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Material Design in Augmented Reality with In-Situ Visual Feedback

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Abstract

Material design is the process by which artists or designers set the appearance properties of virtual surface to achieve a desired look. This process is often conducted in a virtual synthetic environment however, advances in computer vision tracking and interactive rendering now makes it possible to design materials in augmented reality (AR), rather than purely virtual synthetic, environments. However, how designing in an AR environment affects user behavior is unknown. To evaluate how work in a real environment influences the material design process, we propose a novel material design interface that allows designers to interact with a tangible object as they specify appearance properties. The setup gives designers the opportunity to view the real-time rendering of appearance properties through a virtual reality setup as they manipulate the object. Our setup uses a camera to capture the physical surroundings of the designer to create subtle but realistic reflection effects on the virtual view superimposed on the tangible object. The effects are based on the physical lighting conditions of the actual design space. We describe a user study that compares the efficacy of our method to that of a traditional 3D virtual synthetic material design system. Both subjective feedback and quantitative analysis from our study suggest that the in-situ experience provided by our setup allows the creation of higher quality material properties and supports the sense of interaction and immersion.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1. Introduction

Materials in the physical world have unique appearance properties including color, glossiness and spatial texture. The same material may appear quite different under different illumination conditions. Material design is the process of specifying the properties of a virtual surface so that it will have the same appearance as a real world material in different environments. Many software packages (e.g. Maya, Blender) provide material design interfaces. In these interfaces users specify properties with visual feedback provided on a simple geometric form rendered with a simple background (often a checkerboard pattern). Systems have been proposed to provide feedback by rendering more complex geometries in more realistic environments. However, designing materials in a realistic environment has not been studied.

Our paper represents a first step towards quantitatively evaluating the effectiveness of a real environment for material design, by comparing it with material design in the virtual environment. We introduce Augmented Reality (AR) into the process of defining material properties. According to [ABB*01], the definition of Augmented Reality is a system that (1) combines real and virtual objects in a real environment, (2) runs interactively, and in real time; and (3) registers (aligns) real and virtual objects with each other. Our AR-based setup allows material properties selected by the designer to be interactively superimposed on a real 3D object against a real background. The designed materials are rendered in the context that the users are exposed to, which helps users understand better how the materials behave under real lighting and shading conditions. The real-time interaction of AR makes sure that every modification made by users can be interactively viewed.

To test how AR contributes to material design, we build an AR material design prototype, where tracking is enabled to superimpose virtual materials on test objects and lighting conditions are estimated in real time to display material behaviors. To achieve real-time high resolution rendering, we use GPU-based ray-tracing with an irradiance caching algorithm for global illumination. We present a user study to compare the AR material design system with a 3D synthetic virtual material design system. We ask users to match materials to real world target objects on the two systems, and compare their results based on authenticity and similarity to the real materials. We want to compare the two systems to evaluate how the real environment influences users' behaviors during material design process, rather than which system is superior. To achieve our goal, we simplified the AR system to avoid bias caused by system settings.

The study consists of four parts. First, users conduct experiments matching materials. Second, users are asked to fill in a questionnaire after they finish the experiment in order to provide subjective feedback. Third, raters who are familiar with material design are

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asked to rate the designed materials based on the similarity to the real target materials (color, intensity, reflectance behaviors and so on). Finally, we use a light dome to measure the target materials used in the experiment and fit BRDF models to estimate the parameters, which are compared with parameters of designed materials from the two systems. We simplify the material design tasks so that users can focus on how the real and virtual scenes influence the materials. The same rendering system and user interface are used in both the systems to avoid bias.

From the objective and subjective evaluations, we observe the following:

1. Generally, users perform better on the AR material design system compared to the virtual synthetic material design system in terms of efficiency and quality of designed materials.
2. Users report superior experience with the AR material design system because of intuitive interaction style, the use of real lighting conditions and the sense of immersion created by having a realistic background.
3. Our study shows the presence of common preferences and usage patterns across users. For example, users prefer using the color spectrum tool over sliders, and they prefer adjusting parameters one at a time.
4. The geometry consistency (shape and orientation) between reference models and test objects influences the process of material design.

As with any other human experiments, our conclusions apply only within the context of our user study. However, we believe that the trend can be generalized and used for other related applications. We anticipate that our findings will lay out the foundation for lines of research that will further exploit the synergistic combination of AR and material design.

2. Related Work

User Study in Appearance Design Kerr et al. conducted two user studies to evaluate different material design interfaces [KP10] and lighting design interfaces [KP09]. They built a prototype for evaluating and comparing different interfaces and systems involving user studies, where they defined the concept of *matching trial* and *open trial* based on whether an exemplar should be matched, or whether the user should create a new design. We choose the matching trial approach since we want to match the design materials to real world materials. Rather than giving the users image exemplars however, we provide physical exemplars to be matched.

Material Editing Currently, many off-the-shelf software products provide material design features, such as Maya [Aut17] and Blender [Ble02]. Existing tools provide synthetic scenes to set a context within which users design materials. These synthetic background scenes include but are not limit to a grey or checkerboard background, virtual lightings and cameras, and the use of virtual primitives on which the material is applied.

Many systems focus on editing material parameters and modifying BRDF models. Different prototypes can be divided into three categories: physical sliders, perceptual sliders and image navigation. Physical slider is a way to directly modify the parameters of BRDF models (e.g. diffuse, specular) to change materials. Maya uses this method for material design. Perceptual slider is another prototype where each parameter represents a perceptually-meaningful dimension of surface appearance such as luminance and contrast. Pellacini et al. [PFG00] proposed a Ward BRDF model using perceptual parameterization. Westlund et al. [WM01] and Wills et al. [WAKB09] developed different measurements for perceptual parameterizations based on the material surfaces and BRDF models. Image navigation provides users with a group of materials with certain variations. Instead of modifying parameters, users can browse through the materials and pick the one that is closest to their goals. Other lines of work [MAB*97] [NDM06] and software [ADO09] further explored this idea and developed interfaces based on it. The experiment results from [KP10] show that users perform well on both physical sliders and perceptual sliders, but poorly on image navigation. Further, they found no significant difference on performance between physical sliders and perceptual sliders. Therefore, we implement our interface using the physical slider prototype.

Fleming et al. recorded in [FDA03] that users can estimate surface reflectance properties reliably and accurately with the help of realistic illumination, which further stresses the importance of introducing real lighting into material design process. Following this idea, Colbert et al. [CPK06] proposed an intuitive painting mechanism to create physically correct BRDFs with natural environment lighting. However, it is placed in an entirely virtual environment.

