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Does Motion Increase Perceived Magnitude of Translucency?

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Abstract

The visual mechanisms behind our ability to distinguish translucent and opaque materials is not fully understood. Disentanglement of the contributions of surface reflectance and subsurface light transport to the still image structure is an ill-posed problem. While the overwhelming majority of the works addressing translucency perception use static stimuli, behavioral studies show that human observers tend to move objects to assess their translucency. Therefore, we hypothesize that translucent objects appear more translucent and less opaque when observed in motion than when shown as still images. In this manuscript, we report two psychophysical experiments that we conducted using static and dynamic visual stimuli to investigate how motion affects perceived translucency.

Introduction and Background

Translucency is an important attribute of appearance. We interact daily with translucent objects, such as cheese, cream, wax, marble, and human skin. Understanding the visual appearance of translucent objects is important in many fields, such as food industry, dentistry, 3D printing, and computer graphics (e.g. skin rendering) [1]. However, our understanding of the visual mechanisms used by the human visual system (HVS) to distinguish translucent and opaque objects remains limited. Translucency is defined as *"the property of a specimen by which it transmits light diffusely without permitting a clear view of objects beyond the specimen and not in contact with it"* [2].

Unlike perception, the optics of translucency is relatively well-understood. Part of the light gets reflected from the surface, while the rest is refracted and continues propagation inside the translucent material, where it may get scattered, absorbed, or re-emerge from another point of the object. This process is described by the Radiative Transfer Equation (RTE) [3] and three key parameters: σ_a and σ_s - the absorption and scattering coefficients that specify the distance traveled by a photon on average before being absorbed or scattered, respectively; and a phase function, which describes the angular distribution of new directions after scattering. All these parameters are wavelength-dependent. An alternative way to specify σ_a and σ_s is σ_T and albedo, where $\sigma_T = \sigma_s + \sigma_a$, and $albedo = \frac{\sigma_s}{\sigma_T} = \frac{\sigma_s}{\sigma_s+\sigma_a}$.

Even though we can perceive translucency in still images, the separation in the proximal stimulus between contributions of the light reflected from the surface and emerging from the subsurface is an ill-posed problem when the observer, the object, and the illumination are static. The shading distribution characteristic for translucent materials can be simply painted on top of an opaque object. The temporal changes in the distal stimulus provide more information on how much energy is being transmitted through the object [1]. Previous works demonstrated that motion contributes to perception and constancy of a broad range of visual attributes, such as viscosity [4] and glossiness [5, 6, 7], where motion facilitates telling specular reflections and surface texture apart. As for transmission, motion has been shown to influence perceived transparency [8, 9, 10]. The HVS can perceive multiple layers from a 2D retinal image, which it primarily owes to consistency in contours, colors, and intensities among different spatial regions [1]. Spatio-temporal information and dynamic deformations can help to understand which part of the proximal stimulus comes directly from a plain view of the background, which one comes from the overlay, and which is a mixture of the both. Tamura *et al.* [11] conducted binary classification experiments and asked observers to differentiate transparent glass and opaque mirror. They found that dynamic cues play a significant role in this process. An opaque object has an optical flow in the direction of the rotation, while a transparent one has a contribution from the back-side, which rotates in the opposite direction.

Translucent objects oftentimes do not permit seeing the background through them, and hence, the role of motion is more complex than this. The works addressing the role of motion in translucency perception are rather few. In their review, Gigilashvili *et al.* [1] demonstrated a case where motion considerably affects translucency appearance of an object when it gradually moves from a back-lit to a front-lit condition, since illumination direction has a significant impact on translucency [12]. A recent work by Lanza *et al.* [13] reports the experiments where observers had to estimate σ_T by appearance matching in static and dynamic illumination. They also observed the effect of illumination direction on estimated σ_T, but intriguingly, they found no significant difference between static and dynamic lighting. The works by Gigilashvili *et al.* [14, 15] revealed several behavioral trends. The authors observed that when humans try to assess translucency of an object, they use motion whenever they are permitted to do so. Observers either move an object over a heterogeneous background, or move other objects, such as their own fingers, behind the object. Even more frequently, they move objects to put them under a different illumination condition, such as looking through an object toward the light source.

