

MCL-3D: A Database for Stereoscopic Image Quality Assessment using 2D-Image-Plus-Depth Source*

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A new stereoscopic image quality assessment database rendered using the 2D-image-plus-depth source, called MCL-3D, is described and the performance benchmarking of several known 2D and 3D image quality metrics using the MCL-3D database is presented in this work. Nine image-plus-depth sources are first selected, and a depth image-based rendering (DIBR) technique is used to render stereoscopic image pairs. Distortions applied to either the texture image or the depth image before stereoscopic image rendering include: Gaussian blur, additive white noise, down-sampling blur, JPEG and JPEG-2000 (JP2K) compression and transmission error. Furthermore, the distortion caused by imperfect rendering is also examined. The MCL-3D database contains 693 stereoscopic image pairs, where one third of them are of resolution 1024*768 and two thirds are of resolution 1920*1080. The pair-wise comparison was adopted in the subjective test for user friendliness, and the Mean Opinion Score (MOS) were computed accordingly. Finally, we evaluate the performance of several 2D and 3D image quality metrics applied to MCL-3D. All texture images, depth images, rendered image pairs in MCL-3D and their MOS values obtained in the subjective test are available to the public (<http://mcl.usc.edu/mcl-3d-database/>) for future research and development.

Keywords: stereoscopic images, 3D images, depth image based rendering, subjective quality, perceptual quality, image quality assessment, image quality database

1. INTRODUCTION

Stereoscopic multimedia contents become popular nowadays. Since the multi-view image format [1] is costly for visual communication, the 2D-image-plus-depth format [2] is proposed as an alternative, where a texture image and its associated depth image are recorded at a view point simultaneously. For stereoscopic display, the depth image-based rendering (DIBR) technique is applied to the texture and depth images to generate the proper left- and right-views. The 2D-image-plus-depth format has a few advantages, including bandwidth efficiency, interactivity and 2D/3D video content switch, *etc.* [3]. A 3D video coding standard, called MPEG-C part 3[4], has been developed using the Multi-View-plus-Depth (MVD) format. In this work, we address the visual quality assess-

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ment problem using the 2D-image-plus-depth source. With the DIBR technology, the stereoscopic images rendered and displayed on the stereoscopic screen rely on the quality of texture images, depth maps and the rendering technology. Since discomfort caused by watching stereoscopic images may go beyond annoying and lead to psychological dizziness, we cannot over-emphasize the importance of the stereoscopic image/video quality assessment problem.

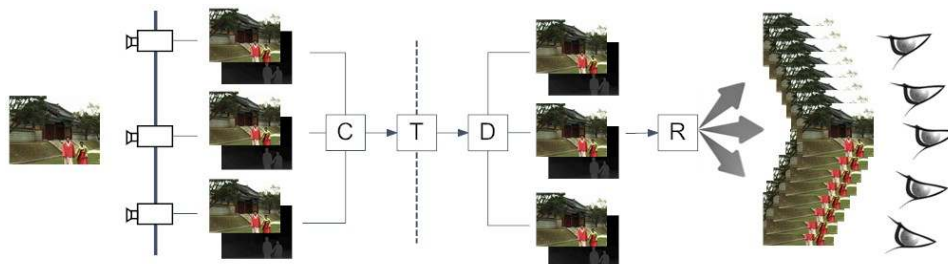


Fig 1. The processing flow of a stereoscopic visual communication system with the DIBR technology.

We show the processing flow of a stereoscopic visual communication system with the DIBR technology in Fig. 1. In this figure, ‘C’, ‘T’, ‘D’, and ‘R’ stand for ‘compression’, ‘transmission’, ‘decompression’ and ‘rendering’, respectively. At the encoder end, the texture and depth images captured at one viewpoint (or multiple viewpoints) are compressed and transmitted separately. At the decoder end, texture and depth maps are decoded and a pair of stereoscopic images can be rendered. Various distortion types can be introduced in each link of the communication system.

The perceived quality of rendered stereoscopic images is of great interest to 3D display system and algorithm designers. To take the video capturing system as an example, additive white noise and Gaussian blur often arise in the image capturing process. The captured visual data can be fed into the media processor for pre- and post-processing. For a system using the DIBR technology, the quality of the rendered stereoscopic images is highly dependent on whether additive noise exists in the texture image or in the depth image. Another example is the measurement of the distortion caused by compression. Currently, the block-based compression scheme and PSNR-based rate-distortion algorithms are still the mainstream for 3D content delivery. However, the blocking effect has a distinct impact on rendered stereoscopic images when it appears in the texture image or the depth map. Therefore, the objective quality metric has to be reevaluated and/or redesigned to allow a better match between human visual experience and the predicted quality score. A suitable database containing subjective test results as the ground truth is essential to the development of a better objective quality metric of rendered stereoscopic images.

