Perceptually Based Radiance Map for Realistic Composition

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***Abstract*—The seamless composition of synthetic objects into real-world scenes requires a high level of detail to convince viewers that the rendered object belongs in the scene. These details include illumination properties that perceptually match the real-world environment. To achieve such effects, image based lighting is often used to emulate real-world lighting. This paper explores the role of lighting, and measures effects of local illumination changes. A psychophysical study is presented that captures the thresholds of the human visual systems ability to perceive inconsistencies in illumination in image composites. Further, a set of optimised parameters for image based lighting is proposed. The results show a significant reduction in memory while maintaining the perceived visual quality of a composite render.**

I. Introduction

Improving techniques for the realistic composition of synthetic objects with real photographs is one of the primary goals in photo-realistic rendering, especially in augmented reality or visual effects in film. The overall aim is to generate seamless mixtures between the computer generated renders of 3D models and real world scenes. The seamlessness is the degree to which the rendered elements of the composite image are indistinguishable from the photographed scene, as determined by the human visual system (HVS).

Global illumination (GI) algorithms provide techniques for generating high quality images of synthetic objects that can be seamlessly blended into an image of a real scene. To achieve photo-realistic output, GI employs a wide range of parameterised processes. These processes are often designed to produce the greatest fidelity under all conditions. In some cases, however, this can result in unnecessary computation. The computation time and the quality of the result can vary greatly based on these parameters, which include; the number of samples taken per pixel, the number of rays and photons, the resolution of textures and radiance maps, and the complexity of geometry and materials. Optimising the values of these parameters is an active and challenging area of computer graphics research.

Given that the ultimate receiver of image information is the HVS, an optimised rendering scheme should achieve efficient computation while maintaining image quality defined by the HVS. Accordingly, recent computer graphics research has begun to focus on human perception [1], [2].

These studies generally take the approach of rendering a reference image with full detail using an unoptimised physically-based photo-realistic rendering algorithm. A test image is also rendered with optimised parameters or algorithms. The test image is then compared with the reference image to evaluate whether the optimisations have maintained image quality. Most of the previous work in this domain follows this methodology [3], [4], [5].

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We propose an alternate method to this kind of study. To better replicate image composition in the visual effects industry, we propose a study without a reference image. This results in the participant using the scene around the synthetic object as an intrinsic reference.

Using the self-referencing test, we conducted a psychophysical study to capture the perceptual range of the HVS. We generated test images that use high dynamic range image (HDRI) radiance maps that mimic the illumination of a real world scene. By manipulating the radiance map, we adjust lighting parameters such as light direction and intensity in various environments. The changes are applied to parts of the scene, which can be regarded as the synthetic object for composition. The composited output image is then shown to the users, where they attempt to detect any changes in the illumination of the objects in the composite.

Based on physically based rendering techniques, we investigate which artefacts are salient amongst high-quality mixed-reality scenes. Further, we run our tests on different geometry and material properties, but limit them to focus our experiment on illumination changes.

As a result of the test, we observe that the HVS is insensitive to changes in light intensity or light direction within a certain range. Based on these observations, we explore the effects of optimising the HDRI radiance maps by reducing the resolution. Our results show that the size of the radiance map can be reduced significantly while maintaining the visual quality of the final composition. This reduction directly results in memory savings; with an average of 99% savings compared to a general studio setup.

II. Related Work

A. Image Composition and Augmented Reality

Image composition has proven to be a difficult task, with research first proposed by Nakamae [6], and a differential rendering technique proposed by Fournier et al. [7].

There are a variety of ways to capture real world lighting information in an environment, all ranging in cost of setup time and complexity [8], [9]. Debevec [10] demonstrated a method of image composition that gave the synthetic object natural

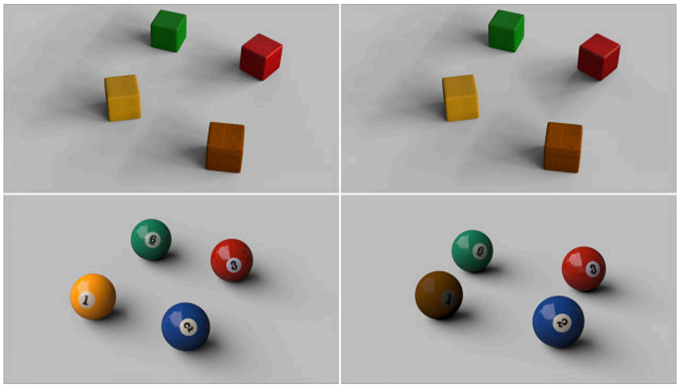

Fig. 1. Examples of the perceptual test images. Local changes have been made within the images. The left images have no alterations, the top-right image has the radiance map altered by rotating it 45 degrees, illuminating only the red block. While on the bottom right, the intensity of the radiance map has been reduced by 87.5%, affecting the outgoing colour intensity of the material as well as shadow detail on the yellow ball. Users generally were able to pick up on both of these modifications.

