Quantitative evaluation of perceived depth of transparently-visualized medical 3D data presented with a multi-view 3D display

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Transparent visualization is used in many fields because it can visualize not only the frontal object but also other important objects behind it. Although in many situations, it would be very important for the 3D structures of the visualized transparent images to be perceived as they are simulated, little is known quantitatively as to how such transparent 3D structures are perceived. To address this question, in the present study, we conducted a psychophysical experiment in which the observers reported the perceived depth magnitude of a transparent object in medical images, presented with a multi-view 3D display. For the visualization, we employed a stochastic point-based rendering

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(SPBR) method, which was developed recently as a technique for efficient transparent-rendering. Perceived depth of the transparent object was smaller than the simulated depth. We found, however, that such depth underestimation can be alleviated to some extent by (1) applying luminance gradient inherent in the SPBR method, (2) employing high opacities, and (3) introducing binocular disparity and motion parallax produced by a multi-view 3D display.

Keywords: Transparent visualization; automultiscopic 3D image; psychophysics.

1. Introduction

In many fields including medical areas, transparent visualization is frequently used because it can visualize not only an object's frontal surface but also its internal structure that otherwise should be occluded and thus invisible. In many situations, it would be very important for the visualized transparent objects to be perceived as they are physically in terms of 3D structure. Some previous studies examined the perception of transparent 3D structure; some studies reported effects of cues^{1,2} to depth perception while others reported effects of different rendering techniques.

Binocular disparity (i.e., differences in the retinal images of the two eyes) is a well-known depth cue which can yield vivid impression of 3D structure when the object is opaque.¹⁻¹² Some studies reported advantages of introducing binocular disparity in the 3D perception of visualized transparent volumes (for review in medical domains, see van Beurden *et al.*¹³).¹⁴⁻¹⁸ For instance, Kersten and coworkers¹⁴ reported that binocular disparity aided to some extent the observers to judge the rotational direction of a purely absorptive cylindrical volume rotated about the vertical axis. Motion parallax is another important cue to depth perception which refers to the relative movement of images across the retina resulting from movement of the observer or the translation of objects across his/her field of view.^{1,2,4-6,19-21} A few studies^{15,22} reported the perceptual advantages of introducing motion parallax in the visualized transparent volumes. Advantages of simulated aerial perspective^{14,15} (i.e., luminance contrast gradient in depth) and objects' edges²³ yielded by different visualization methods²⁴⁻²⁶ have also been reported.

Nevertheless, little is known about the quantitative perceived 3D structure of a visualized transparent object because most previous studies focused on perceptual thresholds of depth ordering or depth-related detection tasks and/or the response time. Other studies just reported the qualitative subjective impressions or preferences. There are, yet, some exceptions; Englund and Ropinski,²⁷ quantitatively examined perceived surface orientations at multiple points on each 3D structure of volume-rendered data as well as the relative perceived depth position of each point using the depth range of the whole 3D structure as the standard. Baer and coworkers²⁸ and Bair and House²⁹ examined perceived surface orientations of surface-rendered data.

Accordingly, to our knowledge, no previous studies have quantitatively examined the perceived depth magnitude (i.e., the distance in the depth direction between the points closest to and farthest from the observer) of a visualized transparent

object. Hence, little is known either about how accurately the depth magnitude of a visualized transparent object would be perceived or about whether the object would be overestimated or underestimated.

In the present study, to reveal how the depth magnitude of a transparent 3D structure is perceived, we conducted a psychophysical experiment that employed the magnitude estimation method.^{30–33} In the experiment, we specifically evaluated the perceived depth magnitude of a closed isosurface of simulated heavy particles irradiation dose embedded in CT volume data of the human head.³⁴ We used such stimuli because as an application such images would be very useful for the doctors to draw up a plan of radiation therapy and to explain the plan to the patient and/or the family. To visualize the transparent 3D structure, we made use of a stochastic point-based rendering (SPBR) method,^{34–36} which was proposed recently as a very efficient technique.^{34,37} Through the experiment, we examined the possible effects of (1) the SPBR-inherent luminance gradient, which will be described in the next section, (2) the opacity, (3) binocular disparity, and (4) motion parallax.

To provide binocular disparity and motion parallax, the images were presented with a multi-view 3D display (*aka* a multiscopic 3D display or an automultiscopic 3D display).^{38–43} This type of 3D display would be useful in many applied situations because it does not require stereoscopic goggles or head-tracking systems, resulting in no experience of annoying flickering of goggles or unstable motion parallax due to the interference with infrared rays from fluorescent lamps^{14,15} in the room.

