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Disparity Remapping Considering the Perception of Depth Structure

Ikuko Tsubaki, Kenichi Iwauchi (Sharp Corp., Chiba, Japan)
Hiroaki Shigemasu (Kochi University of Technology, Kochi, Japan)

Abstract

A disparity remapping method that enlarges disparities inside objects is described. The method also reduces disparity gaps between objects and background. A disparity map is decomposed into a structure component and a high-frequency component, and two components are manipulated independently. Psychophysical experiments are conducted to evaluate the method. The task of participants in the experiments is to judge whether the object is convex or concave. The result of an experiment using random dot stereogram shows that if disparity gap between object and background exists, the detection threshold of depth structure increased. The result of another experiment using stereo pictures whose disparities are inverted inside objects shows that depth structure inside objects becomes more easily detected by the proposed method.

Introduction

Depth perception from binocular stereopsis is not achieved only by the disparity detection, but the conversion process from disparity to depth is necessary. In the conversion process, depth structure is generated from disparities by utilizing various information such as distance information between the observer and the object, and other depth cues. Furthermore, disparities surrounding the object and disparity distribution inside the object are also utilized for the conversion process. Perceived depth of an object varies depending on these information.

Regarding stereoscopic display devices, the images with too large binocular disparity may cause visual discomfort. To avoid this negative effects, the disparity is adjusted within the small range (e.g. 1 deg.). The typical procedure of disparity adjustment is as follows: (1) Estimate a disparity map from the input stereo pair. (2) Remap the estimated disparity. (3) Create a new stereo pair from the remapped disparity and the input stereo pair by depth image based rendering. The characteristics of the disparity remapping strongly affects the perceived depth.

The simplest disparity remapping is linear transformation [18], however it may result in a loss of the perception of depth structure because all disparities become smaller. Nonlinear transformation can compress the disparity range more effectively. There has been much research about nonlinear disparity remapping. They consider various characteristics such as the frequency of the occurrence of disparity values and perceptual saliency [4], the interaction between luminance contrast and disparity perception [2], and the relation between disparity differences between neighboring objects and visual comfort [13]. However, the tendency that a loss of the perception of depth structure is caused does not change. In other words, there exists a trade-off between visual comfort and 3D feeling.

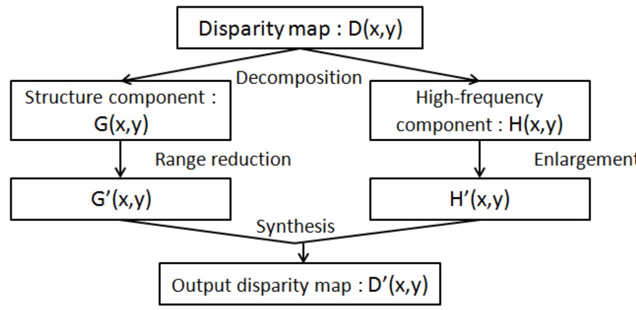

Figure 1. *Proposed disparity remapping method.*

The aim of this paper is to develop a disparity remapping method that overcomes the trade-off for effective 3D presentation. We focus on an effect that disparity gaps between an object and background on the depth perception inside the object. In [14], we proposed a disparity remapping method that enlarges disparities inside objects. In the method, a disparity map is decomposed into structure component and high-frequency component. Then, only the high-frequency component is enlarged (Fig.1). In this paper we present results of evaluation experiments of the method.

Depth Contrast Effect

Visual stimulus which has no disparity variation should be perceived as a frontal parallel plane. However, it can be perceived as a titled plane due to surrounding stimuli. Fig. 2 (a) shows an example stimulus having such effect. Although the center line has no disparity variation and should be perceived on a frontal parallel plane, it is perceived as a tilted line due to disparities of lines on both sides. This phenomenon is called as depth contrast effect and caused by the fact that depth difference from surrounding stimuli is enhanced. This is one example of the fact that the disparity information is not directly perceived as depth. Another example is Craik-O'brien-Cornsweet illusion in depth [1]. As shown in Fig.2 (b), if a stimulus where two planes with equal depth are located on both sides of an edge is observed, one plane is perceived nearer and the other is perceived farther. Like this example, the depth of an object is perceived depending on disparities surrounding the object.