Considering above mentioned observations, we hypothesize that motion contributes to distinguishing translucent and opaque materials, and more specifically, the same translucent object is more likely to be classified as translucent when it is in motion than when observed in a still image. The contribution is the following: first, we experimentally test the hypothesis that motion increases the tendency of a translucent material to be classified as translucent; second, we quantify this impact; and third, we compare the trends between object and background motion cases.

Methodology

We conducted two psychophysical experiments: binary classification and appearance matching. Previous eye-tracking experiments showed that observers mostly fixate on the objects and far less on the background in translucency scaling experiments [16]. Therefore, we used two types of dynamic stimuli: an object rotating around its vertical axis while the background is still, and a still object with a rotating background. We speculate that motion is detected primarily by the foveal vision in the former case and by peripheral vision in the latter – although we do not explicitly test foveal and peripheral viewing modes.

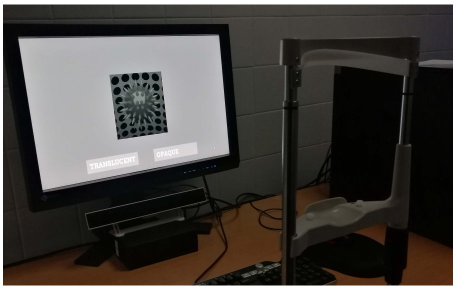

Figure 1: The experimental setup. A chin-rest ensured controlled viewing distance.

Experiment 1: Binary classification

Experimental procedure

Inspired by the work of Tamura *et al.* [11] and their findings about mirror and glass, we conducted a forced-choice binary classification experiment, where the task of the observer was to classify the stimulus material either as opaque or translucent. The experiment was arranged using Psychopy [17] and had two parts. **1. Videos:** Classification of 12 videos as opaque or translucent; the videos were shown in a random order and looped until the observer gave a response; **2. Still images:** Observers classified a total of 36 images (three representative frames from each video, at rotation angles: 0°, 90° and 180°, as in [11]). The experiment was conducted on an Eizo CG246 display, with a resolution of 1920×1080 pixels, calibrated for sRGB encoding (gamma was 2.2). A chin rest was used to ensure a fixed 60 cm viewing distance (see Figure 1). The experiment took 10 minutes on average, and the definition of translucency [2] was provided.

Stimuli and observers

We used Mitsuba [18] to render the stimuli. The 3D model of the *"spiky sphere"* and the background image used for the scene were the same as in [19]. We selected the shape that had a variation of thick and thin parts and could exhibit many translucency cues. Thin parts (spikes in this case) include important cues to translucency [1, 14]. D65 illumination was incident from the top. To cover a broad range of appearances, 6 different materials (M1-M6) were designed varying in wavelength-independent σ_T and albedo[1] (illustrated in Figure 2). Refractive index was fixed to 1.5 (1.0 for the outer medium, assuming vacuum), surface roughness alpha was fixed to 0.05, and isotropic phase function was used for all materials. These six materials were used to generate 12 video stimuli, with two types of motion for each material: rotating object with a still background and a still object on a rotating background. In each video the rotation was done in the [0°, 180°] range, in steps of 5°, producing 37 frames (512×512 pixel) per video, encoded in MP4 format at a speed of 7 FPS and an approximate length of 5 seconds[2]. 17 observers (3 female, 14 male) from 11 different countries took part (average age was 25; SD=2). All of them had a certain knowledge in computer graphics, and normal (20/20) or corrected-to-normal visual acuity. Color vision was not tested, as we use grayscale stimuli.

