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DEPTH PERCEPTION OF DISTORTED STEREOSCOPIC IMAGES

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ABSTRACT

How to measure the perceptual quality of depth information in stereoscopic natural images, especially images undergoing different types of symmetric and asymmetric distortions, is a fundamentally important issue that is not well understood. In this paper, we present two of our recent subjective studies on depth quality. The first one follows the absolute category rating (ACR) protocol that is widely used in general image quality assessment research. We find that traditional approaches such as ACR is problematic in this scenario because monocular cues and the spatial quality of images have strong impacts on the depth quality scores given by subjects, making it difficult to single out the actual contributions of stereoscopic cues in depth perception. To overcome this problem, we carry out the second subjective study where depth effect is synthesized at different depth levels before various types and levels of symmetric and asymmetric distortions are applied. Instead of following the traditional approach, we ask subjects to identify and label depth polarizations, and a Depth Perception Difficulty Index (DPDI) is developed based on the percentage of correct and incorrect subject judgements. We find this approach highly effective at quantifying depth perception induced by stereo cues and observe a number of interesting effects regarding image content dependency, distortion type dependency, and the impacts of symmetric versus asymmetric distortions. We believe that these are useful steps towards building comprehensive 3D quality-of-experience models for stereoscopic images.

Index Terms— depth perception, stereoscopic image, 3D image, image quality assessment, quality-of-experience, asymmetric distortion

1. INTRODUCTION

Depth perception is a fundamentally important aspect of human quality-of-experience (QoE) when viewing stereoscopic 3D images. Recent progress on subjective and objective studies of 3D image quality assessment (IQA) is promising [1, 2] but the understanding of 3D depth quality remains limited. In [3], it was reported that the perceived depth performance cannot always be predicted from displaying image geometry alone while other system factors, including software drivers, electronic interfaces, and individual participant differences may also play significant roles. In [4, 5], it was suggested that depth perception may need to be considered independently from perceived 3D image quality. The results in [4] showed that increased JPEG coding has no effect on depth perception however a negative effect on image quality, while increasing camera distance will increase depth perception. In [6], subjective studies suggested that 3D image quality is not sensitive to variations in the degree of depth perception. Nevertheless, other studies pointed out the importance of depth information for a more general 3D quality perception. In [7], a blurring filter, where the level of blur depends on the depth of the area where it is applied, is used to enhance the viewing experience. In [8], stimuli with various stereo depth and image quality were evaluated subjectively in terms of naturalness, viewing experience, image quality, and depth perception, and the experimental results suggested that the overall 3D QoE is approximately 75% determined by image quality and 25% by perceived depth.

Meanwhile, several studies have been proposed to objectively predict perceived depth quality and thus to predict 3D quality with a combination of estimated depth quality and 2D image quality. In [9], PSNR, SSIM [10] and VQM [11] were employed to predict perceived depth quality, and PSNR and SSIM appear to have slightly better performance. In [12, 13], disparity maps between left- and right-views were estimated using SSIM and C4 [14] and C4 is reported to be better than SSIM on evaluating the quality of disparity maps. You *et al.* [15] evaluated stereopairs as well as disparity maps with respect to ten well-known 2D-IQA metrics, i.e., PSNR, SSIM, MS-SSIM [16], UQI [17], VIF [18], etc. The results suggested that an improved performance can be achieved when stereo image quality and depth quality are combined appropriately. Similarly, Yang *et al.* [19] proposed a 3D-IQA algorithm based on the average PSNR of left- and right-views and the absolute difference with respect to disparity map. In [20], Zhu *et al.* proposed a 3D video quality assessment (VQA) model by considering depth perception and the experimental results showed that the proposed human vision system (HVS) based model performs better than PSNR. However, in [21, 22], comparative studies show that none of these 3D-IQA/VQA models, with or without depth information involved, perform better than or in most cases, even as good as, direct averaging 2D-IQA measures of both views.

In this work, we carry out two subjective experiments on depth quality. The first one adopts a traditional absolute category rating (ACR) [23] approach widely used in general image quality assessment. We find that such an approach is problematic because it is difficult to single out the contributions of stereo information from those of monocular cues. To overcome this problem, we conduct the second experiment where subjects are asked to identify and label depth polarizations. We find the second approach highly effective at quantifying depth perception induced by stereo cues. Furthermore, we carry out a series of analysis to investigate the impacts of image content, distortion type, and distortion symmetricity on perceived depth quality.

