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On the Nature of Perceptual Translucency

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Figure 1: *We encounter materials permitting some degree of subsurface light transport, described as transparent or translucent.*

Abstract
Translucency is an appearance attribute used to characterize materials with some degree of subsurface light transport. Although translucency as a radiative transfer inside the medium is relatively well understood, translucency as a perceptual attribute leaves much room for interpretation. Our understanding of the translucency perception mechanisms of the human visual system remains limited. No agreement exists on how to quantify perceived translucency, how to compare translucency of multiple objects and materials, how translucency relates to transparency and opacity, and what are the perceptual dimensions of it. We highlight the challenges in perception research arisen by these ambiguities and argue for the need for standardization.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [**Computer Graphics**]: Methodology and Techniques—Standards J.4 [**Social and Behavioral Sciences**]: Psychology

1. Introduction

When we speak of translucency, we usually mean materials that at some degree permit subsurface light transport. Several optical material properties are used in the *Radiative Transfer Equation* [Cha60] to characterize the light propagation inside the medium, such as, absorption and scattering coefficients, scattering phase function, and index of refraction.

The human visual system is adept at detecting subsurface light transport, perceiving materials to be translucent. For instance, we do not need prior training to judge whether a material transmits light, or to tell the difference between real human skin and a plastic dummy, between translucent glass and opaque metal. Although perceptual aspects of translucency is a topic of interest in academia [FB05] and industry (e.g. in 3D printing [BATU18, UTB*19]) alike, our knowledge about the psychovisual mechanisms of translucency perception remains limited. Fleming and Bülthoff [FB05] proposed that the human visual system relies on low level image cues to judge translucency. Gkioulekas *et al.* [GXZ*13] studied the impact of the scattering phase function on translucency perception, while Xiao *et al.* [XWG*14] demonstrated that perceptual translucency is not a constant property and it depends on the illumination direction. Despite those attempts, a lot of uncertainties remain about the concept of perceptual translucency. Below, we will discuss multiple challenges we have faced due to this ambiguity throughout the process of psychophysical studies of translucency perception, making results inconsistent and difficult to interpret.

2. Open questions about perceptual translucency

2.1. Definition and conceptual understanding

Translucency is considered a major appearance attribute by the CIE [Poi06, Eug08] alongside color, gloss and texture. No single standard definition of translucency exists. ASTM - Standard Terminology of Appearance [AST17] defines translucency 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."*. According to Gerbino [GSTdW90], *"transparent substances, unlike translucent ones, transmit light without diffusing it."* Eugène [Eug08] also highlights diffusing-blurring nature of translucency, arguing that *"if it is possible to see only a "blurred" image through the material (due to some diffusion effect), then it has a certain degree of transparency and we can speak about translucency"*. However, the author believes that *"a single and simple definition of translucency is unlikely to be achieved."* According to the CIE [Poi06], *"translucency is a subjective term that relates to a scale of values going from total opacity to total transparency."* In non-scientific contexts, *translucent* as an adjective can be used to describe the scattering, as well as clear transparent media [web]. While these definitions usually refer to the physical property of light scattering, the term is still vague in terms of perception, as it does not reflect in what way physical properties relate to appearance (except for "blurring"), making it subject to individual interpretation.

2.2. Perceptual dimensions of translucency

One of the major challenges regarding translucency is to identify its perceptual dimensions. For example, various perceptual dimensions exist to describe color - such as, hue, chromaticity or lightness. The same is true for gloss. Hunter [Hun37] proposed six dimensions of gloss (specular gloss, contrast gloss, distinctness-of-reflected-image, absence-of-bloom, absence-of-surface-texture, and sheen). Pellacini *et al.* [PFG00] identified two perceptual dimensions of gloss: contrast and distinctness. It is not clear yet what would be similar perceptual dimensions for translucency, although there is evidence that they might exist. The authors of this paper have conducted psychophysical experiments studying translucency perception [GTHP18, GUT*19, GDPH20]. We have observed that the subjects find it challenging to interpret the term and to identify the dimensions for quantifying it. They could not decide which cue to prioritize: complexity of light and matter interaction, i.e. preservation of structure of the light - clarity of the image seen-through the material, or preservation of the radiometric values (the amount of transmitted light). What if we compare very dark transparent-looking material with little scattering against the lighter one with less absorption but higher scattering? (refer to Fig. 2). These observations are consistent with Eugène's [Eug08] proposal that *"the concept of translucency can perhaps be regarded as a generic and subjective term, combining the concepts of **clarity** ("ability to perceive the fine details of images through the material") and **haze** ("property of the material whereby objects viewed through it appear to be reduced in contrast")* - also admitting that much work is still needed to clear up these uncertainties.