There have been many attempts to explain these phenomena from a viewpoint of processing mechanism of nerve cells. In an experiment that measured modulation transfer function (MTF) for the sensitivity of disparity perception, the sensitivity for a stimulus where depth varies sinusoidally had a peak in 0.3–0.5 cpd, and deteriorated both in higher and lower spatial frequency [15]. That is, the sensitivity has band-pass characteristics. From this, it

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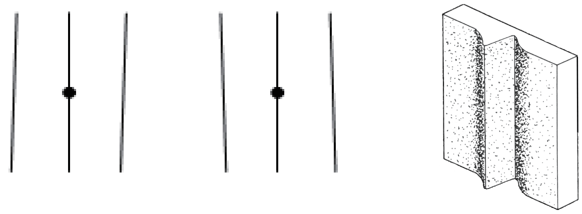


(a) (b)

Figure 2. *(a) Example stimulus which causes depth contrast effect. There is no shift between the center lines in left and right images. The center line should be perceived on the frontal parallel plane. However, it is perceived as a tilted line to the opposite direction from outer lines. (b) COC illusion in depth dimension. Flat areas in left-hand and right-hand sides are located at the same depth. However, they are perceived at the different depth.*

is considered that there is a characteristics of antagonistic center-surround type receptive field and a function of lateral inhibition in disparity perception [1][9][16][10].

We consider that the characteristics is related to the function of depth perception from binocular stereopsis that objects are separated from background and regarded as a group while perception of slight disparity difference inside an object is sacrificed. We also consider that the characteristics may cause "cardboard effect" (see subsection Experiment 1). Therefore, disparity remapping that reduces disparity between an object and background and enlarges disparities inside the object is considered to be effective to make the depth perception inside object clear. However, it is not uncertain whether disparity between object and background affects the sensitivity of depth perception inside the object. It is examined in experiment 1. In the next section, the disparity remapping method developed based on these information is described.

Disparity remapping which enhances disparities inside object

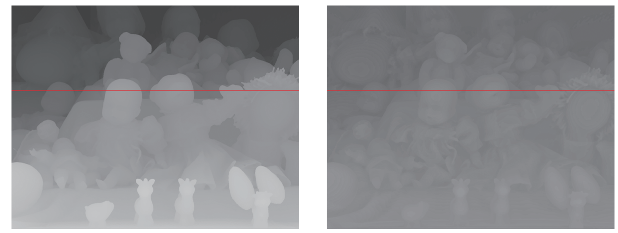
The proposed method manipulates disparities in two manners [14]. One is to decrease disparity gap between an object and background, or between plural objects, with the aim of improvement visual comfort. The other is to enlarge continuous disparity variations inside an object with the aim of improvement 3D feeling. The process flowchart is shown in Fig. 1.

First, the input disparity map $D(x,y)$ is decomposed into structure component $G(x,y)$ and high-frequency component $H(x,y)$. The structure component is defined as spatially low-frequency and large gaps in the input disparity map. By this definition, the positional relationship between background and multiple objects is described in the structure component, and fine concavity and convexity is described in the high-frequency component. The decomposition is achieved by

$$G(x,y)=\sum_{i,j}\alpha_{ij}f(D(x,y),D(x+i,y+j)) \qquad (1)$$

$$\alpha_{ij}=\frac{1}{M}\exp(-\frac{i^2+j^2}{2\sigma^2}),\ M=\sum_{i,j}\exp(-\frac{i^2+j^2}{2\sigma^2})$$

$$f(d_1,d_2)=\begin{cases} d_2 & (|d_1-d_2|\le\varepsilon) \\ d_1 & (|d_1-d_2|>\varepsilon)\end{cases}.$$



(a) Input disparity map (b) Converted disparity map

Figure 3. *Remapping result*

$\sum_{i,j}$ is a short form of $\sum_{i=-w}^{w}\sum_{j=-w}^{w}$, and ε, σ, w are parameters for determining the filter characteristics. An epsilon filter, which is an edge-preserving filter, is utilized in eq.(1). Disparity at the center pixel in a filter window is smoothed using disparities of pixels in the filter window, however only pixels in the window whose disparity differences from the center pixel are larger than ε are used in the smoothing. Then, if the disparity variation inside a object is smaller than ε, and the disparity difference between objects is larger than ε, only pixels in a region inside an object is expected to be used in the smoothing. The high-frequency component $H(x,y)$ is obtained by a simple subtraction. $H(x,y)=D(x,y)-G(x,y)$. By this decomposition, the disparity gaps and the fine continuous variation inside an object are separated.