2. SUBJECTIVE STUDY I

2.1. Image Database and Subjective Test

The WATERLOO-IVC 3D Image Quality Database [1, 2] was created from 6 pristine stereoscopic image pairs and their corresponding single-view images. Each single-view image was altered by three

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types of distortions: additive white Gaussian noise contamination, Gaussian blur, and JPEG compression, and each distortion type had four distortion levels. The single-view images are employed to generate distorted stereopairs, either symmetrically or asymmetrically. There are totally 78 single-view images and 330 stereoscopic images in the database. More detailed descriptions are in [1, 2]. Here we focus on the depth perception part, where the definition of depth quality is the amount, naturalness and clearness of depth perception experience.

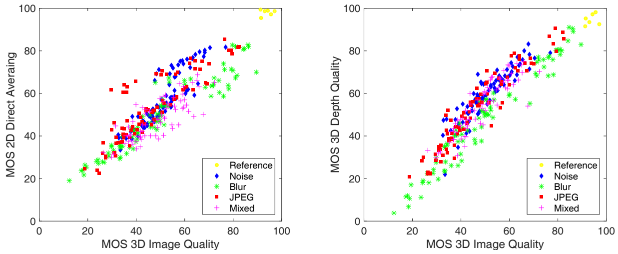
The subjective test was conducted in the Lab for Image and Vision Computing at University of Waterloo. The test environment has no reflecting ceiling walls and floor, and was not insulated by any external audible and visual pollution. An ASUS 27" VG278H 3D LED monitor with NVIDIA 3D Vision$^{\text{TM}}$2 active shutter glasses is used for the test. The default viewing distance was 3.5 times the screen height. In the actual experiment, some subjects did not feel comfortable with the default viewing distance and were allowed to adjust the actual viewing distance around it. The details of viewing conditions are given in Table 1. Twenty-four naïve subjects, 14 males and 10 females aged from 22 to 45, participated in the study. A 3D vision test was conducted first to verify their ability to view stereoscopic 3D content. Three of them (1 male, 2 females) failed the vision test and did not continue with the subsequent experiment. As a result, a total of twenty-one subjects proceeded to the formal test.

Table 1. Viewing conditions of the subjective test

Parameter	Value	Parameter	Value
Subjects Per Monitor	1	Screen Resolution	1920 × 1080
Screen Diameter	27.00"	Viewing Distance	45.00"
Screen Width	23.53"	Viewing Angle	29.3°
Screen Height	13.24"	Pixels Per Degree	65.5 pixels

We followed the ACR protocol and the subjects were asked to rate the depth quality of each image between 0 and 10 pts. A self-training process was employed to help the subjects establishing their own rating strategies with the help of a depth comparison test (stimuli with the same source image but different depth levels were presented to help the subjects establish the concept on the amount of depth), and subjects were introduced to build their own rating strategies. Previous works reported that the perception of depth quality are both highly content and texture dependent [24] and subject dependent [25, 26]. We agree with these observations and believe that it is not desirable to educate the subjects to use the same given rating strategy. Thus after the depth comparison test, the 3D pristine stereopairs were first presented and the subjects were instructed to give high scores (close to 10 pts) to such images, and the 2D pristine images (with no depth from stereo cues) were presented and the subjects were instructed to give low scores (close to 0 pts). Next, stereopairs of different types/levels of distortions were presented and the subjects were asked to practice by giving their ratings on depth quality between 0 to 10 pts. During this process, the instructor also repeated the definition of depth quality and emphasized that there is not necessarily any correlation between depth quality and the type/level of distortions.

In the formal test, all stimuli were shown once. However, there were 12 repetitions, which means that for each subject, her/his first 12 stereopairs were shown twice. The order of stimuli was randomized and the consecutive testing stereopairs were from different source images. 342 testing stereopairs with 12 repetitions were partitioned into two sessions and each single session (171 stereopairs) was finished in 15 to 20 minutes. Sufficient relaxation periods (5 minutes or more) were given between sessions. Moreover, we found that repeatedly switching between viewing 3D images and grading on a piece of paper or a computer screen is a tiring experience. To overcome this problem, we asked the subject to speak out a score, and a customized graphical user interface on another computer screen was used by the instructor to record the score. All these efforts were intended to reduce visual fatigue and discomfort of the subjects.



(a) MOS 3DIQ vs. MOS 2DIQ (b) MOS 3DIQ vs. MOS DQ

Fig. 1. Relationships between 3DIQ and 2DIQ and 3DIQ and DQ in Subjective Study I.

Our preliminary analysis shows that there is a large variation between subjects on depth quality scores as humans tend to have very different perception and/or opinions about perceptual depth quality. The rest of this section focuses on the relationship between depth quality scores and the 3D image quality scores. More detailed analysis of the other aspects of depth quality scores and the details of the aforementioned depth comparison test will be reported in future publications.

