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A Psychophysical Evaluation of Texture Compression Masking Effects

Guillaume Lavoué, *Senior Member, IEEE*, Michael Langer, Adrien Peytavie and Pierre Poulin.

Abstract—Lossy texture compression is increasingly used to reduce GPU memory and bandwidth consumption. However, as raised by recent studies, evaluating the quality of compressed textures is a difficult problem. Indeed using Peak Signal-to-Noise Ratio (PSNR) on texture images, like done in most applications, may not be a correct way to proceed. In particular, there is evidence that masking effects apply when the texture image is mapped on a surface and combined with other textures (e.g., affecting geometry or normal). These masking effects have to be taken into account when compressing a set of texture maps, in order to have a real understanding of the visual impact of the compression artifacts on the rendered images. In this work, we present the first psychophysical experiment investigating the perceptual impact of texture compression on rendered images. We explore the influence of compression bit rate, light direction, and diffuse and normal map content on the visual impact of artifacts. The collected data reveal huge masking effects from normal map to diffuse map artifacts and vice versa, and reveal the weakness of PSNR applied on individual textures for evaluating compression quality. The results allow us to also analyze the performance and failures of image quality metrics for predicting the visibility of these artifacts. We finally provide some recommendations for evaluating the quality of texture compression and show a practical application to approximating the distortion measured on a rendered 3D shape.

Index Terms—Texture compression, psychophysical experiment, image quality assessment, diffuse map, normal map.



1 INTRODUCTION

THREE dimensional graphical objects are now commonplace in many fields of industry, including digital entertainment, computational engineering, and cultural heritage. They commonly consist of geometric surfaces on which one or more textures are mapped to make their rendering more realistic. Multiple texture maps are usually considered (e.g., affecting surface geometry or normal, or reflectance terms such as diffuse, gloss, specular) to reproduce accurately physical characteristics of surface materials (e.g., albedo, microsurface, reflectivity), and thus to generate highly realistic scenes.

These textures are mostly stored in some form of images and, in most cases, subjected to lossy compression. This compression may occur either to fasten streaming and remote visualization of the 3D scene (in that case, variable-bit-rate methods may be used such as JPEG or JPEG2000 [1]) or to reduce storage on the graphics processing unit (GPU) (using GPU-friendly random-access methods such as [2], [3], [4]). As raised by Olano et al. [5], texture compression will always be necessary in interactive applications such as games, since it allows for more texture data to reside on the GPU. That way, compression decreases data transfers to GPU, and it thus reduces latency and/or allows for more detailed textures to be used. Lossy compression introduces artifacts that may impact the visual quality of the rendered 3D scene. Consequently, compression has to be carefully driven and evaluated by accurate metrics. The most common approach in evaluating texture compression is to

use simple metrics (e.g., PSNR) or visual image inspection on individual textures. However, as raised by Griffin and Olano [6], inspecting individual textures is incorrect for two reasons: (1) Texture images are not visualized directly but are mapped onto 3D shapes that are then shaded and rendered according to certain viewpoints and lighting configurations. Therefore, the perception of compression artifacts on a texture image may be very different than their perception on a rendered 3D scene (i.e., after shading, viewpoint selection, and rasterization). (2) One particular shape may often be rendered using several texture maps (e.g., diffuse and normal), even of different resolutions, that interact during rendering and may thus mutually mask their artifacts.

Griffin and Olano [6] have studied the two effects mentioned above (they refer to (1) as *geometric masking* and to (2) as *texture-set masking*). Their results tend to show that they significantly mask compression artifacts and that compression algorithms may be too conservative. However, these results are not based on a psychophysical quality study, but on outcomes from objective metrics (CIELAB $\delta E94$ and SSIM [7]) taken as perceptual oracles of perceived visual quality. As shown by recent studies [8], [9], [10], such image quality metrics may be very poor at evaluating artifacts on rendered 3D surfaces.

The goal of this work is similar to the one of Griffin and Olano [6], i.e., investigating the effect of *geometric* and *texture-set masking* on the perception of texture compression artifacts. However, in addition to using objective metrics, we conducted two psychophysical experiments (Sec. 3). Our statistical analysis (Sec. 4) quantitatively demonstrates the impact of these masking effects on artifact detection thresholds, as well as the influence of light direction and texture content. We also used the psychophysical data

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to evaluate the performance of image quality metrics for predicting the visibility of these artifacts (Sec. 5) and make some recommendations for optimizing the quality of texture compression (Sec. 6). We finally demonstrate the practical use of these recommendations in a realistic application (Sec. 7).

2 RELATED WORK

We are interested in evaluating the quality of rendered scenes, subjected to compression of their texture maps applied on surfaces. We review here, briefly, the existing work in visual quality assessment for 3D scenes; for a more complete recent survey of this field we refer the reader to [11].

Near-threshold Image Metrics. For 2D natural images, research into objective quality assessment metrics is substantially developed [12]. Bottom-up techniques try to mimic the low-level mechanisms of the human visual system (HVS) such as the contrast sensitivity function (CSF), usually modeled by a band-pass filter, and the visual masking effects that define the fact that one visual pattern can hide the visibility of another. They include the Sarnoff Visual Discrimination Model (VDM) [13], the Visible Difference Predictor (VDP) [14], and the more recent HDR-VDP-2 [15], suited for any range of luminance. These bottom-up approaches usually focus on near-threshold visual models and produce maps of just-noticeable differences. They have been extensively used in computer graphics for perceptually-based rendering, e.g., to reduce and/or optimize the number of samples of global illumination algorithms [16], [17], [18], and for simplification and Level of Detail (LoD) selection [19], [20], [21], [22].

Supra-threshold Image Metrics. The near-threshold models described above are usually not suited to characterize supra-threshold perceptual distortions. In contrast, some authors propose top-down metrics that do not take into account any HVS model, but instead that operate based on some intuitive hypotheses of what HVS attempts to achieve when shown a distorted image. The most well-known example is the Structural SIMilarity index (SSIM) [7]. A large number of top-down image quality metrics have been proposed since then [23], [24], [25], the most recent being data-driven, i.e., the metrics are learned based on user studies [26], [27], [28]. Several authors use these top-down metrics for visual quality evaluation in computer graphics. Zhu et al. [29] study the relationship between viewing distance and perceptibility of model details using SSIM [7], while Griffin and Olano [6] use this metric to evaluate the visual impact of texture map compression. SSIM is also used by Brady et al. [30] and Havran et al. [31] to evaluate quality of Bidirectional Reflectance Distribution Functions (BRDFs), using rendered images.

Metrics Dedicated to Rendering Artifacts. Most of the quality metrics presented above have been designed and evaluated on *natural* images with mostly compression/transmission related artifacts (e.g., Gaussian noise, JPEG artifacts). A recent study [8] has shown that

they are not suited for evaluating artifacts introduced by rendering in synthetic images, e.g., aliasing or noise from global illumination approximations. Several authors have recently introduced quality metrics specifically dedicated to this kind of rendering artifacts [32], [33], [34].