Material Display Various systems have been developed to project virtual materials on real world objects. For example, Raskar et al. [RLW00] projected rendered images onto a real object to artificially replace the material properties. Aliaga et al [AYL*12] proposed a system using multiple projectors to superimpose high resolution appearance. Miyashita et al. [MIWI16] presented a material display system to overlay high resolution materials on a physical sphere in a zoetrope using compositing and animation principles. However, the generated materials are still rendered in an ideal synthetic scene (checkerboard in their system) and users cannot move the objects to see how materials change with real lighting in different angles. All systems mentioned above work for static models and some of them are not view dependent, which makes it difficult for the user to physically interact with the targets (e.g. move and rotate) during material design process. Based on Raskar's system, Bandyopadhyay produced a movable 3D painting system [20001] using projectors. To reproduce various materials, Hullin et al. [HIH*13] proposed methods using projection mapping techniques and specialized displays. However, objects and materials in these systems are illuminated by fixed virtual lights without adaptations to real environments.

High Resolution Rendering in Augmented Reality The traditional techniques for high resolution rendering in AR is based on rasterization, and achieve a high rendering speed to support the interactivity of AR. There are many algorithms developed based on this technique. For example, Irradiance Environment Mapping was proposed in [RH01] in order to generate the illumination from real scenes onto virtual objects. Knecht at al. [KTM*10] and Grosch et al. [GEM07] developed algorithms to simulate high-quality diffuse global illumination in AR. However, it is difficult to calculate

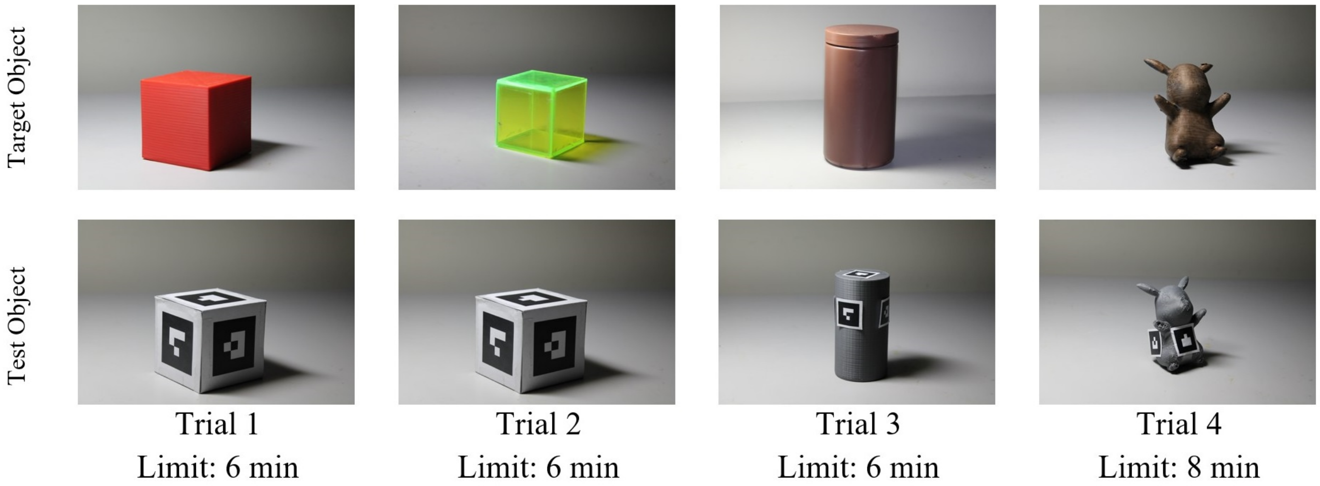


Figure 1: *Top: Target objects with reference materials for all trials. Bottom: Test objects used for AR tracking. Time limits are listed below.*

specular effects such as reflection, refraction and caustics in high resolution using rasterization-based rendering.

Another rendering approach is to use ray-tracing, which can achieve high resolution rendering and accurate light transport calculations. There are many offline ray-tracing rendering algorithms which are used in mixed reality to render virtual objects and simulate global illumination [KHFH11] [Deb08]. Although high resolution and photorealism can be achieved by these algorithms, they cannot be used for interactive material design systems due to the low rendering speed. Kan et al. [KK12] implemented an AR system using GPU based ray-tracing and photon mapping, which provides realistic and physically correct rendering effects. We adopt their algorithm to implement the rendering pipeline of both material design systems, since it can accurately simulate different material reflection behaviors under real lighting conditions.

Global Illumination in Mixed Reality It is important to use global illumination in material design systems since lighting plays a significant role in the simulation of realistic materials. A solution to fast global illumination calculation in mixed reality with automatic 3D scene reconstruction was proposed in [LB12], where the Reflective Shadow Maps [DS05] algorithm is used for the indirect illumination calculation. However, they only support diffuse illumination. Many other algorithms [GSHG98] [GEM07] use preprocessing to calculate the indirect illumination for possible directions and store the irradiance in Spherical Harmonics. Then the irradiance can be dynamically applied in real time according to the directions of incident direct light. However, these methods are limited since they cannot deal with non-static objects and the preprocessing takes time due to the large irradiance volume.

Irradiance caching (IC) proposed by Ward [WRC88] is a widely used algorithm for global illumination. It takes advantage of spatial coherence to accurately interpolate irradiance records in sparse location. Many algorithms have been developed based on this idea, such as IC with Neighbor Clamping [KBPZ06], where the average distance to the nearby geometry is clamped based on the distance to the neighboring cache records, and IC with improved error metrics [SJJ12] [JSKJ12], which improves the cache record placements. Kan et al. [KK13] developed a system using the irradiance caching algorithm to simulate the light transport between virtual objects and real world in mixed reality. They use rasterization to interpolate the indirect illumination between cache records and calculates the direct light using ray-tracing, which achieves real-time rendering. Their work can efficiently simulate physically correct reflection and refraction behaviors under various lighting conditions and we use their algorithms to achieve global illumination.

3. Study Overview

Goal We try to evaluate how providing visual feedback by rendering in an environment familiar to the user influences the performance of 3D material design. To be more specific, we compare the traditional material design in synthetic 3D virtual scenes with a new Augmented Reality material design prototype, in order to test whether users can perform better in designing material appearances with the help of Augmented Reality, and in what aspects Augmented Reality can contribute to their improvements. We mainly focus on the comparison of interaction, lighting and the authenticity of designed materials.

Users In order to draw generalized conclusions, we recruited participants who are familiar with computer graphics and material design, as well as novice users. According to [KP10], novice users are capable of designing and editing complex realistic materials. Furthermore, we want to see if different knowledge levels in material design will lead to different results. We asked all the subjects to rate their level of knowledge regarding material design from 1 to 5 before the experiment (1 represents extremely unfamiliar and 5 extremely familiar). Subjects who rated themselves 1 or 2 in a certain field were considered as novice users and viewed a small lecture to equip them with necessary knowledge.

