Psychophysical evaluations of a current multi-view 3-D display: Its advantages in glossiness reproduction

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Abstract — Although two-view 3-D displays requiring stereo glasses are on the market, the shape of objects they present is distorted when the observer's head moves. This problem can be solved by using a (passive) multi-view 3-D display because such a display can produce motion parallax. Another problem has to do with the surface quality of the presented object, but little is known about the fidelity of such displays as far as the surface quality goes. Previously, it was found that a two-view 3-D display has a problem in which glossiness deteriorates when the observer's head moves and that it can be alleviated by using a head tracker, whose data enables the display to produce correct motion parallax and luminance changes when the viewer's head moves. Here, it was determined whether this problem can be solved by using commercially available multi-view 3-D displays, whose finite number of viewpoints and certain amount of cross-talk, however, make luminance changes inexact and smaller than they should be. It was found that this display can solve the problem to a certain extent.

Keywords — *Surface quality, gloss, appearance reproduction, quantitative evaluation, psychophysics, stereoscopic display, autostereoscopic display, cross-talk.*

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1 Introduction

Two-view (stereoscopic) 3-D displays that require LCD shutter goggles or polarized glasses are becoming increasingly popular consumer items. However, it is known that these types of 3-D displays have a problem wherein the simulated 3-D shape is distorted when the observer's head moves because they cannot produce motion parallax.[1,2] There is another type of 3-D display on the market: a (passive) multi-view 3-D display. This type of display has three or more viewpoints and presents the same number of 2-D images at those points. By using a multi-view 3-D display, the problem of shape distortion can be solved to some extent because the display can produce motion parallax by presenting appropriate 2-D images in accordance with the movements of the observer's head.[3–7] The drawback is that the image change is imprecise because of the finite viewpoint number.[8,9]

Although this difference between these 3-D displays in reproducing the "3-D shape" of the presented object is well known, little is known about whether there are any differences in their reproduction of the "surface quality" of the presented object. The surface quality of the presented objects is very important especially, for instance, for Internet museums (E-museum)[10,11] and for digitally designing vehicles.[12] It has been reported that a high-density directional display produces good surface quality.[13,14] However, again, little is known about the fidelity of the surface quality reproduced by consumer-quality 3-D displays (*i.e.*, two-view and multi-view 3-D displays).

The reproduction of glossiness, a type of surface quality, could be better in multi-view 3-D displays than in two-view ones because glossiness is a surface reflectance property, or more specifically, the reflectance changes with reflection direction,[15,16] which, theoretically, can be estimated from multiple 2-D images from different viewpoints[15] (Fig. 1; for details, see the Introduction and Appendix in Ref. 15).

In fact, we previously found that two-view 3-D displays have a problem when the observer's head is moving; the presented stereoscopic glossy object is perceived as less glossy because the 2-D image presented to each single eye does not change over time, and thus corresponds to a matte (*i.e.*, zero glossiness) surface.[15] In the experiments of that study, the subjects moved their heads laterally and observed a stereoscopic glossy surface presented by a CRT monitor through stereo shutter goggles. We asked them to rate the perceived glossiness, and the results showed that the perceived glossiness was lower when the surface presented to each eye did not change over time on the 2-D CRT screen than when the surface changed in luminance and in its 2-D shape on the screen (*i.e.*, motion parallax) in accordance with the observer's head position (this was done by using a head-tracking system in the control experiment of Experiment 3 of that study). The results remained very similar to those of the control experiment even when the observers did not move their heads when an unchanging surface was presented (the main experiment of Experiment 3). These results suggest that motion parallax and temporal changes in luminance accompanying the observer's head motion (*i.e.*, temporal cues to glossiness[15]) enhance perceived glossiness