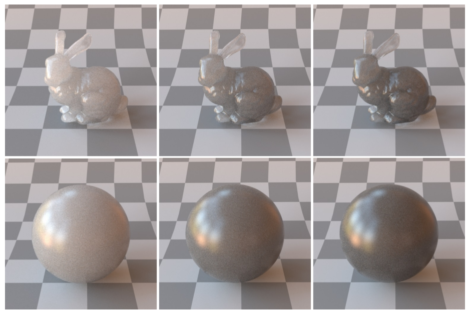

Figure 2: *Objects in the same column are made of the identical material. However, due to smaller scale and presence of thin parts, the Bunny has more cues evoking perception of translucency. Objects in the first column have high scattering and low absorption. In the second column - lower scattering and higher absorption. In the third column - same scattering as in the second column - but higher absorption. How can we compare their perceptual translucency?*

2.3. Relation with transparency and opacity

Another reason why the term leads to confusion is the lack of knowledge how it relates to transparency and opacity. Eugène [Eug08] proposes that translucency is related to transparency and opacity but does not discuss how. Gerardin *et al.* [GSF*19] propose that increasing subsurface scattering of the transparent material makes it translucent and eventually opaque, while adding absorption to a fully transparent material gradually makes it opaque, but never - translucent. This definition was not accepted by some of our subjects.

It is not clear whether transparency, translucency and opacity are on the same line of continuum, whether they are mutually exclusive or they can co-exist. Can a material possess some degree of transparency and translucency, or some degree of translucency and opacity at the same time? When do transparent materials start to be considered translucent, or when do translucent ones become opaque? Transparency and opacity seem to be ranges across the spectrum of light transmission properties rather than extreme discrete points. We have demonstrated that opacity is a subjective term and does not imply complete absence of transmission [GTHP18] (further supported by [GMH19]). It seems that the conceptual boundary between transparency, translucency and opacity is fuzzy - although the amount of translucency could be characterized with a bell-shaped curve that gradually increases, reaching a peak and then decreasing again while moving from transparency to opacity [Per] (refer to Fig. 3).

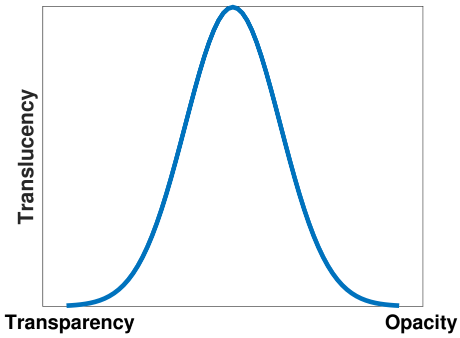

Figure 3: *Translucency might be gradually increasing, reaching its peak and decreasing between transparency and opacity. However, transparency and opacity are unlikely to be discrete points and translucency can co-exist with them.*

2.4. How to quantify perceptual translucency?

Limited knowledge on how to quantify translucency and how it relates to other perceptual properties of subsurface light transport (transparency and opacity) makes it challenging to apply magnitude estimation techniques [Tor58] to quantify translucency of a given material, or psychophysical scaling methods, such as pair comparison and rank order [Eng00], to compare the stimuli with one another. As there is an intuitive spectrum of glossiness properties from a Lambertian matte to a perfect mirror, it has been demonstrated to be feasible to estimate magnitude of glossiness [PFG00], or to identify glossier and less glossy objects when comparing multiple stimuli [THS17, GTPH19]. However, we faced a challenge with interpretation of the term when similar approach was applied to translucency. The subjects found it challenging to rank the stimuli by translucency, from the most translucent to the least translucent one [GTHP18]. What does *more translucent* mean? How would we tell which stimulus is more translucent? (e.g. in Fig. 1 and 2) Is it the one closer to transparency, opacity, or the center of the hypothetical transparency-opacity axis? Does higher scattering or absorption make materials more translucent? When does translucency peak, is correlation between scattering and translucency monotonous? These have been the questions we have not been able to answer.

