Interrelation between gloss and texture perception of 2.5D-printed surfaces

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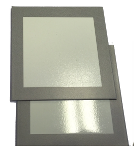
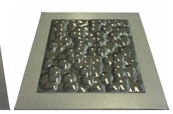
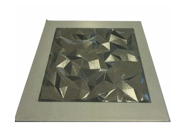
Abstract

The relation between perceived gloss levels and the texture height of a surface (sometimes referred to as bumpiness) has previously been investigated through several psychophysical experiments, which have suggested that a surface is perceived more glossy when the amount of texture is increased, and likewise, a surface is perceived more textured when the gloss level is increased. However, these studies have only been conducted using computer simulations as stimuli instead of physical surfaces or objects. The latter case is investigated in this paper, where physical samples of surfaces varying in surface gloss and texture levels were created by a 2.5D printing system. Psychophysical experiments were then conducted using these samples to investigate the influence of the macroscale texture characteristics on the perceived magnitude of surface glossiness. Although our results show that the influence of the gloss level on the perceived surface texture is negligible, they do confirm the existence of a slight influence of surface texture on the perception of surface glossiness.

Introduction

With the emergence of 2.5D and 3D printing technologies, the reproduction of different surface characteristics beyond colour, such as gloss and physical surface texture, has received more attention. Moreover, for perceptually accurate reproductions, the impact of physical (measurable) surface characteristics on our perception must be considered, including the interrelation of perceptual attributes such as gloss and colour. Previously, we have investigated the psychophysical relationship between physical measurements of gloss and the visual perception of flat printed samples [1]. In this paper, we study the influence of macroscale variations of physical texture on the perception of gloss. Similar to studies investigating the degree of colour constancy, where the perceived colour remains relatively constant independent of texture, context and illumination conditions, several studies [2], [3], [4], [5] have been conducted to investigate the degree of gloss constancy and texture constancy. The relationship between perceived surface texture (or bumpiness) and perceived gloss levels has been investigated [2], [3], using computer simulations for creating stimuli on a display. In these studies, researchers aimed to investigate whether gloss and texture attributes of simulated objects can be defined independently of each other. According to these studies, a surface is perceived more glossy when the amount of texture is increased and, likewise, a surface is perceived more textured when the gloss level is increased. A shortcoming of these studies is that they were only based on simulated materials viewed on a display. Different results may be expected for real surfaces and objects. One can expect that when real surfaces are considered, more accurate estimations of texture and reflection properties can be acquired, in comparison to virtual scenes. In this work, real 2.5D printed samples, varying in gloss and macroscale texture levels, were used in psychophysical experiments in order to investigate the interrelation of gloss and texture perception.

Table 1. Three types of patches used in psychophysical experiment.

			
type	'Flat'	'Bumpy'	'Facet'
colour	black, grey, white	grey	grey
gloss	5 varnish coverages: 0, 10, 20, 30 and 40 %		
texture	flat	6 levels: max height 1.2, 1.8, 2.1, 2.4, 2.7, 3 mm	6 levels: max height 0.75, 1.5, 1.875, 2.25, 2.625, 3 mm
number of patches	15	30	30

Psychophysical Experiment Setup

To investigate the influence of texture on gloss perception and vice versa, a psychophysical experiment was conducted in which observers judged the gloss and texture level of the printed samples based on interval scales of reference samples. The experiment was conducted in a viewing booth with CIED65 illumination, without exterior lighting. In total, 15 colour-normal or corrected to normal observers (6 female and 9 male) participated in the experiment. Their colour vision was tested prior to the experiment using the Ishihara Color Vision [6] and Farnsworth Munsell Dichotomous D-15 (a simplified version of 100-hue test [7]) tests. Moreover, their visual acuity was examined using the Snellen test [8]. Note that, since all the samples used in the experiment were printed with neutral colours, the colour vision tests were not as important as the visual acuity test, required to ensure that observers could clearly see different levels of gloss and tex-

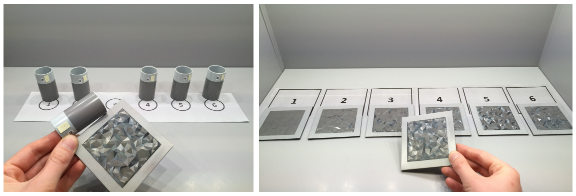


Figure 1. *Left, illustration of perception experiment part A, where observers rank the gloss level of flat and textured patches with respect to a NCS gloss scale of reference patches. Right, in experiment part B observers rank the texture level of samples with respect to a scale of textured samples, ordered from least to most textured surface.*

ture. All observers used a chinrest to maintain a fixed distance to the viewing booth.