In this work, we follow a similar process to build a stereoscopic image quality assessment database and consider a wide range of distortion types occurring in image capturing, compression, transmission and rendering. The resulting database is called the Media Communications Lab 3D (MCL-3D) Database.

Table 1. Summary of 3D image databases.

	<i>LIVE_I</i>	<i>LIVE_II</i>	<i>IVC_3D</i>	<i>IVC_DIBR_Image</i>	<i>EPFL</i>	<i>NB-SA</i>	<i>NB-SS</i>
Scenes	20	8	6	3	10	10	12
Image Resolution	640×360	640×360	512×448 ¹	1024×768	1920×1080	₋ ²	₋ ³
Distortion Types	Blur, Fast-fading, JP2K, JPEG, White noise	White Noise, Blur, JP2K, Fast-Fading	Blur, JPEG, JP2K,	Hole filling	Disparity	JP2K, JPEG, White noise, Gaussian Blur	Gaussian Blur, White Noise, JPEG, JP2K
Distortion Levels	₋ ⁴	₋ ⁵	₋ ⁶	₋ ⁷	10 ⁸	₋ ²	₋ ³
Total Num.	385	368	96	96	100	400	312

1. Image size is not identical in IVC 3D, 512×448 is the mean value provided in the corresponding paper.
2. Horizontal size for the images in NB-SA is not identical, and the levels for different distortion types is not described explicitly.
3. Image size varies from 430×270 to 1024×768 in NB-SS, and the levels for different distortion types is not described explicitly.
4. Different distortion types have different levels in LIVE Phase I.
5. LIVE Phase II has complex level definitions for asymmetrical distortion types.
6. Different distortion types have different levels in IVC 3D database.
7. IVC DIBR database has 7 different hole-filling algorithms, taken as 7 distortion levels.
8. 10 camera configurations, taken as 10 distortion levels.

There are several publicly accessible stereoscopic image databases developed for the quality assessment purpose as listed in Table 1. Only symmetric distortions (*i.e.*, the same distortion type and level) are applied to the left and right images in the LIVE Phase I database [5]. Non-symmetric distortions are considered in the LIVE Phase II database [6] as a generalization. The IVC 3D database [7] and the Ningbo stereoscopic image database with symmetric distortion (NB-SS) [8] are similar to LIVE Phase I yet with a different set of source images. One common concern with these three databases is that the resolution of stereoscopic images is low. Images of higher resolution are adopted by the IVC DIBR [9], EPFL databases [10] and the Ningbo stereoscopic image database with asymmetric distortion (NB-SA) [11]. One unique feature of the EPFL database is that it examines the effect of different disparity values on the resulting visual quality so as to develop a guideline on disparity selection. A similar yet more delicate work is given in [12], where the disparity effect on continuous video is analyzed so that some visual metrics can be fine-tuned for disparity selection in 3D films. The NB-SA database focuses on the visual experience when different distortion is only added on the right eye image. The IVC DIBR database examined the visual quality of rendered stereoscopic pairs with various rendering mechanisms. However, no transmission distortion is considered. Furthermore, distortions were imposed on binocular images directly, which has a more restricted application constraint.

In contrast, distortions are applied to either the texture image or the depth image before stereoscopic image rendering in MCL-3D. The distortion types of consideration include: Gaussian blur, additive white noise, down-sampling blur, JPEG and JPEG-2000 (JP2K) compression and transmission error. The artifact caused by imperfect rendering is also considered. The pair-wise comparison was adopted in the subjective test to be

friendly to viewers, and the Mean Opinion Score (MOS) was computed accordingly. All texture images, depth images, rendered image pairs and their MOS values obtained from the subjective test in MCL-3D are available to the public (<http://mcl.usc.edu/mcl-3d-database/>) for future research and development.

The rest of this paper is organized as follows. The source data, the DIBR rendering process and distortions adopted by the MCL-3D database are detailed in Section 2. The human subject test process is presented in Section 3. Then, we compare several existing 2D and 3D objective image quality assessment methods against the MCL-3D database in Section 4. Finally, concluding remarks and future work are given in Section 5.