2. Stochastic Point-Based Rendering

In the SPBR method, rendering primitives are fully opaque particles that are self-colored 3D points. To render a transparent surface, this method performs the following three-step procedure. First, we generate L sets of particles, each of which is randomly and uniformly distributed on the target surface. Second, each set of particles is projected onto the image plane with particle occlusion to generate L images. Third, averaging the L images generates the final image. Thus, L works as a parameter to tune the statistical rendering quality. Opacity α of any local surface segment can be manipulated by tuning the total number of particles, N , in the segment:

$$\alpha = 1 - \left(1 - \frac{s}{S|\cos\theta|}\right)^{\frac{N}{L}}, \quad (1)$$

where s is the particle cross-section and S is the local surface-segment area where the number of particles is measured, and θ is the angle between the surface normal and the line of sight.

Note that the segment area S is multiplied by the cosine factor in formula (1). Since the particles are distributed uniformly on the surface, the opacity inherently increases as θ increases. This increase in opacity produces a luminance gradient on a smoothly curved surface. This luminance gradient inherent in the SPBR method

could affect perceived depth because such luminance gradient can appear similar³⁶ to shading, which is known as an important cue to depth perception.^{2,44–48}

In some conditions of the following experiment, to examine the effect of this luminance gradient on perceived depth, we eliminate this luminance gradient by using the relationship between the opacity α and the number of particles N . The elimination is realized by properly tuning N according to θ as

$$N = \frac{\ln(1 - \alpha)}{\ln(1 - s/(S|\cos \theta|))} L \quad (2)$$

for each local surface segment, that is, for each polygon. Note that α in Eq. (1) is a function of θ , while α in Eq. (2) is a user-defined constant.

3. Methods

3.1. Subjects

Eleven subjects in their 20s took part in the experiment. All were naive to the purpose of the experiment and had normal or corrected-to-normal visual acuity. All but one was tested on stereo vision, showing that they had normal stereo acuity of at least 1.7 arcmin (Stereo Fly Test, Stereo Optical Company, Inc., Chicago, IL). The remaining one was not tested on stereo vision, yet he reported that in his own research, he could normally see stereoscopic 3D images as 3D through stereo goggles.

3.2. Apparatus

We used a commercially available multi-view 3D display using a parallax barrier (Tridality MV4200, 1920 × 1080, 42-inch, five viewpoints) to present the stimuli. The viewing distance for the best 3D image quality of the display was 350 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 7.8 cm at this viewing distance.

At different viewpoints, different images were visible that should be seen at those points in the simulated 3D scene. As a result, when the subjects viewed the stimuli binocularly, binocular disparity was provided because both the eyes were exposed to different images simultaneously. Similarly, when the subjects moved their heads laterally, motion parallax were provided because each eye was exposed to different images sequentially depending on the head position.

3.3. Stimuli

The stimulus was a 3D image rendered based on the SPBR method using surface data of an isosurface of simulated heavy particles irradiation dose embedded in CT volume data³⁴ of the human head (Fig. 1). The isosurface (the lower green surface in Fig. 1) was rendered also with Phong shading⁴⁹ as well as with (Eq. (1)) or

Fig. 1. Stimulus used in the experiment. The red square point on the green isosurface indicates the frontal point of the isosurface. It was part of the isosurface and thus presented the stimulus on the screen with the proper disparity and motion parallax when they were available.

without (Eq. (2)) luminance gradient inherent in the SPBR method (Fig. 2). In the Phong shading, the surface was Lambertian (i.e., incorporating no specular or ambient components, thus, completely matte) and was illuminated by parallel light from the observer's side, perpendicularly to the screen. In the SPBR method, to

Fig. 2. The isosurface with opacity of 0.1 (left), 0.3 (center), and 0.7 (right), with (top) or without (bottom) luminance gradient inherent in the SPBR method.

Fig. 3. Side view of the isosurface (not presented to the subjects). The right side of the isosurface in this figure was the frontal part of the isosurface in the experiment.

achieve a fine quality of statistical rendering, 500 images (the variable L in Eqs. (1) and (2)) were averaged to generate the final image for each viewpoint. The opacity (the variable α in Eqs. (1) and (2)) was 0.05, 0.08, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, or 0.99. The simulated depth magnitude of the isosurface was 19.2 cm (Fig. 3), that yielded binocular disparity of 3.2 arcmin, assuming the inter-ocular distance was 6.0 cm.