Experiment 2: Appearance matching

Experimental procedure

Since the first experiment has not manifested many cases where motion has large enough impact to flip material category from opaque to translucent, we conducted a second experiment

[1]All coefficients in this manuscript are in a centimeter scale.

[2]The videos can be downloaded from: `https://github.com/davitgigilashvili/Motion-and-Translucency`

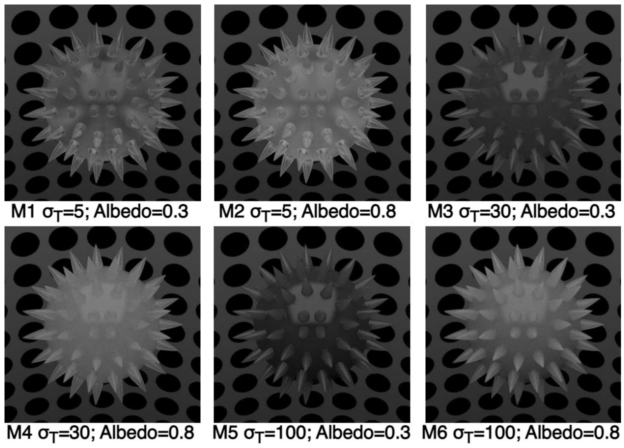

Figure 2: Six different achromatic translucent materials (M1-M6) were used in the experiment. Materials varied in σ_T and albedo (shown below the image in $\frac{1}{cm}$ scale).

to capture subtle differences in apparent translucency induced by motion. Similarly to previous works on translucency perception [12, 13, 20], we used appearance matching. The task was to match the apparent translucency of the materials shown in a dynamic (video) stimulus shown on the left with a still image shown on the right. While the video was fixed per trial, the observer could use arrow keys to toggle between the candidate still images to pick the one with the best match with the video (see Figure 3). In the pilot studies, observers found the navigation confusing if the candidate still images varied both in terms of albedo and σ_T. Hence, on each trial, the candidate images had either the same albedo as the video and varied only in σ_T; or had the same σ_T as the video and varied only in albedo. The objective was to identify whether the video gets matched with the still image of the same material, or with that of more translucent one. However, as shown previously [1], the link between optical properties and translucency is not straightforward. Thus, instead of making assumptions which of the candidate images appeared more translucent, we conducted a third experiment (pair-comparison) as a sub-experiment of *Experiment 2*, where the observers compared nine candidate images in all five sets in terms of translucency. The matching task was performed first using Psychophy [17] followed by pair-comparison on QuickEval [21].

Stimuli and observers

We rendered 45 images in total for five sets of candidate match images (for each of 3 σ_T + 2 albedo levels). Within each set were nine different images that varied either in albedo [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9] or σ_T [1, 5, 10, 20, 30, 40, 80, 90, 100]. We had 14 observers (3 female, 11 male; average age – 25) – with normal (20/20) or corrected-to-normal visual acuity .

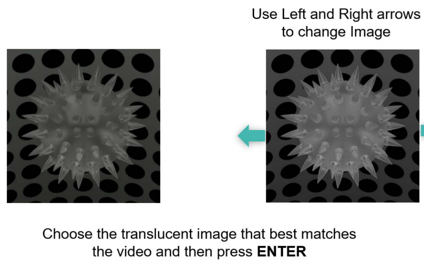

Figure 3: The appearance matching experiment. The left stimulus is a video, and the task is to toggle between still images on the right to find a best match in terms of apparent translucency.

Results

In this section we analyze the results of the two experiments.

Experiment 1: Binary classification

Similarly to Tamura *et al.* [11], we analyzed the percentage of the total trials in which the stimulus was considered translucent and compared the performance among the three conditions: videos with the object rotation, videos with the background rotation, and still images. Although the frames from the both types of videos were studied as still images, no significant difference was observed among them. Furthermore, the observers have been highly consistent for the three frames at 0°, 90° and 180°, from each individual video (the only exception was a rotating object frames for material 3, where the one at 90° appeared considerably more translucent than the other two, which can be explained by non-uniform distribution of the spikes). Therefore, we report an average of all six still image responses for a given material. The results are illustrated in Figure 4.