2.2. Observations and Discussions

In [1, 2], the 2D image quality (2DIQ) and 3D image quality (3DIQ) tests on WATERLOO-IVC 3D Image Quality Database were introduced. The raw 2DIQ and 3DIQ scores given by each subject were converted to Z-scores, respectively. Then the entire data sets were rescaled to fill the range from 1 to 100 and the mean opinion scores (MOS) for each 2D and 3D image was computed. The detailed observations and analysis of the relationship between MOS 2DIQ and MOS 3DIQ and how to predict the image content quality of a stereoscopic 3D image from that of the 2D single-view images can be found in [2, 27].

In this work, the raw depth quality (DQ) scores given by each subject were converted to Z-scores. Then the entire data set was rescaled to fill the range from 1 to 100 and the MOS DQ for each image was computed. Fig. 1 shows the scatter plots of MOS 3DIQ vs. averaging MOS 2DIQ of left- and right-views and MOS 3DIQ vs. MOS DQ. Fig. 1 (a) shows that there exists a strong distortion type dependent prediction bias when predicting quality of asymmetrically distorted stereoscopic images from single-views [1, 2], i.e., for noise contamination and JPEG compression, average prediction overestimates 3DIQ (or 3DIQ is more affected by the poorer quality view), while for blur, average prediction often underestimates 3DIQ (or 3DIQ is more affected by the better quality view).

From Fig. 1 (b), it can be observed that human opinions on 3DIQ and DQ are highly correlated. This is unexpected because 3DIQ and DQ are two different perceptual attributes and the stimuli were generated to cover all combinations between picture qualities and stereo depths. Through more careful observations of the data and discussions with the subjects who did the experiment, we found two explanations. First, psychologically humans have the tendency to give high DQ scores whenever the 3DIQ is good and low DQ scores whenever the 3DIQ is bad and the strength of such a tendency varies between subjects. Second, humans interpret depth information using many physiological and psychological cues [28], including not only binocular cues such as stereopsis, but also monocular cues such as retinal image size, linear perspective, texture gradient, overlapping, aerial perspective, and shadowing and shading [29, 30]. In the real world, humans automatically use all available depth cues to determine distances between objects but most often rely on psychological monocular cues. Therefore, the DQ scores obtained in the current study are a combined result from many monocular and binocular cues, and it becomes difficult to differentiate the role of stereopsis.

However, what we are interested in the current study is to measure how much stereo information can help with depth perception. Based on the explanations above, in the traditional ways of subjective testing like the current one, many depth cues are mixed together and the results are further altered by the spatial quality of the image, making it difficult to quantify the real contributions of using stereoscopic images in depth perception. Thus we design a novel depth perception test, which will be presented in the next section.

3. SUBJECTIVE STUDY II

3.1. Image Database and Subjective Test

We created a new Waterloo-IVC 3D Depth Database from 6 pristine texture images (Bark, Brick, Flowers, Food, Grass and Water) as shown in Fig. 2. All images were collected from the VisTex Database at MIT Media Laboratory [31]. A stereogram can be build by duplicating the image, selecting a region in one image, and shifting this region horizontally by a small amount in the other one. The region will seem to virtually fly in front of the screen, or be behind the screen if we swap two views. In our experiment, six different levels of Gaussian surfaces (with different heights and different widths) were obtained by translating and scaling Gaussian profiles, where the 6 depth levels (where Depth 1 and Depth 6 denote the lowest and highest depths, respectively) were selected to ensure a good perceptual separation. Thus each texture image was used to generate 6 stereopairs with different depth levels. By switching left- and right-views, the hidden depth - Gaussian shapes - could be perceived towards inside or outside and we denote them as inner stereopairs and outer stereopairs, respectively. As such, for each texture image, we have 12 pristine stereopairs with different depth polarizations and depth levels. In addition, one flat stereopair without any hidden depth information was included.

Each pristine stereopair (inner, outer and flat) was altered by three types of distortions: additive white Gaussian noise contamination, Gaussian blur, and JPEG compression. Each distortion type had four distortion levels as reported in Table 2, where the distortion control parameters were decided to ensure a good perceptual separation. The distortions were simulated either symmetrically or asymmetrically. Symmetrically distorted stereopairs have the same distortion type and level on both views while asymmetrically distorted stereopairs have the distortion on one view only. Altogether, there are 72 pristine stereoscopic images and 1728 distorted stereoscopic images (864 symmetrical and 864 asymmetrical distortions) in the database. In terms of the depth polarity, there are 684 inner stereopairs, 684 outer stereopairs and 432 flat stereopairs. An example of the procedure of generating a symmetric blurred stereopair is shown in Fig. 3.