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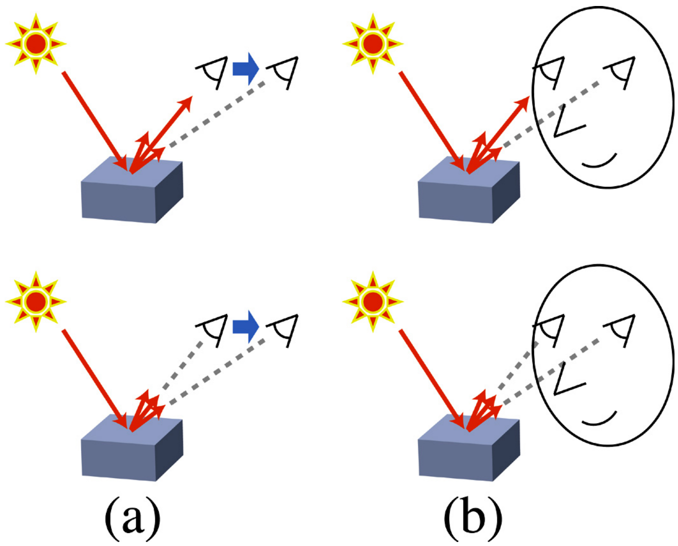

FIGURE 1 — Reflectance, head motion, and stereo viewing. (a) Head motion and reflectances of a glossy (top) and a matte (bottom) surface. When the observer's eye is looking in the direction of the specular reflection of a glossy surface, the luminance of the surface point is high. Once the eye moves out of the specular direction, luminance decreases immediately. In contrast, when viewing a matte surface, the luminance of the surface is unaffected by the location of the eye. Thus, it is theoretically possible to distinguish a glossy surface from a matte one. (b) Stereo viewing and reflectances of a glossy (top) and a matte (bottom) surface. The luminance of the surface for the eye looking in the direction of the specular reflection of the glossy surface is much higher than that for the other eye not looking in the specular direction. In contrast, when viewing a matte surface, the luminance of the surface for one eye is equal to that for the other eye. Thus, it is theoretically possible to distinguish the glossy surface from the matte one (copied from Sakano and Ando 2010).

when viewing stereoscopically. As described above, since, in the real world, when the observer moves his or her head, the luminance of an observed glossy object changes in accordance with the observer's head position, while that of a matte (Lambertian) object does not change, the former results (the control experiment of Experiment 3) also suggest that when a glossy object is presented with a two-view 3-D display without a head-tracking system, the perceived glossiness would be less than it should be. Hereafter, we will refer to this problem as "the weakened-glossiness problem."

The question that we want to address in the present study is whether the weakened-glossiness problem can be alleviated to any extent by using a current (passive) multi-view 3-D display. In our previous study,[15] we continuously changed the luminance and the 2-D shape of the stimulus surface on the screen according to the observer's head position by using a head-tracking system. This condition of temporal changes of the stimulus corresponds to a multi-view 3-D display with an infinite number of viewpoints and a continuous set of viewpoints. In contrast, a real multi-view 3-D display has a finite number of viewpoints and the viewpoints are discrete, resulting in discontinuous changes in luminance and in the 2-D shape of the stimulus accompanying the observer's lateral head motion. Even if the luminance change is smooth owing to cross-talk between the images for the different viewpoints,[17] the temporal profile of the change is still inexact. Thus, it remains to be seen whether a real multi-view 3-D display could alleviate the weakened-glossiness problem.

To address this question, we wanted to determine whether the perceived glossiness of an object surface presented with a multi-view 3-D display is higher when the image changes according to the head motion than when it does not despite the head motion. However, the latter condition (*i.e.*, no image changes with head motion) is almost impossible to achieve. To solve this problem, we have used, instead, the condition under which there are no image changes and no head motion. We believe that this substitution makes sense because we found in our previous study that when the surface image does not change over time, whether the observer moves the head or not does not affect the perceived glossiness of a glossy surface.[15] Similarly, it has been reported that image changes, not head motion itself, affect perceived glossiness.[18]

Thus, in the present study, we tried to determine whether the perceived glossiness of an object surface presented with a multi-view 3-D display is higher when the surface changes over time due to the observer's head motion than when the observer does not move the head and thus the surface does not change either. If the perceived glossiness is higher in the former condition than the latter one, the results would suggest that a multi-view 3-D display, which has a finite number of viewpoints, alleviates the weakened-glossiness problem to some extent.

