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Caustics and Translucency Perception

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Abstract

Caustics projected onto the surface carry very interesting information regarding the material they are cast by. It has been observed in previous studies that caustics could be a widely used cue for translucency assessment by human subjects. We hypothesize that changing the reflectance properties of the surface an object is placed on, and removal of the caustic pattern might impact perceived translucency of the material. We conducted psychophysical experiments to investigate the correlation among caustics, environment colors and translucency perception, and found very interesting indications that materials appear less translucent under the conditions where caustics are absent.

Introduction

According to Lynch [1], caustic is ”three dimensional envelope of imperfectly focused rays” or ”two-dimensional pattern formed when a caustic falls on a surface.” According to Wand and Straßer, *”caustics occur if light is reflected (or refracted) at one or more specular surfaces, focused into ray bundles of a certain structure, and then received as patterns of light on a diffuse surface.”* [2] As many translucent objects cast caustic patterns onto other surfaces, and particularly, onto the surfaces they are located on, we encounter this phenomenon on a daily basis - a glass of water projecting caustic pattern onto the table can be one of the simplest examples among many.

It has been identified in the previous study [3] that caustics could be a significant cue for assessment of material subsurface light transport properties. The observers were asked to order objects from the *Plastique* [4] artwork collection. While many observers used translucency as a primary attribute for ordering, the caustic pattern cast through the object onto the white paper was widely used to assess translucency of the material. This phenomenon is illustrated in Figure 1, where caustic is visible under translucent objects, while it is missing around the opaque one.

In some cases, caustics can be the only cue for translucency perception. For instance, refer to Figure 2. While various cues provide information regarding light transmission properties of the spheres, caustics below sphere E is the only indicator that the object is not opaque. Moreover, indications have been found in [5] that as the human visual system has proposedly limited ability to invert optics [6], and as many caustic patterns have high luminance similar to specularities, internal and external caustics and the glittering effect of the caustic highlights might be mistaken for specular highlights and thus, increase perceived glossiness. This phenomenon is illustrated in Figure 3.

Little is known about the mechanisms of translucency perception, and factors contributing to that. Fleming and Bülthoff [6] proposed that translucency perception is a result of interpretation of simple image cues without inverting the underlying optics. Gkioulekas *et al.* [9] studied the role of phase function in

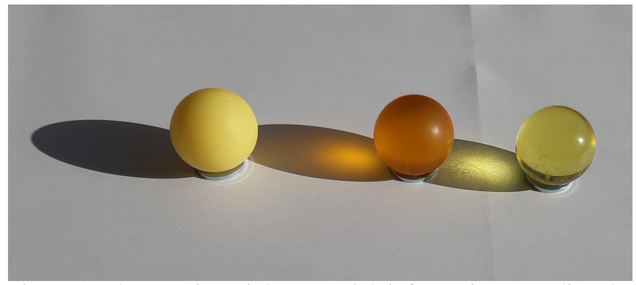

Figure 1: The caustics might carry rich information regarding the material properties. Even without looking at the objects themselves, just by looking at the shadow and caustic pattern, we can deduce the color of the object, as well as some information about its light transmission properties. Illustration taken from [7].

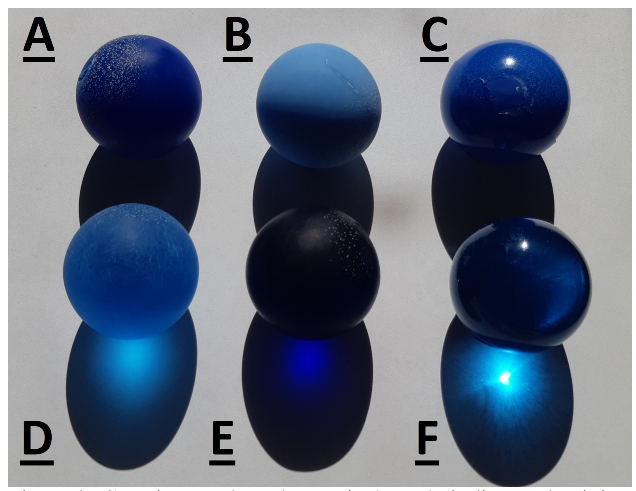

Figure 2: Caustics cast by sphere E is the only indicator that it is a translucent and non-opaque material. Illustration taken from [8].

translucent appearance, while Xiao *et al.* [10] extended the study to interactions among phase function, illumination directionality, and apparent translucency.

