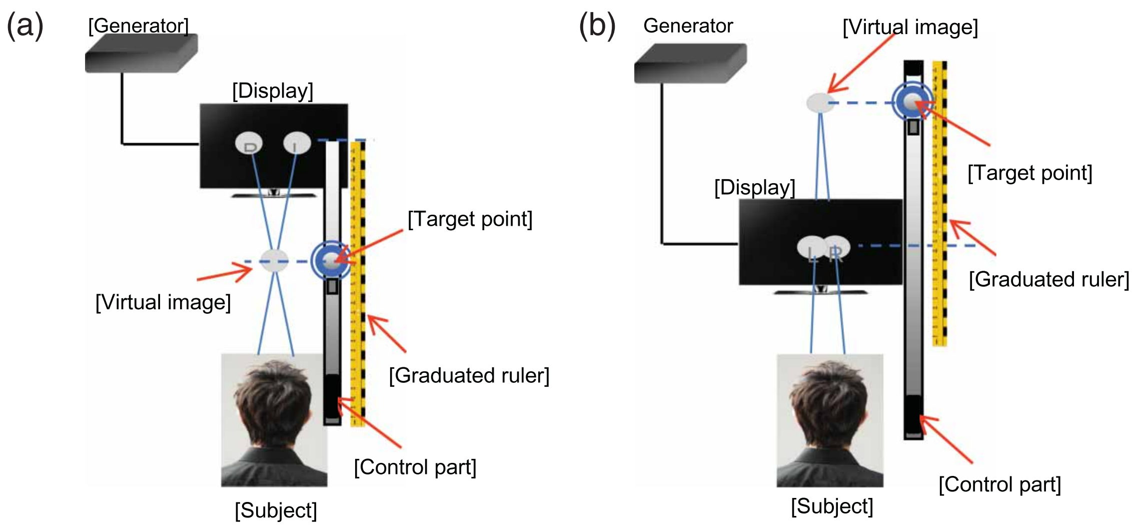

Figure 5. Quantitative-depth measurement system diagram: (a) quantitative-front-depth measurement system and (b) quantitative-rear-depth measurement system.

3.1. Quantitative-depth evaluation method

Quantitative-depth evaluation was conducted for both the front and rear depths. After the inputting of a negative disparity pattern, the target point was fitted onto the virtual image in front of the surface. Then the perceived front depth distance (d_f) was measured with a graduated ruler. The rear depth distance (d_r) was measured in the same way. The d_f and d_r were measured with varying disparity (Figure 5).

3.2. Subjective-comparison evaluation method

In the subjective-comparison evaluation, the subjects compared the perceived depth among the test samples, with varying disparity (Figure 6(a)), and graded the relative depth. An experiment with general 3D contents was also conducted (Figure 6(b)). The contents consisted of a 3D documentary about space. The grading scale consisted of scores from 1 to 5, from 'bad' to 'excellent'. A score of 0 corresponded to the bottom of the 'bad' category while a score of 5 corresponded to the top of the 'excellent' category [9]. Table 1 shows the subjective-comparison grading scale and categories.

3.3. Experiment conditions

Table 2 shows the experiment conditions. The test samples were three types of 3D TVs. The viewing distance was 4H based on Practical Recommendation for 3D Image Safety (Ver. 1.0) [10], which recommends watching 3D TV within over 2H and under 6H. The subjects were five males and five females, and they were made to watch on the vertical line of the test samples.

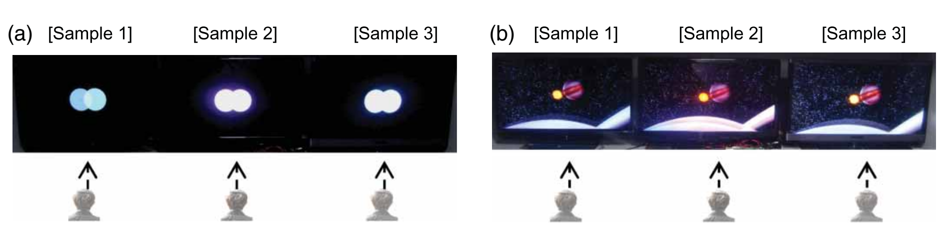

Figure 6. Subjective-comparison evaluation method diagram: (a) subjective-comparison evaluation method with a simple depth pattern and (b) subjective-comparison evaluation method with 3D contents.