2. DESCRIPTION OF MCL-3D DATABASE

2.1 Stereoscopic Image Pair Synthesis System

The stereoscopic image pair synthesis system used to create the MCL-3D database is shown in Fig. 2, where characters O , D and R denote the original input, distorted and rendered outputs, and subscript characters T , D and VL and VR denote the texture image, depth map, rendered left-view and right-view, respectively. First, the original texture image and its associated depth map of three views, denoted by (O_{T1}, O_{D1}) , (O_{T2}, O_{D2}) , and (O_{T3}, O_{D3}) , are obtained by selecting key frames from 3DVC test sequences [13] and used as the input. Distortions of different types and levels were introduced to either the texture image or the depth map, and distorted texture images or depth maps are used as the input to the view synthesis reference software (VSRS) [14] to render the distorted stereoscopic image pair. For the DIBR distortion, we take the original source O_{T2} and O_{D2} as the input, and use four different rendering algorithms to generate the stereoscopic image pair. The VSRS offers a near-perfect stereoscopic image synthesis mechanism. If the original left- and right-views are given, the VSRS can output a near perfect rendered view in between. The rendered left-view and right-view using the original texture images and depth maps, denoted by R_{VL} and R_{VR} , will be taken as the reference for further analysis.

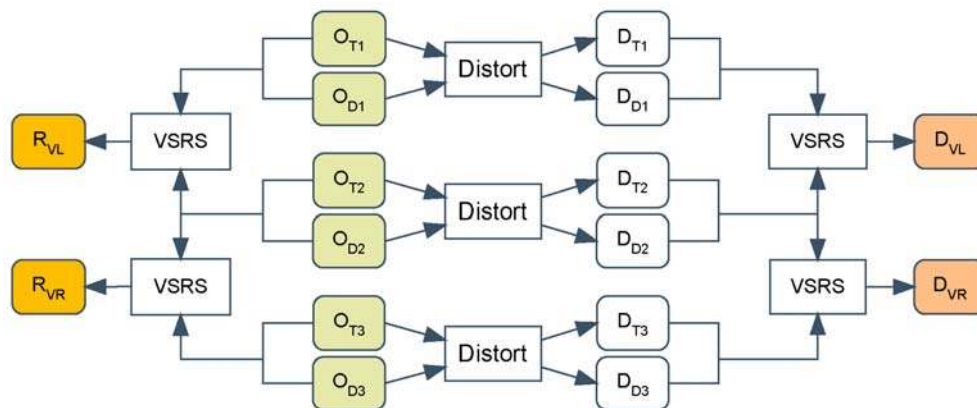


Fig 2. The block-diagram of the stereoscopic image pair synthesis system used to create the MCL-3D database.

2.2 Image and Depth Source

The quality of a database is highly dependent on reference images. The selected images should be representative and with sufficient diversity. In the MCL-3D database, we focus on the quality assessment of images rendered by DIBR technology. The test sequences used in the 3DVC standard can be good candidates, which provide a few multi-view sequences associated with depth maps. All of these sequences were produced with professional equipment by the producer, and rectified before submission to the Joint Collaborative Team (JCT) [13, 15]. The quality of the test sequences were approved by JCT group members. We selected nine of them as the reference images in the MCL-3D database. The images were shown in Fig. 3, and the corresponding description and computed indicators were listed in Table 2. All the nine sequences were provided as uncompressed raw format. The bit depth for both texture images and depth maps are 8 bit. We extracted one frame from each sequence at the time slot with very slow motion while having a perceptible depth of field. The frame numbers along with other description used in MCL-3D were also listed in Table 2.

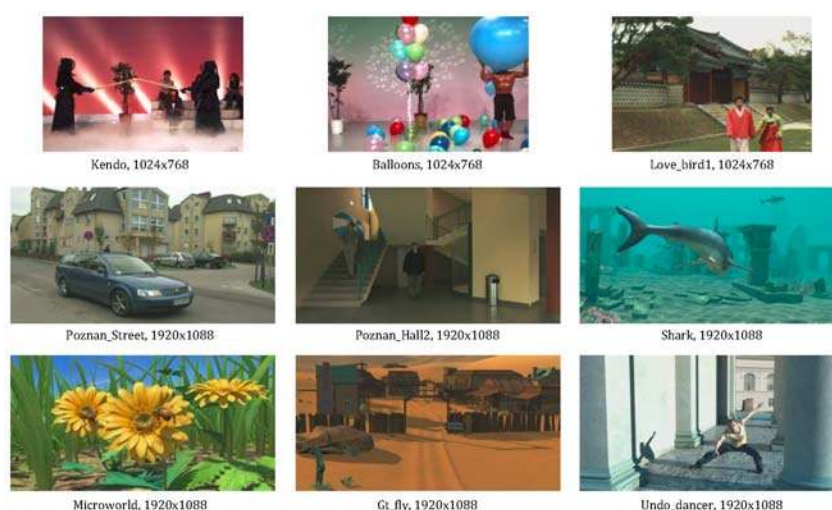


Fig. 3. Reference images in the MCL-3D database.