illumination. This method made use of HDRIs [11] to capture the radiance of the environment, giving realistic lighting and shadows for the synthetic object.

Grosch provided a variation of Debevec's technique [12], improving the speed of differential rendering and correctly accounting for refractions and reflections on the synthetic objects using photon mapping techniques. Knecht et al. [13] used differential rendering techniques as well as instant radiosity to achieve plausible realistic mixed augmented reality in real time.

Lopez-Moreno et al. [14] measured thresholds of the HVS where an object under different illumination was recognised as being incorrectly illuminated, with a focus on illumination direction, object orientation and spatial frequency of textured objects.

Recent work in image composition was conducted by Karsch et al. [15], where they proposed a user friendly, perceptually plausible composition technique requiring little scene information. They also conducted a user study to demonstrate that their compositions are not easily distinguishable from real scenes. Their research is similar to our approach, with the key difference being that our research is predominantly interested in optimisation while maintaining physical accuracy.

B. Human Visual System for Visual Equivalence (with reference test)

Perceptually based rendering is the focus of our research. This approach exploits the nature of the HVS, in order to increase efficiency while maintaining image quality [1], [2]. Ramanarayanan et al. [4] introduced the notion of visual equivalence (VE), which has been another recent focus of computer graphics research [16], [17]. Images have VE if they convey the same impression of the scene appearance, even if they are visibly different. They investigated this idea by testing how materials, geometry and illumination interact and their relative impact on the scene. From this they used visual equivalence predictors (VEPS) as a metric against the distortion of illumination maps.

Krivanek et al. [5] conducted psychophysical experiments to investigate the relationship between the rendering parameters, object properties, and image fidelity.

C. Perceptually Based Rendering Optimisation (with reference test)

Perceptually based rendering involves optimising a rendering system while satisfying the HVS. This avoids the one-to-one simulation of the physical world, by only making computations that are necessary for image detail that the HVS is able to perceive. Yu et al. [3] conducted a psychophysical study, where their results allowed them to find which approximations are perceptually acceptable. [18] conducted a study for perceptually correct shadows, testing image resolution used for lighting. For their resolution test, the study was limited to interior office lighting and a dodecahedron shape. Their test was with reference against a photograph to identify which scene had more natural illumination between the photograph and synthetic scene. Alternatively, we provide an extensive, robust and generalised study of varying scenes, object shapes, and materials designed for mixed reality - showing that these different properties lead to different approximations.

D. Human Visual Perception without Reference Image

Research that conducts perceptual studies without any reference images is limited. Vangorp et al. [19] conducted experiments which illuminated two synthetic objects within the same scene. Their research conducted similar experiments to ours in which there is no reference image but with a different focus. The goal of their study was to observe how shape and material variances dictate perception, but was not to investigate the perceptual study of composition. Our focus is on manipulating scene lighting to observe how it affects the perceived illumination in composite images, as well as optimising radiance maps for composition rendering.

III. EXPERIMENTS

Due to the limited previous work exploring HVS perception of composited scenes, our first task was to observe the HVSs perceptibility to illumination changes in composited scene. We ran two experiments measuring the visibility of illumination changes, namely light direction and intensity. We aimed to observe characteristics of the HVS with respect to the local illumination changes in the composited scene. Furthermore, we extend these results to meaningful parameter optimisations, detailed in section V.

A. Stimuli

Each test image includes four synthetic objects having similar shape and topology. Objects include billiard balls and wooden blocks. In a preliminary study, we used a large image set and a small number of users to narrow down the image set. In the preliminary test we used PBRT [20], and the composition was done using differential rendering [11]. After finding a smaller threshold to focus on, we increased the number of users and decreased the number of test images to capture a significant amount of data on a meaningful range of data. The second survey conducted used Arnold [21], rendering images at 1280x720 resolution. In the composition, one of the objects was rendered with a modification to either the intensity or rotation parameters of the radiance map. An example can be seen in Figure 1.