4. Results and discussion

4.1. Quantitative-depth evaluation results

4.1.1. *Quantitative-front-depth evaluation results*

In the quantitative-front-depth evaluation with negative disparity, the quantitatively measured perceived and calculated depths showed almost the same values, and there was no meaningful dispersion among the subjects and test samples (Figure 7). Even though the perceived depth of LED TV (film pattern retarder (FPR)) was higher than those of the others, the difference (2.6–3.1%) was similar to the display size difference (2-inch gap: Δ2.7%). Therefore, the depth difference between the LED TV (FPR) and the others is caused only by the display size difference and not by the depth feature of the device.

Table 1. Subjective-comparison evaluation grading scale and categories.

Score (x)	Category
$0 \le x \le 1$	Bad
$1 < x \le 2$	Poor
$2 < x \le 3$	Fair
$3 < x \le 4$	Good
$4 < x \le 5$	Excellent

4.1.2. *Quantitative-rear-depth evaluation results*

In the quantitative-rear-depth evaluation with positive disparity, the dispersion among the subjects was larger than that in the quantitative-front-depth evaluation. Furthermore, a larger dispersion was shown in the wider disparity (Figure 8).

Table 2. Experiment conditions.

Classification	Conditions		Note
Test samples (3D TV)	LED TV (S/G)	40-inch FHD	Shutter glasses type
	OLED TV (S/G)	40-inch FHD	Shutter glasses type
	LED TV (FPR)	42-inch FHD	Film pattern retarder type
Illuminance conditions (lx)	150		Illuminance
Pattern dimension (%)	9% circle of display height		0 background level
Measurement distance	215 mm		42-inch 4H (height) reference
Subjects (N)	10 people		Male: 5, female: 5

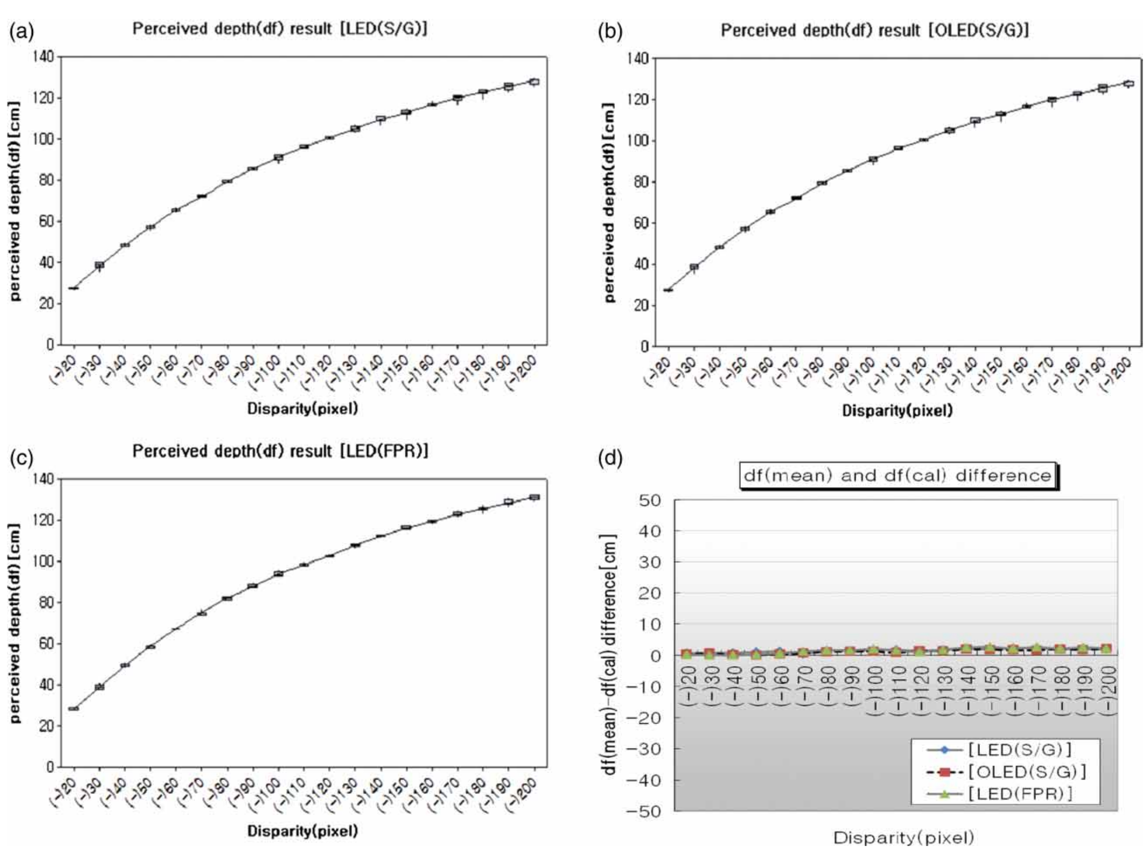

Figure 7. Quantitative-front-depth (d_f) evaluation results, with varying disparity: (a) LED TV (S/G); (b) OLED TV (S/G); and (c) LED TV (FPR). (d) Difference between the mean and calculated values.