Task Since long experiments may cause fatigue, we try to balance between length and complexity of the experiment. On the one hand, we want to complete an adequate number of trials and complex-enough materials for editing to get meaningful results. On the other hand, we try to avoid bias and fatigue caused by a long experiment. Therefore, we designed eight independent trials, half on the AR material design system and half on the synthetic material design system. The total experiment length is set as one hour per person which promises good measurements and results while keeping a low level of fatigue. In each trial, subjects are asked to match as close as possible a material to the surface of a real world model. The material is designed on the same geometry as the real world model. We use the same models on both systems for ease of comparison.

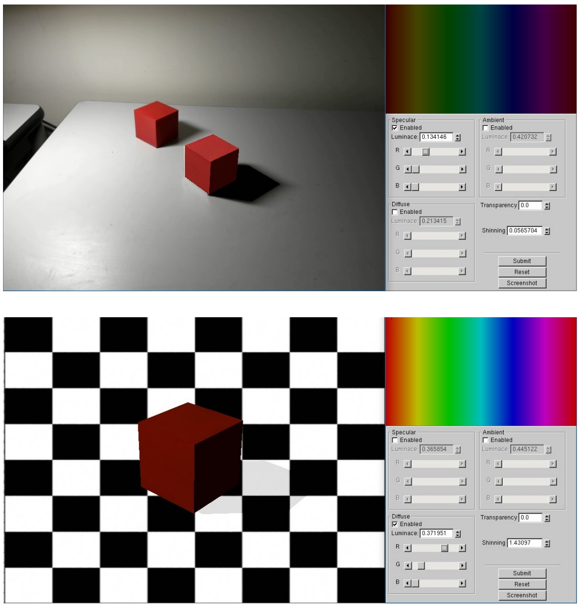
Materials Considering that material design is time-consuming, we simplified the task by providing only a few parameters to edit, so that subjects can focus on the different material behaviors between real and synthetic scenes. The parameters include specularity, diffuse albedo, ambient, transparency and shininess. Taking into account that not all subjects are experienced users in material design, we decided to only provide one BRDF model for the experiment and we chose Phong model for simplicity.

Models and Geometries Four different real models and geometries are chosen as targets in our study, including cubes, cylinders and complex geometries. Tasks are arranged in increasing order of geometry and material complexity. Matching materials to a standard cube with a diffuse surface serves as the warm-up for the subjects, while working on complex geometries with a dark copper material is most challenging since irregular surfaces and their unpredictable behaviors. Subjects were given the real target models and asked to design materials on the exact same geometries on the computer. For all the cubes and cylinders, no textures applied. Complex geometry comes with an initial texture. The real target models are either pre-existing objects or 3D printed with painted materials.

Interaction While Augmented Reality can be presented in various display systems, we stick to computer screens as the display media for both the AR material design system and the synthetic material design system, since we believe that the difference of display devices between AR and synthetic systems might introduce noise and bias in the results. For the AR material design system, models with tracking markers (Figure 1) are superimposed by the designed materials and rendered in the real scene. Subjects can physically interact with the models with overlaid materials using their hands. For the virtual synthetic material design system, the designed materials are placed in a synthetic scene with a checkerboard background. Subjects work on the 2D screen and interact with the object via their mouse.

Lighting In the AR material design system, real world light estimate is used for simulating of global illumination so that the material behaviors under a real environment can be generated. Users can adjust both the light (position and orientation) and the objects to see how materials react to the environment. For the synthetic material design system, we follow the widely used setup, where the lighting is fixed relative to the object.

User Interface Both systems use the same interface for material design (Figure 2). For parameters such as specularity, diffuse albedo and ambient, subjects can edit RGB channels by dragging corresponding sliders. They can also use the spectrum with a luminance slider to directly pick colors. The luminance changes with the RGB value. They can also modify the transparency and shininess by changing the slider. A screenshot button helps subjects to make a screenshot for current material and a reset button give subjects a chance to start over. After finishing the material design, subjects can use a submit button to automatically generate a report recording the material properties they just designed.


Specular ☑ Enabled Luminace: 0.134146
Ambient ☐ Enabled Luminace: 0.420732
Diffuse ☐ Enabled Luminace: 0.213415
Transparency 0.0
Shinning 0.0565704

Specular ☐ Enabled Luminace: 0.365854
Ambient ☐ Enabled Luminace: 0.445122
Diffuse ☑ Enabled Luminace: 0.371951
Transparency 0.0
Shinning 1.43097

Figure 2: *Top: Augmented Reality material design user interface. The front cube is superimposed with user designed material. Bottom: Virtual Synthetic material design user interface. The materials in two systems were designed by same user.*

4. Experiment

We ask subjects to complete eight independent trials, during which their performances and actions are recorded. The trials vary in the geometry of models, target materials and presence of textures.

Preparation We conducted pilot experiments on 5 additional subjects, the results of which are not presented in this paper. We also revisited the trials based on the feedback from pilot experiments.

Trials Subjects were asked to finish all four trials on one system and then switch to the other one. The order of the systems was balanced. We used different real world materials as targets for each trial. We diversified the target materials by choosing materials with different properties and select different geometries. For Trial 1, a fully saturated glossy plastic red cube was used as the target. For Trial 2, the goal was to match a half saturated green glass cube. For Trial 3, the target was a brown cylinder with half diffuse and half specular surface. For the last trial, a complex geometric form (a cartoon character) with copper paint served as the target. For Trial 1 to 3, a glossy diffuse grey cube/cylinder was provided to subjects as the initial state. For Trial 4, a virtual object with the same geometry and texture was given to subjects at the beginning of the trial. Each trial had a fixed time limit, which was set based on the pilot experiments. Subjects could end the trial earlier if they were satisfied with their results.

Procedure Sixteen subjects from different age groups and education background participated in our study. Half considered themselves as novice users. All subjects had normal or corrected-to-normal vision and did not suffer from color blindness. Before the experiment, novice subjects were given a small lecture (around 15 minutes) about material design and Augmented Reality. Before they started the experiment on each system, all subjects were given a training session to help them get familiar with the user interface and basic operations. Only when the experimenter verified that subjects were familiar and comfortable enough with material design and system operation could they start the experiment. Each subject spent around one hour to finish all the trials. To avoid bias, subjects were asked to start with one of the two systems randomly. After finishing all the trials on that system, they switched to the other system.

As part of the experiments, we conducted three different kinds of evaluation: questionnaire, human rating and BRDF parameter evaluation. The first two provide subjective feedback, while the last one gives us objective comparison.