3.4. Viewing conditions and head motion

The subjects viewed the stimuli binocularly except in monocularly viewing conditions. In the monocularly viewing conditions, one of the subject’s eyes was occluded by an opaque eye patch. The binocular conditions enabled stereopsis based on binocular disparity while in the monocular conditions they did not.

The subjects moved their heads laterally in a way that they observed all the five images when they were instructed to move their heads. Otherwise, head motion was restricted with a chin rest. The head motion conditions enabled depth perception based on motion parallax while in the other conditions they did not.

3.5. Procedure and task

The experiment was conducted in a normally lit room. During the experiment, the subjects kept seated on a chair placed right in front of the center of the display.

The subjects were asked to write down the perceived depth magnitude of the isosurface (i.e., the distance in the depth direction between the point on the surface that was closest to the subjects, namely the red square point, and the perceptually farthest point from the subjects), giving a number based on the assumption that the length of one side of a green square (shown in the upper right in Fig. 1) was 1.0. The correct answer was 7.1.

The stimulus was presented until the subject accomplished the task. There was no time limitation to perform the task, but most subjects accomplished each task

within 20 s. Each subject carried out the task for all 96 conditions (two for luminance gradient $\times$ 12 for opacity $\times$ 2 for head motion $\times$ 2 for viewing condition). The order of the conditions was randomized.

4. Results and Discussion

4.1. Underestimation

The depth magnitude of the isosurface was underestimated in all the conditions (Fig. 4). The mean ratio of perceived-to-simulated depth was as small as 28%. Such

Fig. 4. Effects of the SPBR-inherent luminance gradient and the opacity on perceived depth magnitude. Both binocular disparity and motion parallax (upper left), only disparity (upper right), only motion parallax (lower left), or neither (lower right) was available. The ground truth was 7.1 (the horizontal dashed lines), thus, the depth was underestimated in all the conditions. Error bars indicate one standard error of the mean. LG, luminance gradient inherent in the SPBR method.

depth underestimation has been previously reported for opaque objects defined by shading,^{8,46–48} shading with disparity⁸ or texture gradient.⁴⁶ Among such studies, Bülthoff and Mallot⁸ reported larger underestimation for larger depth of a shaded sphere elongated in depth when it was presented non-stereoscopically. Since the present stimulus was long in the depth direction (Fig. 3), the present results were consistent with the previous report⁸ at least as far as the stimulus was presented non-stereoscopically. Effects of disparity will be discussed later.

4.2. Effects of the SPBR-inherent luminance gradient

Introducing the luminance gradient inherent in the SPBR method alleviated the underestimation of the perceived depth magnitude in many conditions (Fig. 4). This effect was statistically confirmed by four-way repeated-measures ANOVA (luminance gradient, opacity, binocular disparity, and motion parallax) as the significant main effect of the luminance gradient ($p = 0.03$). This improvement by the luminance gradient was salient when the opacity was as low as from 0.05 through 0.1 (Fig. 4) although the interaction between the luminance gradient and the opacity was not statistically significant ($p = 0.17$). Because little is known about the human visual system to perceive the 3D structure of a transparent object,² it is difficult to explain thoroughly why the SPBR-inherent luminance gradient enhanced the perceived depth. Nevertheless, for such low opacities, as can be seen in the upper and lower left panels in Fig. 2, the luminance gradient looked somewhat like shading and enhanced luminance contrast within the isosurface. As mentioned in the Introduction, shading is well known as an important cue to depth perception.^{2,8,9,44–48} In addition, it has been reported that higher luminance contrast generally induces larger perceived depth.^{45,50–58} Thus, the improvement by the luminance gradient might have resulted from visual interpretation of the luminance gradient as shading along with the higher luminance contrast.

The improvement by the luminance gradient was also salient when binocular disparity was available (two upper panels of Fig. 4; significant interaction between the luminance gradient and disparity, $p < 0.00001$; Tukey's HSD test, $p < 0.05$). This combination effect of the luminance gradient and binocular disparity might be attributed to the fact that the luminance gradient enhanced the luminance contrast of the isosurface contour against the background (Fig. 2). The sufficient luminance contrast of an object's contour is known to be important for the human visual system to detect binocular disparity, and consequently, to perceive depth.^{1,2} Thus, the luminance gradient inherent in the SPBR method seems to contribute to increasing the accuracy of perceived depth based on binocular disparity.