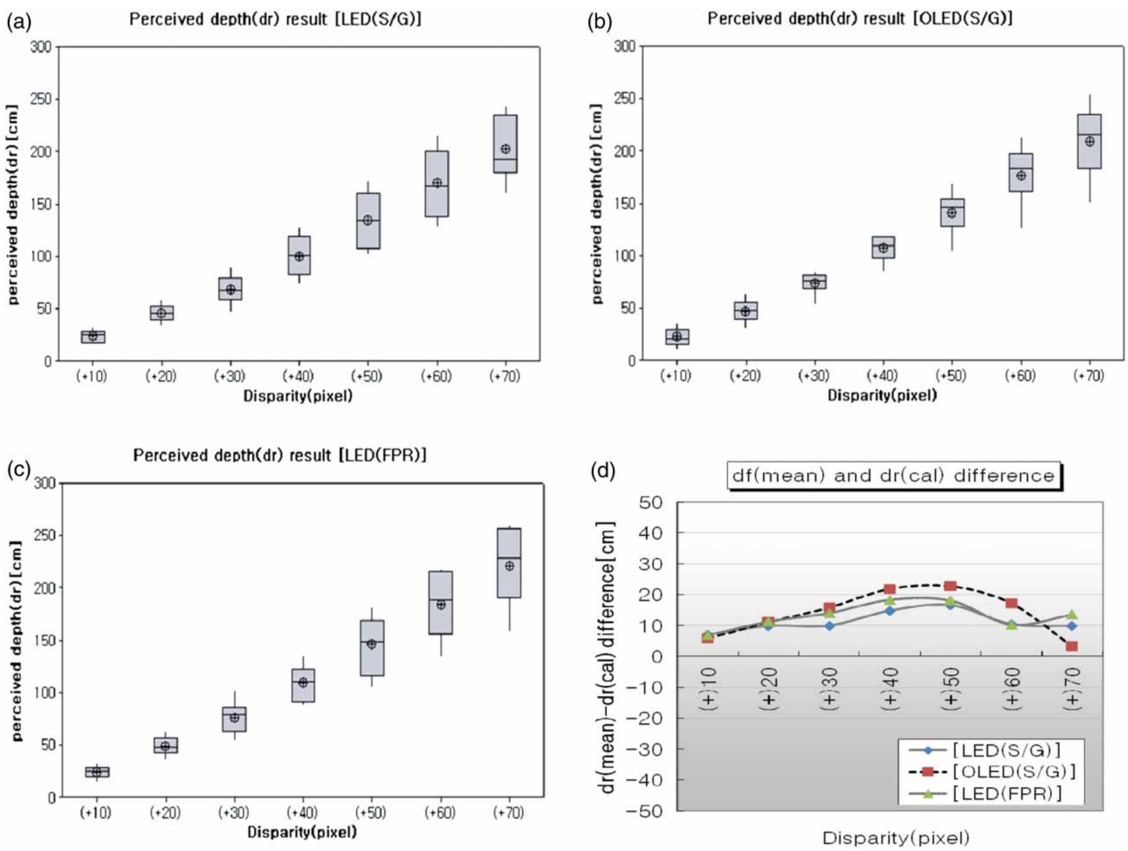

Figure 8. Quantitative-rear-depth (d_r) evaluation results, with varying disparity: (a) LED TV (S/G); (b) OLED TV (S/G); and (c) LED TV (FPR). (d) Difference between the mean and calculated values.

It was assumed that the reason for the dispersion was the measurement method that was used. In the case of the front depth measurement, the virtual images were made in front of the display surface. Therefore, the subjects could easily fit the target point onto the virtual image. As the virtual image of the rear depth, however, was made behind the surface, it was too far to enable the subjects to exactly fit the target point onto the virtual image. Moreover, the target point was located outside the display surface. These factors caused the dispersion in the rear depth measurement. Even though the dispersion was large, a similar tendency was found among the test samples, as shown by the minimal difference between the mean and calculated values (Figure 8(d)). LED TV (FPR) had the highest perceived rear depth, but this was due to the display panel size difference, as with the front depth evaluation. The results of the quantitative-perceived-depth evaluation showed that the perceived depth (d_f, d_r) was not influenced by the display device features because the distance between the display surface and the virtual image was geometrically settled with the image disparity, eye disparity, and viewing distance. Therefore, the most influential factor for the quantitative perceived depth in 3D displays is the disparity of the left and right images in the contents.

