On the Acquisition and Reproduction of Material Appearance

Aditya Sole, Davit Gigilashvili, Helene Midtfjord, Dar'ya Guarnera, Giuseppe Claudio Guarnera, Jean-Baptiste Thomas, and Jon Yngve Hardeberg(✉)

The Norwegian Colour and Visual Computing Laboratory, NTNU – Norwegian University of Science and Technology, Gjøvik, Norway
jon.hardeberg@ntnu.no
http://www.colourlab.no

Abstract. Currently, new technologies (*e.g.* 2.5D and 3D printing processes) progress at a fast pace in their capacity to (re)produce an ever-broader range of visual aspects. At the same time, a huge research effort is needed to achieve a comprehensive scientific model for the visual sensations we experience in front of an object in its surrounding. Thanks to the projects *MUVApp: Measuring and Understanding Visual Appearance* funded by the Research Council of Norway, and *ApPEARS: Appearance Printing—European Advanced Research School* recently granted by the European Union, significant progress is being made on various topics related with acquisition and reproduction of material appearance, and also on the very understanding of appearance. This paper presents recent, ongoing, and planned research in this exciting field, with a specific emphasis on the *MUVApp* project.

Keywords: Colour · Gloss · Translucency · Texture · BRDF · Goniometry · Imaging · Soft metrology

1 Introduction

Humans are highly skilled in assessing the appearance of objects. By comparing the relative qualities of materials, such as whether they are flexible/rigid, soft/hard, smooth/rough, rotten/fresh, precious or cheap, we can for instance quickly tell if these are pleasing or may do us harm. Understanding the appearance of materials is also of great importance for commercial products. How these materials are used for different requirements and applications can be a key differentiator to the success or failure of a product. In computer vision, recognising materials is a key challenge, for instance for scene understanding.

The visual appearance of a material is generally classified into four appearance attributes (colour, gloss, translucency, and texture) that interact with each other [4]. This interaction is very complex and processed by the brain together with other information such as memory and viewing environment, to finally determine the perceived appearance of a surface or object. We can consider the study of appearance as an extension of colour science.

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Visual appearance and material perception is drawing the attention of more and more vision scientists. Also within the field of imaging and printing there is an established interest in visual appearance, as evidenced for instance by the establishment of a conference series at the Electronic Imaging Symposium entitled Material Appearance.[1]

The reflectance properties of a material can be physically described by the spatially-varying Bidirectional Surface Scattering Reflectance Distribution Function (sv-BSSRDF) [32], which is an 8-dimensional function for each wavelength for non fluorescing materials. The simple BRDF model assumes that light entering a material exits at the same position. Simple measurements in fixed illumination and viewing geometries are commonly used to assess colour or gloss. Multi-angle instruments and BRDF measuring instruments have been developed to assess goniochromism, *i.e.* the dependency of perceived colour on the illumination and viewing geometry, which is especially important for special effect coatings, but also significant for other materials such as dyed papers [31]. A number of devices have been developed for specific applications, and the design of each of these devices is typically optimised for a specific parameter, while restricting other features. As a result, two instruments can give significantly different measurements.

Quantification of visual appearance requires modelling the relationship between physical stimuli (such as BRDF or a contrast-gloss physical measure) and psychophysical visual appearance attributes. The appearance of an object is however not determined solely by its sv-BSSRDF, as the viewing environment and the observer also significantly impacts on it. Some aspects of the problem are relatively well understood and can be solved with simpler measurement techniques, as for instance colour appearance modelling in the case of planar diffuse reflective surfaces under certain surround and illumination conditions, while for more complex object properties and illumination geometries research is needed. BRDF/BSSRDF models are also successfully used for photorealistic rendering of appearance in computer graphics, including translucency [20].