Printed Gloss and Texture Samples

A series of patches was printed using an Océ 2.5D prototype printing system that has the capability of printing several types of textures in different elevations and various gloss levels by means of varnish deposition. The printed patches were categorised in three groups: 'Flat', 'Bumpy' ellipsoids, and macroscopic 'Facets'. Each patch was a square of 7 by 7 centimetres, surrounded by a light grey (matte) frame of one centimetre. The flat patches were printed in white, grey and black to investigate the effect of colour on gloss perception, while the textured patches were printed only in grey.

Gloss variations

Each group of patches ('Flat', 'Bumpy', and 'Facet') contained 5 variations of gloss, which were obtained by depositing varnish coverages of 0, 10, 20, 30 and 40 percent. The physical gloss levels of the patches were measured using a MG628-F2 multi-angle gloss meter, by measuring the amount of specular reflection under a 60/60 geometry. The patches show gloss variations in the range of 10 to 90 Gloss Units (GU). A GU is defined by normalising the specular reflection measurements to 100 GU for a glossy reference material with a refractive index of 1.567 [9].

Texture variations

In addition to the five gloss variations, six levels of texture were applied on the 'Bumpy' and 'Facet' surfaces as summarised in Table 1. The texture of 'Bumpy' patches was created according to the surfaces used by Ho et al. [2], and was adjusted to fit to the dimensions of the printout. A grid of 14 by 14 points was considered on each sample of 7 by 7 cm. The points of the grid were randomly displaced in the x and y direction so that:

$$\begin{aligned} x_{i,j} &= 0.5i + 0.1\mathrm{U}[-1,1] \\ y_{i,j} &= 0.5j + 0.1\mathrm{U}[-1,1] \end{aligned} \tag{1}$$

where $i, j = 1....14$ and $\mathrm{U}[-1,1]$ is a random number drawn from a uniformly distributed set of random variables between -1 and 1. Ellipsoids were centred on each point $(x_{i,j}, y_{i,j})$ with principle axes in the x, y and z directions and radii of 0.5 cm in the x and y axes. For a sample with texture level b, the z-radius Rz (cm) of the ellipsoid on each point was determined by:

$$Rz_{i,j} = 0.03(b+4)\mathrm{U}[0,1] \tag{2}$$

where the radius in the z-direction is chosen from the uniformly distributed random values between 0 and the maximum texture height based on the texture level b. Although Ho et al. [2] used quadratic spacing to obtain intermediate texture levels, we employed linear spacing for creating different texture elevations ($Rz \sim b$). Therefore b was chosen as 0, 2, 3, 4, 5, and 6 for six texture levels respectively, as shown in Table 1. Note that the ellipses generally intersect and that the printed texture height on a given location is determined by the maximum height of the ellipses on the particular location.

The macroscopic 'Facet' patches were created according to the surfaces used by Ho et al. [10], and were adjusted to fit to the dimensions of the printout. These surfaces were made by connecting triangular facets with random orientation. A grid of 14 by 14 points was considered for each sample with the size of 7 by 7 cm. The points of the grid were displaced in the x and y directions, so that:

$$\begin{aligned} x_{i,j} &= 0.5i + 0.24\mathrm{U}[-1,1] \\ y_{i,j} &= 0.5j + 0.24\mathrm{U}[-1,1] \end{aligned} \tag{3}$$

where the variables are defined as in equation (1). The surface height $z_{i,j}$ (cm) was determined randomly on each location $(x_{i,j}, y_{i,j})$ based on the texture level such that:

$$z_{i,j} = 0.0375(b+2)\mathrm{U}[0,1] \tag{4}$$

The surface height between different grid points was interpolated from the set of neighbouring grid points (i, j), $(i, j+1)$, $(i+1, j+1)$ and $(i+1, j)$ where the surface was locally approximated as a combination of two triangular facets, with the edge randomly selected as one of the diagonals (either connecting (i, j) and $(i+1, j+1)$ or connecting $(i, j+1)$ and $(i+1, j)$). For the printed patches, b was chosen as 0, 2, 3, 4, 5, and 6 for six texture levels respectively, with the resulting maximum texture height Rz as shown in Table 1. For both sets of patches, the different levels of texture are introduced only by scaling the surface elevation, keeping the spatial variation of the surface texture unchanged. The edge of the elevated surface was smoothened so that no vertical slopes were visible on the sides.