Rendering caustics in computer graphics is a computationally costly process. Although caustics might have negligible role in some contexts, they play an important role in photorealism of some scenes [2, 11]. Kán and Kaufmann [12] have shown that caustics increase perception of realism in augmented reality, although it does not have the vital importance. However, Papadopoulos and Papaioannou [13] illustrate that caustics play a very significant role in realistic appearance of underwater scenes.

While, on the one hand, some studies highlight importance of caustics in realistic appearance, and on the other hand, the studies about translucency perception focus on the translucent object itself, to the best of our knowledge, no work has been done upto date to investigate the importance of the external caustics as a

Figure 3: The caustics might contribute to glossiness perception. While the surface properties of all nine objects are identical, many subjects consider translucent ones more glossy, as caustics and back-reflected light are either mistaken for specular highlights, or increase total luminance and ”shininess” of the object.

cue for translucency perception. We have conducted a study to identify whether presence of caustics and the reflection properties of the surface they are projected onto play any role in perceived translucency. The study revealed interesting trends that definitely deserve further follow-up in the future.

The paper is organized as follows: in the next section we present the experimental setup and stimuli generation process. Afterwards, the results are presented and discussed. Finally, we outline the directions for the future work.

Experimental Setup

We conducted psychophysical experiments in order to observe whether presence or absence of caustics could impact perceived translucency of a given material.

Stimuli

We rendered 30 images using Mitsuba Physically-based renderer [14]. We used bidirectional path tracer to render glass objects in 5 different shapes: sphere, cube, Stanford bunny, elephant, and wineglass - all of them placed in the Cornell box. Each object was rendered with 6 different degrees of transparency-translucency. While intrinsic material properties remained the same, translucency was manipulated using the *alpha* parameter, which ”specifies the roughness of the unresolved surface micro-geometry using the root mean square (RMS) slope of the micro-facets” [14]. In other words, we manipulate light transmission properties by changing surface scattering, while volume scattering properties remain the same. The material property was loaded from the .mtl material library. For each of the color channels, ambient component was set to 0, while diffuse and specular components were set to 0.6 and 0.9, respectively. The refractive index was set to 1.5. The *alpha* values were equidistantly sampled between 0 and 1.

The shapes are illustrated in Figure 4. The impact of the *alpha* value on the material appearance of the object, is illustrated in Figure 5. It is worth mentioning that while smooth surfaces look more transparent, rough surfaces start looking translucent never reaching full opacity (although opacity does not necessarily imply complete absence of transmission as observed in [8, 7]) and even the roughest object has some degree of light transmission property. In this case, we expect relative judgement of translucency rather than an absolute one.

Afterwards we had to render identical objects but without caustics in order to compare perceived translucency between the two setups. We considered six different ways of removing caustics:

1. Using a rendering technique that does not produce caustics (with caustics ”off”). However, the results would have been physically inaccurate.

2. Manually editing images in the graphics editor. This methodology will end in physically inaccurate and unrealistic results.

3. Rendering a fully opaque object of the identical shape, cropping the translucent object, and placing into the render in place of the opaque object. This result is also physically inaccurate and unrealistic.

4. Varying refractive index that is directly correlated with the caustics phenomenon. This is an interesting direction that we think of addressing in the future, but at this stage, we focused on single material property for all test samples avoiding an additional degree of freedom.

5. Occluding caustics with other objects. The methodology is promising, but considering that we had to accommodate occlusion of objects with various shapes and sizes, judgment of complex scenes that vary among images might have caused confusion among subjects, and also might be challenging to interpret due to the unintended side-effects occluding objects bring into the scene.

6. Making the floor most of the caustics are projected onto fully absorbing black. Although we cannot remove internal caustics this way, and some other cues are also impacted (e.g. lightness) in addition to caustics, the result is physically accurate, the scene structure remains the same (unlike the occlusion option), and understanding the impact from the surface color itself might have an application in the real world. Therefore, we opted for the latter approach.