Second, the dynamic range of the structure component is reduced by linear transformation for the purpose of decreasing the continuous disparities between objects, or between background and objects. And then, the dynamic range of the high-frequency component is enlarged by linear transformation for the purpose of enhancing the variations inside objects.

$$G'(x,y)=aG(x,y)+b, \qquad H'(x,y)=cH(x,y), \qquad (2)$$

where $a(<1), b$ and $c(>a)$ is a parameter for determining the compression rate of the disparity range, offset and the degree of expansion, respectively.

Finally, the final disparity map $D'(x,y)$ is obtained by adding the reduced structure component $G'(x,y)$ and the enlarged high-frequency component $H'(x,y)$.

$$D'(x,y)=G'(x,y)+H'(x,y). \qquad (3)$$

The feature of this method is that the degrees of disparity enlargement inside objects and of the reduction between objects can be controlled independently. Furthermore, the proposed remapping is spatially variant in the whole map while the conventional remapping is invariant. In other words, pixels which originally have the same disparity will have different disparities each other after the proposed remapping while such pixels will have the same disparity after the conventional remapping. This feature allows us to reduce the dynamic range of disparities efficiently.

Experiments

We performed two types of experiments to study the effect of the proposed disparity remapping. Experiment 1 was performed with random dot stereograms to study whether the detection threshold of disparity was changed by reduction of disparity between object and background. Experiment 2 was performed with stereo pictures to study whether depth structure inside object became easy to be perceived by the proposed disparity remapping.

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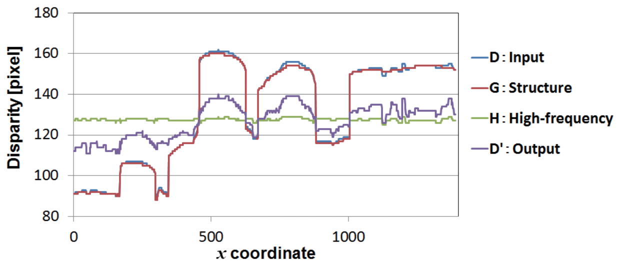

Figure 4. *Structure component, High-frequency component, and Converted disparity*

The task of both experiments was to judge whether the surface inside objects is convex or concave.

Experiment 1

(1) Purpose

Conventionally, the disparity range reduction is performed by compressing disparities uniformly in the whole disparity map. A large disparity gap between an object and background could still be perceived after the uniform compression. However, small depth structure such as the surface of a human face could hardly be perceived. Furthermore, "cardboard effect", which is a phenomenon that objects look like a combination of flat planes, could be easily caused. There is a possibility that disparity gaps disturb the detection of depth structure inside an object like depth contrast effect and it is a cause of the cardboard effect. If the detection of small continuous depth structure is improved by narrowing wide disparity gaps, there is a possibility that narrowing of disparity gaps itself makes the cardboard effect difficult to occur. However, by conventional methods, disparities inside object are also decreased when the range of the whole disparity map is compressed. Therefore, even if it is true that narrowing of disparity gaps itself makes the cardboard effect difficult to occur, the effect of narrowing gaps may become unaware by the effect of decreasing inside object.

For this reason, we studied in experiment 1 whether the size of disparity gaps between object and background affects the detection of depth structure inside the object by manipulating the disparity inside the object and the disparity gaps independently.