4.2. Subjective-comparison evaluation results

In the subjective-comparison evaluation results with simple disparity patterns, the OLED TV (S/G) showed the highest score in both the front and rear depths among the test samples. On the other hand, lower scores were shown with wider disparity by the LED TV (S/G) and LED TV (FPR) compared with the OLED TV (S/G) (Figure 9).

In the comparison of 5-min 3D contents, the OLED TV (S/G) also showed the highest score, as in the comparison with simple disparity patterns (Figure 10). A survey parallel to the subjective comparison, regarding the reason for the low depth sensitivity score, was conducted. In the survey, the items that lowered the depth sensitivity were organized into four factors that were assumed to influence the depth sensitivity: image overlap, contrast, sharpness, and brightness. The subjects were made to choose from among such factors that which they perceived to lower the depth sensitivity the most. Most of the subjects chose image overlap as the factor that made them most uncomfortable perceiving the depth (Figure 11).

Left- and right-image overlap is generally a key factor influencing 3D displays. It is also called *crosstalk.* Crosstalk influences visual comfort [11]. That is, less crosstalk improves visual comfort, which in turn improves

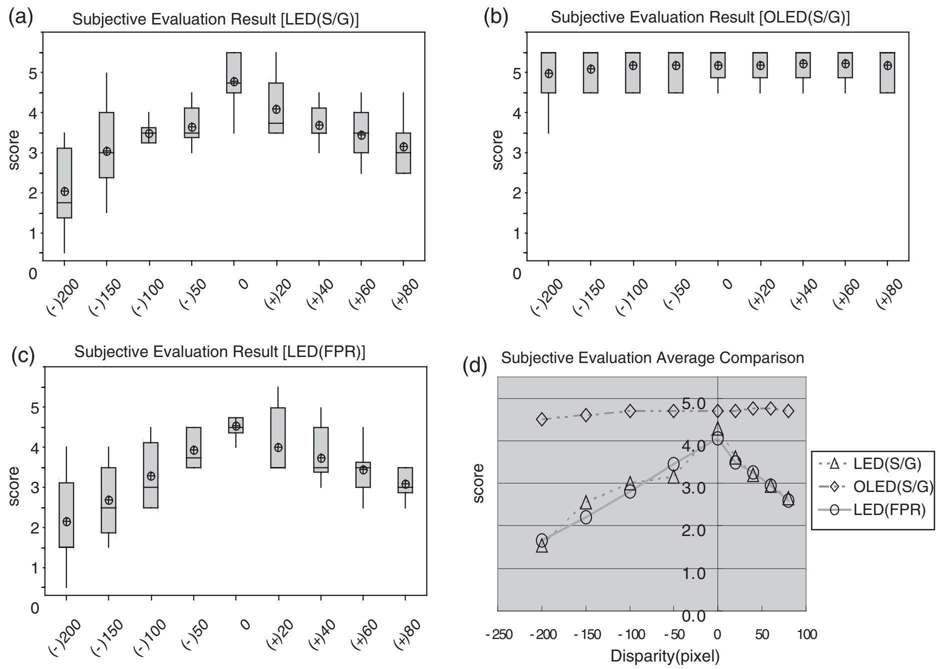

Figure 9. Subjective-comparison evaluation results with a simple depth pattern and varying disparity: (a) LED TV (S/G); (b) OLED TV (S/G); and (c) LED TV (FPR). (d) Mean value comparison.

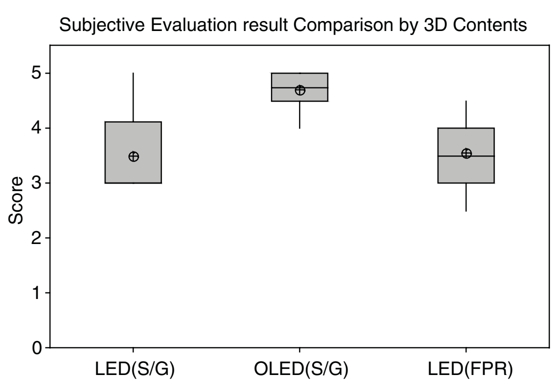

Figure 10. Subjective-comparison evaluation results with 3D contents.