Questionnaire After finishing all the trials, subjects completed a questionnaire immediately, where they rated how satisfied they were with their result for each trial on a scale of 1 to 5 (1 represents worst and 5 represents best). Subjects were also asked to rate both the systems in the following categories: (1) lighting setup, (2) interaction style, (3) overall performance and (4) personal preference. Subjects could also leave feedback for each system.

Rating We introduced 10 raters from those who were familiar with material design into our experiment during the evaluation process. Their goal was to compare the authenticity of materials designed by subjects from both systems. Raters voted for the designed materials that had better performance (more similar to the target material and fit better in the environment) and select reasons (multiple selections) from provided options (color, intensity under lighting, diffuse and specular behavior) for each vote. Raters did not participate in the matching trial to prevent bias. Since our goal is to improve the authenticity of the materials in real environment, we used the AR system for rating. During the rating process, all the designed materials were imported into a new real environment (scene), which was different from the scene used for experiment. We used a new environment so that the raters would be evaluating the similarity of the materials, rather than the similarity of a particular view or image. Raters were blinded to the order of subjects' results and the information on which system produced the result.

BRDF Parameters Evaluation To fully evaluate the authenticity of designed materials from both systems, we first estimate the BRDF parameters of our real target materials, and then compare them with the subject-specified BRDF parameters from the matching trials using mean squared errors. We focus on the estimation of diffuse and specular since those parameters play important roles in material appearances.

To estimate the BRDF parameters, we use a dome with 45 light sources. With 3D coordinates recorded, these light sources are located on four different layers towards the center of the bottom circle where test materials are put. The first two layers have 15 light sources each, the third layer has 10 light sources, and the highest layer has 5 light sources. There is a camera right at the apex of the dome to capture raw responses. We use an achromatic striped spectralon that has the pure diffuse reflectance of 0.12, 0.25, 0.50, and 0.99 to calibrate the system. Coefficients are calculated to represent how the response corresponds to the diffuse albedo and to compensate for the light color. After recording 45 images for these four materials, we compute the average color of the object region as a BRDF measurement, and then fit the Phong model to estimate the parameters of diffuse ρ_d, specular ρ_s. To avoid overfitting, we interactively try different shininess n and set an upper bound to minimize the fitting error.

Similar to the method in [NDM05], we consider each average color as a BRDF sample of the material and we can plot 45 sampling points of response with respect to the incident angle θ for RGB channels of each material. We assume that the specular component is not significant for light sources on the first two layers, so we fit a pure diffuse model to estimate ρ_d. With ρ_d fixed, we use the rest data to fit the whole Phong model with the parameters of ρ_s. Fitting the BRDF model can be considered as an optimization problem, and we use linear least squares in this process.

$$\rho_d = \underset{\substack{0<\rho'_d<1 \\ i \text{ on layer 1 and layer 2}}}{\operatorname{argmin}} \left[S(\theta_i,\phi_i) - M_{\rho'_d,0,0}(\theta_i,\phi_i)\right]^2$$

$$\rho_s, n = \underset{\substack{0<\rho'_s<1,0<n'<5 \\ i \text{ on layer 3 and layer 4}}}{\operatorname{argmin}} \left[S(\theta_i,\phi_i) - M_{\rho_d,\rho'_s,n'}(\theta_i,\phi_i)\right]^2$$

Where $S(\theta_i,\phi_i)$ is the BRDF sample values and $M(\theta_i,\phi_i)$ represents the Phong model we want to fit, where its subscripts are the parameters used in the Phong model. We fix the shininess at a time so that we can separate the linear components, which improves the efficiency and stability of the optimization, and we iterate the shininess to converge to the global minimum.

5. System Implementation

In this section, we describe the implementation of the AR material design system. Figure 4 shows system setup.

System Structure Our system includes two high resolution cameras for input, a PC for processing and a monitor for display. One of the cameras is used for real-time video input and the other one is used to capture the environment image for environment mapping and real world light source estimation. For each frame, the images from both cameras are converted to HDR by using inverse tone mapping. Image of the real scene captured by the first camera is used for marker detection to provide the location for virtual object registration and relative camera position. The environment image captured by the second camera is used for environment mapping and the estimated light source information is used to set up the virtual lighting. Then, all the calculation and estimation results are passed to a GPU ray-tracing pipeline for rendering, the result of which is composited with real scene images and delivered to an output device. The processing of video input (including rendering and composition) and light source estimation run on two different

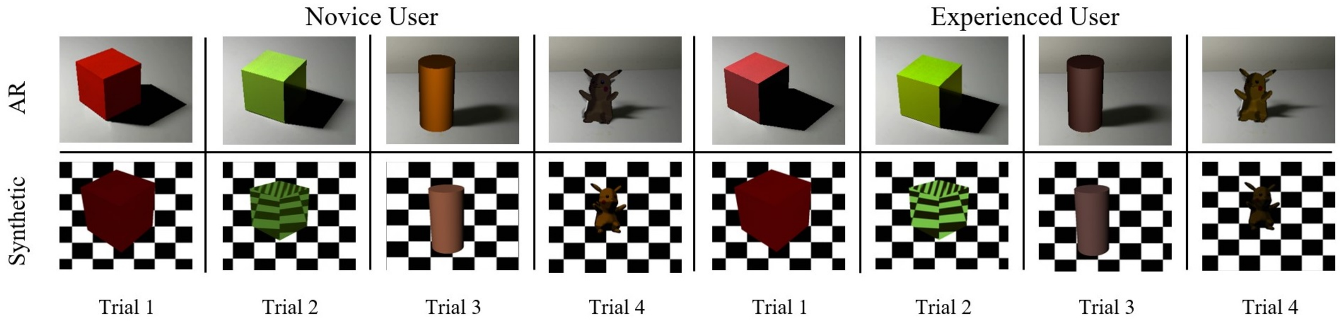


Figure 3: *Example of designed materials of two subjects using different systems.*

Figure 4: *Augmented Reality system setup. The camera on the tripod is used for real time video input and the camera on the table is used to capture environment image for environment map and light source estimation.*

threads to make sure the calculation is fast enough for real-time interaction.

Rendering To generate more realistic material appearances, we use global illumination in both the AR material design system and the synthetic material design system. We follow the methods in the paper [KK13] to use the differential irradiance caching algorithm in combination with ray-tracing to enable multiple bounces of global illumination. Monte Carlo integration in GPU ray-tracing is used to evaluate differential irradiance at irradiance cache records in one pass. Diffuse light transport between virtual and real worlds can be efficiently calculated in our system to produce a high-quality result while preserving interactivity. The NVIDIA OptiX ray-tracing engine [PBD*10] is used to take full advantage of parallel power of GPUs. We use GPU ray-tracing where differential irradiance is evaluated at the locations of cache records. We calculate direct illumination and specular indirect illumination by ray-tracing.