(2) Stimulus and apparatus

Random dot stereogram patterns were used to control disparities strictly. The pattern for left and right eye was presented to left and right eye respectively using a mirror stereoscope in order to avoid crosstalk (Fig. 5). The random dot stereogram patterns were displayed on a CRT display (EIZO 21inch FlexScan T961, 1024 × 768 pixels), which has high time resolution. The object surface had the shape of a cosine wave of half period and displayed at the center of the screen. Both objects whose surface was convex and concave were utilized (Fig. 6). Ten different level of disparities inside the object were prepared for each participant, and the thresholds were determined by constant method. The size of the object was 6.7 × 6.7 deg, and the size of the background was 13.3 × 20 deg (width×height). The number of dots in background and object was 15,000. Luminance was 1.72 cd/m^2 of the black background and 35.5 cd/m^2 of the white dots. An example stimulus is shown in Fig.7.

Four levels were set for the disparity between object and background: 0, 15, 30, and 60 min. The stimuli displayed on the CRT screen were viewed by participants thorough the mirror stereoscope with four mirrors and the optical path length was set to 80 cm. A partition was placed at the center to avoid crosstalk. A chin rest was used to stabilize the head of the participants. A fixation cross was added at the center of the object, and participants were instructed to fixate on the fixation cross during a task.

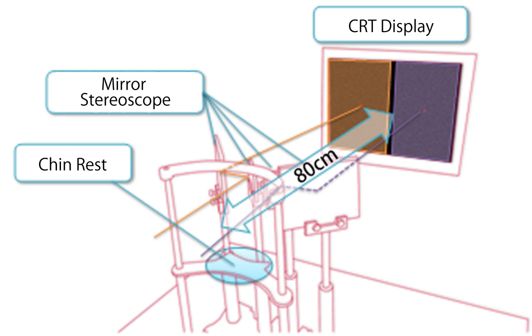

Figure 5. *Experiment 1. Stimulus presentation system.*

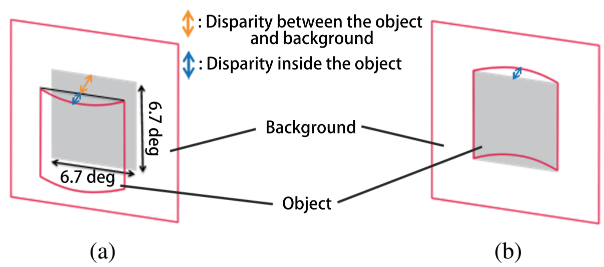

Figure 6. *Pattern diagrams of stimuli. (a) Condition where the object's surface is convex in shape and there is a gap between background and the object. (b) Condition where the object's surface is concave in shape and there is no gap between background and the object.*

(3) Participants

Five male adults who have normal eyesight (including corrected eyesight) and stereo vision participated.

(4) Procedure

Each participant was seated in a chair and viewed stimuli through the mirror stereoscope under a condition that his head was stabilized by the chin rest. The task of participant was to judge whether the object is convex or concave. After observing a stimulus for 500 msec, the participant pushed "up arrow" key in a keyboard if he perceived the object was convex, and pushed "down arrow" key if he perceived the object was concave. This was considered as one trial. 200 trials (10 levels of disparity inside object × 4 levels of disparity between object and background × 5 times of repetition) were conducted in a random order in a session. 6 sessions (1200 trials) were conducted. A five-minute break was given after each session.

Ten levels of disparity inside object were (-5, -4, -3, -2, -1, 1, 2, 3, 4, 5 min) for a participant experienced in psychophysical experiments, (-15, -12, -9, -6, -3, 3, 6, 9, 12, 15 min) for three participants who were not experienced in psychophysical experiments, and (-50, -40, -30, -20, -10, 10, 20, 30, 40, 50 min) for a participant whose depth perception is relatively poor.

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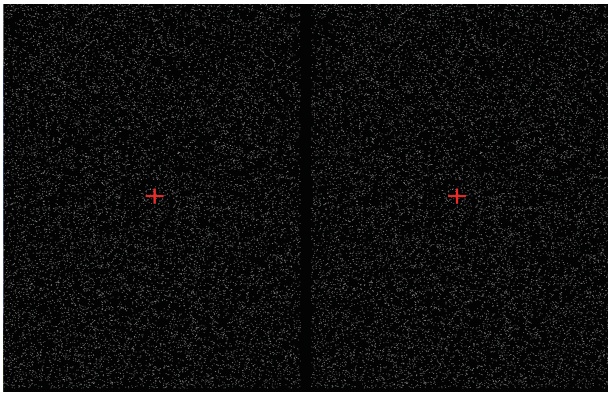

Figure 7. Example stimulus of random dot stereogram.