In order to focus our test on the illumination changes, the geometric models in the scene were either cubes or spheres. The cubes were modelled as wooden blocks, with mostly diffuse material. Specular components are also an important source of information for visual perception [22]. For this reason, billiard balls were modelled, with a specular material. Previous research has shown that spheres are the least discriminating shape with respect to material properties [19], which influenced our choice for using spheres in conjunction with a shiny material type.

The tests were split into categories based on the rendered images lighting parameters. The variation of the lighting parameters were simulated by the manipulation of the HDRI radiance maps:

- **Illumination direction:** The reference objects were rendered with the correct lighting direction. The test object was rendered with the lighting direction changed in increments of five degrees, from the zero to forty-five degrees (see Figure 2). The range is filtered based on the pilot user tests.
- **Illumination intensity:** The reference objects were rendered with the correct lighting intensity. The test object was rendered with the different values of the intensity of the HDR radiance map, where intensity is defined as a scalar of the light intensity from the radiance map. The intensity value is reduced by 50% in each succession (see Figure 2).

The tests are further subdivided into different lighting environments. Three HDRI radiance maps were created to represent real world environments:

- **Sunny radiance map:** Bright, outdoor scene with dominant sun light.
- **Overcast radiance map:** Outdoors, under partial shelter during wet weather and an overcast sky.
- **Indoor radiance map:** Indoor environment with multiple light sources emitting from the windows and indoor artificial lights.

B. Procedure

We produced 9 variations of direction and 5 variations of intensity changes. We produce this set of adjustments for each category, which is a combination of shapes, materials, and lighting environments. This comes to a total of 54 direction adjustment images, and 30 intensity adjustment images. We also submitted 1 image per category that had no adjustments, which is an additional 12 images, bringing the total to 96 test images (see table I).

The test images are shown to the user without a reference image. Because there are signs of consistent degradation between images (such as growing shadow angle changes), the order of images was randomised and included images with no adjustments. The randomness and range of scenes and object types reduced the likelihood that users could detect

TABLE I. GROUPS OF STIMULI IN THE PERCEPTUAL STUDY

	Sunny	Overcast	Indoor
Direction	10 diffuse	10 diffuse	10 diffuse
	10 specular	10 specular	10 specular
Intensity	6 diffuse	6 diffuse	6 diffuse
	6 specular	6 specular	6 specular

patterns. The participants were asked if they could identify the areas which has been adjusted within the test image, and how noticeable this adjustment was. The categories were labelled as follows: 0. (Not noticeable - Cannot identify any adjustments), 1. (Slightly noticeable), 2. (Moderately noticeable), 3. (Very noticeable), and 4. (Extremely noticeable), adapted from Meilgaard et al. [23], and they were asked which object had the modification. If the user could not correctly identify the adjustment in the correct part of the image, then we regard that they could not distinguish the change in illumination.

In the preliminary test, the images were viewed on a calibrated Dell U2212HMC monitor. Users could move onto the next image using their keyboard. Our preliminary study was made up of 20 participants, all of whom were shown all 96 images. Due to the large sample of images, users were allowed to take breaks. All participants had normal or corrected-to-normal vision, and have a background in computer graphics.

IV. Observation and Analysis

From the results of our test, we observed characteristics of the HVS relating to the perception of illumination changes in a composited scene. The results provided a perceptual basis for the next step: optimising the radiance map.

A. Observation of Light Direction Change

We tested the ability of the HVS to perceive light direction changes. This was investigated by rotating the radiance map from 0 to 45 degrees in 5 degree increments between the preliminary and final survey. The final survey results are shown in figure 3, showing the range between 5 and 30 degrees. It is shown that due to the block's shape, in scene's without sharp lighting (indoor, overcast), it is difficult to judge the correct angle of the shadow. Balls were all generally noticeable at 15 degrees of rotation, and highly noticeable from 35 degrees onward.

B. Observation of Light Intensity Change

We tested the ability of the HVS to perceive light intensity changes. It was simulated by reducing the overall intensity values of radiance map in increments of half the intensity value. The results are shown in figure 4. We observed that while intensity has an effect on shadow, the texture colour is much more noticeably affected prior to any noticeable shadow changes.