Experiment Tasks and Reference Scales

The psychophysical experiment consisted of two tasks, where observers were asked to rate the gloss and texture level of the printed samples based on interval scales of respectively gloss and texture reference samples, as illustrated in Figure 2.

Task A - gloss scaling

To investigate the influence of texture on the perceived glossiness, a gloss scaling experiment was performed. The reference gloss scale consisted of 6 samples with medium grey (NCS

Table 2. Reference samples from the NCS gloss scale

Sample [scale value]	name	gloss level [GU]
1	matte	6
2	semi-matte	12
3	satin matte	30
4	semi-gloss	50
5	glossy	75
6	high gloss	95

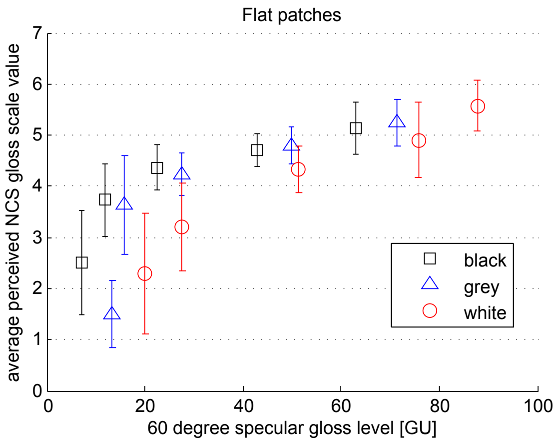


Figure 2. *Average of perceived gloss levels on the NCS gloss scale versus the 60° specular gloss measurements for 'Flat' black, grey, and white patches. Although the large standard deviation, which indicates the disagreement between the 15 observers, the graph shows that for patches of similar gloss level measurements, the lighter patches are perceived less glossy.*

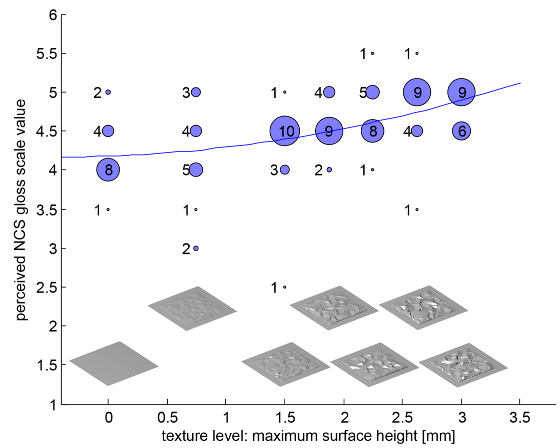


Figure 3. *Bubble chart indicating the number of observers that rated the gloss level of each of the seven patches as a particular value on the NCS gloss scale. The patches have identical physical gloss level (20% varnish, 27 GU) and varying texture levels (from 0 to 3 mm of maximum height). A trend is visible that the glossiness of a sample is rated higher for larger texture levels.*

S 5000-N) colour, ranging from a 'Matte' to 'High Gloss' appearance (i.e. 6 to 95 GU). The samples were selected from the NCS Gloss Scale fan deck. The gloss levels of these patches, measured as 60° angle of specular reflection, are indicated in Table 2. The samples were attached to cylindrical tubes providing simultaneously different geometries for gloss perception.

First, the 15 'Flat' patches were given to the observers one by one and in a random order. They were asked to compare each given patch to the reference scale, and to assign the gloss scale value of the reference sample that matches in glossiness with the test sample. Next, observers were presented with the 60 textured samples and asked to compare its glossiness with the reference samples and to select the reference sample with the same perceived gloss as the test sample, as shown in Figure 1.

Assignments of intermediate gloss scales by the step of 0.5 (i.e. 0.5, 1, 1.5, ..., 6, 6.5), were also allowed. Observers needed around 35 minutes to complete this part of the experiment, indicating an average of 30 seconds to assess the gloss level of each patch.

Task B texture scaling

In the second part of the experiment, the 6 NCS gloss levels were replaced by a scale of textured samples, as shown in Figure 1.