2 Methods

2.1 Apparatus

We used a commercially available multi-view 3-D display using a parallax barrier (NEWSIGHT, Inc., 45-in. 3-D-Display D, 45 in., eight viewpoints) and a personal computer (DELL, Inc., Precision T7400, 3.2-GHz CPU, 3.25-GB RAM, graphic card: NVIDIA Quadro FX 5800) to present the stimuli. The resolution of the display behind the barrier was 1920 × 1080 pixels (Sharp, Inc., LC-45GD1E, TFT Active Matrix LCD, 98.6 × 55.5 cm). The viewing distance for the best 3-D image quality of the display was 480 cm. In the experiment, the subjects viewed the display at this distance. The distance between the two closest viewpoints (*i.e.*, centers of the viewing zones) was 6.0 cm at this viewing distance.

We measured the luminance of the display using a photometer (Konica Minolta Sensing, Inc., LS-110) and corrected luminance gamma non-linearity using software (Nvidia control panel). The maximum luminance at the center of the display measured from the central viewpoint was 19.2 cd/m^2 when a single corresponding image (uniform white over the display) was presented. The luminance was 2.25 times larger when the uniform white images for all eight viewpoints were presented than when only the single corresponding image was presented. This luminance ratio reflects the magnitude of cross-talk between the views of the display.

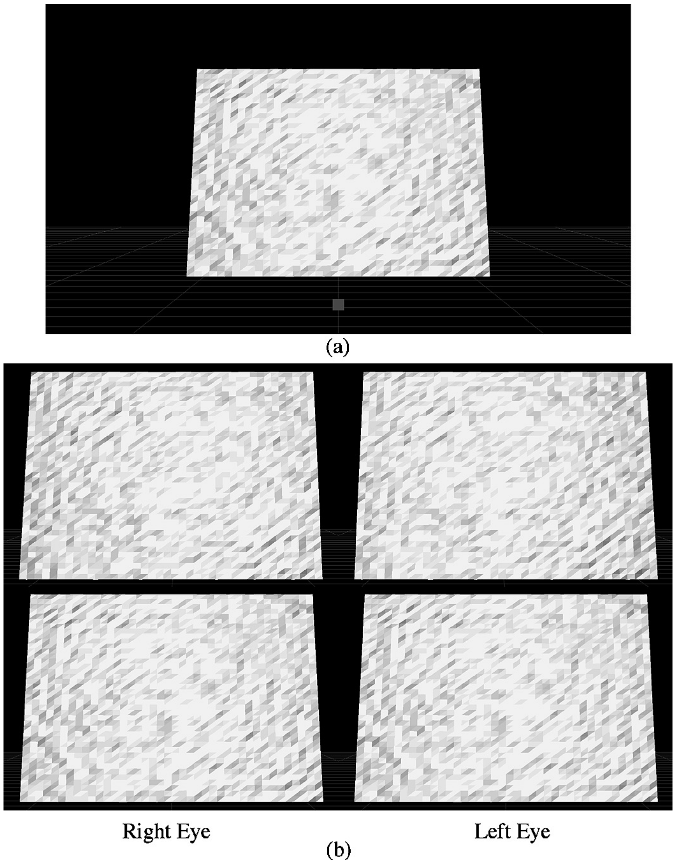

FIGURE 2 — Examples of the stimuli used in the experiment. (a) An entire 2-D stimulus image. (b) Cropped stereo-pair images of the 3-D (top) and 2-D (bottom) stimuli. Note that the value of the specular reflectance is raised to 0.9 in the images from 0.6 to compensate the weakened effects of the 3-D presentation by viewing in a lit room.

2.2 Stimuli

The stimulus was an achromatic computer-generated display that simulated a glossy and bumpy surface (Fig. 2). The bumpy surface was elaborated as follows. First, a flat square (49.3 × 49.3 cm) in the frontal plane was divided into 1600 small squares. Second, each small square was divided into two triangles. Third, each vertex of the triangles was assigned a random pedestal depth ranging between 0.31 mm close to and 0.31 mm far from the subject. Finally, the entire bumpy surface was then slanted 45° with its top away from the subject around the middle horizontal axis.