Light Estimation We use a camera to capture the environment and estimate the light source to simulate the material behavior under real lighting conditions. Following the method mentioned in [KK12], we use the image-based lighting technique to estimate the real light in the environment for AR system. After acquiring the basic lighting information, we apply adjustments to the estimated light source based on the difference of position and orientation of the real object (markers) between frames. The adjustment ensures that the relative position and orientation between virtual light and virtual object remain the same with the real situation, especially when a subject physically interacts with the real object. To reduce computational cost, we do not directly perform the transformation of real object on the virtual object. The whole system is set up in a controlled lighting environment for accurate light estimation.

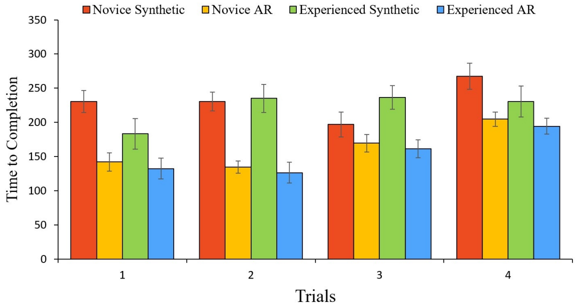


Figure 5: *Average time to completion for all trials over novice and experienced users (in seconds).*

Tracking For Augmented Reality, tracking is important since it provides location and orientation for 3D virtual object registration. In our AR material design system, we use the multi-marker tracking technique provided by ARToolKit [KB99]. We use multi-marker tracking instead of single-marker tracking because we want the designed materials to entirely overlay and move smoothly with the real object. A single marker can easily be occluded when subjects try to physically interact with the real object. Using multi-markers, at least one marker can be detected, even if some markers are hidden. We carefully designed and measured the location and orientation of multi-markers before the experiment to ensure accurate tracking and material overlay.

The synthetic material design system uses the same rendering pipeline. Since the whole scene is virtually generated with the checkerboard background, there is no need for video input, real light estimation and tracking.

Hardware Description We use a 24-inch HP Compaq LA2405wg screen with 1920 × 1080 resolution for display. The systems ran on a computer with Intel Core i7 3.30GHZ CPU, 16 GB RAM and NVidia GeForce GTX1080 GPU. The two cameras used for video input and environment map are Logitech BRIO 4K pro and Logitech HD C615 respectively.

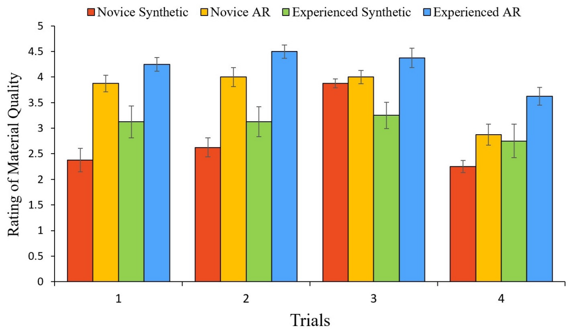


Figure 6: *Average material quality rating over novice and experienced users.*

6. Evaluation

As mentioned in Section 4, we present an analysis for the data collected from our experiment in three different steps. First, we evaluated the data and feedback from subjects and questionnaires. Second, we collected results from raters and analyzed the reasons they selected for each vote. Last, we compared the subject-defined material parameters with our estimated BRDF parameters of real target materials. We use repeated measures analysis of variance (ANOVA) [Ste12] to compute statistical significance. This method is appropriate to calculate correlations with within-subject factors (in our experiment, each subject using two systems) and violates the assumption of independence in standard one-way ANOVA. A p value represents the confidence of difference between two sample groups. A p value below 0.05 indicate 95% confidence of difference.

Time to Completion We recorded the time that each subject used for each trial. Subjects were usually able to finish each trial within the time limits. Figure 5 shows the average time to completion for each trial over novice and experienced users. Time to completion on synthetic system is significantly higher than AR system for all trials ($p < 0.030$) for all users. Not unexpectedly, novice users spent more time on both systems compared to experienced users (except trial 3 on synthetic system) due to the lack of familiarity with the task.

Satisfaction for Material Quality Subjects were asked to rate their own results for each trial after the experiment on a scale from 1 to 5, with 1 being the worst and 5 being the best. Results were rated in terms of the closeness the designed materials and real target materials. Screenshots were provided so that subjects could compare their results with the real target materials. Figure 6 shows the average rating results for each trial.

Subjects rated their work on the AR system significantly higher than their work on the synthetic system ($p < 0.045$). We believe the behaviors of novice users on Trial 3 differs because it was difficult for novice users to duplicate the same size of specular highlight on the real target object. According to our observations, for trial 3, novice users gave up trying earlier on both systems due to the impatience caused by failed attempts, which lead to less time spent on this trial compared with experienced users and more similar self-ratings between two systems. The average rating of experienced users is relatively higher than that of the novice users on both systems ($p < 0.011$), which can be explained by the fact that experienced users were more familiar with material design tasks and could create results that met their expectations. Compared with other trials, ratings for trial 4 were relatively lower, indicating that all users were unsatisfied with their results for complex geometries.

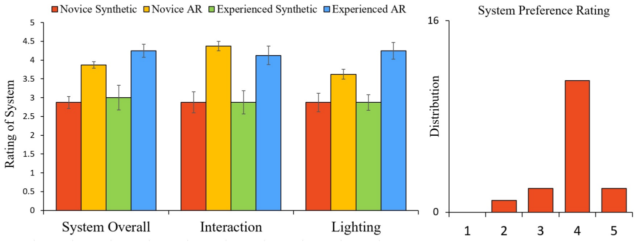


Figure 7: *Left: Average system rating over novice and experienced users in terms of overall system performance, interaction and lighting setup. Right: Distribution of preference rating. 1 represents preferring synthetic system most and 5 represents preferring AR system most.*

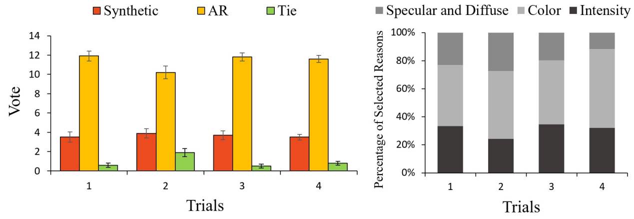


Figure 8: *Left: Average number of votes for each system over all trials. Right: Percentage of selected reasons of votes for AR systems.*

Subjective System Ranking and Rating Subjects rated each system in three different categories based on their preferences (lighting, interaction style, system overall) on a scale from 1 to 5, with 1 being the worst and 5 being the best. They were also asked to rate their preferences over two systems, with 1 preferring synthetic system most and 5 preferring AR system most. Average ratings are shown in Figure 7. In all categories, the AR system outranks the synthetic system ($p < 0.001$) for both novice and experienced users. No statistical difference was observed between ratings of novice and experienced users ($p > 0.181$). The majority of subjects preferred the AR system over synthetic system.