Material perception is a very complex process, and the appropriate dimensions, feature spaces and perception metrics are only beginning to be studied. It has been shown [30,45] that image statistics are promising for the problem of material recognition. However, for applications in training and design, the specification of material attributes are needed independently of a particular image, for example, a surgical training simulator must present different visualisations for various shapes and views, while an automotive design system must simulate the end product in different environments and weather conditions. The appearance of a material needs to be understood over the entire space of potentially relevant images – this is in part what makes material appearance modelling more challenging than understanding colour reproduction in the field of imaging. However, recent progress in soft metrology, computer graphics, virtual reality and neuroscience that allow us to explore a larger range of properties and imaging scenarios now allow us to tackle this more complex problem of material appearance.

[1] http://www.electronicimaging.org/.

2 Knowledge Challenges and Research Opportunities

Despite the importance of material perception, vision scientists have tended to simplify the research questions by using only simple flat and matte stimuli for their experiments to understand visual appearance, and disregarding the complexity of real world surfaces [2]. Recent progress in computer graphics have enabled vision scientists to simulate photo-realistic appearances of objects on the computer screen, but only a relatively small number of studies have used this approach to investigate the material perception of real objects [7]. On the contrary, the use of direct methods of measuring material properties of real objects have a long history in industrial applications [18,19], but were often specific to certain product types, and cannot be generalised to other materials or products. To know the exact relationships between human perception and physical properties, the measurement of physical properties should be precise and comprehensive, but such measurements are time consuming and expensive and inadequate, impossible, or *e.g.* limited to homogeneous materials without scattering for ellipsometry.

The measurement of the physical properties that, either singly or in combination, are related to psychophysical sensations is formally defined as soft metrology by the CIE [4]. Although aspects like colour appearance in fixed viewing geometries are reasonably well understood, key measurement challenges need to be overcome to measure and predict material appearance in a given environment. Taking into account optical properties such as gloss, colour, texture and translucency, image-based systems to estimate the BRDF [12,13] and sv-BSSRDF of 3D objects will offer fast measurements but also enable the building of visual appearance models with support of image statistics. Many studies on gloss have been performed on flat homogeneous surfaces without scattering (for ellipsometry) and assessing the perceived gloss of 3D objects raises a number of new problems related to the interaction of spatially varying visual attributes and viewing environment such as inter-reflection. The context or environment surrounding the object plays an important role in material perception [6]. While in many previous studies material surfaces are simulated by displaying rendered stimuli on a flat monitor, future work should explore the use of immersive Virtual Reality environments. In fact, even though the simulated physical and optical processes are elaborate, displaying a simulation just on a 2D monitor might not fully convey the appearance of a material, since a significant portion of the environment surrounding the observer is left outside the field of view. In order to overcome this drawback, it is important to generate samples that can be used as real physical objects to study material perception.

The *MUVApp: Measuring and Understanding Visual Appearance* project tries to address some of the above challenges to understand and study visual appearance. It is funded by the Research Council of Norway and supports 3 doctoral and 3 post-doctoral positions over a period of 5 years for research and networking activities. As illustrated in Fig. 1, it aims towards expanding key knowledge and understanding in the field of visual appearance reproduction and develop methodology to measure and understand visual appearance.

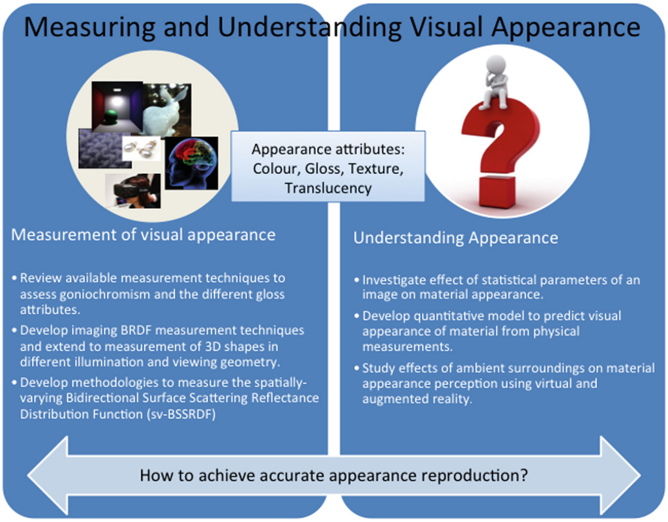


Fig. 1. MUVApp project research overview.