C. Analysis of the HVS

Based on the results, we observed that the HVS is surprisingly insensitive to localised changes in illumination direction in a composited image. For the light direction test, it began to become noticeable from 15 degrees, it became increasingly noticeable from 30 degrees onward. These abnormalities were

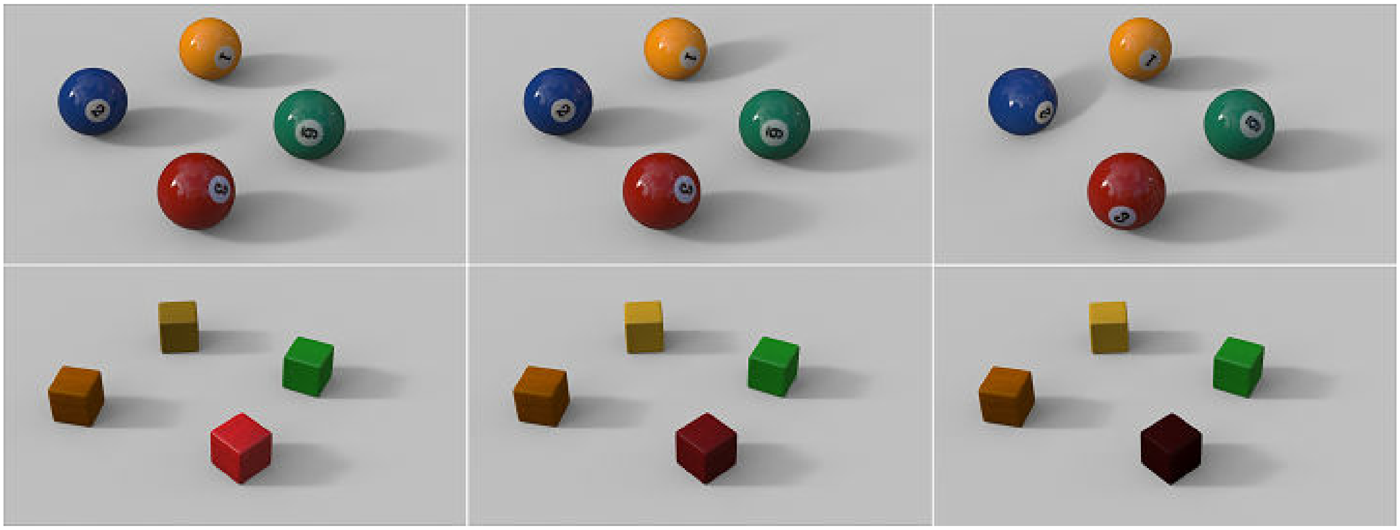

Fig. 2. The first row shows an example of test images with changed direction of illumination. Adjustments from the top left: (yellow, 5 degrees), (yellow, 25 degrees), (blue, 45 degrees). The second row shows an example test image with intensity changes. Adjustments from the bottom left: (yellow, -50%), (red, -75%), (red, -87.5%).

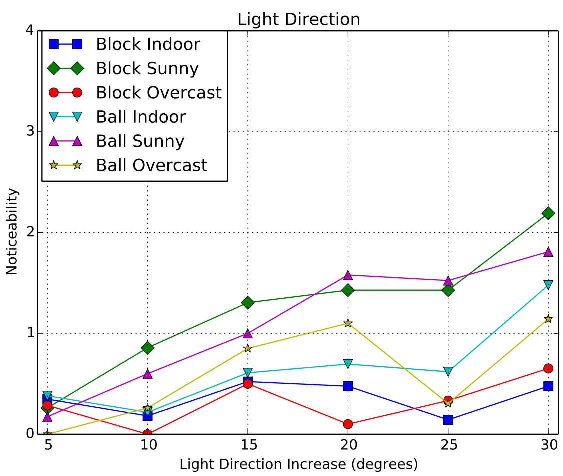

Fig. 3. Observation of the HVS based on light direction changes. The Y axis represents the users scale, and each category on the X axis represents an increment in illumination direction (starting from 5, ending on a 35 degree adjustment).