For each image, we provide the subjects with four available choices to respond, i.e., inner, outer, flat and unable to decide. The motivation of introducing the last choice is that for many distorted stereopairs, the subjects can perceive the existence of depth information but feel difficult to make confident judgements on depth polarity.

(a) Bark (b) Brick (c) Flowers

(d) Food (e) Grass (f) Water

Fig. 2. The 6 texture images used in Subjective Study II.

Table 2. Value ranges of control parameters to generate image distortions

Distortion	Control Parameter	Range
Noise	Variance of Gaussian	[0.10 0.40]
Blur	Variance of Gaussian	[2 20]
JPEG	Quality parameter	[3 10]

There are three important features of the current database. First, the depth information embedded in each stereopair is independent of its 2D scene contents, such that subjects can only make use of stereo cues to identify depth change and judge the polarity of depth. Second, the database contains distorted stereopairs from various distortion types, allowing us to compare the impacts of different distortions on depth perception. Third, the current database contains both symmetrically and asymmetrically distorted stereopairs, which allows us to directly examine the impact of asymmetric distortions on depth perception. This may also help us better understand what are the key factors that affect depth quality in stereoscopic images.

The subjective test was conducted in the Lab for Image and Vision Computing at University of Waterloo with the same test environment, the same 3D display system, and the same viewing conditions as described in Section 2. Thus here we only describe some important differences from Subjective Study I. Twenty-two naive subjects, 11 males and 11 females aged from 21 to 34, participated in the study and no one failed the vision test. As a result, a total of twenty-two subjects proceeded to the formal test. The training process is fairly straightforward. Twelve stereopairs with different depth configurations including polarities and levels were presented to the subjects. Subjects were asked to speak out their judgements for these training stereopairs as an exercise. Then a multi-stimulus method was adopted to obtain subjective judgements for all test stereopairs. Each stimulus contains six stereopairs with the same depth level and the same image content but different depth polarity or image distortion. These six stereopairs were aligned with sufficient boundaries and displayed in actual pixels. All stimuli were shown once and the order of stimuli was randomized. 75 stimuli were evaluated in one

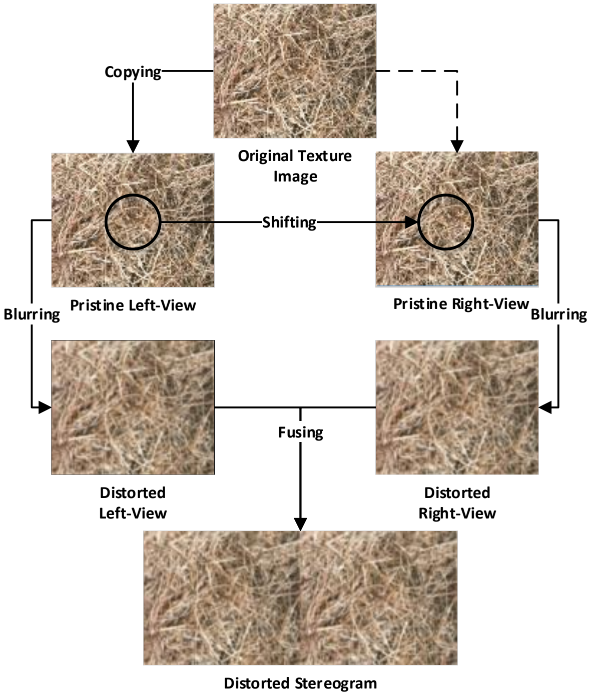


Fig. 3. Procedure of generating a symmetric blurred stereoscopic image in Subjective Study II.

session and each session was controlled to be within 20 minutes. Similarly, subjects only needed to speak out their judgements and an instructor was responsible for recording subjective results.

We observe a significant variation between subjects' behaviors, which is expected as humans exhibit a wide variety of stereoacuity and stereosense [32]. The rest of this section focuses on the impacts of depth level, depth polarity, image content and image distortion. More detailed analysis of the other aspects of the subjective data will be reported in future publications.