3 Optical Measurements and Functions of Appearance

Measuring physical properties of the material is important to understand visual appearance of the given material/object. These measurements help in material identification (whether it is food, textile, skin, metal, paper or plastic) by their correlation to the total appearance of an object as defined by CIE [4]. Next, we describe some of our different approaches towards appearance measurement.

3.1 Image Based Goniometric Measurements

For non-diffuse materials like metallic inks, measurements using the standard geometries as defined by CIE [3] are not sufficient to understand its visual appearance. Goniometric measurements are therefore performed to measure these materials at multiple illumination and viewing directions. Performing such a large set of measurements can be expensive and time consuming. Image based measurement setups are therefore proposed [17,28,39,43], which can be fast and cheap but less accurate compared to the reference goniospectrophotometers and commercially available multi-angle spectrophotometers. We propose such [28,43] an image based measurement setup to measure thin, flexible and homogeneous object material like printed paper material typically used in the packaging industry [37,39]. Such a setup can perform fast measurements and in line with production of these print and packaging materials. This can be an advantage over using the reference goniospectrophotometers and multi-angle spectrophotometers. The obtained measurements can be fitted to different surface reflection models to simulate and study the bidirectional reflectance properties of diffuse packaging material (wax-based inks printed on a packaging paper material) as demonstrated in [34,38,39]. The measurement setup has been evaluated against commercially available goniospectrophotometers and the accuracy of the image based setup is calculated by means of a propagation-of-error analysis [36]. Further, we have investigated the suitability of using such a measurement setup to measure materials with a complex visual appearance. These complex materials showed non-diffuse and gonio-chromatic properties which were difficult to model using well established reflection models [35].

3.2 Image Statistics and Contrast Measures

We have also investigated how contrast measures correlate with gloss perception in specific cases [42]. Indeed, contrast has been shown to play a role in gloss perception in the general case, *e.g.* [26,27]. We made the observation that contrast metrics should correlate to contrast gloss in specific conditions, and we conducted an experiment to observe this correlation. We investigated how the state of the art of perceived image contrast metrics agreed with gloss perception for a specific viewing condition. Though preliminary, those results were promising. We are conducting further studies toward this direction to strengthen and limit those observations. Indeed, the results presented in [42] are strongly impacted by the effect of the background on the perceived image contrast computation, while we would prefer that the metrics only describe the near-to-specular area. Secondly, the samples were very simple in this experiment, and we probably described only a physical parameter of the generative model of BRDF used to generate the objects. This work is not expected to result in a model of contrast perception, neither a model of gloss perception. Instead, it will help defining the limits of the contribution of contrast in the perception of gloss, and to establish which contrast metrics is more suitable as a gloss indicator for some industries, *e.g.* the painting industries.

3.3 Colour and Spectral Image Acquisition

Acquisition of faithful colour data is indeed an important component of appearance measurements, often overlooked in the computer graphics and vision fields. Hence, we focused on the development of an effective technique for absolute colorimetric camera characterisation, suitable for use in a wide range of applications, including image-based reflectance measurements, spectral prefiltering and spectral upsampling for rendering and to improve color accuracy in HDR imaging. As demonstrated in [14], the characterised camera can be used as a 2D tele-colorimeter to obtain an estimate of the distribution of luminance and chromaticity in a scene, in physical units (cd/m^2). Besides the aforementioned applications, such a characterised camera can be used for radiometric compensation, to project images on unoptimised surfaces [15] while compensating for the spatially varying background (see Fig. 2).

Beyond colour imaging, spectral and polarisation imaging may bring precious additional information to compute appearance attributes. The Spectral Filter Array technology [25] enables snapshot spectral imaging, which is valuable for

(a) (b) (c)

Fig. 2. In (a), textured surface used for projection. In (b), Uncompensated image projected on the textured surface. In (c), the compensated image, projected on the same surface. The estimation of the surface gamut partly relies on a camera characterised with our method [14].

computer vision. One advantage of this technology is that it is a very good candidate to perform multi-angle measurements and that the point of view of the imaging device is at a single location, differently from light-field cameras.