Among the nine selected images, ‘Kendo’ and ‘Balloon’ are from the Tanimoto Laboratory of Nagoya University, ‘Love_bird1’ is from the Electronics and Telecommunications Research Institute (ETRI), ‘Poznan_street’ and ‘Poznan_hall2’ are from the Poznan University of Technology, ‘Microworld’ and ‘Shark’ are from the National Institute of Information and Communications Technology, and ‘Gt_fly’ and ‘Undo_dancer’ are from the Nokia Corporation. The spatial resolution of the first three images is 1024*768 while that of the last six images is 1920*1088. The Spatial Information (SI) for each texture image, as defined by ITU-T recommendation P.910 [16]¹, is calculated to demonstrate the variety of selected contents. The SI is also calculated for the depth map, called the depth spatial indicator (DSI) [17], to capture the characteristics of depth variation in the spatial domain.

¹ The ‘max{f}’ was not applied, since we only evaluate single frame.

Table 2. Description and computed indicators of images used in MCL-3D database.

	Owner & provider	Spatial Resolution	Camera space	Views	Frame No.	Source Compression	SI	DSI
<i>Kendo</i>	Nagoya ¹	1024×768	5cm	1,3,5	3	No	45	25
<i>Balloon</i>	Nagoya ¹	1024×768	5cm	1,3,5	3	No	43	32
<i>Love_bird1</i>	ETRI ²	1024×768	3.5cm	4,6,8	3	No	57	8
<i>Poznan_street</i>	PUT ³	1920×1088	13.75cm	5,4,3	239	No	58	23
<i>Poznan_hall2</i>	PUT ³	1920×1088	13.75cm	7,6,5	118	No	21	9
<i>Shark</i>	NICT ⁴	1920×1088	CG ²	1,5,9	242	No	42	36
<i>Microworld</i>	NICT ⁴	1920×1088	CG	1,5,9	242	No	62	50
<i>Gt_fly</i>	Nokia ⁵	1920×1088	CG	9,5,1	122	No	48	33
<i>Undo_dancer</i>	Nokia ⁵	1920×1088	CG	1,5,9	110	No	57	22

1. Nagoya University – Tanimoto Laboratory, Japan.

2. Electronics and Telecommunications Research Institute, Republic of Korea.

3. Poznan University of Technology, Poznań, Poland.

4. National Institute of Information and Communications Technology, Japan.

5. Nokia Corporation, Finland.

2.3 Distortion Types and Levels

In a communication system that adopts the 3DVC coding standard, distortions may come from various stages such as image acquisition, compression, transmission and rendering. Gaussian blur and additive noise may occur in the acquisition stage. The image and the depth map may be down-sampled to accommodate multiple display devices before compression. For efficient transmission, all images should be compressed, which leads to blockiness and compression blur. Transmission errors may occur in the transmission stage. A rendering algorithm will be adopted to render multiple views for display. Some of these distortions were investigated before as shown in Table 1. We include distortions of all above-mentioned cases in the MCL-3D database.

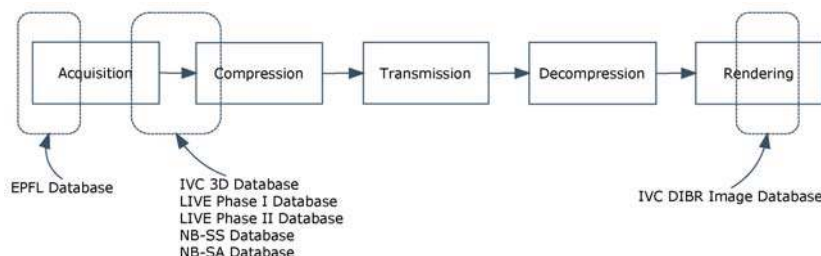


Fig. 4. The entire processing flow and the corresponding distorted part for each database.

Based on the recommendations of ITU [16, 18, 19] and VQEG [20, 21], we consider five quality levels in subjective tests. The original reference stereoscopic images have the ‘excellent’ quality while the other 4-level distorted images were controlled by parameters corresponding to different distortion types. The distortion caused by imperfect rendering has not been well studied before. Typically, only the mid-view image and

² CG is short for Computer Graphics.

its depth map are taken as the input, and a stereoscopic image pair is rendered using a hole filling technique. In our experiment, we take O_{T2} and O_{D2} as the input to generate the stereoscopic image pair. Distortion types are summarized in Table 3 and explained below.

Gaussian Blur

Many parameters have to be calibrated [10] during the acquisition of high quality stereoscopic images, wherein the focal length is a critical one. Texture images from any view will be blurred due to an improper focal length. Depth maps could be either acquired by equipment [22, 23] or estimated by depth estimation algorithms [24]. It was claimed by some researchers [2, 9] that the visual experience can be improved by applying some blur to the depth map before rendering. Its effectiveness can be studied using MCL-3D. We used ‘GaussianBlur()’ function in the OpenCV [25] library to add the Gaussian blur effect and controlled distortion levels by varying the standard deviation parameter of the kernel. Their values were set to 11, 21, 31 and 41 for four distortion levels.