The goal of this experiment was to investigate the possible influence of the surface glossiness on the judgement of the texture level. Therefore, a reference scale of textured samples was created. Observers were then presented 30 textured samples and asked to assign the texture scale value of the reference sample that matches in texture with the test sample. The texture scale reference scale consisted of 6 textured matte patches (13 GU) from the 'Facet' type. Observers were then presented all 30 textured ('Facet') patches and asked to assign a texture level to each of them, by comparing the patches to the reference scale. Tilting the patches and reference patches was only permitted in small angles, to avoid examination of the patch from its side. The task was repeated a second time now using the most glossy (72 GU) patches as a reference scale. Due to the time restriction in conducting psychophysical experiments, only the textured samples with 'Facet' appearance were used in this part of the experiment, which took the observers around 20 minutes on average.

Results

From the psychophysical experiment, the following results were obtained:

Perceived gloss magnitude vs. measured gloss value

From the observers' judgement of the gloss scale value of each printed patch in task A, average gloss scale values were determined among the 15 observers. The average of perceived gloss scales together with the corresponding standard deviations vs. measured gloss values at 60° specular angle, are presented in Figure 2.

First, a large variation between the assigned gloss scale values of each patch is observed among the observers, indicated by the relatively large standard deviations.

Furthermore, an influence of the sample's colour on the perceived level of surface glossiness is visible. As mentioned previously, the samples were printed in 5 different gloss levels by variations in the amount of varnish, deposited from 0 to 40% in steps of 10%. However, for the black, grey, and white samples, printed with the same amount of varnish, different gloss values were measured, indicating higher gloss measurements for lighter samples. Nevertheless, Figure 2 indicates different psychophysical relationships for the several colours, which suggests that for samples with the same physical gloss level (as determined using a gloss meter), the magnitude of the perceived gloss level is greater for darker colours, which is in accordance with the result found in [11]. This effect can be explained by the measurement system, where a gloss meter measures the total light reflecting in the specular direction, both the diffuse and the specular component. Therefore, the gloss meter may present higher gloss values for

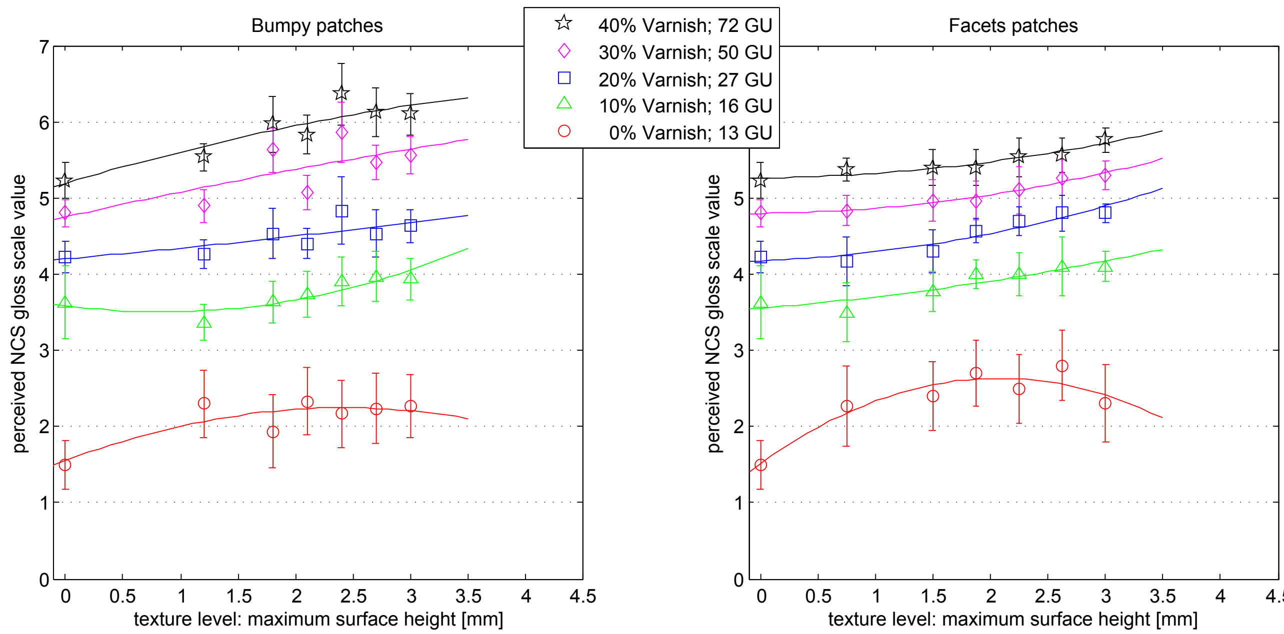


Figure 4. *Relationships between the amount of surface texture and the perception of the surface gloss level, for 'Bumpy' (left) and 'Facet' patches (right). For display purposes, the standard deviations were multiplied by a factor of 0.5.*

lighter samples as there is more diffuse reflection in the specular direction.