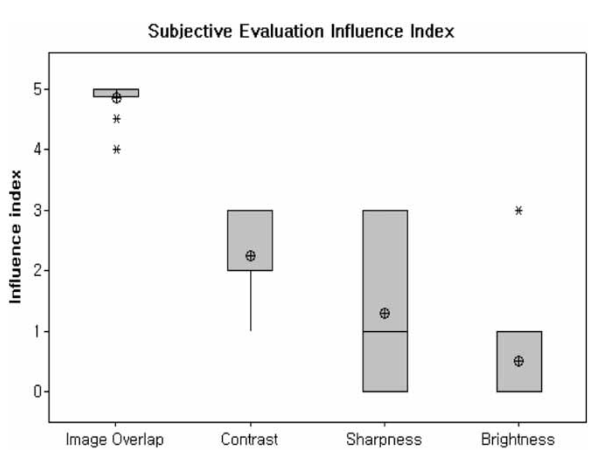

Figure 11. Subjective-comparison evaluation influence index.

the depth sensitivity. As such, crosstalk indirectly influences the depth sensitivity.

Based on the survey results, low contrast had the second lowest depth sensitivity score. It is not certain that the contrast feature directly influences the depth sensitivity in 3D displays, but contrast certainly influences the image quality of 3D displays. Therefore, it can be assumed that the high contrast of the OLED TV (S/G) positively influenced its 3D image quality and made the subjects perceive depth easily. Other factors (e.g., sharpness, brightness) were pointed out by some subjects as lowering the depth sensitivity. It was assumed, however, that these factors do not significantly influence the depth sensitivity. The results of the crosstalk measurement showed that the OLED TV (S/G) had the lowest crosstalk among the samples (Figure 12). It was black-to-white crosstalk measured with a 9% circle pattern, the same as the experiment pattern and the mean value of the left and right eyes. In the contrast ratio, the OLED TV (S/G) showed the highest ratio, with the same pattern as crosstalk among the samples. Based on the measured data, the result of the survey analysis corresponded with the subjective-comparison evaluation result. In other words, the OLED TV (S/G) obtained the highest score in the subjective evaluation, and the subjects pointed out crosstalk and low contrast as the prime reasons for this. The measured data corresponded with the reasons. The quantitative-depth evaluation focussed on separately fitting the target point onto the virtual image for each test sample. Therefore, crosstalk and contrast were not influential. On the other hand, crosstalk and contrast were shown to

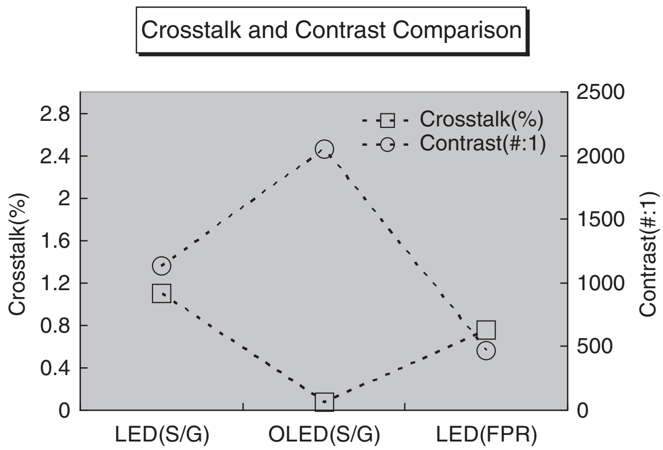

Figure 12. Optical-characteristics comparison.

have influenced the perceived depth in the comparison of the results of the subjective evaluation, in which the test samples were simultaneously compared.

5. Conclusion

It was shown in this paper that the optically calculated depth was almost the same as the quantitative perceptual depth in the quantitative and subjective evaluations. It was also proved that the virtual-image position is influenced by the image disparity, eye disparity, and viewing distance. In the experiment that was conducted, the OLED TV (S/G) showed the highest perceptual-depth sensitivity among the test devices in the subjective evaluation. It was found that crosstalk was the most influential factor, followed by contrast.

The experiment results showed that the key factor for quantitative-depth settlement is disparity, and that perceptual depth by subjective evaluation depends on the crosstalk and contrast. As such, low crosstalk and appropriate disparity are the factors that influence 3D depth sensitivity the most.

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