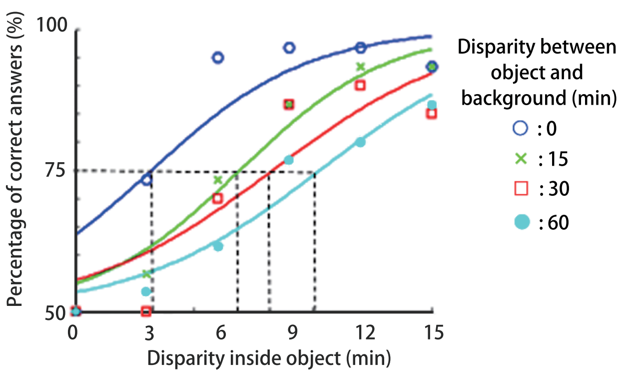

Figure 8. Example result of percentage of correct answers for a participant for each object-background disparity condition. Depth detection thresholds for the participant are derived from disparities inside object at points where the percentage of correct answers are 75% on fitting curves (using logistic function).

(5) Results

Percentage of correct answers is plotted as a function of disparity inside object for each object-background disparity condition, and is fitted to a logistic function. The points where the percentage of correct answers is 75% are considered as thresholds to determine whether the participant can judge convex or concave. The points where the disparity inside object were zero were set to 50% of correct answers as a theoretical value. The fitting is executed including these points. A typical result of a participant is shown in Fig. 8. A graph of average detection threshold of convexity and concavity for each participant is shown in Fig. 9. The abscissa axis shows the disparity between object and background.

One-way repeated ANOVA is performed to examine statistically the effect of disparity gaps between object and background on detection threshold of concavity and convexity. As a result, effects of the disparity gaps are recognized ($F(4,12) = 11,21, p < .01$). Although there is large difference between condition which the object-background disparity is 0 min and other conditions, there are no significant differences among conditions which the object-background disparity are positive.

(6) Discussion

The results show that as thresholds are different between zero and positive object-background disparity conditions, disparity gaps between object and background inhibit depth detection inside object. This result is similar as a preceding study [11] which examined the cardboard effect.

As just described, there are difference of thresholds between zero and positive object-background disparity conditions, however there are no significant difference of thresholds among positive object-background disparity conditions. Therefore, it is shown that the difference of disparity gaps between object and background does not affect the perception sensitivity of depth structure inside object, and it is suggested that reduction of disparity gaps between object and background itself does not have the effect of detecting depth structure inside object easily.

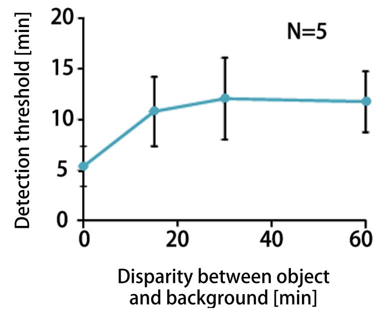

Figure 9. Effect of disparity gap between object and background on depth detection threshold.

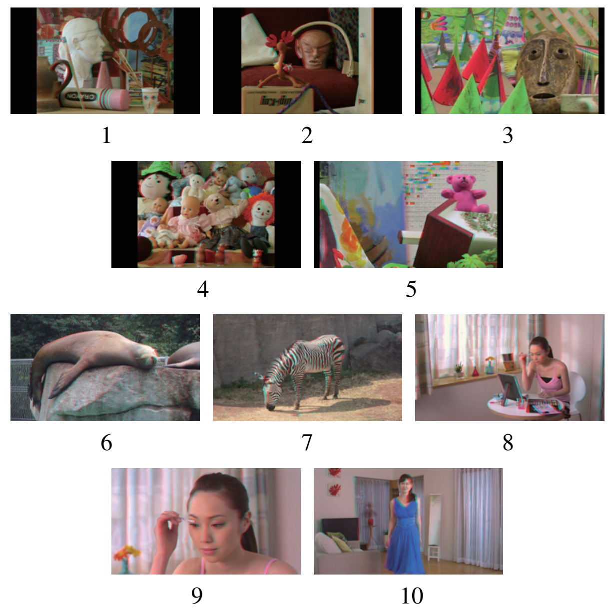

Figure 10. Stereo pictures for experiment 2

Experiment 2

(1) Purpose

The result of experiment 1 suggested that the effect of reinforcing depth perception inside object is not produced only by reduction disparity gap between object and background. Therefore, if the disparity inside object is fixed, the reduction of disparity gap