Metrics for 3D Mesh. While the metrics above operate in image space, several authors have proposed metrics that operate directly in the space of 3D meshes. They mostly rely on geometry characteristics, such as curvature [35], dihedral angles [36], or roughness [37]. Some of them combine geometry difference with a difference in diffuse texture maps [10], [38].

Metrics for BTF. Filip et al. [39] and Guthe et al. [40] introduce quality metrics for Bidirectional Texture Functions (BTFs), with the goal of driving their compression. Jarabo et al. [41] evaluate the impact of approximate filtering on the appearance of BTFs, with respect to their characteristics (e.g., structure, roughness, contrast). While the purpose of this latter study is different from ours, it has been inspiring to us since we also want to evaluate the impact of different characteristics (texture content, compression strength, lighting) on the detection of artifacts.

The objective of our experiment is to study the impact on rendered images of artifacts coming from texture compression (diffuse and normal). Collected data will allow us to assess if image quality metrics presented above are able to correctly evaluate the perceptual impact of such artifacts.

3 PSYCHOPHYSICAL EXPERIMENTS

We conduct two psychophysical studies to explore masking effects caused by the normal map on the perception of the diffuse map compression artifacts and vice versa. Here we describe the dataset and protocol in more details.

3.1 Stimuli

3.1.1 Texture Maps

We selected four pairs of diffuse/normal texture maps and a *flat* stimulus, all illustrated in Figure 1. They represent typical materials used by designers and exhibit a variety of characteristics, and thus of potential masking effects. The diffuse maps come from photographs of real surfaces, and normal maps have been created from the diffuse maps (a standard process in texture design). Their characteristics are detailed in Table 1 in the form of high-level properties inspired from previous work on texture [42] and BTF [41] classifications.

TABLE 1
 Characteristics of our five texture pairs.

	Texture content	Normal amplitudes
Flat	Uniform	Zero
Stones	Random (non-uniform), sharp sparse edges	Low
Water	Random (non-uniform), Low Frequency	Low
Hedge	Random (uniform), Medium frequency	High
Fabric	Structured (uniform), High frequency	High

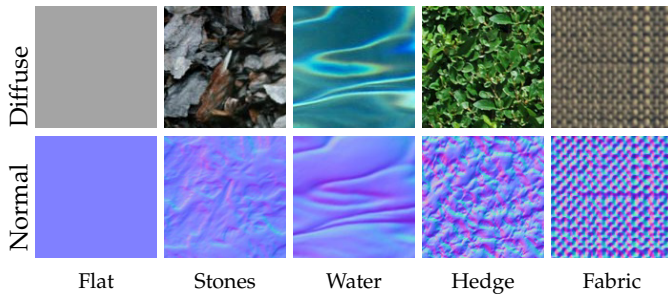


Fig. 1. Our five reference diffuse (top) and normal (bottom) texture maps.

Following Griffin and Olano [6], we have considered texture maps corresponding to a traditional real-time shading workflow, as opposed to a Physically-based Rendering (PBR) workflow. In traditional real-time shading, the diffuse texture maps contain not only the albedo but also contain pre-rendered photometric effects to ensure the rendered surface has visible features whatever lighting conditions. Examples are global illumination effects such as ambient occlusion which occur in Hedge, and specular reflections and refraction which occur in Water.

Figure 2 illustrates the rendering of our texture pairs (individual and combined together), mapped on a plane and lit using directional lighting. As can be observed in this figure, diffuse and normal maps are strongly correlated. However, this does not impact the generality of our study since in our psychophysical experiments every diffuse map is combined with every normal map.

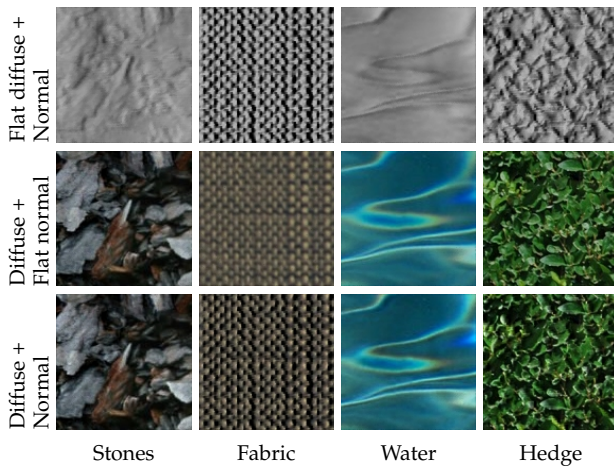


Fig. 2. Rendered texture maps (normal only, diffuse only, and both), on a textured Lambertian 3D square lit from the left.

We specifically selected small texture patches (128×128) to restrict where the user is looking, and to prevent long spatial exploration that could potentially occur with larger stimuli.

3.1.2 Compression

These texture maps have then been compressed by the ASTC algorithm [3]. ASTC is a lossy block-based compression algorithm that represents the state of the art in terms of performance. It encodes each block using 128 bits; hence, by adjusting the size (in texture pixels, i.e. texels) of the blocks, it can produce a large variety of output qualities. The

larger the block size is, the more efficient is the compression, and the larger (and more visible) are the block artifacts. For each reference texture map, we created 5 lossy compressed versions corresponding to 5 block sizes: 6×6 , 8×8 , 10×10 , 12×10 , and 12×12 , that correspond respectively to bit rates: 3.56, 2.00, 1.28, 1.07, and 0.89 bits per pixel. These sizes have been adjusted during a pilot experiment in order to enclose the detection thresholds for all our reference diffuse and normal maps. We used the ARM Mali GPU Texture Compression Tool [43] with compression mode set to *fast*. Normal maps were compressed using the *normal_psnr* mode. Examples of compression artifacts are illustrated in Figure 3. One can observe that block artifacts highly depend on the maps. For instance, 8×8 artifacts are clearly identifiable in the Water diffuse map but much more difficult to perceive in the Fabric one.

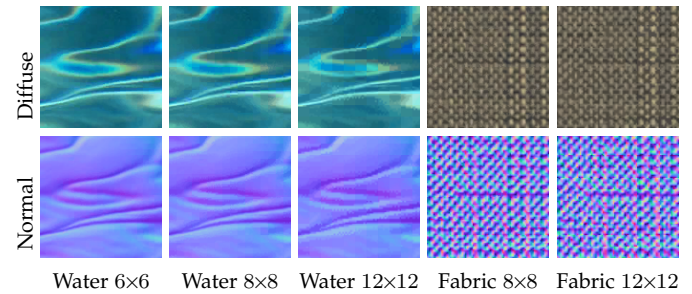


Fig. 3. Examples of compressed diffuse (top) and normal (bottom) texture maps, for different block sizes of the ASTC algorithm [3].