The luminance intensity of each surface facet (*i.e.*, triangle) was determined from the Phong lighting model[15,19–22]:

$$I = I_{\mathrm{in}} R_{\mathrm{d}} \cos\theta + I_{\mathrm{in}} R_{\mathrm{s}} \cos^{n} \alpha + I_{\mathrm{s}} R_{\mathrm{a}}, \tag{1}$$

where I is the intensity of the surface, I_{in} is the intensity of incident light (1.0), I_{a} is the intensity of ambient light (1.0), R_{d} is the diffuse reflectance (0.05), R_{s} is the specular reflectance (0.6), R_{a} is the ambient reflectance (0.05), n is the index determining the highlight size (128), θ is the angle of incidence, and α is the angle between the cardinal direction of specular reflection and the direction towards the viewpoint. In this model, the ambient reflection was substituted for mutual illumination for convenience although the amount of this reflection was inexact. The surface was illuminated by simulated white parallel light from above.

The display presented the stimuli in 2-D or in 3-D. The 2-D stimulus was viewed without head motion (2-D condition). The 3-D stimulus was viewed with head motion (3-D dynamic condition) or without it (3-D static condition). The 3-D dynamic stimulus changed passively over time due to the subject's head motion while the 3-D static stimulus did not change over time. Note that these two stimuli were physically identical on the display and that the 2-D image on the display that presented to each viewpoint did not change over time in both stimuli. The only difference between the two stimuli was that the subject moved his or her head laterally in the 3-D dynamic condition while the subject's head remained still in front of the display in the 3-D static condition. That is, different images became visible one after another when the subject moved his or her head laterally, resulting in the dynamic stimulus, while the visible images remained the same when the subject did not move the head, resulting in the static stimulus.

2.3 Head motion and viewing condition

In the 3-D dynamic condition, the subjects made two laps of lateral head motion starting and ending in front of the center of the display. The end-to-end distance of the head motion was about 36 cm, which allowed the subjects to view all eight 2-D images. To control the head movements, before the experiment, the subjects practiced moving the head smoothly in the horizontal directions so that the subjects could do so observing all eight views in a fixed time (4 sec). We also instructed the subjects to minimize the vertical and tilt movement of the head. In the experiment, the experimenter (the first author) made sure by observation that the subjects moved the head smoothly and naturally, but not necessarily at a constant speed.

In the 3-D static and the 2-D conditions, the subjects viewed the stimuli with the head kept still in front of the center of the display. Before the experiment, the subjects practiced stabilizing the head right in front of the center of the display. The subjects also practiced alternating head stabilization with lateral head movement. The experimenter made sure by observation that the subject's head was stable when it should be although we did not measure the head movements in this study.

To control eye movements, the subjects were instructed to fixate the approximate center of the display during the experiment. The subjects viewed the stimuli binocularly except in monocularly viewing conditions described below. In the monocularly viewing conditions, one of the subject's eyes was occluded by a black opaque eye patch.

2.4 Compared conditions

To examine the advantages of a multi-view 3-D display over a two-view 3-D display, we compared the 3-D static stimulus with the 3-D dynamic one in terms of the perceived glossiness. To examine the effect of stereoscopic presentation, or in other words, the effect of binocular cues to glossiness (*i.e.*, image differences between the two eyes),[15] the effect of temporal cues, and the combined effect of these cues, we also compared the following stimulus pairs: the 2-D stimulus with the 3-D static one, the 3-D static stimulus with the 3-D dynamic one viewed monocularly in both conditions, and the 2-D stimulus with the 3-D dynamic one, respectively.

2.5 Procedure and task

The experiment was conducted in a darkened room. During the experiment, the subjects kept seated on the chair placed right in front of the center of the display. The heights of the subjects eyes were almost the same as the middle level of the display.

In each trial, the paired stimuli described above presented alternately. The stimuli were presented until the subject responded. The presentation duration of each stimulus was 3.87 sec, and the inter-stimulus interval (ISI) was 0.13 sec.