After defining the imaging pipeline for snapshot HDR spectral imaging [24], we handled the illumination [22,23] and the demosaicing [1,41]. We plan to extend this pipeline to the joint spectral and polarization imaging and to use this technology to capture data to measure appearance.

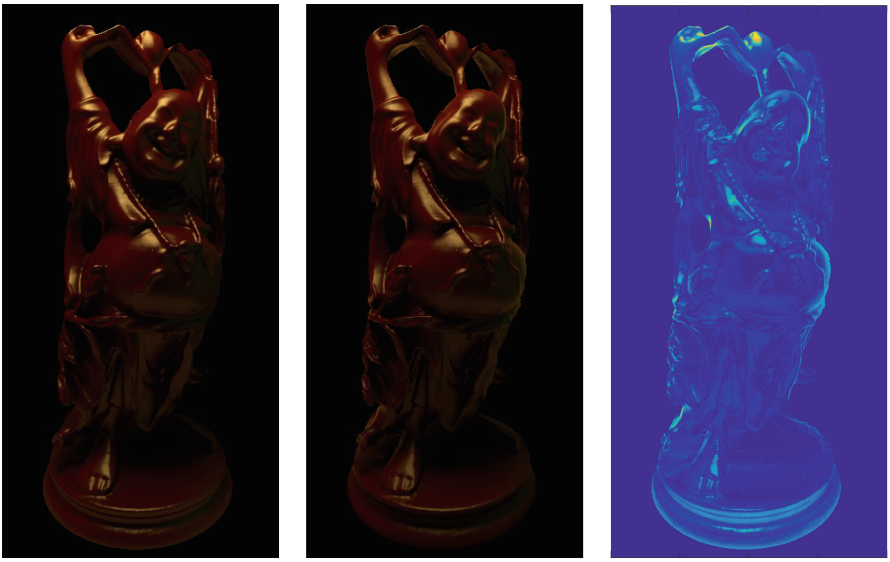
3.4 The Case of Textiles

The appearance of textiles is particularly interesting. In the context of the contract furniture business, woven cloth model acquisition must be rapid, since the volume of cloth swatches that need to be routinely processed is huge. Furthermore, results must be renderable in high quality even on a mobile device. To address such needs, a novel image-based technique was developed, for reverse engineering woven fabrics at a yarn level, which determines, from a single digital image, captured with a DSLR camera under controlled uniform lighting, the woven cloth structure and reflectance properties [16]. The developed technique finds applications also in other fields, and it is suitable for VR [16].

In the same direction, we also captured a database of hyperspectral images of textures, largely composed of textile. HyTexiLa [21] is available online and was, so far, used to study texture classification and to simulate imaging processes.

3.5 Appearance Translation Across Material Models

The production of 3D digital media content often requires collaboration among several departments, which exchange data and material models in order to simulate the visual appearance of objects and environments. A range of modelling and rendering tools is usually involved. Digital content could also be initially created with one material model, subsequently upgraded or changed over the lifespan. A lack of standards to exchange material parameters and data (between tools) requires the artists in digital 3D prototyping and design to manually match the appearance of materials to a reference image. To address the aforementioned issue, we developed a novel BRDF remapping technique, that automatically computes a mapping to match the appearance of a source material model [11]. Most notably, results obtained show that even when the characteristics of the models are substantially different, such as in the case of a phenomenological model and a physically-based one, the remapped renderings are indistinguishable from the original source model (Fig. 3).



(a) (b) (c)

Fig. 3. Remapping from a phenomenological model, with no support for the Fresnel effect (a) to a physically based model (b). In (c) we report the error map. The appearance is correctly preserved, while the differences are mostly localised around the silhouette and due to the Fresnel effect, implemented in (b) but not in (a).

4 Visual Processes of Appearance Understanding

Eugène [5] defined appearance as "the visual sensation through which an object is perceived to have attributes as size, shape, colour, texture, gloss, transparency, opacity etc." However, he highlighted the lack of consensus on uniform description of appearance and mentioned that "this topic requires much more reflection and research". Next we describe briefly some of our attempts at achieving a better understanding of how we perceive and understand appearance.