We conducted one-way balanced repeated-measures analysis of variance (ANOVA) to test whether the three conditions (still, background and object motion) had a significant effect on the frequency of the six materials being considered translucent. We failed to reject the null hypothesis that the translucency is identical among the three different observation conditions ($F(2,15) = 0.11; p > 0.05$). Thus, for the six materials in question the impact of motion is not statistically significant.

If we have a closer look at each individual case, we will see that there is a consensus among the observers that highly transmissive materials (those with low σ_T) are translucent regardless the viewing condition (dynamic or static). The same can be said about the opacity of the material with high σ_T. Interestingly, the materials with medium σ_T exhibit more variation between the three conditions, where the stimuli with rotating background are least likely to be classified as translucent – even less than in still images. This may be an indication that the reason why we couldn't reject the null hypothesis may be the low statistical power and limited range of objects and materials addressed.

Experiment 2: Appearance matching

Although *Experiment 1* failed to show a large enough effect to flip material category from opaque to translucent, it may still have impact on the magnitude of perceived translucency. First, we report the results of the pair comparison experiments to learn how σ_T and albedo affect translucency, which is an interesting question in itself. The Z-scores [22] for the five sets of candidate match images are shown in Figure 5 (calculated using MATLAB Colour Engineering Toolbox [23]). An increase in σ_T decreases translucency when albedo is fixed. For materials with relatively large σ_T, high albedo is associated with more translucency, while albedo has negligible impact on translucency for low σ_T materials, as all look very transmissive. These trends emerge from mean Z-scores. However, low number of observers leads to high variance, and the 95% confidence intervals are often overlapping. Hence, more observers are needed in future studies.

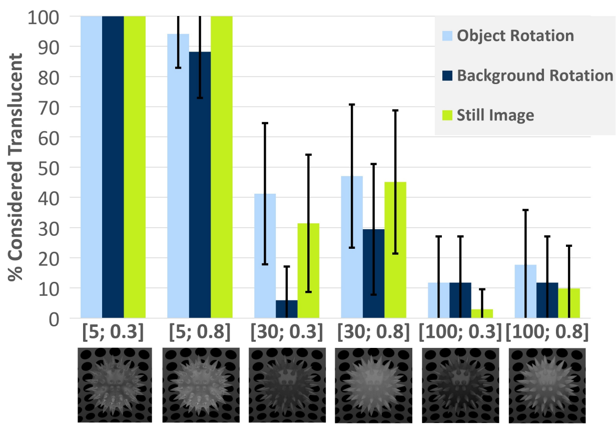

Figure 4: The percent of the trials when a given material was classified as translucent in stimuli with object rotation (light blue), background rotation (dark blue), and still image (green). The pairs of numbers below the bars indicate σ_T and albedo, respectively, while the image also illustrates the appearance of a given material. The error bars specify the 95% confidence interval (not calculated when 100% of the observers agree).