In order to quantitatively compare the perceived glossiness of the paired stimuli, we used the magnitude estimation method (*i.e.*, rating task). In each trial, the subject orally reported the perceived glossiness of one stimulus in terms of a number relative to which the glossiness of the other stimulus was assumed to be ten. Zero meant no glossiness (completely matte). The subjects were explicitly allowed to report any number that was equal to or higher than zero, including ten and higher numbers. The subjects reported the glossiness of the following stimuli: the 3-D static stimulus for the pair of (3-D static, 3-D dynamic) both in the monocularly and binocularly viewing conditions, and the 2-D stimulus for the pairs of (2-D, 3-D static) and of (2-D, 3-D dynamic). Each combination of conditions was repeated ten times for each subject.

2.6 Subjects

One author and three subjects naive to the purpose of the experiments participated in the experiment. All had normal or corrected-to-normal visual acuity. All had experienced other experiments on binocular stereopsis, and we confirmed that they had normal stereovision.

3 Results and discussion

3.1 Central findings

As shown in Fig. 3, the perceived glossiness of the 3-D static stimulus was significantly lower than that of the 3-D dynamic

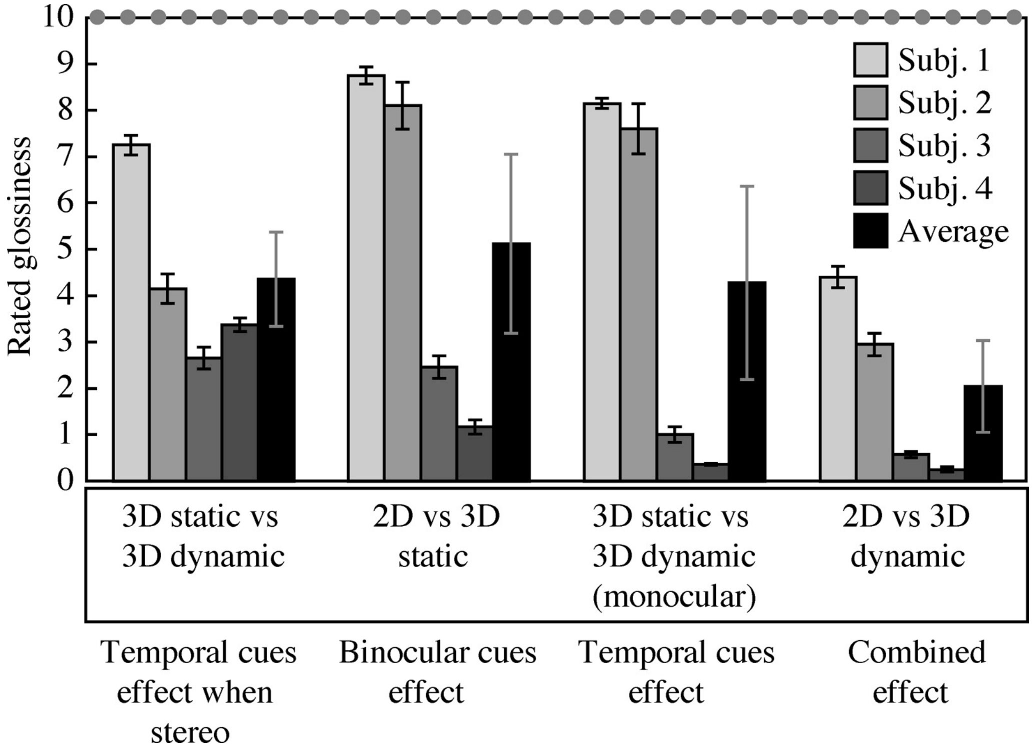

FIGURE 3 — Results of the experiment. The rated glossiness of one stimulus when glossiness of the other stimulus was assumed to be ten. The rated stimuli were the 3-D static, 2-D, 3-D static monocular, and 2-D stimuli for the paired stimuli of (3-D static, 3-D dynamic), (2-D, 3-D static), (3-D static monocular, 3-D dynamic monocular), and (2-D, 3-D dynamic), respectively. Error bars indicate ±1 SEM. The dotted line indicates the glossiness of the non-rated (*i.e.,* standard) stimulus.