3.2. Depth Perception Difficulty Index (DPDI)

For each test image, there are 3 possible ground-truth polarity answers - inner, outer and flat. Meanwhile, pooling the subjective judgements on the image lead us to four percentage values, denoted by $\{P_{\text{in}}, P_{\text{out}}, P_{\text{flat}}, P_{\text{unable}}\}$, corresponding to the percentages of subject judgements of inner, outer, flat and unable to decide, respectively. Given these values, we define a novel measure named Depth Perception Difficulty Index (DPDI), which indicates how difficult it is for an average subject to correctly perceive the depth information in the image. Specially, if the ground-truth is an inner image, we define

$$\begin{aligned} \text{DPDI} &= \min\{1, P_{\text{flat}} + P_{\text{unable}} + 2 \times P_{\text{out}}\} \\ &= 1 - \max\{0, P_{\text{in}} - P_{\text{out}}\}. \end{aligned} \tag{1}$$

Similarly, for an outer image

$$\begin{aligned} \text{DPDI} &= \min\{1, P_{\text{flat}} + P_{\text{unable}} + 2 \times P_{\text{in}}\} \\ &= 1 - \max\{0, P_{\text{out}} - P_{\text{in}}\}. \end{aligned} \tag{2}$$

This DPDI is bounded between 0 and 1. In the extreme cases, when we have $\{100\%, 0, 0, 0\}$ for inner images or $\{0, 100\%, 0, 0\}$ for outer images, DPDI is 0; when we have $\{25\%, 25\%, 25\%, 25\%\}$, which is equivalent to the case of random guess, DPDI equals 1.

3.3. Analysis and Discussions

Table 3 shows the mean DPDI values for different depth levels for the cases of all images, inner images and outer images. Unsurprisingly, DPDI drops with increasing depth in each test group. A much more interesting observation here is that with a given level of depth, inner images generally have lower DPDI values and the difference in mean DPDI values between inner and outer images increase with the level of depth. This indicates that it is easier for humans to perceive depth information when objects appear to be behind the screen than the opposite.

Table 3. DPDI values of different depth levels

Depth Levels	Inner	Outer	All
Depth 1	0.9196	0.9146	0.9171
Depth 2	0.7605	0.7883	0.7744
Depth 3	0.5829	0.6721	0.6275
Depth 4	0.4095	0.5732	0.4914
Depth 5	0.3409	0.5008	0.4209
Depth 6	0.2811	0.4474	0.3643

Table 4 reports the mean DPDI values for different background image contents. First, it appears that DPDI is highly image content dependent as it varies significantly across content. In general, it seems that DPDI decreases with the increase of high-frequency details, which is consistent with the previous vision research [33] that stereo gain is higher for the high spatial-frequency system than the low spatial-frequency system. Second, although inner images always have higher DPDI values, the gap between inner and outer images is image content dependent.

Table 4. DPDI values of different image content

Image Content	Inner	Outer	All
Bark	0.4831	0.5793	0.5339
Brick	0.7562	0.9226	0.8209
Flowers	0.4232	0.4985	0.4545
Food	0.4948	0.6007	0.5448
Grass	0.2646	0.4315	0.3620
Water	0.8712	0.8846	0.8794

Table 5 shows the mean DPDI values of different distortion types and levels. First, across distortion types, it can be observed that noise contamination has more impact on depth perception than JPEG compression and Gaussian blur. Second, more interestingly, although the cases of symmetric distortions double the total amount of distortions than asymmetric distortions (because the same level of distortions is added to both views), the DPDI gap between asymmetric and symmetric distortions is distortion type dependent. The gaps in the case of noise contamination is much higher than those of Gaussian blur and JPEG compression. The point worth noting is that adding blur or JPEG compression to one view of stereopair results in similar difficulty in depth perception as adding the same level of distortion to both views. This is quite different from the distortion type dependency in 3D image quality perception, as shown in Fig. 1 (a). It is interesting to note that some of our new observations are somehow consistent with previous vision studies [34, 35]. For example, in [35], Hess *et al.* found that stereoacuity was reduced when one view was severely blurred by filtering off high spatial frequencies and loss of acuity was much less severe when both views are blurred.

The discovery of this distortion type dependency in depth perception not only has scientific values in understanding HVS with

Table 5. DPDI values of different distortion types and levels

Distortions	All	Level 1	Level 2	Level 3	Level 4
Noise Sym.	0.7986	0.6275	0.7412	0.8838	0.9419
Noise Asym.	0.6504	0.5215	0.6477	0.7058	0.7500
Blur Sym.	0.5470	0.4962	0.4912	0.5492	0.6515
Blur Asym.	0.5431	0.3902	0.4975	0.6048	0.6528
JPEG Sym.	0.5660	0.4444	0.5278	0.6187	0.6730
JPEG Asym.	0.5473	0.4470	0.5265	0.5871	0.6679

depth perception, but is also desirable in the practice of 3D video compression and transmission, where it has been hypothesized that only one of the two views need to be coded at high rate, and thus significant bandwidth can be saved by coding the other view with low rate. Meanwhile, mixed-resolution coding and postprocessing techniques (deblocking or blurring) have been proposed to improve the efficiency of stereoscopic video coding in the literature [36, 37, 38]. Here our new observations indicate that asymmetric compression and asymmetric blurring will influence the perceived 3D depth quality. Therefore, the current study suggests that mixed-resolution coding, asymmetric transform-domain quantization coding, and postprocessing schemes need to be carefully reexamined and redesigned to maintain a good tradeoff between perceptual 3D image quality and depth quality.