4.1 Methods, Terminology, and Data

During our investigation of the state of the art, we have observed a dichotomy between the different research fields concerned with appearance. First, the terminology is not very clear, *e.g.* translucency refers clearly to the intrinsic optical property of scattering for the metrologist, while it may be considered as a perception feature for a psychologist. Second, there is quantity of quantitative research that describes very well a small part of the material appearance, but it is difficult to figure out a general hypothesis. Third, most of the work is conducted in virtual reality and it is not quantified how the findings relate to real optical properties of the material. To address these shortcomings we have realised a collection of real objects to generate research hypotheses through qualitative research and validate the state-of-the-art in real conditions; the *Plastique* collection [40].

4.2 Investigations

A behavioural investigation of the assessment of visual appearance was conducted [9]. Human observers were asked to describe the appearance of the physical objects from the *Plastique* collection, and perform appearance-based ranking tasks in uncontrolled similar to real-life conditions. The primary objective was to generate research hypotheses and outline future projects that eventually should lead to better insight into appearance perception. The study has revealed significant role of shape, colorant concentration and surface coarseness in translucency and gloss perception. One of the examples of shape outweighing the perceptual impact of intrinsic material properties is shown in Fig. 4. Further studies are currently being conducted to identify factors impacting translucency perception.

A study on the effect of blurring on translucency perception [8] revealed the interesting trend that identical objects are perceived less translucent when observed in blurred images. Images from the Flickr Material Database [33] were used (Fig. 5).

When describing appearance, it is interesting to understand if and why some attributes may appear more salient and prioritized by human observers. In another study [10] we analyzed how people cluster objects from the *Plastique* collection by their appearance, or how they order them in space "in a natural way". Apart from anticipated cross-individual similarities, very interesting cross-individual differences have been also observed (refer to Fig. 6) that opened a whole new direction for further study about the impact of individual subject background and experience on appearance assessment.

Related to the goal of developing a standard for ink opacity within ISO TC130, a psychophysical experiment was performed [29], where naïve observers rated the opacity of white ink, with different ink film thickness (IFT), printed on 3 different substrates. Five potential opacity metrics were tested. The proposed metrics showed good correlation with the visual assessments, and the metric of relative CIE lightness provided the most linear result.

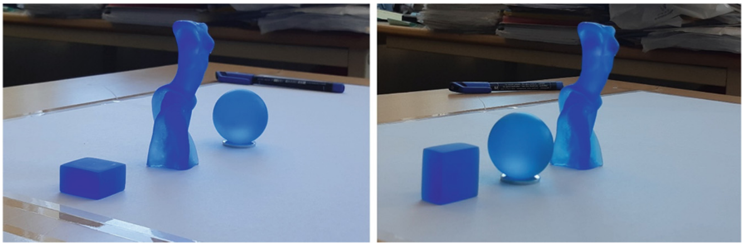


Fig. 4. Considering its compact shape and high amount of colorant, the parallelepiped was almost unanimously ranked least translucent. However, decisions of the human subjects were inconsistent regarding a sphere and a female bust: although dye concentration in the sphere is obviously lowest, there was no statistically significant difference in perceived translucency between the sphere and the bust. One of the hypotheses we are currently examining further is that presence of the thin areas in the female bust compensates for the intrinsic material properties, and thus, shape can significantly impact translucency perception. Left: an example of the *sphere* being considered more translucent by an observer. Right: the *bust* being found more translucent.