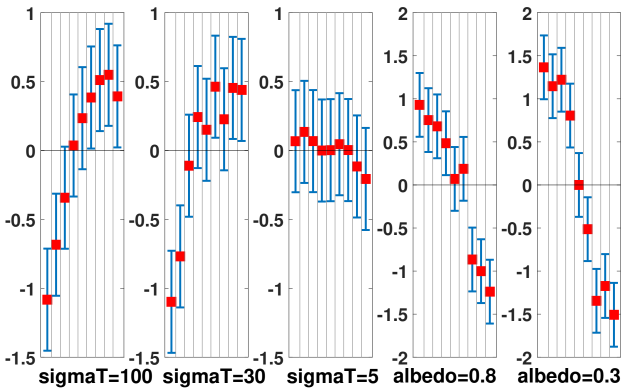

Figure 5: Z-scores for pair comparisons among nine images in each of the five sets used as candidate match images. The red square corresponds to mean Z-score, while the whiskers mark the 95% confidence interval. The parameters below the plots (either σ_T or albedo) show the value of the parameter that was fixed within a given set. Those that vary in albedo take the following values from left to right, respectively: [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9]; as for σ_T the values in each plot are [1, 5, 10, 20, 30, 40, 80, 90, 100]. While σ_T makes materials more opaque, high albedo is usually associated with more translucency, but only for the materials with above certain level of σ_T.

Figures 6-7 show the results of appearance matching for fixed albedo and fixed σ_T cases, respectively. We calculated mean value of the matched parameter across all observers and conducted two-sample t-tests to assess whether the difference between the ground truth and matched parameters, as well as between matched parameters for object and background rotations, were statistically significant. Figure 6 shows that albedo was matched very precisely. The difference for low σ_T needs to be taken with care, since albedo makes negligible perceptual difference for this material (see Figure 5). On the other hand, observers systematically underestimated σ_T in videos when σ_T was high, but not for low σ_T materials. For M4 (σ_T=30; albedo=0.8), rotating object was matched with σ_T lower than ground truth, and with higher-than-ground-truth σ_T for rotating background case.

Discussion

We could not reject the null hypothesis that a given material is equally likely to be classified as translucent both in videos and still images. Therefore, it may be tempting to conclude that we observed translucency constancy, and the spatio-temporal cues do not affect perceived translucency. However, *Experiment 2* showed that while albedo assessment is more accurate, the videos of the materials with σ_T are often matched with the still images of materials with lower σ_T. Pair comparisons showed that σ_T is negatively correlated with translucency. Hence this can be

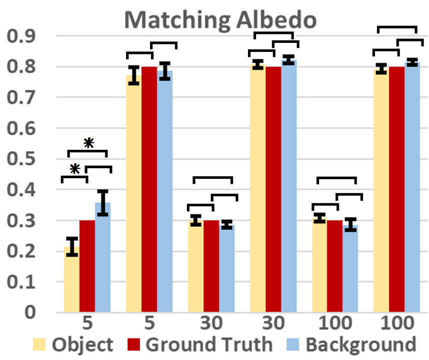

Figure 6: Vertical axis corresponds to albedo. Red bar shows the ground truth parameter, while yellow and blue bars show matched albedo in videos with object and background rotation, respectively. The error bars indicate standard error. Numbers below shows fixed σ_T. If there is an asterisk on top of a horizontal bar connecting a pair of vertical bars, the difference between the respective conditions is statistically significant at the 5% significance level.

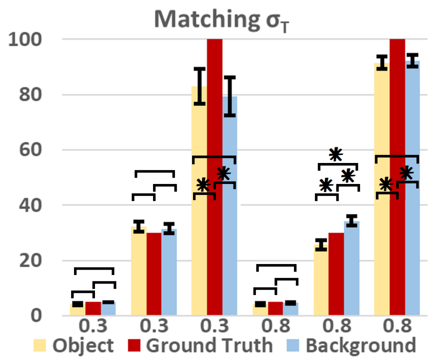

Figure 7: Vertical axis corresponds to σ_T. Numbers below the bars show albedo. All other marking is the same as in Figure 6.

an indication that motion increases the magnitude of perceived translucency for high σ_T materials. We hypothesize that simplicity in albedo matching can be attributed to the fact that lightness is a strong and reliable cue to albedo [19], while the cues to assess the extinction coefficient of the material are more complex.