3.4. Impact of Eye Dominance

Eye dominance is a common visual phenomenon, referring to the tendency to prefer the input from one eye to the other, depending on the human subject [39]. When studying visual quality of asymmetrically distorted images, it is important to understand if eye dominance plays a significant role in the subjective test results. For this purpose, we carried out a separate analysis on the impact of eye dominance in the depth perception of asymmetrically distorted stereoscopic images. The side of the dominant eye under static conditions was checked first by Rosenbach's test [40]. This test examines which eye determines the position of a finger when the subject is asked to point to an object. Among twenty subjects who finished the formal test Subjective Study II, ten subjects (6 males, 4 females) had a dominant left eye, and the others (5 males, 7 females) are right-eye dominant.

The DPDI for each image in Waterloo-IVC 3D Depth Database were computed for left-eye dominant subjects and right-eye dominant subjects, denoted as $\mathrm{DPDI_L}$ and $\mathrm{DPDI_R}$, respectively. We employed the one-sample t-test to obtain a test decision for the null hypothesis that the difference between $\mathrm{DPDI_L}$ and $\mathrm{DPDI_R}$, i.e., $\mathrm{DPDI_D} = \mathrm{DPDI_L} - \mathrm{DPDI_R}$, comes from a normal distribution of zero-mean and unknown variance. The alternative hypothesis is that the population distribution does not have a mean equaling zero. The result h is 1 if the test rejects the null hypothesis at the 5% significance level, and 0 otherwise. The returned p-values for symmetric and asymmetric images are 0.3448 and 0.3048, respectively, thus the null hypothesis cannot be rejected at the 5% significance level, which indicates that the impact of eye dominance in the perception of depth quality of asymmetrically distorted stereoscopic images is not significant.

It is worthy noting that in [27] we found that the eye dominance effect does not have strong impact on the perceived image content quality of stereoscopic images. These two observations are consistent with the "stimulus" view of rivalry that is widely accepted in the field of visual neuroscience [41]. A comprehensive review and discussion on the question of "stimulus" rivalry versus "eye" rivalry can also be found in [41, 42].

4. CONCLUSIONS

We carried out two subjective studies on depth perception of stereoscopic 3D images. The first one follows a traditional framework where subjects are asked to rate depth quality directly on distorted stereopairs. The second one uses a novel approach, where the stimuli are synthesized independent of the background image content and the subjects are asked to identify depth changes and label the polarities of depth. Our analysis shows that the second approach is much more effective at singling out the contributions of stereo cues in depth perception, through which we have several interesting findings regarding distortion type dependency, image content dependency, and the impact of symmetric and asymmetric distortions on the perception of depth. These findings provide useful insights in the future development of comprehensive 3D QoE models for stereoscopic images, which have great potentials in real-world applications such as asymmetric compression of stereoscopic 3D videos.

5. REFERENCES

[1] J. Wang and Z. Wang, "Perceptual quality of asymmetrically distorted stereoscopic images: the role of image distortion types," in *Proc. Int. Workshop Video Process. Quality Metrics Consum. Electron.*, Chandler, AZ, USA, Jan. 2014, pp. 1–6.

[2] J. Wang, K. Zeng, and Z. Wang, "Quality prediction of asymmetrically distorted stereoscopic images from single views," in *Proc. IEEE Int. Conf. Multimedia and Expo*, Chengdu, Sichuan, China, July 2014, pp. 1–6.

[3] N. S. Holliman, B. Froner, and S. P. Liversedge, "An application driven comparison of depth perception on desktop 3D displays," in *Proc. SPIE. 6490, Stereoscopic displays and virtual reality systems XIV*, San Jose, CA, USA, Jan. 2007.

[4] P. Seuntiens, "Visual experience of 3D TV," *Doctor Doctoral Thesis, Faculty Technol. Manage., Eindhoven University of Technology*, 2006.