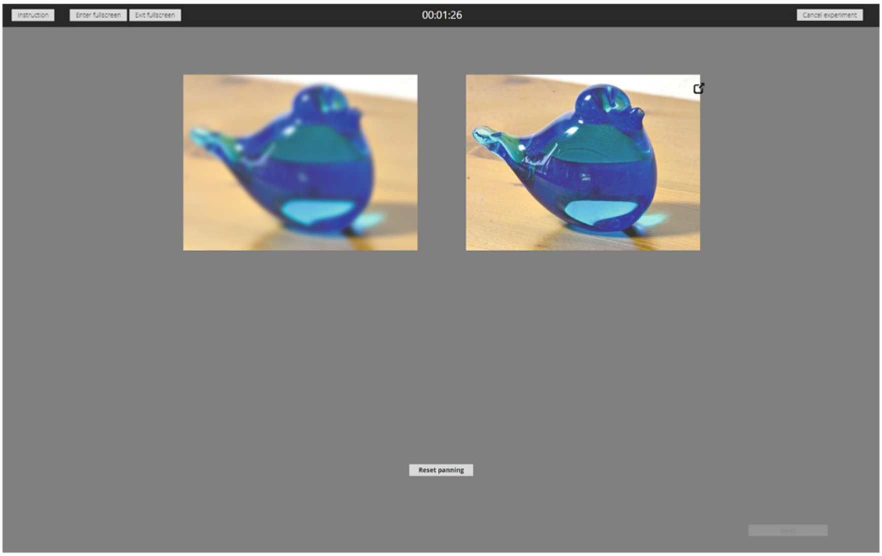


Fig. 5. A sample screen from a pair-comparison psychometric experiment carried out using the QuickEval web-based tool [44]. Human subjects were shown images of the glass objects with varying degree of Gaussian blur and asked to assess which object appeared more translucent. The study revealed that higher the image blur, less translucent is the object perceived.

Fig. 6. Human observers were found to mostly use the colour attribute (either alone or in combination with translucency) to group those objects. In this group of objects, colour was prioritized for different reasons explained in the paper [10]. However, the number of groups for a given data set varied significantly. The left image illustrates grouping into 3 simple categories: "blue", "yellow", and "white"; The middle 4 categories: "blue", "yellow", "white", and "transparent"; while the right image is an example of clustering into 5 groups: "yellow", "orange", "dark blue", "pale blue", and "white". (Color figure online)

5 Conclusion and Perspectives

Visual appearance is still a very open research field, and, through our *MUVApp* projects we currently undertake an innovative transdisciplinary scientific approach involving fields like imaging science, vision science, and computer graphics. With support from this projects we aim to gain new knowledge of how human beings perceive the visual appearance of materials, objects and scenes, and to develop new methodologies for measuring and communicating visual appearance and appearance-related material and object properties.

In this paper we have summarised some of the recent and ongoing research activities and results within this project. For details, we would encourage the readers to refer to the cited articles. The understanding and hence control over the perception, measurement and eventually reproduction of visual appearance has potentially a very high societal impact. It is expected to be very potent in conjunction with the rapidly developing field of additive manufacturing (3D printing) for applications for instance in automotive industry, cultural heritage, and reconstructive surgery.

The capability to reproduce visual appearance using additive manufacturing techniques like 3D printing or 2.5D relief printing is still in its infancy. Additive manufacturing has more degrees of freedom than 2D printing for creating appearance effects beyond colour – such as gloss, translucency or goniochromatic effects – by mixing, for instance, transparent and opaque materials to control translucency, or by adding micro-facets on the object's surface to control directional reflectance. In many applications 3D printed objects must satisfy appearance as well as mechanical criteria, *e.g.* skin and dental prostheses. However, missing technology to match the desired appearance currently significantly limits the printer's applicability. The *ApPEARS* project funded by the European Union will address these limitations, exploring the complete material appearance reproduction workflow, from capturing optical material properties, communicating related appearance attributes, to modelling and controlling 2.5D/3D printing systems beyond colour.

ApPEARS focuses on the following key objectives: measurement and visual evaluation of material properties, reproduction of complex surface appearances, and predicting and minimizing reproduction errors. The exploitation of this complete reproduction workflow into high-impact application areas requires the development of end-use applications, combined with specialized training. With a start date in 2019 *ApPEARS* will train a group of 15 early stage researchers into highly-skilled researchers, who will form the next generation of scientists, engineers, designers and entrepreneurs in the field of visual appearance and printing. For more information refer to http://www.appears-itn.eu.

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