Raters' Evaluation Raters were asked to go through all subjects' results for each trial, and were asked to compare the two materials from the two systems respectively, which were designed by the same subject, and gave votes based on the authenticity of materials and similarity to real targets (see Figure 8). We can see that the number of votes for the AR system is significantly higher than that of the synthetic system ($p < 0.001$). No statistical difference was observed between trials ($p > 0.801$). To further explore why raters prefer results from AR system, we analyzed the reasons tied to each rating for AR (details in Section 4). Intensity and color are the main reasons ($p < 0.041$) that raters preferred the AR system over the synthetic system, and there is no significant difference between the ratings for intensity and color. We can make two conclusions based on the data. Our results agree with made in [KP10] that color is a very important factor in overall material appearance.

Object	ρ_d_R	ρ_d_G	ρ_d_B	ρ_s_R	ρ_s_G	ρ_s_B
Red Cube	0.8669	0.0874	0.0788	0	0.0405	0.0469
Cylinder	0.2509	0.128	0.0789	0.173	0.1815	0.2015
Complex Geometry	0.2346	0.1389	0.079	0.1784	0.1245	0.0775

Table 1: *Estimated BRDF parameter values for all target objects in experiment.*

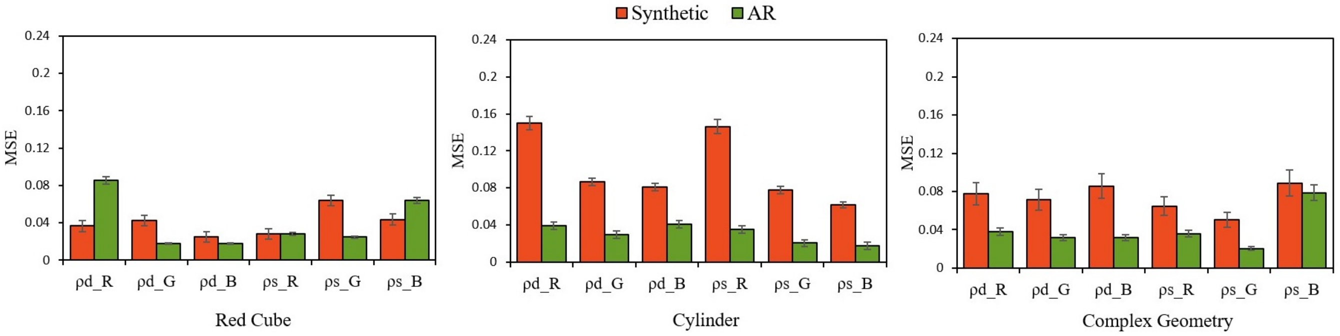


Figure 9: *Mean square errors between user defined material BRDF parameters and estimated BRDF parameters over two systems.* ρ_d *and* ρ_s *represent diffuse and specular respectively with RGB three dimensions.*

We also conclude that with the help of real scenes in AR, users can perform better in color and intensity adjustment for material design.

BRDF Parameter Comparison Table 1 shows the estimated BRDF values of the target materials we used in our experiment, except for Trial 2, which involves with transparent material which cannot be accurately measured using the light dome, we focus on the BRDF parameter comparison for other trials. To qualitatively compare the overall performance of each system, we analyze the mean square error between user defined material BRDF parameter values and estimated BRDF parameter values. The lower mean square error (MSE) indicates that user designed materials are closer to the real target material on average. Figure 9 shows that the MSE values over all parameters of the AR system are relatively lower than that of the synthetic system, except some parameters for the red cube. This could be partly due to the high saturation of the material, which is not close to natural materials and influences users judgement of color. In addition, the dark side of the red cube with attached shadow could have given subjects an impression of a darker material appearance in the AR system against the real scene with controlled lighting.

7. Workflow Observation

In this section, we discuss behaviors of subjects during the experiment. Unless stated otherwise, our observations apply to both novice users and experienced users.

Lighting Adjustment For the AR material design system, the majority of subjects made small lighting adjustments, including lighting intensity and orientation, in simple geometry trials (cubes and cylinders) before they started to edit the materials, even if everything in the scene was pre-calibrated. Based on their own judgements, they adjusted the lighting and shading of test objects to match real target models. However, for the trial using complex geometry models, only a few subjects adjusted the settings at the beginning. This leads us to believe that users do care about the lighting and shading of the materials and how materials react to the real environment. Given more freedom of control, they would like to explore different lighting possibilities based on their own preferences and judgements, which might be beyond their capabilities since lighting design is another complex task.It also suggests that different people have different perceptions and sensitivities on how lighting changes materials. The sensitivity to lighting decreases when the geometry complexity increases. In other words, people may not be able to perceive how lighting changes materials when complex models are used for material design. It is worth mentioning that after subjects finished the lighting adjustment at the beginning, they were inclined to keep the light source fixed without modifying it for the rest of the trial.

Geometry Consistency Based on our observations, many subjects rotated and moved the test objects to match the orientation of real target objects at the beginning of each trial for both systems, which suggests that users do care about the geometry consistency (shape and orientation) of models used for material design. To further test our observation, we conducted a sub-experiment. Instead of real target objects, we used images as references. The object orientations in the images were different from the initial orientations of the test objects. We asked five subjects to design materials on both systems using the images. In this situation, all subjects started trials by modifying the orientations of the test object based on the given images. Based on these results, we believe that geometry consistency does influence the material design process, and for 3D material design, it would be better to keep the test objects and references in the exactly same shape and orientation.

Object Interaction Subjects were more likely to interact with the objects superimposed with applied materials in the AR system than the virtual objects in the synthetic system. For the AR system, subjects often rotated the objects to see materials on different sides during the matching trials, while for the synthetic system, most of the subjects stick to the positions and orientations of the virtual objects after the adjustments at the beginning. These observations also agree with the rating on interaction from the questionnaires.

Real Scenes vs. Synthetic Scenes We noticed that users prefer real scenes in the AR system to the virtual checkerboard background in the synthetic system. When asked "which background do you prefer most, real scene or checkerboard?", 14 out of 16 subjects chose real scene. Subjects commented, "I felt like it was very realistic when working in a real scene, while the checkerboard gave a sense of fake and weird", and "It (the real scene) is better to judge the reflection, especially for the transparent one (Trial 2)". These are some typical comments that many subjects mentioned or expressed in similar ways. Their preferences also agree with their ratings and performances mentioned in Section 6. However, a minority of subjects mentioned that the rendered materials were a little bit too perfect compared to the real scene. We believe that the contrast is caused by the difference of noise in captured video input. Adding noise and distortion into rendered materials can be considered as future work to register the virtual materials better into real scenes.