stimulus ($t_3 = 5.58$; $p < 0.01$ for all subjects). As described in Introduction, the perceived glossiness of the 3-D static stimulus would be almost equivalent to the perceived glossiness of the 3-D stimulus with no temporal changes viewed with head motion. In the real world, when the observer moves his or her head, the luminance of an observed glossy object changes in accordance with the observer's head motion, while that of a matte (Lambertian) object does not change. Thus, the results suggest that the problem of an object presented with a two-view 3-D display being perceived as less glossy as a result of the lack of image changes when the head moves (*i.e.,* the weakened-glossiness problem) can be alleviated to some extent by the use of a commercially available multi-view 3-D display that has a finite number of viewpoints (eight viewpoints in this case) and a certain amount of cross-talk. In other words, these results suggest that a current multi-view 3-D display is better than a two-view 3-D display without head tracking in terms of glossiness reproduction when a viewer moves his or her head.

Similarly, the perceived glossiness of the 2-D stimulus was significantly lower than that of the 3-D static stimulus ($t_3 = 2.53$, $p < 0.05$ for all subjects, Fig. 3). As described in Introduction, in the real world, when viewing a glossy object binocularly, the two eyes would experience luminance differences while a matte (Lambertian) object produces zero luminance difference. Thus, these results suggest that the problem of an object presented in 2-D being perceived as less glossy as a result of the lack of image differences between the two eyes is to some extent solved by the use of a multi-view 3-D display without head motion. In other words, the results suggest that a current multi-view 3-D display is better than a 2-D display in glossiness reproduction when the displays are viewed without head motion.

Even when the display was viewed monocularly, the perceived glossiness of the 3-D static stimulus was significantly lower than that of the 3-D dynamic stimulus ($t_3 = 2.75$, $p < 0.05$ for all subjects, Fig. 3). These results reflect the effectiveness of image changes accompanying head movements (*i.e.,* temporal cues) in glossiness perception when monocularly viewing a current multi-view 3-D display that produced inexact luminance changes owing to the finite number of viewpoints and the cross-talk between the views. The results also suggest that even when the observer views the display monocularly, the weakened-glossiness problem can be alleviated. In other words, the results suggest that a current multi-view 3-D display is better than a two-view display in glossiness reproduction even when the displays are viewed monocularly with head movements.

In qualitative concordance with the three results above, the perceived glossiness of the 2-D stimulus was significantly lower than that of the 3-D dynamic stimulus ($t_3 = 8.04$, $p < 0.005$ for all subjects, Fig. 3). These results reflect the combined effects of image changes accompanying head movements (*i.e.,* temporal cues) and image differences between the two eyes (*i.e.,* binocular cues) in glossiness perception. These results suggest that a multi-view 3-D display is better than a 2-D display in glossiness reproduction when the head moves.

3.2 Individual differences

As can be seen in Fig. 3, there were large individual differences in the rated glossiness, especially in the comparison pairs of (2-D, 3-D static) and (3-D static monocular, 3-D dynamic monocular). These differences could reflect individual differences in to what extent the perceived glossiness depended on binocular cues (*i.e.,* luminance differences between the eyes and the binocular disparity distribution of the surface)[15] and temporal cues (*i.e.,* luminance changes over time and the motion parallax distribution of the surface) compared with monocular static (*i.e.,* pictorial) cues. That is, if a certain subject relies heavily on binocular cues, for instance, the rated glossiness of the 2-D stimulus should be lower because the glossiness specified by the binocular cues was zero in the 2-D stimulus, but it was a certain value (as determined by the stimulus Phong parameters R_s and possibly α) in the 3-D static and 3-D dynamic stimuli.

There is a possibility that glossiness perception from binocular cues could depend on interocular distance and that the individual differences in interocular distance could contribute to the individual differences in the rated glossiness. To examine this possibility, we measured interocular distances of the subjects using a pupilometer (Topcon digital PD meter PD-5) and compared them with the rated glossiness results. The results showed that the subjects' interocular distances ranged from 6.15 to 6.65 cm and that the subjects whose interocular distances were wide tended to show lower glossiness rating in the comparison pairs of (2-D, 3-D static) and (3-D static monocular, 3-D dynamic monocular) ($r = -0.909$, $p = 0.091$; $r = -0.915$, $p = 0.085$, respectively). For the comparison pairs of (3-D static, 3-D dynamic) and (2-D, 3-D dynamic), on the other hand, showed no significant correlation ($r = -0.482$, $p = 0.518$; $r = -0.788$, $p = 0.212$, respectively). These results could imply the relationship between the glossiness perception and interocular distance. For instance, wide interocular distances could enhance the use of binocular cues. In that case, the temporal cues could also be assigned large weights in glossiness perception owing to the possible mechanisms shared with binocular cues.[15] However, to clarify the relationship between the interocular distance and glossiness perception, further study is required.