Experimental Conditions

We hypothesize that introduction of the black floor makes objects look less translucent. The example of the effects of the floor color is shown in Figure 6. In order to test the hypothesis, we conducted an online user study (also referred to as ”psychophysical experiment”) using QuickEval [15] web-based tool. We used category judgement psychometric scaling protocol, where observers had to assign objects to one of the six categories varying from the most translucent to the least translucent, i.e. most opaquish one. To facilitate decision-making for the observers, we took two measures:

1. Placed an additional spherical object in all test images, in order to enable subjects judge material consistently across different shapes.

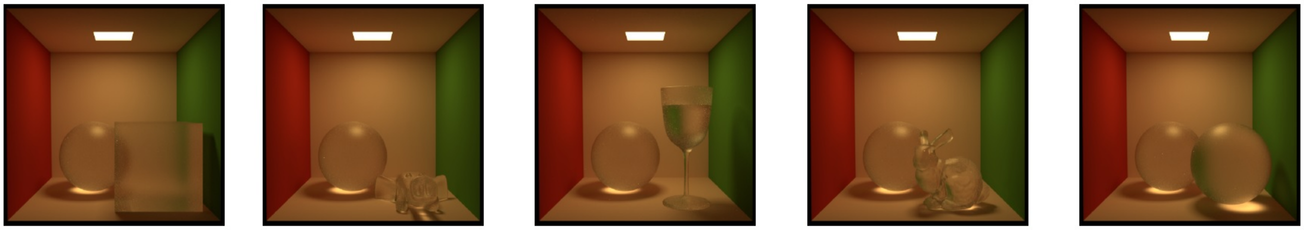

Figure 4: Five different shapes have been used in the study. The illustrated images are rendered with *alpha* value equal to 0.2.

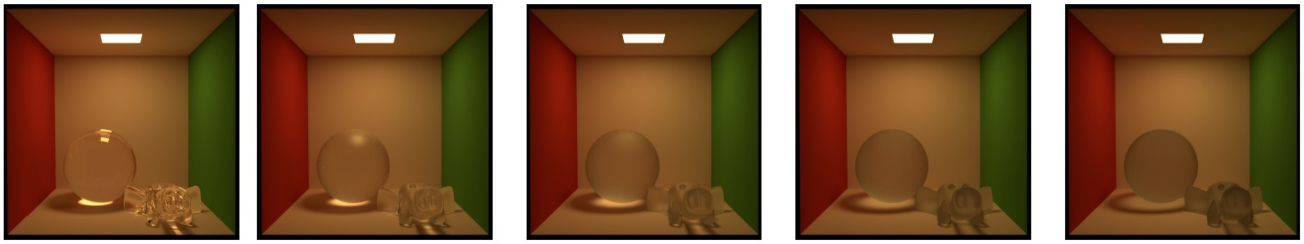

Figure 5: The impact of the *alpha* value on the material appearance illustrated with the example of the elephant shape. *Alpha* is equal to 0, 0.2, 0.4, 0.6, and 0.8, from left to right, respectively.

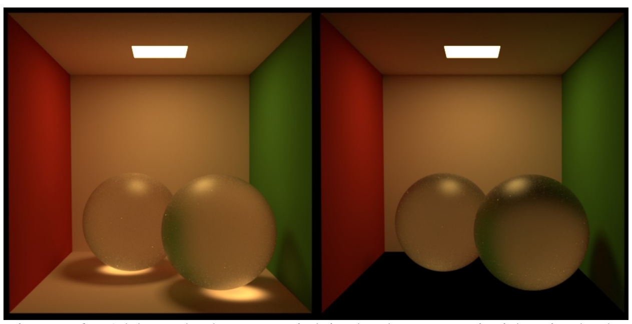

Figure 6: Although the material in both scenes is identical, the floor color changes its appearance.