The state-of-the-art works experimenting on translucency perception avoid quantifying translucency and abstain from comparing *more* and *less translucent* stimuli. They rather encapsulate this in matching and similarity detection tasks, asking observers to match the stimuli by appearance [XWG*14, XZG*19, FB05] and/or to select similar ones by translucency [GXZ*13, GUT*19]. While this task is less ambiguous and easier to interpret for the subjects, it has not been demonstrated up-to date that the human visual system can isolate translucency from total appearance. This creates the risk the observers making up their own rules matching the stimuli by total appearance, by lightness, or any property other than translucency. If the definition of translucency is not clear, how can they judge translucency similarity?

2.5. Translucency constancy of objects and materials

Similarly to our work [GTHP18], Nagai *et al.* [NOT*13] asked subjects to identify *more translucent* stimulus, interpreting it as having stronger subsurface scattering. However, definition of translucency as a material property does not adequately convey the complex nature of translucent appearance. We believe that in addition to physical material properties at least three other factors - illumination geometry, the size of the object and its shape should be considered. An object looks more translucent [XWG*14, FB05, GTHP18] and less opaque [GMH19] in back-lit conditions. It has been shown that scale and overall thickness of the object [FB05, UTB*19], as well as presence of thin regions [GTHP18, GUT*19] impact perceived translucency.

The majority of the observers in our studies [GTHP18, GUT*19] had difficulty comparing objects with different shapes due to the ambiguity between object-specific translucency and translucency as a shape-independent physical material property (e.g. what if a material is fully transparent, but complex shape, surface geometry or roughness do not permit to see-through the object - is it still transparent?) Moreover, it was problematic to come up with a single translucency measure for an object with a complex shape and varying thickness (refer to a female bust with thick torso and thin cloth areas in Fig.1). Hutchings [Hut94] proposes that heterogeneous material might have *"more than one colour, perhaps more than one translucency, gloss, or surface irregularity"* that no appearance profile system can deal with. Should translucency of an object be assessed as a whole, as a global attribute, or should it be taken as a local, region-specific one?

We believe perceptual translucency is a context-dependent attribute with limited constancy and mapping physical material properties with a visual attribute is a surjective but non-injective function - several different physical properties evoking identical perception of translucency. If we draw a parallel with color, material translucency could be analogous with spectral reflectance as an objective physical material property, and object translucency - with color, both being perceptual by definition. However, there exist physiological color matching functions with no interpretation, while no physiological functions have been found or described so far for perceived translucency. This could be explained with a fact that perception of translucency is a more complex phsychovisual phenomenon, involving spatial properties, contrast and various image cues [FB05]. As it is possible to fix physiological state, there exists a standard observer for color. However, physiology of translucency perception is not understood, leaving room for further research. While perceived translucency would more logically be compared with color appearance, no translucency counterpart is identified for colorimetry yet. It is likely that translucency measurement will be context-specific, customized to individual circumstances.

3. Conclusion

To summarize, our experience with psychophysical experiments has shown that there is an obvious need for translucency measurement, comparison and definition standards. The lack of an established procedure for perceptual translucency measurement makes tasks ambiguous and inconsistent. There is a clear disagreement among observers regarding its dimensionality. Although they always found a strategy to tackle a particular task, their "solutions" do not necessarily express what they perceive. A rigorous future work is needed to identify perceptual dimensions of translucency, if any. Revealing particular dimensions will make psychophysical measurements more consistent and easier to interpret. The definitions of translucency imply an absolute, objective attribute of a specimen. We believe the definition should reflect its situation-dependence and perceptual nature, proposing the following re-formulation of [AST17]: *"translucency - the property of a specimen by which it evokes perception of subsurface light transport **under given conditions**."*

References

[AST17] ASTM E284-17 Standard Terminology of Appearance. ASTM International, West Conshohocken, PA. URL: https://doi.org/10.1520/E0284-17. 2, 4

[BATU18] Brunton A., Arikan C. A., Tanksale T. M., Urban P.: 3D printing spatially varying color and translucency. *ACM Transactions on Graphics (TOG) 37*, 4 (2018), 157:1–157:13. 1

[Cha60] Chandrasekhar S.: Radiative transfer. (1960) Dover Publications Inc. New York, pp. 1–53. 1

[Eng00] Engeldrum P. G.: *Psychometric scaling: a toolkit for imaging systems development*. Imcotek, 2000. 3

[Eug08] Eugène C.: Measurement of "total visual appearance": a CIE challenge of soft metrology. In *12th IMEKO TC1 TC7 Joint Symposium on Man, Science Measurement* (2008), pp. 61–65. 2