3.1.3 Rendering

Normal Masking Experiment

The first experiment studies the masking effects caused by the *normal map* on the perception of the *diffuse map* compression artifacts. For each compressed diffuse texture image, except for *Flat* (4 maps \times 5 compression levels = 20 images), we make one rendering with every normal map (5 maps) and using 2 light directions; we thus rendered 200 images.

For rendering, the diffuse and normal images are mapped onto a geometric 3D square of Lambertian reflectance. We set a directional light from the left with two directions: 0° and 42.5° from the normal direction of the square. The scenes are rendered by ray-tracing using the Mental Ray software [44]. Figure 4 illustrates some rendered results.

The rendered images of resolution 128×128 respect the usual setting of one pixel per texel for ideal rendering.

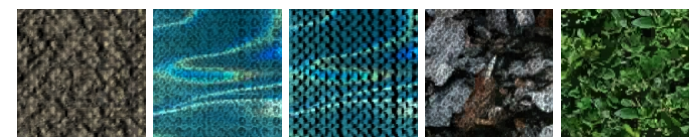


Fig. 4. Examples of stimuli for the Normal Masking experiment. Triplets indicate: diffuse map, normal map, light direction. Light comes from the left. Diffuse maps are compressed with block size 10×10 .

Fig. 4. Examples of stimuli for the Normal Masking experiment. Triplets indicate: diffuse map, normal map, light direction. Light comes from the left. Diffuse maps are compressed with block size 10×10 .

Diffuse Masking Experiment

The second experiment studies the masking effects caused by the *diffuse texture maps* on the perception of the *normal*

maps compression artifacts. For this experiment we remove the *Stones* stimulus since its normal map is of low amplitude and compression artifacts remain invisible whatever our compression parameters. Consequently, we select the 3 remaining normal maps \times 5 compression levels, and render with 4 diffuse maps (Flat, Fabric, Water, and Hedge) using 2 light directions; we thus render 120 images. To emphasize the visual impact of normals, we select 2 light directions: 27° and 72° from the viewing direction, also coming from the left. We do not select the 0° direction since the effects of normals on the surface would be too small for human subjects to perceive artifacts. Figure 5 illustrates some rendered results. Note that images are not normalized, i.e., scenes lit from 72° s are darker.

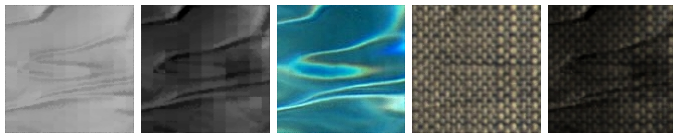


Fig. 5. Examples of stimuli for the Diffuse Masking experiment. Triplets indicate: diffuse map, normal map, light direction. Light comes from the left. Normal maps are compressed with block size 12×12 .

3.2 Procedure

Our two psychophysical experiments aim to measure thresholds for detecting artifacts. They follow the same randomized two-alternative-choice (2AFC) design. Each subject is shown triplets of rendered images, corresponding to the same diffuse/normal map combination. Images are displayed on a 50% grey background and the order of triplets is randomized. The reference rendering (without any compression) is displayed in the center. On left and right, two test images are displayed. One is the same as the reference and the other involves a compressed map (either diffuse or normal, depending on the experiment); their position (left or right) is randomized. Subjects were asked: "Which image is different from the reference?" and clicked on the corresponding image. They were given a maximum of 8 seconds; after this time, a pop-up window asked them to choose. As in [39], this time limit aims to prevent subjects from making an exhaustive pixel-wise comparison of the images.

All stimuli were presented on a calibrated 17.3" LCD display (1920×1080 pixel resolution) in a dark room. A chinrest was used to keep constant viewing distance of 0.35m, corresponding to an angular resolution of 33.5 pixels per degree. With our setting, each image subtends approximately 3.8° of visual angle. 22 paid subjects participated in the experiments. All were students from McGill university, aged between 18 and 33, with normal or corrected-to-normal vision. Each subject completed the two experiments. 11 did the Normal Masking one followed by the Diffuse Masking one, and 11 did the inverse. They took on average 35 minutes in total to perform both experiments.

4 DATA ANALYSIS

In this section we study the effect of light direction and texture content on the compression error *detection threshold*. We investigate, in particular, the involved masking effects.

4.1 Normal Masking Experiment

In this experiment, the normal texture potentially masks the compressed diffuse texture. Figure 6 illustrates the raw results of this first experiment. The detection probabilities are displayed for each set of conditions. Green indicates visual equivalence to the reference (75% 2AFC threshold), while red means a visual difference. Figure 7 summarizes these results using boxplots of detection probabilities. Table 2 provides results of pairwise t-tests between each condition. We chose to represent these tables as $n \times (n - 1)$ matrices (for comparing n conditions), instead of $n \times n$ symmetric matrices with empty main diagonals. Each cell considers, for the two conditions, the distributions of detection probabilities. The following paragraphs discuss the effects of each parameter. Note that when the Flat normal is used (first row of Figure 6), what we are examining is not masking, but rather whether the compressed textures are distinguishable from original ones.

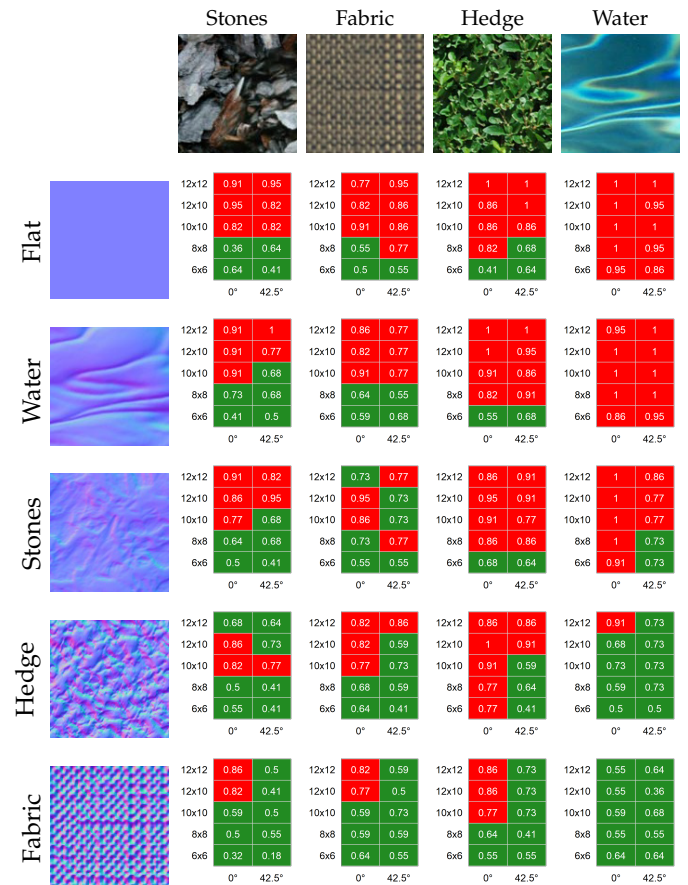


Fig. 6. Results of the Normal Masking experiment. Detection probabilities P are given for each pair of diffuse/normal maps, and for each compression level and light direction. Green means that rendered images are considered identical ($P < 0.75$), while red means that visible differences are detected ($P \geq 0.75$).