[5] R. G. Kaptein, A. Kuijsters, M. T. M. Lambooij, W. A. IJsselsteijn, and I. Heynderickx, "Performance evaluation of 3D-tv systems," in *Proc. SPIE 6808, Image Quality and System Performance V*, San Jose, CA, USA, Jan. 2008.

[6] W. J. Tam, L. B. Stelmach, and P. J. Corriveau, "Psychovisual aspects of viewing stereoscopic video sequences," in *Proc. SPIE 3295, Stereoscopic Displays and Virtual Reality Systems V*, San Jose, CA, USA, Jan. 1998, pp. 226–235.

[7] M. Zwicker, S. Yea, A. Vetro, C. Forlines, W. Matusik, and H. Pfister, "Display pre-filtering for multi-view video compression," in *Proc. Int. Conf. Multimedia*, Sept. 2007, pp. 1046–1053.

[8] M. Lambooij, W. IJsselsteijn, D. G. Bouwhuis, and I. Heynderickx, "Evaluation of stereoscopic images: beyond 2D quality," *IEEE Trans. Broadcasting*, vol. 57, no. 2, pp. 432–444, June 2011.

[9] S. L. P. Yasakethu, C. T. E. R. Hewage, W Fernando, and A Kondoz, "Quality analysis for 3D video using 2D video quality models," *IEEE Trans. Consumer Electronics*, vol. 54, no. 4, pp. 1969–1976, Nov. 2008.

[10] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli, "Image quality assessment: From error visibility to structural similarity," *IEEE Trans. on Image Process.*, vol. 13, no. 4, pp. 600–612, Apr. 2004.

[11] M. H. Pinson and S. Wolf, “A new standardized method for objectively measuring video quality,” *IEEE Trans. Broadcasting*, vol. 50, no. 3, pp. 312–322, Sept. 2004.

[12] A. Benoit, P. Le Callet, P. Campisi, and R. Cousseau, “Using disparity for quality assessment of stereoscopic images,” in *Proc. IEEE Int. Conf. Image Process.*, San Diego, CA, USA, Oct. 2008, pp. 389–392.

[13] A. Benoit, P. Le Callet, P. Campisi, and R. Cousseau, “Quality assessment of stereoscopic images,” *EURASIP journal on image and video processing*, Oct. 2008.

[14] M. Carnec, P. Le Callet, and D. Barba, “An image quality assessment method based on perception of structural information,” in *Proc. IEEE Int. Conf. Image Process.*, Barcelona, Spain, Sept. 2003, vol. 3, pp. 185–188.

[15] J. You, L. Xing, A. Perkis, and X. Wang, “Perceptual quality assessment for stereoscopic images based on 2D image quality metrics and disparity analysis,” in *Proc. Int. Workshop Video Process. Quality Metrics Consum. Electron*, Scottsdale, AZ, USA, Jan. 2010, pp. 61–66.

[16] Z. Wang, E. P. Simoncelli, and A. C. Bovik, “Multi-scale structural similarity for image quality assessment,” in *Proc. IEEE Asilomar Conf. on Signals, Systems, and Computers*, Pacific Grove, CA, USA, Nov. 2003, pp. 1398–1402.

[17] Z. Wang and A. C. Bovik, “A universal image quality index,” *IEEE Signal Processing Letters*, vol. 9, no. 3, pp. 81–84, Mar. 2002.

[18] H. R. Sheikh and A. C. Bovik, “Image information and visual quality,” *IEEE Trans. Image Processing*, vol. 15, no. 2, pp. 430–444, Feb. 2006.

[19] J. Yang, C. Hou, Y. Zhou, Z. Zhang, and J. Guo, “Objective quality assessment method of stereo images,” in *Proc. 3DTV Conf., True Vis.-Capture, Transmiss. Display 3D Video*, Potsdam, Gernamy, May 2009, pp. 1–4.

[20] Z. Zhu and Y. Wang, “Perceptual distortion metric for stereo video quality evaluation,” *WSEAS Trans. Signal Proc.*, vol. 5, no. 7, pp. 241–250, July 2009.

[21] A. K. Moorthy, C. Su, A. Mittal, and A.C. Bovik, “Subjective evaluation of stereoscopic image quality,” *Signal Processing: Image Communication*, vol. 28, no. 8, pp. 870–883, Sept. 2013.

[22] M. Chen, L. K. Cormack, and A.C. Bovik, “No-reference quality assessment of natural stereopairs,” *IEEE Trans. Image Processing*, vol. 22, no. 9, pp. 3379–3391, Sept. 2013.