[FB05] Fleming R. W., Bülthoff H. H.: Low-level image cues in the perception of translucent materials. *ACM Transactions on Applied Perception (TAP) 2*, 3 (2005), 346–382. 1, 3

[GDPH20] Gigilashvili D., Dubouchet L., Pedersen M., Hardeberg J. Y.: Caustics and translucency perception. In *Material Appearance 2020, IS&T International Symposium on Electronic Imaging* (2020), Society for Imaging Science and Technology, pp. 033:1–033:6. 2

[GMH19] Gigilashvili D., Mirjalili F., Hardeberg J. Y.: Illuminance impacts opacity perception of textile materials. In *Color and Imaging Conference* (2019), Society for Imaging Science and Technology, pp. 126–131. 2, 3

[GSF*19] Gerardin M., Simonot L., Farrugia J.-P., Iehl J.-C., Fournel T., Hébert M.: A translucency classification for computer graphics. In *Material Appearance 2019, Electronic Imaging* (2019), Society for Imaging Science and Technology, pp. 203:1–203:6. 2

[GSTdW90] Gerbino W., Stultiens C. I., Troost J. M., de Weert C. M.: Transparent layer constancy. *Journal of Experimental Psychology: Human Perception and Performance 16*, 1 (1990), 3. 2

[GTHP18] Gigilashvili D., Thomas J.-B., Hardeberg J. Y., Pedersen M.: Behavioral investigation of visual appearance assessment. In *Color and Imaging Conference* (2018), no. 1, Society for Imaging Science and Technology, pp. 294–299. 2, 3

[GTPH19] Gigilashvili D., Thomas J.-B., Pedersen M., Hardeberg J. Y.: Perceived glossiness: Beyond surface properties. In *Color and Imaging Conference* (2019), no. 1, Society for Imaging Science and Technology, pp. 37–42. 3

[GUT*19] Gigilashvili D., Urban P., Thomas J.-B., Hardeberg J. Y., Pedersen M.: Impact of shape on apparent translucency differences. In *Color and Imaging Conference* (2019), Society for Imaging Science and Technology, pp. 132–137. 2, 3

[GXZ*13] Gkioulekas I., Xiao B., Zhao S., Adelson E. H., Zickler T., Bala K.: Understanding the role of phase function in translucent appearance. *ACM Transactions on graphics (TOG) 32*, 5 (2013), 1–19. 1, 3

[Hun37] Hunter R. S.: Methods of determining gloss. *NBS Research paper RP 958* (1937), 19–39. 2

[Hut94] Hutchings J. B.: Appearance profile analysis and sensory scales. In *Food Colour and Appearance*. Springer, 1994, pp. 142–198. 3

[NOT*13] Nagai T., Ono Y., Tani Y., Koida K., Kitazaki M., Nakauchi S.: Image regions contributing to perceptual translucency: A psychophysical reverse-correlation study. *i-Perception 4*, 6 (2013), 407–428. 3

[Per] Unpublished personal communication with Prof. Holly Rushmeier of Yale University. 2

[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* (2000), ACM Press/Addison-Wesley Publishing Co., pp. 55–64. 2, 3

[Poi06] Pointer M.: A framework for the measurement of visual appearance. *CIE Publication. CIE 175:2006 ISBN: 978 3 901906 52 7* (2006). 2

[THS17] Thomas J.-B., Hardeberg J. Y., Simone G.: Image contrast measure as a gloss material descriptor. In *International Workshop on Computational Color Imaging* (2017), Springer, pp. 233–245. 3

[Tor58] Torgerson W. S.: Theory and methods of scaling. 1958, Wiley: New York. 3

[UTB*19] Urban P., Tanksale T. M., Brunton A., Vu B. M., Nakauchi S.: Redefining a in RGBA: Towards a standard for graphical 3D printing. *ACM Transactions on Graphics (TOG) 38*, 3 (2019), 1–14. 1, 3

[web] Merriam-Webster Dictionary. https://www.merriam-webster.com/dictionary/translucent. Accessed: 2020-11-06. 2

[XWG*14] Xiao B., Walter B., Gkioulekas I., Zickler T., Adelson E., Bala K.: Looking against the light: How perception of translucency depends on lighting direction. *Journal of Vision 14*, 3:17 (2014), 1–22. 1, 3

[XZG*19] Xiao B., Zhao S., Gkioulekas I., Bi W., Bala K.: Effect of geometric sharpness on translucent material perception. *bioRxiv* (2019), 795294. 3