Additive White Noise

In digital image capturing systems, CMOS or CCD sensors are used to capture R/G/B color light intensities. The intensity is later transformed to the voltage and quantized to digital pixel values. Interference is ubiquitous in electronic circuits. It appears in form of additive white noise in the texture or depth image. The ‘randn()’ function in the OpenCV library was used to generate additive noise whose levels were controlled by selecting four standard deviation values (5, 17, 33 and 53).

Down-sampling Blur

To be adaptive to varying transmission bandwidth conditions, scalable video coding schemes have been proposed by researchers [26-28]. In these proposed schemes, the captured texture image or depth map will be down-sampled before compression. Another scenario is that the captured image may be down-sampled to fit a different spatial resolution requirement. We would like to acquire the ground-truth of such cases. The ‘resize()’ function in OpenCV is used for down-sampling and up-sampling. Four different down-sampling blur levels with a sampling ratio of 5, 8, 11 and 14 were included.

JPEG and JP2K Compression

Compression is always applied to images and video to remove redundancy. The appearance caused by commonly used compression techniques is blockiness and loss of high frequency component. We applied JPEG and JP2K compression to source images as representative of such kind of distortion. For JPEG compression, we utilized the ‘imencode()’ function in OpenCV with four quality levels (30, 12, 8 and 5). For JP2K compression, we utilized the Kakadu [29] package with four compression parameters (200, 500, 900 and 1500) for four distortion levels.

Transmission Error

Transmission errors like packet loss or bit error is unavoidable over unreliable channels such as those in wireless networks. The error pattern is quite different from

other regular distortion types. The transmission error distortion is added to evaluate the quality degradation under this scenario. We used the OpenJPEG library to encode source images and then applied unequal protection and error correction codes in the JPWL mode. Some bit errors were added to the compressed bit-streams. At the decoder side, the errors were partly corrected. With the assistance of protection methods, it is difficult to build a simple relationship between the bit-error rate and the visual quality of the decoded image. Thus, we used 80 seeds to generate a group of error-corrupted images and selected 4 from them to obtain 4 transmission error levels.

Rendering Distortion

Stereoscopic images were rendered based on the texture and the depth map images using the DIBR technology. Typical rendering errors include the black hole [30] and the boundary blur, which tend to appear with imperfect rendering techniques [9]. We selected several representative ones, including DIBR without hole filling [3], DIBR with filtering [2], DIBR with in-painting [31], and DIBR with hierarchical hole filling [3, 32, 33].

Table 3. Distortion generation mechanism and the associated level parameters.

<i>Distortion type</i>	<i>Method</i>	<i>Level parameters</i>
Gaussian blur	'GaussianBlur()' in OpenCV	Standard deviation of the function kernel, 11, 21, 32 and 41 for 4 levels
Additive white noise	'randn()' in OpenCV	Standard deviation parameter, 5,17,33 and 53 for 4 levels
Down-sampling blur	'resize()' in OpenCV	Sampling ratio, 5, 8, 11 and 14 for 4 levels
JPEG compression	'imencode()' in OpenCV	Quality level parameter, 30, 12, 8, and 5 for 4 levels
JPEG2000 compression	Kakadu package	Compression parameter, 200, 500, 900 and 1500 for 4 levels
Transmission error	OpenJPEG lib with JPWL mode	Different levels set by visual check
Rendering distortion	Different hole filling algorithms	4 algorithms corresponding to 4 cases

3. SUBJECTIVE TEST

For the subjective test, the test environment was set up according to the ITU recommendations [16] and a pairwise comparison method was adopted. Testing results were verified after the subjective test procedure.

ITU and VQEG are two organizations working on the standardization of subjective test methods. Both of them have published recommendations on subjective test procedure for 2D images [19], 2D videos [16] and stereoscopic images [18, 34]. They can be roughly classified into four groups according to score levels and stimulus numbers as shown in Table 4.

It was mentioned in [35, 36] that the continuous scale score does not improve the precision of test results. For the ACR and ACR-HR method, the same score may have a different meaning for a different assessor. Even for the same assessor, the rating criteria may vary along test time. Besides, it is difficult for assessors to differentiate weak impairments without explicit comparison. For this reason, we focus on methods with double stimulus and discrete scores.

Table 4. Recommendations for subjective test methods.