When disparity was not available, however, the luminance gradient decreased the perceived depth for the intermediate or high opacities (two lower panels in Fig. 4) although this effect was not statistically significant (Tukey's HSD test, $p > 0.05$). This result might be due to the slightly lower luminance contrast between the bright frontal part and the dark hillside (i.e., in frontal view, the dark

annular part between the center and the surrounding contour) of the isosurface with the SPBR-inherent luminance gradient than that without the luminance gradient (upper and lower right panels in Fig. 2). As mentioned above, higher luminance contrast generally produces larger perceived depth.^{45,50–58} This lower luminance contrast within the isosurface with the SPBR-inherent luminance gradient was caused by introducing the bright luminance gradient on the dark hillside with the large slant (Fig. 3). This darkness of the hillside with the large slant resulted from the dark area behind the isosurface as well as lighting from the observer's side in the Phong shading. Therefore, these results imply that effects of the SPBR-inherent luminance gradient depend on the 3D shape of the object, the lighting direction for the shading, luminance of the area behind the object, opacity, and availability of disparity.

4.3. Effects of opacity

The perceived depth substantially increased with opacity and thus got closer to the ground truth (Fig. 4). This effect of opacity was statistically confirmed by simple regression analysis as well as ANOVA. For every curve in Fig. 4, regression slopes were significantly larger than zero ($p < 0.001$, $R^2 > 0.69$ for every slope). The ANOVA also showed the significant main effect of opacity ($p < 0.00001$). This salient effect of opacity seems to be again due to an increase in the luminance contrast (or luminance difference) between the frontal part and the hillside covered with shading (Fig. 2). Nevertheless, since the advantage of the transparent visualization is the visibility of surfaces behind others, adopting too high opacities might not be appropriate for some applied situations.

With regard to shape from shading, it might be important to note that when perceiving it, the human visual system admittedly often assumes that light comes from above^{2,44,45} (or more precisely, with a slight leftward bias^{59,60}). This “light-from-above” assumption is often demonstrated by showing that a circle containing a vertical luminance gradient with brighter upper part and darker lower part appears convex while a circle with the opposite gradient appears concave.^{2,44} However, in the current stimuli, the light came from the observer's side in the Phong shading of the isosurface. Consequently, unlike in the “light-from-above” case, the bright surface part was the surface part, the normal of which was close to the normal of the screen, not necessarily the upper part of the isosurface even if the surface part was convex. Nevertheless, the isosurface appeared 3D. This phenomenon might partially be attributed to the “dark-is-deep” rule^{58,61–64} in shape-from-shading, which is another assumption that “light-from-above”, and is most pronounced when the lighting is diffuse⁶¹ or comes from the viewing direction.⁶⁵ This assumption causes the darker part to appear farther from the observer as in the present experiment. In fact, it has recently been reported that the “light-from-above” assumption is weak⁶⁶ and the human visual system switches between the “light-from-above” assumption and the “dark-is-deep” rule depending on the situation.⁶⁴ Nevertheless, the bright

annular part located just inside the outer contour of the isosurface (upper and lower right panels in Fig. 2) appeared farther than the darker hillside, as reported in the diffuse lighting case,⁶¹ implying that the lighting direction was estimated correctly based on the luminance distribution of the whole isosurface⁶⁷ or on the depth consistency with binocular disparity and/or motion parallax when they were available.

4.4. Effects of binocular disparity and motion parallax

Introducing binocular disparity (or more accurately, binocular observation of multi-view 3D images) produced more accurate perceived depth, no matter whether motion parallax was available or not (triangular symbols versus square symbols in Fig. 5; the main effect of disparity in ANOVA, $p < 0.00001$). On the other hand, introducing motion parallax (or more accurately, lateral head motion while observing multi-view 3D images) increased the accuracy of perceived depth with statistical significance only when disparity was not available (triangular symbols versus circular symbols in Fig. 5; no significant main effect of motion parallax, $p = 0.13$; significant interaction between disparity and motion parallax, $p < 0.00001$; significant effect of motion parallax when disparity was not available in Tukey's HSD test, $p < 0.05$). These results suggest that binocular disparity and motion parallax can alleviate depth underestimation of a transparently visualized object to some extent.

Fig. 5. Effects of binocular disparity and motion parallax on perceived depth magnitude (replotted from Fig. 4). Luminance gradient was applied (a) or not (b). The horizontal dashed lines indicate the ground truth (7.1). BD, binocular disparity; MP, motion parallax. Error bars indicate one standard error of the mean.