One-Parameter-at-a-Time The most noticeable trend of material editing is that subjects prefer to focus on one parameter instead of modifying multiple parameters simultaneously. To be more specific, given RGB three dimensions (luminance is calculated based on these dimensions) for parameters such as specular, diffuse and ambient, subjects were more likely to work on one parameter until they were content with the appearances. However, it does not mean that subjects would fix the parameter values permanently after they modified them. Based on our observations, subjects revisit some parameters to further polish their work after the whole appearance was roughly settled .

Spectrum vs. Sliders We noticed that subjects spent more time picking colors directly from spectrum instead of dragging sliders in both systems. This applies to the majority of novice users and some experienced users. This fact suggests that subjects, especially novice users, may not be able to precisely anticipate color when dragging a slider in RGB color space. On the contrary, spectrum can provide a more intuitive display of color and is preferred among subjects. However, we also notice that even if working on spectrum, subjects were not able to pick their preferred color in their first few attempts. They were inclined to narrow down to a small range in the spectrum, and blindly try different colors until they were satisfied or gave up. Based on these observations, we believe that adding more features on spectrum, such as range selection and zoom-in to provide more accurate interpolation and detailed color display, may help users for color selection.

8. Discussion and Conclusions

In this section, we draw conclusions for our experiment based on evaluations and observations. We want to remind our readers that our conclusions are drawn from a limited number of test cases and only apply to experiments we conducted. Also, we stress that the main goal of our paper is not to prove that one system is better than the other. Instead, we want to explore how a real environment influences material design and user behavior.

Comparison of Material Design Systems Overall, we found that users perform better on the Augmented Reality material design system in terms of efficiency and quality of designed materials, regardless of their experience level. They also have better user experience on the AR system than the traditional synthetic system, which makes them prefer the AR system.

Interaction Based on users' feedback, users are more willing to interact with real objects in the AR system than manipulating virtual objects in the synthetic system. It is easier and more intuitive for users to perform physical interaction and observe material behaviors, which makes them feel confident in material design process.

Lighting Lighting setups influence users behaviors in material design. Users prefer the adjustable lighting setup in the AR system compared to the fixed lighting in the synthetic system. Given more freedom of control for lighting, users can try different lighting conditions in order to observe how materials adapt to the environment.

Background Scenes We find users prefer real scenes as background during material design instead of virtual scenes. The real scenes give users a realistic and immersive feeling, and can be used to generate authentic reflection, especially for mirror and glass materials.

Influence of Geometry Consistency Geometric properties, such as shape and orientation of the models used for material design, influence how users perceive materials. Users are inclined to adjust and match the geometry properties of test objects based on the target models. With the same shape and orientation, users can directly observe the behaviors of target materials and use them as references, which helps them match material appearances.

Common Workflow There are common patterns in editing material parameters among our subjects. We notice that most subjects are inclined to use color spectrum rather than RGB sliders to define a color. Our subjects also prefer to edit one parameter at a time, especially when the parameter has multiple editable dimensions. Revisiting modified parameters happens when results are close to targets and small modifications are needed.

Limitation and Future Work There are some limitations to our work. First, considering the potential fatigue of tedious parameter adjustments, we only provided a limited number of parameters and BRDF models for users to edit. Secondly, target materials used for references in our experiment are relatively simple, because we use real life materials instead of synthetic material sample images, which are often used in virtual environment material design tasks. Since our goal is to evaluate the influence of real environment on material design, real objects serve our purpose better. Moreover, we use the same display format for both systems to present the designed materials to avoid bias. However, we believe there are many better display formats for AR, such as multiple projection and head mounted devices, which can be considered as future work to further improve user experience.

9. Summary

This paper presents a first step towards quantitatively evaluating the performance of material design in real environment. To compare with the traditional 3D virtual synthetic material design system, we created an Augmented Reality material design prototype, where users can observe their designed materials against real environment with physically correct material behaviors under real lighting conditions. They can also interact with the test object superimposed by the virtual materials in real life, which enhances user experience during the design process. To further evaluate the influence of real environment on material design, we conducted a user study where we asked subjects to design materials based on real world materials on both AR and virtual synthetic systems. The evaluation for the user study includes three parts: (1) subjects' feedback collected from questionnaires, (2) human rating for subjects' results based on authenticity and similarity to target materials and (3) comparison between estimated BRDF parameters and subject-defined material parameters.

Our results show that compared to the traditional virtual synthetic material design system, Augmented Reality material design has better performance in terms of efficiency, authenticity of designed materials and user experience. The advantage of AR material design system is that it can provide more intuitive interactions and display different material behaviors influenced by estimated real lighting conditions. We also evaluated workflow patterns based on our subjects' behaviors, such as the preference of spectrum over sliders and editing one parameter at a time.

We acknowledge that we have studied only a small subset of factors and models that influence material design, and we believe Augment Reality material design systems can be further improved in the future. Expanding material models and parameters and introducing more immersive display formats would be of interest.

References

[20001] Dynamic shader lamps: Painting on movable objects. In *Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR'01)* (Washington, DC, USA, 2001), ISAR '01, IEEE Computer Society, pp. 207–. 2

[ABB*01] AZUMA R., BAILLOT Y., BEHRINGER R., FEINER S., JULIER S., MACINTYRE B.: Recent advances in augmented reality. *IEEE computer graphics and applications 21*, 6 (2001), 34–47. 1

[ADO09] ADOBE SYSTEMS INC : Photoshop cs 4, 2009. 2

[Aut17] AUTODESK INC: Maya 2017, 2017. 2

[AYL*12] ALIAGA D. G., YEUNG Y. H., LAW A., SAJADI B., MAJUMDER A.: Fast high-resolution appearance editing using superimposed projections. *ACM Trans. Graph. 31*, 2 (Apr. 2012), 13:1–13:13. 2

[Ble02] BLENDER FOUNDATION : Blender, 2002. 2

[CPK06] COLBERT M., PATTANAIK S., KRIVANEK J.: Brdf-shop: Creating physically correct bidirectional reflectance distribution functions. *IEEE Computer Graphics and Applications 26*, 1 (2006), 30–36. 2

[Deb08] DEBEVEC P.: Rendering synthetic objects into real scenes: Bridging traditional and image-based graphics with global illumination and high dynamic range photography. In *ACM SIGGRAPH 2008 classes* (2008), ACM, p. 32. 3

[DS05] DACHSBACHER C., STAMMINGER M.: Reflective shadow maps. In *Proceedings of the 2005 symposium on Interactive 3D graphics and games* (2005), ACM, pp. 203–231. 3