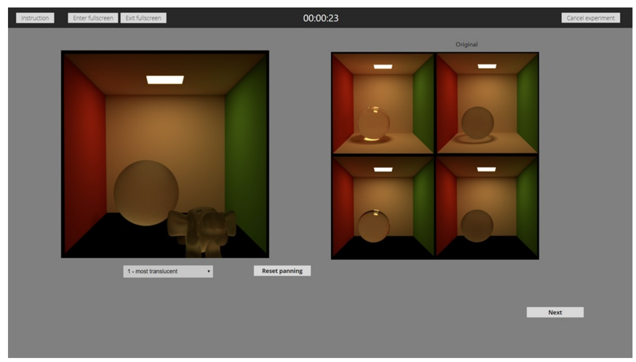

Figure 7: A sample scene from the experiment. The task is to select a category from the dropdown menu for the test material shown on the left side. The reference spheres with *alpha* equal to 0 and 1, are displayed for facilitating the judgement.

2. Illustrated the reference spheres with the two extremes of *alpha* value under two different conditions, in order to facilitate scaling between the extremes. Having access to the extremes of the dataset ensures that observers make relative judgements, as they are not expected to perform absolute judgement based on a very small subset of the transparency-translucency-opacity spectrum. A sample scene from the experiment is shown in Figure 7.

In total 50 observers participated in the study. 13 observers were asked to rank objects by translucency, without providing a definition or interpretation of translucency. 37 observers were given more detailed instructions, as follows: *"Assess translucency of the material in the left image on 1-6 scale using a dropdown menu. 1 - most translucent, 6 - least translucent, i.e. closer to opacity. Sample materials of maximum (left column) and minimum (right column) translucency are illustrated on the right hand side of the panel."* However, both groups demonstrated identical trends, and thus, below we will only report aggregated results.

Results

If we assume that observers have used an equally spaced scale for their judgments, we can compare mean observer scores (category) for each shape and alpha value between the two setups. The mean observer scores and their 95% confidence intervals are shown on Figure 8. The lower category values correspond to more apparent transparency-translucency, while higher values correspond to more opacity. As we see in the figure, the mean observer-assigned category is larger (i.e. more opaque and less translucent) in the presence of the black floor for all shapes and all levels of alpha. For the vast majority of the cases, there is no overlap between the 95% confidence intervals that makes us conclude that the difference is significant and deserves further attention. The most apparent exceptions where confidence intervals overlap are smoothly-surfaced objects. This might be explained with the fact that these objects are transparent and highly specular (glossy), standing out from the rest of the stimuli, making match between the two setups easier for the observers. This might be an indication that floor color and caustics removal have larger impact on translucency perception rather than on transparency perception, further supporting our proposal in [16] that translucency and transparency cues differ significantly.

Considering the above-mentioned observation, it is likely that the assumption about an evenly spaced scale does not hold. Therefore, we applied Torgerson's categorical judgement model [17] (as cited in [18]), finding z-scores and corresponding scale