Compression Quality. The compression quality obviously influences the perceived visibility of artifacts. Larger block

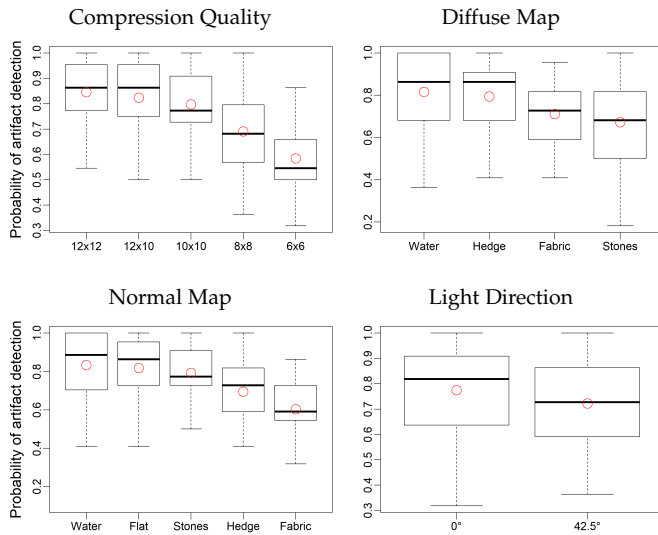


Fig. 7. Boxplots of detection probabilities obtained for the different conditions of each parameter, for the Normal Masking experiment (diffuse maps are compressed). Mean values are displayed as red circles.

TABLE 2

P-values from pairwise paired t-test (Bonferroni-corrected) between all conditions, for the Normal Masking experiment.

Compression Quality					Diffuse Map		
	12×12	12×10	10×10	8×8	Water	Hedge	Fabric
12×10	1.000	-	-	-	Hedge	1.000	-
10×10	0.122	1.000	-	-	Fabric	<0.001	<0.001
8×8	<0.001	<0.001	<0.001	-	Stones	<0.001	<0.001
6×6	<0.001	<0.001	<0.001	<0.001			0.280

Normal Map					Light Direction	
	Water	Flat	Stones	Hedge	42.5°	0°
Flat	1.000	-	-	-	<0.001	
Stones	0.303	1.000	-	-		
Hedge	0.001	0.002	0.011	-		
Fabric	<0.001	<0.001	<0.001	0.003		

sizes induce block artifacts that are both larger in size and in amplitude. Still, it is interesting to observe that there are no significant differences in detection probabilities between 10×10 , 12×10 , and 12×12 (see Table 2).

Diffuse Map. The content of the diffuse map influences the detection probabilities. Hedge and Water diffuse maps seem to be the most sensitive to compression, as illustrated by the large number of red cells in the last two columns of Figure 6, as well as their boxplots from Figure 7 (top right). Reasons are different: Hedge has many high-contrast sharp edges that are easily damaged by block artifacts, while Water is quite smooth with very low intrinsic masking effects.

Normal Map. When looking at Figures 6 and 7 (bottom left) it appears obvious that the normal map strongly influences the perception of diffuse map artifacts. For example, in Figure 6, for the Water diffuse map, visible differences are perceived for all compression ratios when combined with the Flat normal map, while no difference is perceived when combined with Fabric. The two critical factors that determine masking effects are frequency and amplitude. In Figure 7, Hedge and Fabric normal maps, which have highest

frequency and amplitude, lead to significantly lower detection probabilities (see also Table 2, bottom left). A closer look reveals that for a given high amplitude (Hedge and Fabric), masking effects increase with frequency. Indeed, Fabric is of higher frequency and Fabrics masking effects are clearly stronger. Similarly, for a given low amplitude (Water and Stones), a high frequency and noisy texture provides slightly higher masking effects. However, low amplitude normal maps (Water and Stones) are not significantly different from the Flat one and lead to high detection probabilities.

When carefully looking at Figure 6, the normal masking effects are slightly more complex. Indeed, all artifacts on the Water diffuse map are almost completely masked by Hedge and Fabric normal maps. However, the masking effects of these two normal maps are much lower for the other diffuse maps (i.e., Stones, Fabric, and Hedge). The masking effects brought by a normal map actually depend on the diffuse map content. Note that a strong correlation between diffuse and normal maps (as we have when we combine a diffuse/normal pair) does not seem to lower or increase the masking effects.

Light Direction. A significant impact due to light direction is observed. First, when the angle between light direction and surface normal increases, then the rendered image is darker, thus decreasing the contrast of the signal. Second, this masking is reinforced by the fact that non-perpendicular lighting emphasizes the influence of the normal map (which thus increases contrast-masking effects).

4.2 Diffuse Masking Experiment

In this experiment, the diffuse map potentially masks the compressed normal map. As above, Figure 8 illustrates raw results, Figure 9 summarizes these results using boxplots of detection probabilities, and Table 3 provides results of pairwise t-tests between each condition. The following paragraphs discuss the effects of each parameter.

Compression Quality. We observe that when compressing normal maps, the level of compression has less impact on the perception of artifacts than when compressing diffuse maps. The visibility of artifacts actually mostly depends on the diffuse masking, as detailed below.

Normal Map. When looking at Figure 9 (top right) one could state that the content of the normal map itself does not seem to have a significant influence on the perception of artifacts. This is confirmed by Table 3 (top right). However, Figure 8 clearly shows that the normal map does have an influence, that is very strongly related to the masker. Indeed, as illustrated in the first two rows of Figure 8, with a weak masking (Flat or Water diffuse map), the Water normal map is the most sensitive to compression. However, when the Fabric diffuse map is applied (strong masking) then the inverse effect is observed (see the third row of Figure 8): artifacts are more perceived on Fabric and Hedge normal maps than on Water. Like in the previous experiment, and even stronger, we observe an important interaction between diffuse and normal maps in the perception of artifacts.

Diffuse Map. As stated before, the masking effects brought by the diffuse map depend on the normal map content.