	<i>Discrete Score</i>	<i>Continuous Score</i>
<i>Single Stimulus</i>	ACR ¹ , ACR-HR ²	SSCQE ³
<i>Double Stimulus</i>	DCR ⁴ , DSIS ⁵ , CCR ⁶ , DSCS ⁷ , PC ⁸	DSCQS ⁹

1. ACR: Absolute Category Rating.
2. ACR-HR: Absolute Category Rating with Hidden Reference.
3. SSCQE: Single stimulus continuous quality evaluation.
4. DCR: Degradation category rating.
5. DSIS: Double Stimulus Impairment Scale.
6. CCR: Comparison Category Rating.
7. DSCS: Double Stimulus Comparison Scale.
8. PC: Pair Comparison.
9. DSCQS: Double Stimulus Continuous Quality Scale.

Double stimulus methods give assessors two items which lead to an easier decision procedure. However, the 5 or 7 choices still confuse the assessor to some extent. It is somehow difficult to tell the relative quality is ‘about the same’, ‘slightly better’ or ‘better’. The pair comparison methods, which were introduced in [34], largely simplified the decision procedure. Its superiority to other method has been demonstrated in several experiments [9, 37-40].

Based on the above considerations, we adopted the pairwise comparison method in the MCL-3D database. The pairwise comparison method has solid mathematical foundation [41-43] and is extensively used for resource ranking and recommendation systems. Generally speaking, two stereoscopic image pairs are viewed by an assessor simultaneously and, then, the assessor selects the preferred one so as to assign a point score.

The point score of a stereo image pair will accumulate across multiple rounds of pairwise competition, and the final point score is properly normalized to yield the final opinion score for the same assessor. The opinion scores of multiple assessors are averaged to result in the final mean opinion score (MOS) for each stereoscopic image pair.

The subjective test environment is described below. The display equipment was 46.9" LG 47LW5600. Assessors were seated 3.2 meters [18] away from the display screen and equipped with polarized glasses. The images were resized by the cubic function to fit the screen size before display, and the gap between two images was padded with grey levels as specified in [18]. During the comparison, both image pairs were resized simultaneously, and the relative quality difference was kept. With the pair comparison method, an assessor can point out slight difference between two items. The distortion levels were designed to make the quality gap large enough so that the resizing will not affect the pair comparison result.

For each assessor, all 77 image pairs in one set were tested in one session. We developed a program with a proper GUI interface to control the quality assessment process for each assessor. The Swiss competition rule was applied for pair selection [9]. We set up 9 tours where stereoscopic image pairs with the same point score were compared in the same tour. The winning pair received one point while the losing pair received no point. Consequently, the cumulative point scores of all image pairs range from 0 to 9 after 9 tours. Before the subjective test, as a regular procedure, the assessors were tested to have normal ocular visual acuity and color vision, and stereopsis and binocular acuity tests according to [18] Annex 1 were also conducted. All the assessors passed these tests.

For each assessor, the actual test time ranged from 12 to 15 minutes, which complies with the recommendation in ITU-R Rec. BT.500 [19]. After the subjective test, we conducted a short interview with the assessor for their evaluation experience. The assessors were students from the University of Southern California in USA. Among the 270 assessors, there were 170 males (63%) and 100 females (37%). In order to investigate the score difference between experts and non-experts, we asked assessors about their familiarity on stereoscopic images. Among them, 34 (or 13%) were experts and 236 (or 87%) were non-experts. The age distribution of the assessors is given in Fig. 5.

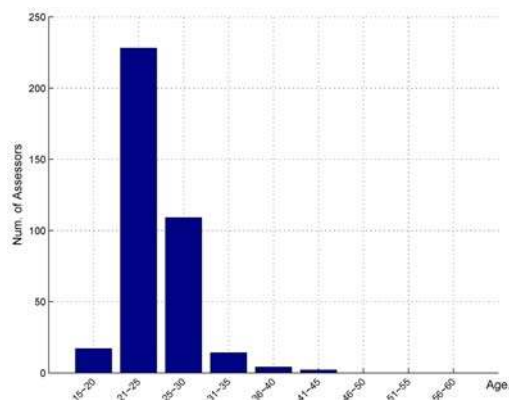


Fig. 5. The age distribution of assessors.

We collected 30 opinion scores for each distorted image pair. The subjective test results were further filtered by a screening process [19]. Since the standardization of the screening process for pair comparison results has not been published, and the existing screening method only fits for a specified subjective test method, we checked the test results following the existing specifications as much as possible. In building the MCL-3D database, the highest 10% and the lowest 10% scores for each image were treated as outliers and discarded. The final MOS was calculated as the mean of remaining 24 opinion scores. The recommended number of assessors is 15 by ITU [19] and 24 by VQEG [9] for images. Bosc [9] tested the number of assessors for the subjective test for synthesized 3D view and concluded that the minimum number is 32 for ACR and less than 24 for pairwise comparison. Thus, our MOS calculation does meet the requirements of all above recommendations.