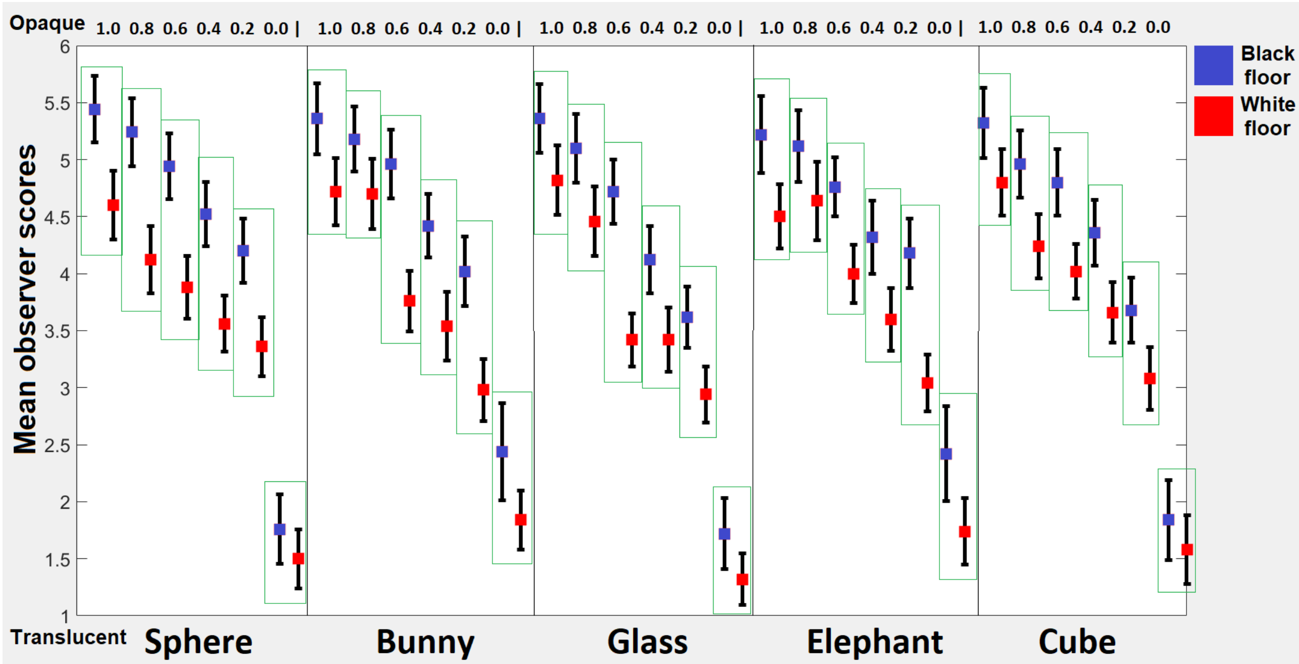

Figure 8: Vertical axis corresponds to mean observer scores, while the results are grouped by shape horizontally (bottom horizontal axis). The top horizontal axis corresponds to alpha values for a given shape. Squares correspond to mean observer scores for a given shape and alpha value. The blue squares signify materials shown on a black floor, while red squares correspond to materials shown on a regular Cornell box floor. The whiskers extend to the 95% confidence interval for mean observer scores. For clarity's sake, the results for each black-floor / white-floor pair of a given object are separated with a green rectangular frame from the results for other objects.

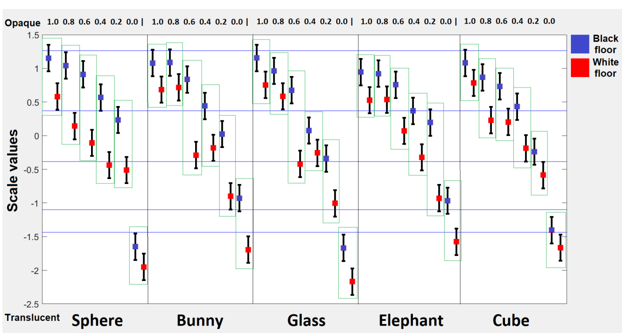

Figure 9: Vertical axis corresponds to scale values derived from Torgerson's categorical judgement model. Blue horizontal lines mark category boundaries. Note that equal variance is assumed for all samples.

values and category boundaries. The results are illustrated in Figure 9. The figure shows that the trend is identical to the one observed for mean observer scores in Figure 8. Interestingly, despite no overlap between the 95% confidence intervals, some materials fall in the same category both in case of white – and black-floor scenarios. This could indicate that 6 categories are not enough to adequately quantify translucency levels within this dataset and denser sampling of the potential categories is needed across the transparency-translucency-opacity spectrum.

Furthermore, it is interesting to figure out, whether the impact is identical for all shapes. For illustration's sake, the latter results are sorted by alpha value in Figure 10. Although the separation between two floor setups stands out, the confidence intervals overlap among all or most shapes for a given alpha value and floor color. Even if the shape could potentially impact the results, presence of the spherical object in all scenes might have compensated that effect. This should be considered in the future and the material should be shown only in one particular shape at a time. In some cases, e.g. Bunny with alpha=0.6, the impact of the floor change is very apparent. One of the explanations for this fact is the sequence the images were shown to the observers. When the material or shape is identical between two consecutive trials, the toggling effect impacts observer responses, and the assumption that all observations are independent does not hold anymore (refer to [19] about toggling and change blindness).