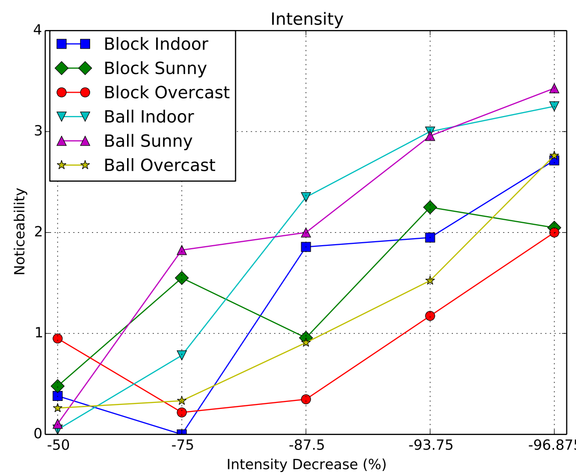

Fig. 4. Observation of HVS based on light intensity changes. The Y axis represents the users scale, and each category on the X axis represents a decrease in illumination intensity (starting from a 50% reduction from the original radiance map, and decreasing a futher 50% on each category).

typically recognised by the agnle of the specular highlight or shadow area. Intensity changes showed a steady increase in noticeability and was more apparent than the shadow changes. The intensity changes were predominantly recognised from the expected texture colour of an object, this was slightly more noticeable in the diffuse material.

Based on our observation of the HVS, we concluded that changing of the resolution of the HDRI radiance map may not significantly affect visual quality of the composited images. This assumption is evaluated by additional user testing in section V, as well as the identification of the optimal range of radiance map resolution in various environments with differing materials.

V. Results

A. *Perceptually Optimised Resolution of Radiance Maps*

From the initial study, we found that there was some threshold that could be exploited with shadow and intensity. Reducing the radiance map has similar effects. For example, a small radiance map will create offset shadows or narrow shadows. We conducted the same experiment as outlined in section III. We produced 7 variations of each category with a reduced radiance map resolution, and one extra image with no adjustments in each category. This is a total of 48 images to run the experiment with. From this, we chose the radiance map resolution that was optimised before being noticeable. This can be seen in the shadow result for the quad scene on the specular object. The resolution 79x40 still maintains the same visual

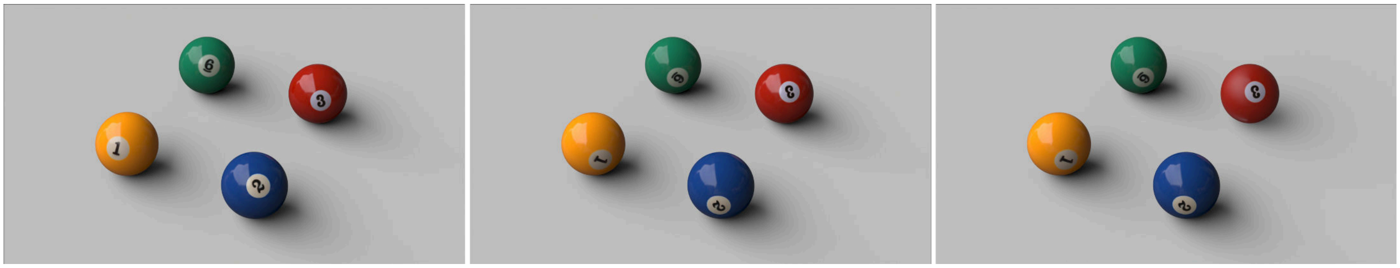

Fig. 6. From the perceptual study we find the optimal parameters for a range of radiance maps. The red ball is rendered, from the left with a radiance map of 5024x2512, the optimal solution then rendered at 79x40, and the lowest quality solution was rendered at 20x10 on the right.

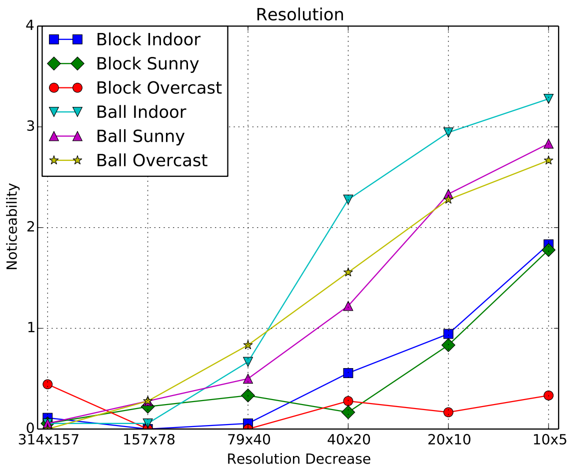

Fig. 5. Observation of the HVS based on the radiance map resolution. The Y axis represents the users scale, and each category on the X axis represents a decrease in resolution. We find visual equivalence at 79x40 resolution is maintained for all scene, object and material types.

quality as a radiance map with a resolution of 5024x2512. This is a saving from approximately 43mb to 17kb.We also find that diffuse objects can be further reduced down to 20x10 resolution. See figure 6 for the final output image, and figure 5 for the user study results. We had a total of 30 participants in the survey for the resolution test.