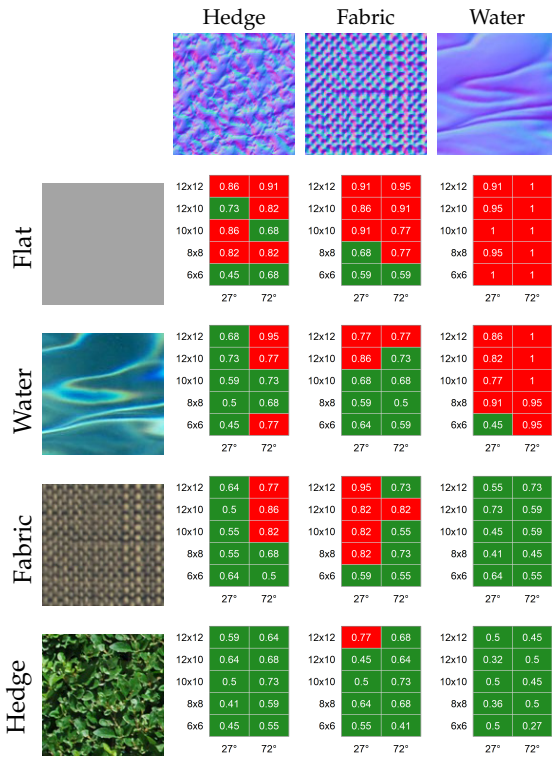


Fig. 8. Results of the Diffuse Masking experiment. Detection probabilities P are given for each pair of diffuse/normal maps, and for each compression level and light direction. Green means that rendered images are considered identical ($P < 0.75$), while red means that visible differences are detected ($P \geq 0.75$).

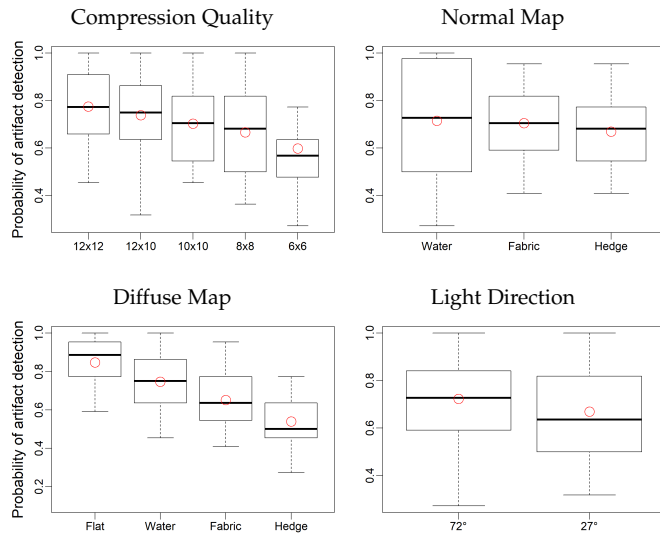


Fig. 9. Boxplots of detection probabilities obtained for the different conditions of each parameter, for the Diffuse Masking experiment (normal maps are compressed). Mean values are displayed as red circles.

However, significant effects of diffuse maps can be observed (see Figure 9, bottom left). As for normal masking, frequency appears to be a determining masking factor: for a given contrast (e.g., Water and Fabric have approximately the same), higher frequencies produce much higher masking effects (see Fabric). The contrast also plays an important role since Hedge (high contrast) leads to higher masking

effects than Fabric, whereas having a lower frequency. The last observation is that even a smooth low frequency diffuse map like Water does have masking effects, as compared to Flat. This last finding is particularly important since it clearly emphasizes the usefulness of taking into account masking effects when compressing normal maps. As for the normal masking experiment, we do not observe an influence of the correlation between diffuse and normal maps on the masking effects.

Light Direction. Finally, light direction has a slight but significant impact of the perception of artifacts. Indeed, normal compression artifacts are more easily perceived for grazing light angles (72°). However, surprisingly, this effect also depends on the compressed normal map (see left and middle columns of Figure 8).

TABLE 3
 P-values from pairwise paired t-test (Bonferroni-corrected) between all conditions, for the Diffuse Masking experiment.

Compression Quality	Normal Map			
	12x12	12x10	10x10	8x8
12x10	1.000	-	-	-
10x10	0.020	1.000	-	-
8x8	<0.001	0.128	1.000	-
6x6	<0.001	0.002	0.030	0.595

Diffuse Map	Light Direction	
	72°	27°
Water	0.002	-
Fabric	<0.001	0.159
Hedge	<0.001	<0.001

4.3 Inconsistencies

As can be seen in Figures 6 and 8, some inconsistencies are present in the subjective data. For instance in Figure 6, the strongest 12×12 texture compression is less visible than 12×10 and 10×10 ones when compressing the Stones diffuse map, combined with the Hedge normal map. A closer look at the data reveal that these inconsistencies occur when the compressed content is in the middle or high frequencies and is somehow noisy (diffuse Stones, diffuse Fabric, normal Hedge, and normal Fabric). In these cases, we observed that a strong compression makes the compressed content convey a better perceptual similarity to the original one than for a weaker compression. For the case of the Stones diffuse map compression cited above, the 10×10 compression produces slight smoothing because the quantization removes some edges; however, at higher compression rates (e.g., 12×12), some new edges are created by the larger quantization artifacts that make the images appear more similar to the original.

5 EVALUATION OF IMAGE QUALITY METRICS

In this section we study the performance of state-of-the-art image quality metrics in predicting the psychophysical data, i.e., the visual impact of texture compression artifacts.

5.1 Metric Selection

Over the last decade, the field of image quality assessment has been extremely active as hundreds of related methods can be found [45]. For the present study, we selected metrics either known for their efficiency or for their widespread use in the community. We opted for the well-known structural similarity index (SSIM) [7] and its multi-scale extension MS-SSIM [46]; these top-down approaches remain among the top-performing ones. We also selected the bottom-up visible difference predictor from Mantiuk et al. [15]: HDR-VDP-2. Since the latter metrics only consider luminance, we selected the recent color-based approach from Preiss et al. [25]: iCID. Finally, we included PSNR as standard baseline, often used in practical applications.

In order to fully explore their possibilities, we ran these metrics using different sets of parameters. For SSIM and MS-SSIM, we considered four sizes of local windows. HDR-VDP-2 is highly tunable: visual resolution, peak sensitivity, and surrounding luminance. For the resolution, we considered 33.5 pixels per degree, which corresponds to our experimental setting, and we explored the peak sensitivity parameter within [1.3,3.0]. Surrounding luminance was set to the mean of the image, as this provided the best results. For these sets of parameters, we selected two kinds of output from HDR-VDP-2: the probability P of detection (we selected the mean and maximum values of the per-pixel probabilities, best results were provided by the mean), and the quality prediction Q proposed in the extension by Narwaria et al. [47]. For the iCID metric, we considered four versions by varying the weights of lightness, chroma, and hue, and by omitting or not, chroma contrast and chroma structure (as recommended by the authors). All these parameters are detailed in Table 4.

TABLE 4

Tested parameters of image quality metrics. Best parameter values (when testing on both datasets) appear in bold.