Another explanation is that the magnitude of perceived glossiness depends upon multiple gloss attributes (such as contrast and specular gloss, as described by Hunter [12]) and do not solely depend on the measured specular reflection.

Effect of macroscopic surface texture on perceived gloss

In order to investigate the effect of the macroscopic surface texture on the perceived gloss level, for each set of patches with identical reflection properties, the observers' judgement of the gloss scale value was compared to the amount of applied surface texture. In Figure 3, the observers' judgements of the gloss scale values are shown for seven patches with varying amount of texture. As can be seen from Figure 3, the gloss level of more textured patches was rated slightly higher than that of flatter patches (with identical reflection properties).

The average gloss scale values of the textured patches were calculated for all patches as well as the standard deviation among the observers and plotted in Figure 4. Here, the average observers' judgement of the gloss scale value is plotted against the amount of surface texture that was applied for both the 'Bumpy' and 'Facet' patches. The figure indicates an influence of the macroscopic texture on the perceived level of gloss. Based on observations of the results and previous literature [2], [**?**], we expected the curves to follow a second order polynomial curve, which was therefore determined for each group of the patches with identical reflection properties. Thus, five curves were plotted, according to five different gloss levels, one for each texture type.

As can be seen in Figure 4, the type of texture influenced the visual gloss perception so that the 'Bumpy' samples were perceived slightly glossier than the 'Facet's. This can be explained by the fact that specular highlights are more visible on 'Bumpy' patches, because each bump covers a wide variety of surface normals and produces therefore almost always a specular highlight independently from the sample's orientation. This is in contrast to the 'Facet' samples, which contain only a few surface normal orientations and thus less specular highlights.

In general, a slight influence of the amount of surface texture on the perceived glossiness is visible in Figure 4, showing the tendency that surfaces are generally perceived glossier when the amount of surface texture is increased. However, for both 'Bumpy' and 'Facet' patches printed with 0% varnish coverage (i.e. 'Matte' samples), the results show a non-monotonic relationship, where from a certain texture level, further increase of surface texture results in lower perceived gloss levels. A similar effect has been previously observed by Qi et al [13]. In their experiments, using computer generated images, observers were asked to judge the glossiness of simulated stimuli with different roughness level. According to their experiments, increasing the macroscale roughness increases the perceived level of surface glossiness; however it eventually drops to a certain roughness level. This can be explained by the amount of specular reflections that are visible on the surface. We know that the gloss level of a surface (specifically in printed samples) is mainly judged by the amount of specular reflections observed from a surface. When surfaces are highly textured (e.g. the 'Facet' patches, used in our experiments), the specular reflections are not clearly visible on the steep slopes with respect to the limited illumination/viewing geometry, provided by the experimental condition when the sample is only slightly tilted.

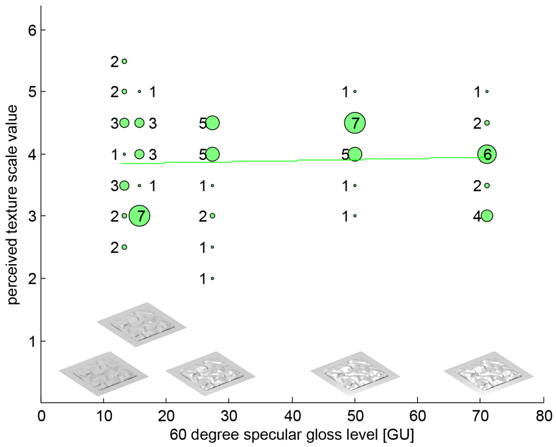


Figure 5. Bubble chart indicating the number of observers that rated the texture scale values of each of the five 'Facet' patches as a particular level on the texture scale. The presented patches have identical texture levels (texture level 4) and varying gloss level (from 13 to 72 GU).