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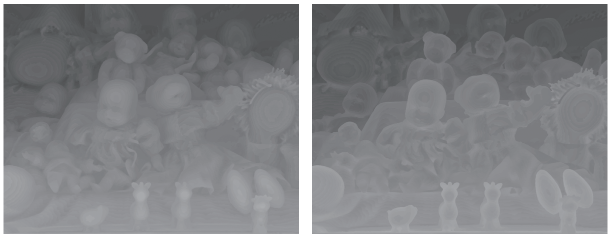
Table 1. Parameters

	$c/2$	σ	w	ε
Filter A	10	100	50	5
Filter B	10	100	100	10



(a) Convex surface (b) Concave surface

Figure 11. *An example of converted disparity map (Filter A).*

does not make perception of depth structure inside object easily. In experiment 2, a psychophysical experiment was performed to examine the effect of enlarging disparity inside object.

(2) Stimulus and apparatus

We used ten stereo pictures and the processed pictures in which disparity between object and background is reduced and disparity inside objects are enlarged using the proposed method. Each ten stereo pictures includes one or more intelligible objects such as human, animal, and still life. These stereo pictures are shown in Fig. 10. Pictures 1-5 were got from Middlebury Stereo Datasets [5]. Disparity maps of 1-5 were also got from the site and used for the experiment. Pictures 6 and 7 were shot with a digital camera (FinePix REAL 3D W1). Pictures 8-10 were got from NICT 3D standard test contents [6]. Disparity maps of 6-10 were estimated by dynamic programming method. Two parameter sets (Filter A, B) were used for disparity remapping (Table 1). After disparity remapping, stereo pictures were regenerated using a method in [19].

Furthermore, a concave disparity map was generated for each stereo picture by inverting the high-frequency component. Surface inside objects became concave by this process. As the structure component was not inverted, the disparity gaps were not changed. Stereo pictures were also generated using the concave disparity maps. Both stereo pictures remapped by the proposed method and inverted were used for the experiment. The task of participant was to judge whether convex or concave. Percentage of correct answers was used as an index to know if the participant perceived depth structure inside the objects correctly.

An example of concave disparity map is shown in Fig. 11 (b). Fig. 11 (a) shows normal remapped result by the proposed method, which was enhanced convexity. A stereo picture of concave objects was generated for each original picture, remapped picture using filter A, and remapped picture using filter B. Therefore, the stimuli for this experiment were 60 stereo pictures (3 types of enhancement (original, filter A, filter B) $\times$ 2 types of surface (convex, concave) $\times$ 10 original stereo pictures). These stimuli were displayed on a 46 inch 3D liquid crystal television (AQUOS LC-46LV3) with side-by-side format. Stimuli for left and right eyes were displayed alternately in a frame sequential

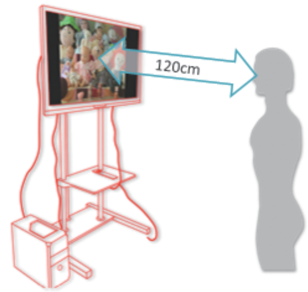


Figure 12. *Experiment 2 environment.*

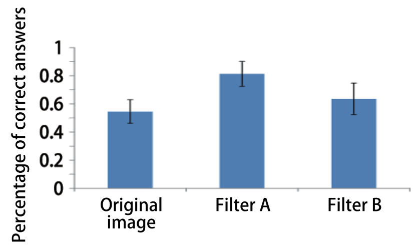


Figure 13. *Effect of the disparity remapping.*

manner. Viewing distance was 120 cm.

(3) Participants

Five male adults who have normal eyesight (including corrected eyesight) and stereo vision participated.