Finally, we plotted mean observer scores as a function of alpha surface roughness for each shape and floor color (Figures 11). As we can observe in the figure, the mean observer scores are always lower when floor is "white", i.e. caustics are visible. Perceived translucency decreases monotonously with the increase of alpha. The correlation between alpha and mean observer scores look linear and Pearson's linear correlation coefficient equals to 0.92 if all points are included, and increases up-to 0.98, if transparent smooth objects are excluded. The apparent drop in mean observer values when alpha equals to 0, is further indication that transparency and translucency judgments might differ by nature.

Discussion

We see clear indications that objects shown on the black surface look less translucent to human observers, even though the observers had a reference where they could observe appearance change between the two setups. The reference could potentially help them match the identical material between the two conditions, but we observe that the difference is significant even with

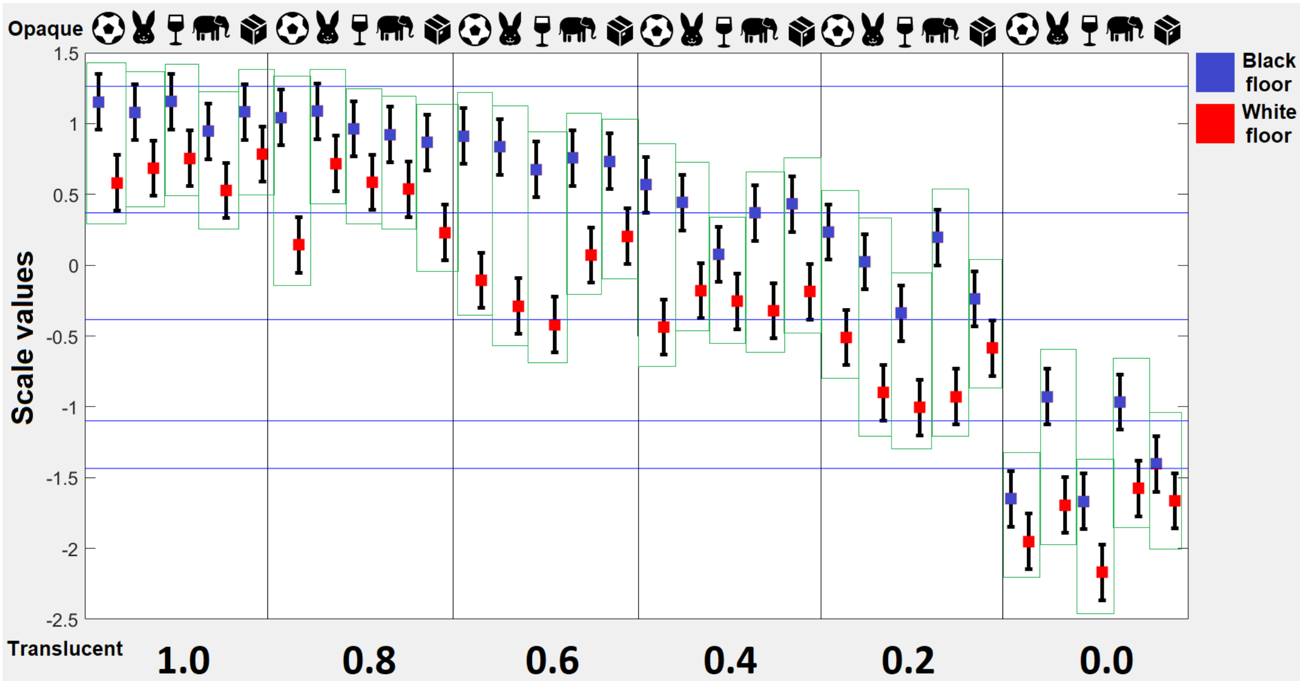

Figure 10: The results reported in Figure 9 but grouped by alpha values. The icons in the top horizontal axis correspond to spherical, Bunny, wineglass, elephant, and cube shapes, respectively. We observe no significant difference among shapes for a given alpha and floor.