B. Composition with a Photograph

Finally, we have applied our results to composite the synthetic objects with the real photograph as shown in Figure 7 and 8. The background photographs are taken in the same lighting environment as the HDRI radiance map and the differential method is utilised to composite the synthetic objects. The HDRI radiance map is the only lighting source in the scene. This makes the task more challenging than a standard production set-up, such as for a movie. This is because artificial light sources would usually be added to match shadows and highlights. Gamma correction was applied to match the composite rendered local scene with the actual photograph. As shown in Figure 8, perceptually optimised image based radiance maps provide promising results even for composition with real photographs. Figure 7 in contrast shows an unoptimised solution which is perceptually equivalent.

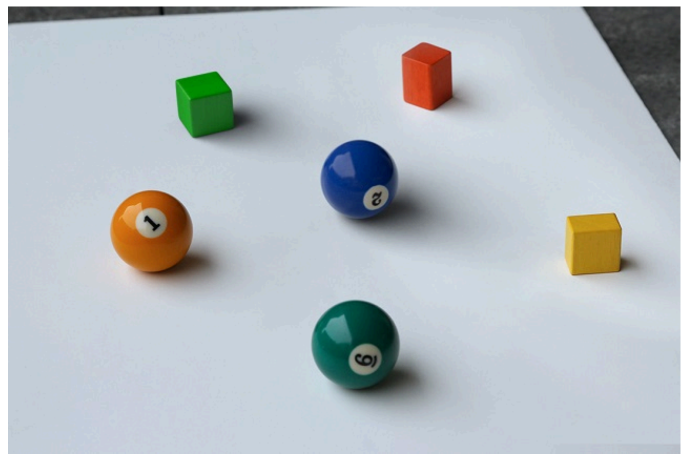

Fig. 7. The synthetic object composition into a photograph rendered with a large sized radiance map of 5024x2512 resolution. The blue billiard ball and green block is synthetic.

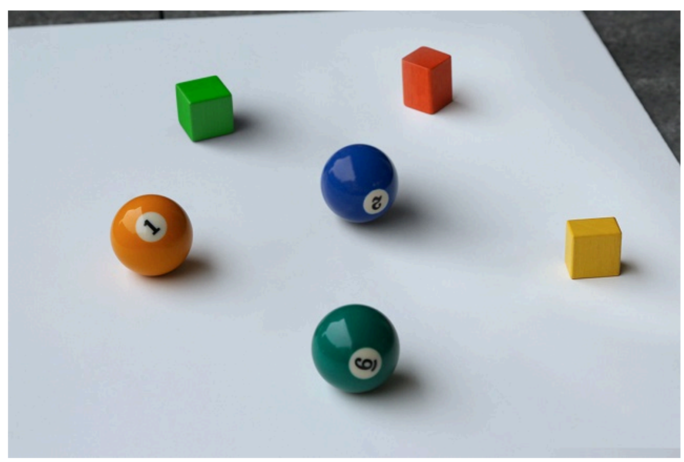

Fig. 8. The synthetic object composition into a photograph rendered with an optimised radiance map of 79x40 resolution. While this has reduced the radiance map resolution considerably, we still maintain image quality. The blue billiard ball and green block is synthetic.

VI. Conclusion and Discussion

In a series of psychophysical tests with human subjects, we observed that the HVS is insensitive to local illumination changes in both light direction and intensity changes, if no reference images are given explicitly. This observation lead to additional tests to identify the perceptible range of HDRI radiance map resolutions. Our results show that there can be a significant reduction made to lighting resources while maintaining the visual quality of composition. This allows for large memory savings with no cost to visual quality. We approximately save an average of 99% of memory for a HDRI radiance map in a general production setup.

During our literature survey, we could not find sufficient references to identify characteristics of HVS for image composition. Our experiments can guide the overall set up for psychophysical tests of image composition that do not make use of explicit reference images. The observed results can provide background to understand the perceptual constraints and the role of illumination.

Although our study is mainly focused on optimising image based radiance maps, the approach can be extended to identify optimal ranges of other parameters such as materials, illumination models, or shape variations that are related to image composition. Considerations can also be made with video instead of still images. Furthermore, a comparative study between filtering algorithms for resolution reduction will have varying effects. We leave these topics for possible future study.

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