(4) Procedure

Each participant wore liquid crystal glasses and observed stimuli standing in a dark room (Fig. 12). After stimulus was displayed for 1000 msec, the participant judged whether the object is convex or concave. The participant pushed "up arrow" key in a keyboard if he perceived the object was convex, and pushed "down arrow" key if he perceived the object was concave. This was considered as one trial. Three trials were conducted for each stimulus in a session. A five-minute break was given after each session. Three sessions (total 540 trials = 60 stimuli $\times$ 3 trials $\times$ 3 sessions) were conducted. Stimuli were displayed in a random order to control order effect.

(5) Results

We consider that objects' depth structure of picture 6 in Fig. 10 was not perceived because percentage of correct answers is less than 60%, and eliminates the picture 6 from analysis of the results. There are no corresponding points of both eye images such as distinct texture inside objects. That might be a reason why depth structure of picture 6 was not perceived. Fig. 13 shows average percentage of correct answers for 9 pictures excluding picture 6. The results of three images (original, processed with filter A, processed with filter B) are shown in this figure. Fig. 14 shows percentage of correct answers of each 9 picture.

The results of this experiment show that the percentages of correct answers of processed images are higher than the original image. The effect of the proposed disparity remapping are recognized from the result of one-way repeated ANOVA ($F(2,6) = 7.69, p < .05$). Furthermore, one-sample paired t-test was performed to compare the chance level (i.e. 50% of correct answers).

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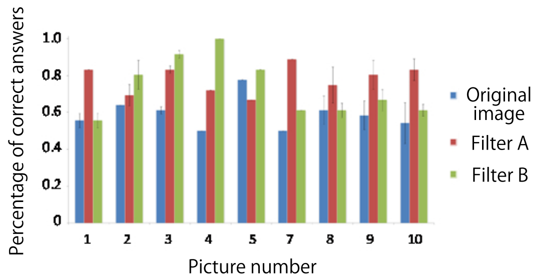

Figure 14. Effect of the disparity remapping in each image.

The results show that processed images with filter A have significant difference and significantly higher percentage of correct answers than the chance level ($t(4) = 8.33, p < .01$).

(6) Discussion

The results indicate that the disparity remapping method that reduces disparity gaps between object and background and enlarges disparity inside object is effective to reinforce depth perception inside object. We consider this effect is caused mainly by enlarging disparities inside object because there are no effect of disparity gaps between object and background in experiment 1.

Although the percentage of correct answers of filter A is higher than that of filter B on average, filter B has higher percentage of correct answers than filter A in some pictures (picture 2, 3, 4, 5). Therefore, further work is needed to determine appropriate parameters.

The percentage of correct answers of original images is very low and almost equal to the chance level. We consider that this is due to "Hollow Face Illusion" [3] [8], which is a phenomenon that a certain type of object such as a face looks like convex by top-down knowledge that the surface is convex even if the depth structure generated by binocular disparity cue is concave.

Conclusion

We examined the effects of the disparity remapping method that reduces disparity gaps between object and background and enlarges disparities inside the object. The psychophysical experiment using random dot stereograms showed that difference of disparity gaps between object and background does not affect perception sensitivity of depth structure inside the object at least in the range of less than 1 deg. The experiment using stereo pictures where the object surface is changed from convex to concave showed that the present method had an effect of making perception of depth structure inside the object clear.

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Author Biography

Ikuko Tsubaki received her BS in physics from Tokyo Institute of Technology (1995) and her PhD in informatics from Tokyo University (2004). She works for Sharp Corporation. Her research interest is image processing and computer vision.

Kenichi Iwauchi received his BS in material engineering form Tokyo University of Science (1992) and his PhD in ergonomics from Utsunomiya University (2011). He works for Sharp Corporation. His research interest is image processing.

Hiroaki Shigemasu received his PhD in psychology from the University of Tokyo (2005). After he worked in Intelligent Modeling Laboratory at the University of Tokyo, and in Intelligent Sensing System Research Center at Toyohashi University of Technology as a research fellow, he has worked in School of Information, Kochi University of Technology since 2009. His work has focused on investigating the mechanism of human 3D perception using psychophysical and functional brain imaging method.