Metric	Parameter	Values
SSIM [7]	Local Window Size	8, 11, 14 , 17 pixels
MS-SSIM [46]	Smallest Local Window	2, 3 , 4, 6 pixels
HDRVDP2. P [15]	Peak sensitivity	1.3· 1.46 ·3.0
HDRVDP2. Q [47]	Peak sensitivity	1.3· 2.06 ·3.0
iCID [25]	Chroma contrast & struct.	keep, remove
iCID [25]	Stronger weight of hue	yes , no

5.2 Evaluation Measure

Our objective is to evaluate the performance of the metrics described above in predicting the perceived visibility of artifacts. This is a binary classification problem (i.e., visible or not visible), hence we evaluate the performance using the Receiver Operating Characteristic (ROC) curve, which represents the relation between sensitivity (true-positive rate) and specificity (true-negative rate) by varying a decision threshold on the metric output. The area under the ROC curve (AUC) can be used as a direct indicator of the performance (1.0 corresponds to a perfect classification, 0.5 corresponds to a random one). For each metric, instead of a single AUC value, we compute an AUC distribution using a bootstrap technique [48]: The AUC is computed 2000 times,

each time on a random set of images having the same size as the original dataset; this random set is generated by sampling with replacement. The bootstrap distribution allows for statistical testing and its percentiles provide the 95% confidence interval.

5.3 Performance Comparison on Rendered Images

In this first study, image metrics are applied on rendered images. We evaluate the performance of the metrics on each dataset separately (resp. from normal masking and diffuse masking experiments) and on both datasets together (i.e., on all images). Figure 10 illustrates the AUC values for these three settings, and the ROC curve for the last one. The following sub-sections respectively present the performance of metrics and analyze their failures.

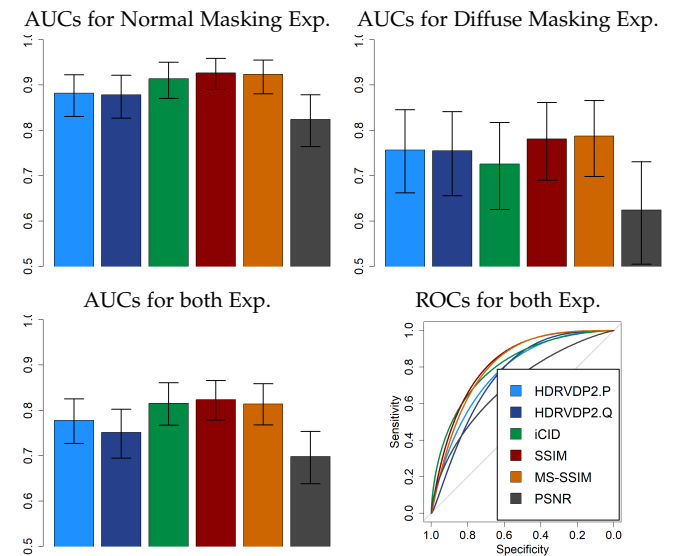


Fig. 10. AUC values (with 95% confidence interval) for several image quality metrics applied on the rendered images. AUCs are computed on each dataset and on both together. ROC curves are also illustrated for this latter case. Metrics are represented by different colors detailed in the legend of the plots.

5.3.1 Overall Performance

When compression is applied on the diffuse texture (Normal Masking Experiment), then SSIM provides the best performance, while not significantly better than MS-SSIM and iCID (P-value resp. equal to 0.10 and 0.58). In that case, HDR-VDP-2 (both Q and P) performs significantly worse than its counterparts, except of course PSNR, which provides the worst results.

When compression is applied on the normal texture (Diffuse Masking Experiment), all metrics provide weaker performance, suggesting that compression artifacts applied on normal maps may be more difficult to predict. iCID provides the worst results, which is logical since it is based mostly on chrominance, while the normal map artifacts introduce mostly luminance impairments. MS-SSIM provides the best results, without being significantly different from SSIM and HDR-VDP-2.

Finally, when considering both datasets together, we challenge the capability of metrics to generalize over different

artifacts. In that case, iCID, SSIM, and MS-SSIM show a statistically equivalent performance. However, ROC curves show that iCID is better on high specificity (i.e., low false-positive rate).

5.3.2 Analysis of Metric Failures

To understand more precisely the metric failures, we generated for each metric the classification results obtained at the Youden cut-point of the ROC curves, i.e., maximizing *sensitivity + specificity*. The obtained classifications are detailed in Figures 11 and 12 and their analysis is detailed below.

Normal Masking dataset. As can be seen in Figure 11, the PSNR metric completely underestimates the visibility of artifacts on the Water diffuse map, as compared with other maps. The reason is that this metric is unable to take into account the intrinsic masking effects inherent to the compressed texture content, which makes artifacts less visible when applied on a middle-high-frequency content (and thus more visible on low-frequency areas such as Water). HDR-VDP-2 and SSIM are better for this task but still tend to underestimate the visibility of Water artifacts for low compression strengths. We also observe that HDR-VDP-2 underestimates the effect of lighting for the Edge diffuse map, when strong maskers are present (Fabric and Edge). SSIM is slightly better for this task while PSNR completely fails. Note that iCID and MS-SSIM results are similar to SSIM's, and HDR-VDP-2.Q is similar to HDR-VDP-2.P; their figures are available in the supplementary material.

Diffuse Masking dataset. For this dataset, once again, PSNR greatly underestimates the visibility of artifacts on the low-frequency Water normal map, while overestimates those from the high-frequency Fabric map. The iCID metric shares the same problem for this dataset. HDR-VDP-2 and SSIM better handle these intrinsic masking effects, however they still underestimate the Water artifacts for the 72° lighting. Note that for this dataset, SSIM results are similar to MS-SSIM's, and HDR-VDP-2.Q is similar to HDR-VDP-2.P; their figures are available in the supplementary material.

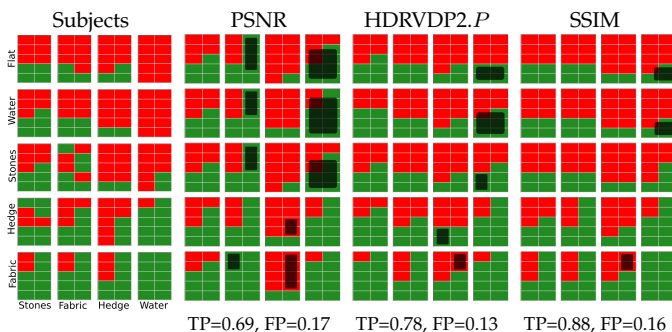


Fig. 11. Classification obtained for different metrics at the maximum value of Youden's index, for the Normal Masking experiment. Main differences w.r.t. the human-perceived classification are spotted in black.