[23] K. Wang, M. Barkowsky, K. Brunnström, M. Sjöström, R. Cousseau, and P. Le Callet, “Perceived 3D TV transmission quality assessment: multi-laboratory results using absolute category rating on quality of experience scale,” *IEEE Trans. Broadcasting*, vol. 58, no. 4, pp. 544–557, Dec. 2012.

[24] P. Seuntiens, L. Meesters, and W. Ijsselsteijn, “Perceived quality of compressed stereoscopic images: Effects of symmetric and asymmetric JPEG coding and camera separation,” *ACM Trans. on Applied Percep.*, vol. 3, no. 2, pp. 95–109, Apr. 2006.

[25] W. Chen, J. Fournier, M. Barkowsky, and P. Le Callet, “Exploration of quality of experience of stereoscopic images: Binocular depth,” in *Proc. Int. Workshop Video Process. Quality Metrics Consum. Electron*, Scottsdale, AZ, USA, Jan. 2012, pp. 116–121.

[26] M. Chen, D. Kwon, and A.C. Bovik, “Study of subject agreement on stereoscopic video quality,” in *IEEE Southwest Symp. Image Anal. & Interpretation*, Santa Fe, NM, USA, Apr. 2012, pp. 173–176.

[27] J. Wang, A. Rehman, K. Zeng, S. Wang, and Z. Wang, “Quality prediction of asymmetrically distorted stereoscopic 3D images,” *IEEE Trans. Image Processing*, vol. 24, no. 11, pp. 3400 – 3414, Nov. 2015.

[28] M. Mehrabi, E. M. Peek, B. C. Wuensche, and C. Lutteroth, “Making 3D work: a classification of visual depth cues, 3D display technologies and their applications,” in *Proc. 14th Australasian User Interface Conf.*, 2013, pp. 91–100.

[29] D. F. McAllister, *Stereo computer graphics and other true 3D technologies*, Princeton University Press, 1993.

[30] T. Okoshi, *Three-dimensional imaging techniques*, Elsevier, 2012.

[31] “The Vision Texture Database,” `http://vismod.media.mit.edu/vismod/imagery/VisionTexture/vistex.html`.

[32] C. M. Zaroff, M. Knutelska, and T. E. Frumkes, “Variation in stereoacuity: normative description, fixation disparity, and the roles of aging and gender,” *Investigative ophthalmology & visual science*, vol. 44, no. 2, pp. 891–900, 2003.

[33] C. M. Schor and I. Wood, “Disparity range for local stereopsis as a function of luminance spatial frequency,” *Vision Research*, vol. 23, no. 12, pp. 1649–1654, 1983.

[34] R. T. Goodwin and P. E. Romano, “Stereoacuity degradation by experimental and real monocular and binocular amblyopia.,” *Investigative Ophthalmology & Visual Science*, vol. 26, no. 7, pp. 917–923, 1985.

[35] R. F. Hess, C. H. Liu, and Y. Z. Wang, “Differential binocular input and local stereopsis,” *Vision Research*, vol. 43, no. 22, pp. 2303–2313, 2003.

[36] L. Stelmach, D. Tam, W. J.and Meegan, and A.é Vincent, “Stereo image quality: effects of mixed spatio-temporal resolution,” *IEEE Trans. Circuits and Systems for Video Tech.*, vol. 10, no. 2, pp. 188–193, Mar. 2000.

[37] H. Brust, A. Smolic, K. Mueller, G. Tech, and T. Wiegand, “Mixed resolution coding of stereoscopic video for mobile devices,” in *Proc. 3DTV Conf., True Vis.-Capture, Transmiss. Display 3D Video*, Potsdam, Germany, May 2009, pp. 1–4.

[38] P. Aflaki, M. M. Hannuksela, and M. Gabbouj, “Subjective quality assessment of asymmetric stereoscopic 3D video,” *Signal, Image and Video Process.*, vol. 9, no. 2, pp. 331–345, Mar. 2015.

[39] A. Z. Khan and J. D. Crawford, “Ocular dominance reverses as a function of horizontal gaze angle,” *Vision Research*, vol. 41, no. 14, pp. 1743–1748, June 2001.

[40] O. Rosenbach, “On monocular prevalence in binocular vision,” *Med Wochenschrift*, vol. 50, pp. 1290–1292, 1903.

[41] R. Blake, “A primer on binocular rivalry, including current controversies,” *Brain and Mind*, vol. 2, no. 1, pp. 5–38, Apr. 2001.

[42] A. P. Mapp, H. Ono, and R. Barbeito, “What does the dominant eye dominate? A brief and somewhat contentious review,” *Perception & Psychophysics*, vol. 65, no. 2, pp. 310–317, Feb. 2003.