Effect of surface glossiness on perceived texture level

Task B was designed to investigate the influence of surface glossiness on the perceived level of surface texture. In Figure 5, the observers' judgements of the perceived texture level are indicated for six patches with varying amount of glossiness and identical texture level. The figure shows a large variation between observer judgements and no significant influence of the surface gloss level on the perceived surface texture, which indicates the texture constancy regardless of the glossiness level. This is, however, in contrast to findings in related work, [2] where the influence of surface glossiness on the perceived surface texture was explained by a monotonically increasing trend, indicating that samples with higher gloss levels are generally perceived more textured.

The reason for deviating results can be related to two different types of experiments using display-based (static) simulated surfaces (in [2] and [13]), and real 2.5D printed samples (in this paper). In general, in experiments with conditions which are more similar to real world situations, observers have more freedom and can acquire more information (e.g. BRDF, 3D depth information by stereo vision); thus, more accurate judgements are potentially possible.

Conclusions and Discussion

In this paper, psychophysical gloss and texture scaling experiments were conducted in order to investigate the effect of surface texture on perceived gloss level and vice versa.

A relatively small, but noticeable, influence of surface texture was found, in terms of texture type ('Bumpy' and 'Facet') and texture height, on the perceived magnitude of the surface glossiness. The textured samples were perceived glossier than the 'Flat' patches, and the perceived glossiness of the 'Bumpy' patches was also judged slightly higher compared to the 'Facet' patches.

The relationship between the surface texture and the perceived gloss was shown to be represented by a monotonically increasing function (second degree polynomial) for most cases. This results in the fact that a surface with height variations between 0 and 0.75 mm and a gloss level of 72 GU, was perceived equally glossy as a surface with height variations between 0 and 3 mm and a gloss level of 50 GU (Figure 4). However, a drop in the perceived gloss level was observed for the 'Matte' samples printed with 0% varnish coverage, when the texture level was increased to a certain point. This effect is in accordance to a related work [13].

We did not find any noticeable influence of the surface glossiness on the perceived level of surface texture which is in contrast to findings in related studies, [2] and [10]. A reason to these deviating results can be related to the experimental conditions where real 2.5D printed samples and display-based simulated surfaces were used.

Although different research has been performed in order to study the perception of gloss and texture and their interactions using display-based images, few studies were conducted on physical samples or cross-media experiments. In order to further investigate the criteria affecting the gloss and texture constancy, conducting more comprehensive psychophysical experiments using real-world objects (e.g. 2.5D and 3D printed samples) with more variations in colour, gloss, and texture is considered as an outlook to this work.

Acknowledgements

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Author Biography

Teun Baar recently finished a PhD at Mines-Telecom, Paris in collaboration with Océ-CANON, after receiving his Masters degree in Applied Physics from the Delft University of Technology. In his research, Teun focused on the optimization of print quality with multi-channel printing systems, in particular 3D printing and the perception and control of print surface characteristics such as color, gloss, and BRDF. His research interests include reproduction and perception of material appearance, 3D printing, color science, and surface perception, among others.

Sepideh Samadzadegan received her MSc in Media Technology and Engineering (Advanced Computer Graphics) from the Linköping University, Norrköping Campus, Sweden, in 2012. She is currently an EU-researcher involved in the Colour Printing 7.0 (CP 7.0): Next generation multi-channel printing project following her PhD at Technische Universität Darmstadt, Germany. Her research interests include colour and spectral imaging, reproduction and perception of material appearance, using 2.5D/3D printing technology.

Philipp Urban received the M.S. degree in mathematics from the University of Hamburg, Germany, in 1999 and the Ph.D. degree from the Hamburg University of Technology in 2005. From 2006 to 2008, he was a Visiting Scientist with the Munsell Color Science Laboratory, Center for Imaging Science at the Rochester Institute of Technology in Rochester NY and headed afterwards the Color Research Group at the Institute of Printing Science and Technology, Technische Universität Darmstadt, Germany. Since 2013 he has been Head of the Competence Center 3D Printing Technology at the Fraunhofer Institute for Computer Graphics Research IGD in Darmstadt. His research interests include 3D printing, spectral imaging, image quality and material appearance reproduction.

Dr. Maria V. Ortiz Segovia is the leading scientist of the color and image processing team in Océ, France. She is in charge of conducting collaborations and partnerships in between Océ and different universities, laboratories and research institutions worldwide. She received her PhD degree from Purdue University in 2011 and has been working in the field of printing since 2006. Her research interests include material reproduction, image quality, color imaging, and 3D printing, among others.