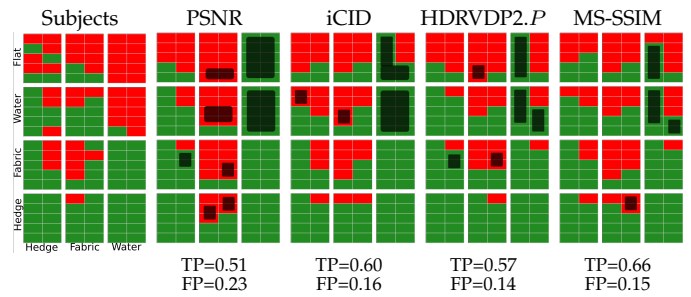


Fig. 12. Classification obtained for different metrics at the maximum value of Youden's index, for the Diffuse Masking experiment. Main differences w.r.t. the human-perceived classification are spotted in black.

5.4 Performance Comparison with Unknown Rendering Parameters

In this section, we investigate how to predict the visual impact of artifacts, when the rendering parameters are unknown. This scenario corresponds to the most realistic use-case where the designer determines the compression level of the texture maps before any rendering and even without knowing the rendering parameters. In that case we consider two possibilities: either the metric is computed using only the compressed map (the masking map is ignored), or the metric is computed on a rendered image, with arbitrary light direction (in that case we selected a direction different from the images of the datasets). For comparison we also include results obtained when the metrics are computed on the rendered images from the datasets (as in the previous section). For this study, we consider the image metric that provided the best results in the study above, i.e., SSIM (with a 17×17 local window), as well as PSNR, commonly used by designers to evaluate and select the appropriate compression level. Figure 13 illustrates the results.

As can be seen in the figure, applying PSNR directly on the texture map provides a very poor prediction of the perceived visibility of artifacts (see the lightest-grey bars in the histograms). Applying SSIM directly on the texture map (lightest-red bars) is better but remains quite inefficient, especially for predicting artifacts from the normal maps (top right histogram). When the metrics are computed on rendered images with arbitrary light directions (medium-grey and medium-red bars), then results are much improved for both SSIM and PSNR. This implies that it is crucial to take into account the masking effects that occur during rendering, even in an approximate way (i.e., with arbitrary rendering parameters). As illustrated in the top row histograms, AUC values obtained when SSIM is computed on an arbitrary rendering (medium-red bars) are quite close to what is obtained when using the exact same rendering parameters than in the psychophysical tests (dark-red bars). The difference between those two settings is larger when merging both datasets together (see bottom right histogram), meaning that it is more difficult to find a unique threshold on the metric outcome that will predict correctly the visibility of both diffuse and normal map compression artifacts.

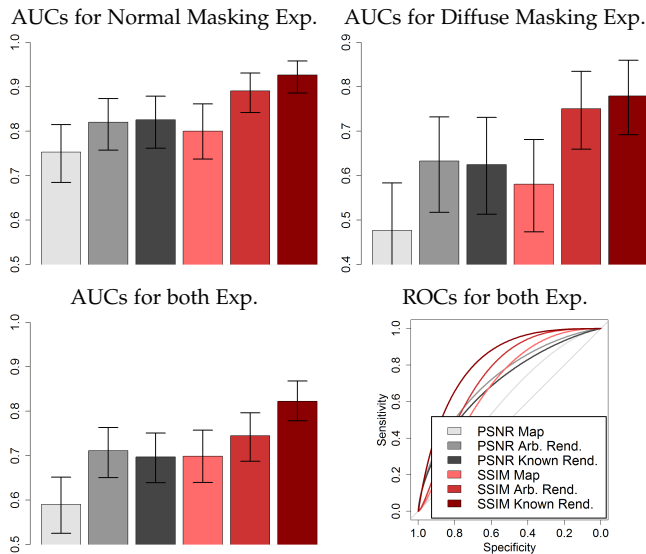


Fig. 13. AUC values (with 95% confidence intervals) for SSIM and PSNR applied on the texture maps (*Map* in the legend), on rendered images with arbitrary light directions (*Arb. Rend.*), and on the original rendered images from the experiments (*Known Rend.*). AUCs are computed on each dataset and on both together. ROC curves are also illustrated for this latter case. Metrics are represented by different colors detailed in the legend of the plots.

6 RECOMMENDATIONS AND DISCUSSION

Our analysis of artifact perceptual impacts (Sec. 4) and metric performance (Sec. 5) reveals several interesting findings and allows us to make useful recommendations for texture map compression.

First, Figures 7 and 9 illustrate that it is impossible to find a unique compression parameter for which artifacts remain invisible whatever the texture map. Indeed, even at the highest bit rate (i.e., smallest 6×6 block size), compression produces visible artifacts on certain texture maps when there is no masking. On the contrary, artifacts produced by the strongest compression (12×12) may be completely masked in some cases. So the conclusion that can be drawn here is that fixing the compression parameter to a single value for all texture maps is not a good way to proceed. It appears necessary to quantify the loss of quality due to compression.

As stated in the introduction, and as raised by Griffin and Olano [6], the most common approach in evaluating the quality loss due to texture compression is to use PSNR directly on the texture maps. However, as shown in Figure 13, it appears as a very bad strategy, since this process provides results close to random for predicting visibility of artifacts (see light-grey bars, $AUC=0.60$ when considering both datasets).

Figure 13 also shows that using a perceptual metric is far more efficient than PSNR, and in particular, SSIM (with the appropriate scale) provides the best results. As illustrated in Figure 13, like for PSNR, applying this perceptual metric directly on texture maps provides very bad results. The best way to predict the perceptual impact of artifacts is to apply this perceptual metric on rendered images. Since in most cases, the rendering parameters are not known beforehand, the metric could be applied on a simulated rendering using

an arbitrary light direction. The simplest way to proceed is to render both maps on a geometric square and then apply the perceptual metric on the resulting image. Such quick evaluation process, illustrated in the section below, can easily be integrated to a texture compression tool and would provide a significant improvement in visual quality estimation.

7 PRACTICAL APPLICABILITY

To illustrate the process recommended above, we propose a practical application where we approximate the distortion present on a real 3D scene by running a metric on a simple rendering of a geometric square using an arbitrary light direction. We selected six 3D graphical assets (human characters) typical in games, which were put in a realistic pose, lit by sunlight and rendered using global illumination (see the first image in Figure 14). We applied either diffuse or normal texture compression using two strengths (10×10 and 12×12) and measured the *ground-truth* distortion maps using the SSIM metric on rendered images (see the third image in Figure 14). We then computed what we call the *approximated* distortion maps by running the SSIM metric on a geometric square mapped with both texture maps and lit by an arbitrary directional light (we selected three directions: 42° , 27° , and 13° from the normal direction of the square). We then texture mapped these approximated distortion maps onto the 3D object shapes (see the fourth image in Figure 14) and computed the correlation with the ground-truth distortion maps. In practice, we obtained 72 approximated maps (6 objects \times 2 compression strengths \times 2 compressed map types \times 3 light directions). Note that correlations are computed over the rendered shapes only, and after median filtering to reduce noise. As *baselines* we applied the same process with distortion maps obtained by running the SSIM metric directly on the compressed texture maps (either diffuse or normal) without rendering, as illustrated in the fifth image in Figure 14.