Lanza *et al.* [13] could not find any significant difference between static and dynamic illuminations, which is consistent with our findings; however, they noticed that change of illumination geometry significantly affects perceived translucency. One potential reason why we did not observe as stronger impact of motion, as in earlier demonstrations [1, 15], is the fact that the illumination direction (from the top) remains fixed despite rotation. In the work by Gigilashvili *et al.* [15], the most common reason to move the objects in translucency assessment process was to change the illumination geometry and to inspect them on a back light. There are additional differences from prior works. For instance, they used simpler shapes, such as spheres, cubes, and bust figures with thin flat areas that permitted to see the background through the object [1, 11, 15]. In our case, the spikes were the only areas where background could be seen for highly scattering materials. However, spikes may occupy too small part of the field-of-view (FoV) the background to be discernible through them. We believe the Lucy shape used by Lanza *et al.* [13] suffers from the same problem. On the other hand, for highly transmissive materials, spikes may create a visual texture that masks the background and makes it less discernible. Future works should use simpler blob-like shapes. Finally, Gigilashvili *et al.* [15] use physical objects with direct interaction, while our environment was achromatic, had lower dynamic range, and was altogether less realistic than real-life interaction. These shortcomings should be addressed in future works.

Interesting trend was observed for M4 in both experiments: a rotating object and even still images were considered more translucent than a static object on a rotating background. This is consistent with the latest finding by Huang and Zaidi [10]: if our visual acuity is not enough to see the background through the spikes, we have T-junctions rather than X-junctions, and while motion increases apparent transparency for X-junctions, T-junctions appear more opaque when moved. Another explanation can be above-mentioned hypothesis that background motion is primarily detected by the low-acuity peripheral vision. This should be tested in explicit foveal and peripheral viewing modes.

Finally, we also investigated optical flows in our stimuli to compare them with those of Tamura *et al.* [11]. The optical flow between the last two frames and the histogram of the phase angles are given in Figure 8 on the example of M1 and M6. The shape of the histograms for these two very different materials looks qualitatively similar. A transmissive object (M1) has a considerable portion of the opposite motion due to the contribution from the back side of the object, as in [11]. The opposite motion is also present in the spikes of M6 – however, this may not be as noticeable as in M1, since the spikes occupy smaller part of the FoV. Future works should use eye tracking to reveal how fixation patterns vary between static and moving stimuli, and whether observers attend to the regions with the opposite flow.

Conclusions

We conducted two psychophysical experiments to investigate whether motion increases the tendency of the materials with certain degree of subsurface light transport to be classified as translucent. Firstly, we conducted binary classification experiment where observers had to classify materials either as opaque or translucent in videos and still images. Afterward, we asked them to match materials by appearance between dynamic and static scenes. We found no statistically significant differences in binary classification. In matching experiments, observers systematically underestimate extinction coefficient for some materials in the dynamic stimuli, while this is not the case for others. Although matched and ground truth optical properties are statistically significant, future work is needed to understand whether this optical differences yield perceptually noticeable difference.

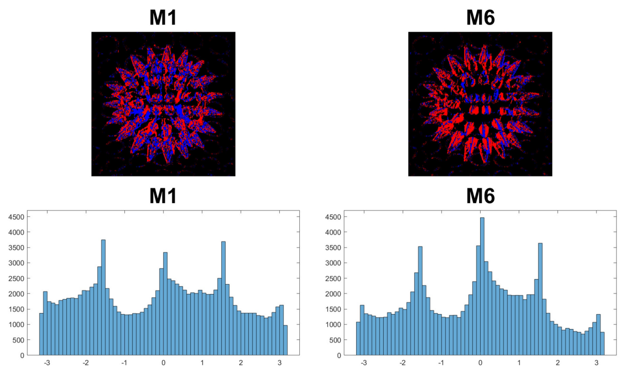

Figure 8: The optical flow between the last two frames of M1 and M6 materials (top row) from object rotation videos, and the histograms of the phase angles of the flow in radians. Only the points with non-zero flow are included in histograms. In the optical flow plot, the flow in the direction of the object rotation is marked with red, and the opposite direction is marked with blue.

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