Although the effects of introducing disparity and motion parallax were statistically significant, the effects were somewhat moderate, given the many previous studies reporting substantial effects of disparity¹⁻¹⁰ and motion parallax^{1,2,4-6,19-21} on the perceived depth of an opaque object. More specifically, some studies reported that underestimation of depth magnitude of an opaque object was markedly alleviated by introducing binocular disparity.^{8,68,69} Among such studies, as described above, Bühlhoff and Mallot⁸ used a shaded sphere elongated in depth as a stimulus that was somewhat similar to our stimuli. Their results showed that the depth was largely accurately perceived when the stimulus was presented stereoscopically and the physical elongation was 1.0 or 2.0. On the other hand, in the present experiment, which used stimuli with the ratio of depth to height of 1.6, the mean ratio of perceived to simulated depth was still as small as 39%, even for the opacity of 0.99, which was almost opaque.

The lack of prominent effects of disparity and motion parallax in the present experiment could be due to several possible factors. When compared with Bühlhoff and Mallot,⁸ first, the viewing distance was larger in the present study (350 cm) than in the previous one (120 cm).⁸ In general, the effects of disparity on depth perception decrease with the viewing distance⁷⁰⁻⁷² because the amount of disparity rapidly decreases with the viewing distance.^{1,2,69} Therefore, even if disparity alleviates depth underestimation, at a large viewing distance as in the present study, effects of disparity are smaller, resulting in a substantial amount of residual underestimation. Second, an appreciable amount of crosstalk between views of the 3D display used in the experiment could have contaminated depth perception from disparity⁷³⁻⁷⁵ and motion parallax.⁷⁵ The luminance measured at the central viewpoint was 1.38 times higher when the uniform white images for all five viewpoints were presented than when only the single image for the central viewpoint was presented. This luminance ratio reflects the magnitude of crosstalk between the viewpoints of the 3D display.^{11,12,31} On the other hand, Bühlhoff and Mallot⁸ used shutter glasses with unknown amount of crosstalk. Therefore, the effect of crosstalk could be another possible cause of difference in the experimental results.

Moreover, when compared with many other previous studies reporting substantial effects of disparity¹⁻¹⁰ and motion parallax,^{1,2,4-6,19-21} the first additional possible cause is the fact that the stimulus used in the present experiment contained no visible textures. Texture is generally important for the human visual system to match visual features of both eyes' images to detect binocular disparity and motion parallax, and consequently, to perceive depth.^{1,2,8,58} Adding texture on the surface or the surrounding objects^{68,69} could enhance alleviation of depth underestimation. The second additional possible cause is the fact that the motion parallax yielded by the 3D display used in the present experiment was discontinuous because the display presented only five different images that were visible from five different viewpoints (or more accurately, viewing zones). This discontinuity could also have

impaired depth perception from motion parallax.³¹ The discontinuity of motion parallax can be alleviated by use of a multi-view 3D display with more than five views, and be practically avoided by use of a 3D display that employs head-tracking systems.³²

4.5. Limitations

A limitation of the present study is that we cannot dissociate accuracy from the magnitude of the perceived depth because depth was underestimated in all the conditions and thus larger perceived depth meant more accurate perceived depth. To dissociate accuracy from magnitude, use of an object with a smaller depth to width ratio^{8,76} and/or with a glossy surface⁷⁷ could be effective because the depth of such an object might be perceived larger and could possibly be overestimated taking previous studies into account. Despite this limitation, the results of the present study would still be of substantial benefit because depth magnitude is underestimated in many cases.^{8,46–48,68,69} As is often the case with experimental studies, another limitation might be the generality of the conclusions; namely, for the present study, it remains to be seen whether the conclusions of the present study still hold even for other rendering types of stimulus such as volume-rendered data embedded in surface-rendered data, or for other conditions of the stimulus such as stimuli that contain surface texture gradient, different object color, different object shape, or different background luminance. In spite of these limitations, we believe we gained new insight concerning human perception of 3D transparent objects, especially in relation to surface–volume fusion.

5. Conclusion

We conducted a psychophysical experiment and found that the following factors can improve the accuracy of perceived depth of a transparent object visualized by the SPBR method: The luminance gradient inherent in the SPBR method, high opacities, binocular disparity, and motion parallax. They all alleviated perceptual underestimation of the depth magnitude. The improvement by the SPBR-inherent luminance gradient was salient when the image was presented stereoscopically or the opacity was low. The effects of binocular disparity and motion parallax were somewhat moderate, considering well-known substantial effects of these depth cues on the perceived depth of an opaque object. To develop a method to make full use of these depth cues, further study would be required.

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