Despite a large variation in perceived glossiness between subjects, all subjects judged consistently that the 2-D stimulus was less glossy than the 3-D static and 3-D dynamic stimuli, implying that all subjects depended on the binocular cues to a certain extent. Similarly, they judged consistently that the 3-D static stimulus was less glossy than the 3-D dynamic stimuli both in the monocular and binocular cases, implying that all subjects depended on the temporal cues to a certain extent and that the use of a multi-view 3-D display is advantageous for glossiness reproduction.

3.3 Limitations in glossiness reproduction using a multi-view 3-D display

As described above, we found that the use of a multi-view 3-D display with a finite number of viewpoints solves the weakened-glossiness problem to some extent. Another interesting question might be whether this solution is complete or partial; in other words, whether a multi-view 3-D display has limitations regarding its ability to deal with the weakened-glossiness problem. There is a possibility that this solution is partial because of the following three reasons. First, as described in Introduction, a multi-view 3-D display has a finite number of viewpoints and the viewpoints are discrete, resulting in discontinuous changes in luminance and in the 2-D shape of the stimulus accompanying the observer's lateral head motion. Even if the luminance change is smooth owing to cross-talk between the images for the different viewpoints,[17] the temporal profile of the change is still inexact. Second, a multi-view 3-D display often has a large amount of cross-talk,[23] as was observed in the display used in the present study. The cross-talk reduces both luminance differences between the two eyes and luminance changes accompanying lateral head movements. These reductions could deteriorate perceived glossiness because the reduced luminance differences and reduced luminance changes simulate lower glossiness than intended by binocular and temporal cues, respectively,[15,16,24] smaller interocular luminance differences and smaller luminance changes produce lower perceived glossiness,[15,25,26] and perceived glossiness depends strongly on these binocular[15,25–38] and temporal[15,25,31,32,39] cues to glossiness. Third, the viewing distances for the best 3-D image quality of some multi-view 3-D displays are very long. In these cases, the glossiness reproduction of an object with low glossiness could be inexact because when viewing a real surface or a simulated one presented with a 3-D display, a very long viewing distance causes a very small angular difference from the observed surface between the two eyes or eye locations before and after head movements and thus the luminance difference between the two eyes or luminance change accompanying the head motion is very small, which could be invisible or unable to be reproduced owing to the limitation in the number of gray levels of the display.

To examine whether the solution using a multi-view 3-D display is complete or partial, one might think of a direct comparison of the results of the present study with those of our previous study using a CRT, stereo shutter goggles, and a head tracking system[15] because in the latter study, we continuously changed the images according to the observer's head position and the magnitude of cross-talk was small. However, we do not think this comparison is a good method because there were many differences in experimental conditions, including stimulus size (in visual angle and in inch), viewing distance, luminance, color, and reflectance parameters of the stimulus surface. Instead of comparing different displays, we plan to investigate, by using a CRT, stereo shutter goggles, and a head-tracking system, how many viewpoints (or how short the distance between the neighboring viewpoints) are required as well as how much cross-talk would be allowed for good glossiness reproduction.

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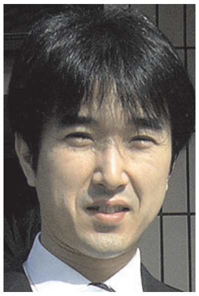

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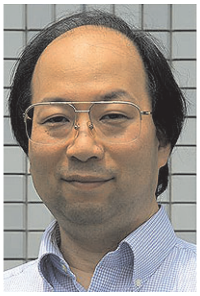

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