this factor. It is worth mentioning that changing the floor color does not only remove caustics, but also affects other cues, like lightness - objects becoming darker, as no light is reflected back from the floor. While the cues used for translucency perception by the human visual system is not well understood, removal of caustics might not be the only explanation for the observed trends in the experiment. It is important to isolate caustics in future studies. However, the primary challenge is that either rendered images will be physically inaccurate that we never encounter in real lives, or physically accurate techniques to remove caustics from the scene will also affect cues other than caustics. As this work is the first step towards this direction, the proper trade-off needs to be found and implemented in the future for in depth analysis of the question. In addition to this, changing floor color removes just that portion of caustics which is projected on the floor, while caustics projected onto other surfaces, yet less apparent, still remain visible (e.g. refer to Figure 4, middle image – the caustics cast by the wineglass are visible on the green wall). Whether this cue was used by subjects remains unanswered within the scope of this study. Besides, we have observed the linear correlation between surface roughness and perceived translucency. The role of surface scattering in translucent appearance and its relation with subsurface scattering is an interesting question to be addressed in the future.

Finally, the study comes with one limitation that is also worth discussing. If we refer to Figure 5, the objects become darker as roughness increases. This can be intuitive at first glance due to facet shadowing and masking. However, model's failure to take interreflections between facets into account leads to energy loss, and might be contributing factor in rougher objects' dark appearance. This is a common problem microfacet-based models usually suffer from at some extent [17]. No single straightforward approach exists to solve this problem and several compensation techniques have been proposed to mitigate its effect [18, 19]. However, different techniques might lead to perceptually different results and assessment of their physical accuracy is beyond the scope of this paper. Besides, we want to highlight that we do not ask subjects for absolute translucency assessment. We show the extremes, the brightest and darkest objects, and ask observers to locate the test objects on a scale relative to these two. In this case, we assume that the impact of the energy loss might not have the critical importance. Although this question can be addressed in follow-up studies.

Conclusion and Future Work

We hypothesize that placing objects on a black floor that in itself leads to disappearance of the caustic pattern projected onto it, makes objects look less translucent. We have conducted psychophysical experiments to test this hypothesis. Considering above-presented results, we have clear indications that introduction of the black floor decreases perceived degree of translucency for a given material. However, whether this phenomenon can be attributed to absence of caustics only, or whether other cues affected by the floor color contributed to apparent translucency as well, needs further investigation.

While we discussed fully absorbing black floor and a binary case, between caustics and no caustics scenarios, floors with different reflection properties should be studied in the future in order to observe, whether sharpness or shininess of the caustics matter and at what extent. If we refer to Figure 1 again, we can see that sharpness and shininess of the caustics can give us a hint about translucency or transparency of the orange and yellow objects. For this purpose, real as well as synthetic stimuli can be used, where the floor will be colored in different levels of gray and have

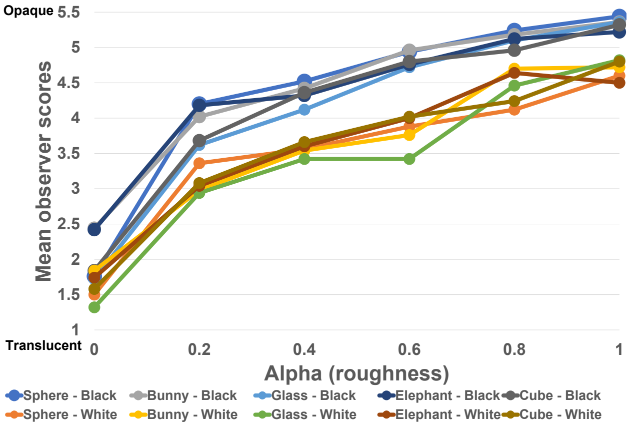

Figure 11: Mean observer score as a function of alpha with visible linear correlation between the two. Visible caustics always lead to lower mean scores. The line is fit for clarity's sake.

different roughness as well. Furthermore, we believe that the impact of shape deserves further attention in the future, in order to understand how shape impacts perceived translucency and to isolate what is the role of caustics cast by a particular shape.

Finally, considering the richness of the information embedded in caustics, we believe caustics could facilitate measurements. In case the straightforward correlation between material properties, shape and 2-dimensional caustic pattern is found, caustics can be used in image-based measurements of material properties. On the other hand, the potential existence of "caustic metamers", i.e. two different materials producing identical caustics, might limit the method. To the best of our knowledge, this methodology has not been studied yet and its limits are yet to be understood.

Acknowledgements

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