[FDA03] FLEMING R. W., DROR R. O., ADELSON E. H.: Real-world illumination and the perception of surface reflectance properties. *Journal of Vision 3*, 5 (2003), 3–3. 2

[GEM07] GROSCH T., EBLE T., MUELLER S.: Consistent interactive augmentation of live camera images with correct near-field illumination. In *Proceedings of the 2007 ACM symposium on Virtual reality software and technology* (2007), ACM, pp. 125–132. 2, 3

[GSHG98] GREGER G., SHIRLEY P., HUBBARD P. M., GREENBERG D. P.: The irradiance volume. *IEEE Computer Graphics and Applications 18*, 2 (1998), 32–43. 3

[HIH*13] HULLIN M. B., IHRKE I., HEIDRICH W., WEYRICH T., DAMBERG G., FUCHS M.: Computational Fabrication and Display of Material Appearance. In *Eurographics 2013 - State of the Art Reports* (2013), Sbert M., Szirmay-Kalos L., (Eds.), The Eurographics Association. 2

[JSKJ12] JAROSZ W., SCHÖNEFELD V., KOBBELT L., JENSEN H. W.: Theory, analysis and applications of 2d global illumination. *ACM Transactions on Graphics (TOG) 31*, 5 (2012), 125. 3

[KB99] KATO H., BILLINGHURST M.: Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In *Augmented Reality, 1999.(IWAR'99) Proceedings. 2nd IEEE and ACM International Workshop on* (1999), IEEE, pp. 85–94. 6

[KBPZ06] KRIVÁNEK J., BOUATOUCH K., PATTANAIK S. N., ZARA J.: Making radiance and irradiance caching practical: Adaptive caching and neighbor clamping. *Rendering Techniques 2006* (2006), 127–138. 3

[KHFH11] KARSCH K., HEDAU V., FORSYTH D., HOIEM D.: Rendering synthetic objects into legacy photographs. In *ACM Transactions on Graphics (TOG)* (2011), vol. 30, ACM, p. 157. 3

[KK12] KÁN P., KAUFMANN H.: High-quality reflections, refractions, and caustics in augmented reality and their contribution to visual coherence. In *Mixed and Augmented Reality (ISMAR), 2012 IEEE International Symposium on* (2012), IEEE, pp. 99–108. 3, 6

[KK13] KÁN P., KAUFMANN H.: Differential irradiance caching for fast high-quality light transport between virtual and real worlds. In *Mixed and Augmented Reality (ISMAR), 2013 IEEE International Symposium on* (2013), IEEE, pp. 133–141. 3, 6

[KP09] KERR W. B., PELLACINI F.: Toward evaluating lighting design interface paradigms for novice users. In *ACM SIGGRAPH 2009 Papers* (New York, NY, USA, 2009), SIGGRAPH '09, ACM, pp. 26:1–26:9. 2

[KP10] KERR W. B., PELLACINI F.: Toward evaluating material design interface paradigms for novice users. In *ACM Transactions on Graphics (TOG)* (2010), vol. 29, ACM, p. 35. 2, 3, 7

[KTM*10] KNECHT M., TRAXLER C., MATTAUSCH O., PURGATHOFER W., WIMMER M.: Differential instant radiosity for mixed reality. In *Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on* (2010), IEEE, pp. 99–107. 2

[LB12] LENSING P., BROLL W.: Instant indirect illumination for dynamic mixed reality scenes. In *Mixed and Augmented Reality (ISMAR), 2012 IEEE International Symposium on* (2012), IEEE, pp. 109–118. 3

[MAB*97] MARKS J., ANDALMAN B., BEARDSLEY P. A., FREEMAN W., GIBSON S., HODGINS J., KANG T., MIRTICH B., PFISTER H., RUML W., RYALL K., SEIMS J., SHIEBER S.: Design galleries: A general approach to setting parameters for computer graphics and animation. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 1997), SIGGRAPH '97, ACM Press/Addison-Wesley Publishing Co., pp. 389–400. 2

[MIWI16] MIYASHITA L., ISHIHARA K., WATANABE Y., ISHIKAWA M.: Zoematrope: A system for physical material design. *ACM Trans. Graph. 35*, 4 (July 2016), 66:1–66:11. 2

[NDM05] NGAN A., DURAND F., MATUSIK W.: Experimental analysis of brdf models. *Rendering Techniques 2005*, 16th (2005), 2. 5

[NDM06] NGAN A., DURAND F., MATUSIK W.: Image-driven navigation of analytical brdf models. In *Proceedings of the 17th Eurographics Conference on Rendering Techniques* (Aire-la-Ville, Switzerland, Switzerland, 2006), EGSR '06, Eurographics Association, pp. 399–407. 2

[PBD*10] PARKER S. G., BIGLER J., DIETRICH A., FRIEDRICH H., HOBEROCK J., LUEBKE D., MCALLISTER D., MCGUIRE M., MORLEY K., ROBISON A., ET AL.: Optix: a general purpose ray tracing engine. In *ACM Transactions on Graphics (TOG)* (2010), vol. 29, ACM, p. 66. 6

[PFG00] PELLACINI F., FERWERDA J. A., GREENBERG D. P.: Toward a psychophysically-based light reflection model for image synthesis. In *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 2000), SIGGRAPH '00, ACM, pp. 55–64. 2

[RH01] RAMAMOORTHI R., HANRAHAN P.: An efficient representation for irradiance environment maps. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (2001), ACM, pp. 497–500. 2

[RLW00] RASKAR R., LOW K., WELCH G.: *Shader Lamps: Animating Real Objects with Image-Based Illumination*. Tech. rep., Chapel Hill, NC, USA, 2000. 2

[SJJ12] SCHWARZHAUPT J., JENSEN H. W., JAROSZ W.: Practical hessian-based error control for irradiance caching. *ACM Transactions on Graphics (TOG) 31*, 6 (2012), 193. 3

[Ste12] STEVENS J. P.: *Applied multivariate statistics for the social sciences*. Routledge, 2012. 7

[WAKB09] WILLS J., AGARWAL S., KRIEGMAN D., BELONGIE S.: Toward a perceptual space for gloss. *ACM Trans. Graph. 28*, 4 (Sept. 2009), 103:1–103:15. 2

[WM01] WESTLUND H. B., MEYER G. W.: Applying appearance standards to light reflection models. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 2001), SIGGRAPH '01, ACM, pp. 501–51. 2

[WRC88] WARD G. J., RUBINSTEIN F. M., CLEAR R. D.: A ray tracing solution for diffuse interreflection. *ACM SIGGRAPH Computer Graphics 22*, 4 (1988), 85–92. 3