The final MOS for each stereoscopic image pair in the MCL-3D database is shown in Fig. 6. The averaged MOS with respect to a specific distortion type is shown in Fig. 7, where 1 to 24 are with the distortion only on the texture part, 25 to 48 are with the distortion only on the depth part, 49 to 72 are with the distortion on both parts, and 73 to 76 are results obtained by four different rendering algorithms. The distortion types are arranged from the lowest degree to the highest degree according to the following order: 1) additive noise, 2) Gaussian blur, 3) JP2K compression, 4) JPEG compression, 5) down-sampling blur, and 6) transmission loss. In other words, No. 1-4 are with additive noise from the lowest degree to the highest degree. No. 5-8 are with Gaussian blur from the lowest degree to the highest degree, and so on.

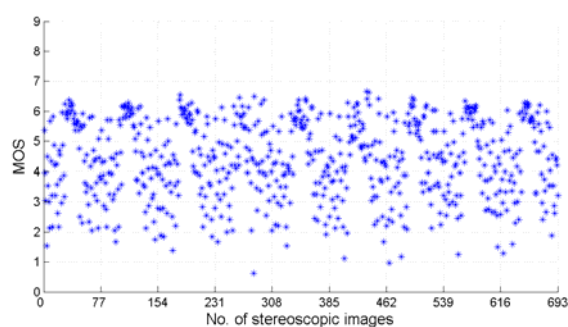


Fig. 6. MOS for MCL-3D stereoscopic image pairs.

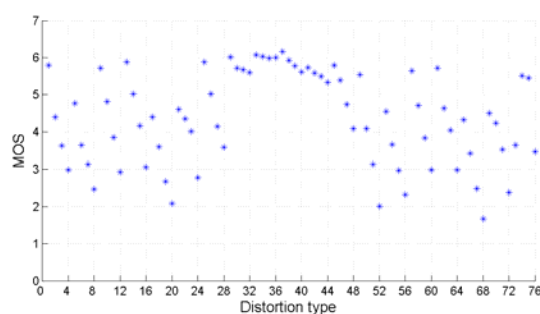


Fig. 7. Averaged MOS for different distortion types.

It is observed that, when the distortion is on the depth part, the blur-like distortions such as the Gaussian blur, JP2K, JPEG and down-sampling blur (Image #29-44) do not harm image quality much. In contrast, additive white noise (Image # 25-28) and transmission loss (Image #45-48) on the depth image is more critical. They damage the whole rendered image through the DIBR process. When the same distortion level is applied to the texture part and the depth part, the distorted texture image is more obvious to human eyes so that its MOS is lower.

A summary of the MCL-3D database is given in Table 5.

Table 5. Summary of MCL-3D database.

<i>Main Characters</i>	<i>MCL 3D database</i>
<i>Scenes</i>	9
<i>Image resolution</i>	6 with 1920×1080 3 with 1024×768
<i>Distortion types</i>	Gaussian blur, Down-sampling blur, Additive white noise, JPEG compression, JP2K compression, Transmission error, Rendering algorithm
<i>Distortion levels</i>	4
<i>Total num. of image pairs</i>	693
<i>Subjective test method</i>	pair comparison
<i>No. of assessors</i>	270
<i>Scale of MOS</i>	0..9

4. PERFORMANCE COMPARISON OF OBJECTIVE QUALITY INDICES

In this section, we compare the performance of several objective quality indices against the MCL-3D database.

4.1 Performance of 2D IQA Indices

There are quite a few 2D image quality assessment methods proposed in literature [44]. Traditionally, image distortion indices focus on fidelity by measuring the exact difference between the distorted and the reference images; *e.g.* the mean-squared error (MSE), the Peak Signal to Noise Ratio (PSNR), *etc.* The fidelity concept has been scrutinized and challenged by researchers recently. New image quality indices were proposed. Examples include the Noise Quality Measure (NQM) [45], the Universal Quality Index (UQI) [46], the Structural Similarity Index (SSIM) [47], the Multi-scale Similarity Index (MS-SSIM) [48], the Feature Similarity Index [49], the visual information fidelity (VIF) [50], the pixel-based VIF (VIFP) [50], the visual signal-to-noise ratio (VSNR) [51], the image fidelity criterion (IFC) [52], PSNR-HVS [53] and C4 [54].

We applied these quality indices to the left- and the right-views of the stereoscopic image pairs and obtained their mean as the quality score. We conducted this test on the MCL-3D database as well as two other stereoscopic image databases; namely, LIVE Phase I [49] and IVC 3D [7]. The Pearson Correlation Coefficient (PCC) and the Spearman rank order correlation coefficient (SROCC) between the MOS and the objective scores are shown in Table 6. We see that both the PCC and SROCC values of these indices are less than 90% against MCL-3D. There is certainly room for further improvement for the algorithms.