Results are presented in Figure 15. More results are detailed in the supplementary material, together with all stimuli and distortion maps. We observe that the approximated distortion maps reach a mean correlation of 0.59 with the ground-truth distortion maps. This is reasonable and significantly better than results obtained by running the metric on the compressed maps alone (0.47 mean correlation). The performance of our approximation remains stable among light directions and reasonably stable among 3D shapes, whereas one asset led to significantly weaker results (*Lumber*, with a mean correlation of 0.41). Artifacts due to normal map compression appear more difficult to predict, than those due to diffuse map compression. The projection and shading on a real shape logically has a great impact on these artifacts as compared to our approximation on a geometric square.

Limitation. Precisely evaluating the perceptual impact of texture compression for an arbitrary 3D scene is highly complex, particularly when rendering parameters are not known beforehand. We showed that approximating the distortion using a flat Lambertian surface with an arbitrary directional lighting leads to improved and more stable results as compared to a baseline computation

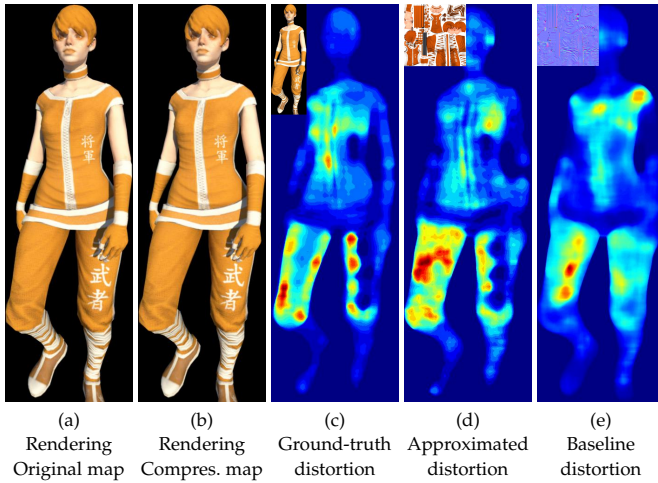


Fig. 14. Illustration of the performance of our recommended distortion approximation. (a) Rendering of a 3D shape mapped with uncompressed diffuse and normal maps; (b) rendering after compression of the normal map (10×10); (c) ground-truth distortion obtained by computing the SSIM metric on the rendered images; (d) our approximation obtained by computing the metric after mapping diffuse and normal maps on a geometric square and rendering under a 13° directional light (0.76 correlation with ground-truth), and (e) baseline distortion obtained by computing the metric directly on the compressed normal map (0.54 correlation). At the top left of each distortion map, we display the image on which the distortion has been computed.

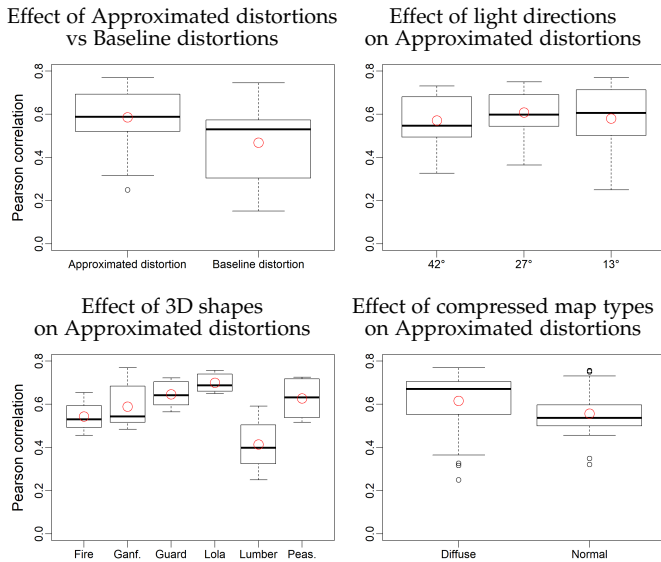


Fig. 15. Boxplots of Pearson correlations with ground-truth distortion. *Top-left*: Results obtained by Approximated and Baseline distortions (for all map types, lighting directions, and shapes). *Other panels*: Effects of the different factors on the Approximated distortions. Mean values are displayed as red circles.

on texture map only, i.e., a better ability to predict the real distortion that is caused by texture compression. An improved prediction would require to account for many additional factors: distortion due to projection on the 3D shape and foreshortening, self-visibility/occlusion over the surface, projected shadows and self-shadowing, non-uniform resolution of the texture map (in terms of texels per pixel), glossiness/"metalness" of material, silhouettes, inter-reflections, and much more complex light transport

of global illumination effects. Our findings constitute an important first step toward the full understanding of the perceptual impact of texture compression. Future work will explore all these factors to find improved ways to predict their effects without requiring the full rendering.

8 CONCLUSION

In this work, we presented a psychophysical experiment that investigates different masking effects in the perception of texture compression artifacts. We show that strong compression artifacts can be hidden by contrast masking, while less severe artifacts may be visible when no masking occurs. We analysed how amplitude and frequency influence masking effects and showed that these masking effects also depend on the interaction between diffuse and normal maps. Our analysis also emphasizes the significant impact of lighting in the perception of artifacts.

Our psychophysical data also allow us to evaluate the performance of image quality metrics in predicting the visibility of artifacts in different scenarios (on texture maps and on rendered images, with or without knowing the light direction) and to analyze their failures. We find that computing PSNR on texture maps is particularly inefficient and that a perceptual metric, such as SSIM, computed on a rendered image (even with an arbitrary lighting) provides much better performance.

Our dataset should stimulate research about visual quality metrics; indeed, even computed on a rendered image, we have shown that the best metrics are still far from reaching a perfect classification of visible distortions. In particular, the failures of the complex bottom-up HDR-VDP2 metric indicate that work is still needed to better predict human vision even in controlled condition. As raised by recent surveys [11], the future of quality metrics may rely on an appropriate combination of low-level psychophysical models and machine learning techniques.

For compressing the texture we used the ASTC algorithm, which has the benefit of being random-access (i.e., each block of texture can be accessed and decompressed independently by the GPU) while being able to provide a large range of bit rates by varying the block size. Many other compression algorithms exist that may introduce different kinds of artifacts, depending on the transforms they use. For instance, the JPEG algorithm considers a fixed block size and quantizes Discrete Cosine Transform (DCT) coefficients. As part of future work, we would like to investigate the variability of our results according to the nature of compression artifacts.

Finally, as stated in Sec. 3, we have considered texture maps corresponding to a traditional real-time shading workflow, where the diffuse texture contains not only the base color of the material but also some illumination effects (e.g., ambient occlusion, global illumination, etc.). We plan to make similar psychophysical studies with physically-based rendering (PBR) materials, i.e., represented for instance by albedo, "metalness", and roughness texture maps.

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