Table 6. Performance comparison of 2D objective quality indices applied to MCL-3D, LIVE Phase I and IVC databases.

<i>Metric</i>	<i>MCL-3D</i>		<i>LIVE Phase I</i>		<i>IVC</i>	
	<i>PCC</i>	<i>SROCC</i>	<i>PCC</i>	<i>SROCC</i>	<i>PCC</i>	<i>SROCC</i>
<i>C4</i>	0.8683	0.8690	0.9078	0.9144	0.7874	0.7304
<i>IFC</i>	0.7395	0.7398	0.5466	0.9071	0.7051	0.6135
<i>MS_SSIM</i>	0.8656	0.8763	0.7382	0.6093	0.7676	0.6919
<i>NQM</i>	0.8684	0.8694	0.8349	0.8461	0.6816	0.5973
<i>PSNR_HVS</i>	0.8783	0.8857	0.7563	0.8042	0.7089	0.6374
<i>PSNR</i>	0.8320	0.8405	0.6482	0.6529	0.5843	0.5554
<i>SSIM</i>	0.7654	0.7834	0.6977	0.6616	0.6817	0.6478
<i>UQI</i>	0.7372	0.7551	0.9007	0.8974	0.5706	0.5244
<i>VIFP</i>	0.7770	0.7897	0.8266	0.8681	0.7355	0.6869
<i>VIF</i>	0.7762	0.7929	0.8883	0.9002	0.7971	0.7083
<i>VSNR</i>	0.8289	0.8370	0.7317	0.7847	0.6723	0.6110

4.2 Performance of 3D IQA Indices

Several IQA indices have been developed to target at stereoscopic image pairs. Campisi [55] conducted a preliminary test on the acuity difference between different eyes and found no apparent difference. Ryu [56] proposed an extended version of the SSIM index based on a binocular model. Their index uses a fixed set of parameters and is not adaptive to asymmetric distortions. Ko [57] introduced the structural distortion parameter (SDP), which varies according to different distortion types. The SDP was employed as a control parameter in a binocular perception model to provide robust QA results for both symmetric and asymmetric distortions. Gorley [58] used the difference of relative contrast between the reference image pair and distorted image pair to derive the quality index. Benoit[7] extracted the disparity maps from both the reference and the distorted image pairs, calculated the distortion between them, and integrated it with other factors to form the final quality index. Sazzad [59] exploited the disparity map and performed several integration methods to derive the quality index.

We evaluated four indices against the MCL-3D, the LIVE Phase I, and the IVC databases, *i.e.*, Method A [56], Method B [7], Method C [55], Method D [57]. The PCC and SROCC results are shown in Table 7. We see that these 3D IQA indices do not show much superiority over 2D IQA indices. How to derive a better 3D IQA index is still a challenging problem.

Table 7. Benchmarks of 3D quality assessment metrics.

<i>Metric</i>	<i>MCL-3D</i>		<i>LIVE Phase I</i>		<i>IVC</i>	
	<i>PCC</i>	<i>SROCC</i>	<i>PCC</i>	<i>SROCC</i>	<i>PCC</i>	<i>SROCC</i>
Method A	0.8419	0.8503	0.6775	0.6075	0.7579	0.6869
Method B	0.7545	0.7672	0.8174	0.8493	0.2851	0.4916
Method C	0.8683	0.8690	0.9067	0.9133	0.7873	0.7295
Method D	0.8910	0.8880	0.9080	0.9050	0.8410	0.8030

5. CONCLUSION AND FUTURE WORK

3D technology is on its way to become a norm, and consumers have a strong demand on high quality 3D contents. The process of 3D content making demands strenuous efforts. One of the key problems is the assurance of perceptual quality. Multi-view video plus depth is regarded as the core technology for the next generation 3D broadcasting system. Nevertheless, the quality metric issues have not been well addressed for this technology. The appearance of rendered stereoscopic images is quite different from that of 2D images. New metrics have to be developed to solve this problem. However, there was no prior image database designed for the DIBR technology.

In this work, a detailed description of a stereoscopic image quality assessment database called MCL-3D was given, and the performance benchmarking of several known 2D and 3D image quality metrics using the MCL-3D database were presented. Distortions applied to the texture image or the depth image before stereoscopic image rendering included Gaussian blur, additive white noise, down-sampling blur, JPEG and JPEG-

2000 (JP2K) compression and transmission error. Subjective tests conforming ITU recommendations were conducted, and the paired comparison method was used to obtain reliable mean opinion scores. Furthermore, we evaluated the performance of several 2D and 3D image quality metrics applied to MCL-3D. The MCL-3D database is available to the public for future research and development. It can be used for in-depth study on 3D perception of the human visual system as well as the design and performance evaluation of 3D content delivery systems.

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