The influence of lighting on visual perception of material qualities

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ABSTRACT

We studied whether lighting influences the visual perception of material scattering qualities. To this aim we made an interface or "material probe", called MatMix 1.0, in which we used optical mixing of four canonical material modes. The appearance of a 3D object could be adjusted by interactively adjusting the weights of the four material components in the probe. This probe was used in a matching experiment in which we compared material perception under generic office lighting with that under three canonical lighting conditions. For the canonical materials, we selected matte, velvety, specular and glittery, representing diffuse, asperity, forward, and specular micro facet scattering modes. For the canonical lightings, we selected ambient, focus and brilliance lighting modes. In our matching experiment, observers were asked to change the appearance of the probe so that the material qualities of the probe matched that of the stimuli. From the matching results, we found that our brilliance lighting brought out the glossiness of our stimuli and our focus lighting brought out the velvetiness of our stimuli most similarly to office lighting. We conclude that the influence of lighting on material perception is material-dependent.

Keywords: Material perception, lighting perception, material qualities, optical mixing

1. INTRODUCTION

As part of the EU Marie Curie PRISM project, one of our goals is to understand the relations between material and lighting perception of real objects in natural scenes. Novel aspects of our approach are that i) we developed a probing method to test perceptual material qualities in a purely visual way, and ii) we considered generic materials including not only matte-glossy variations but also other opaque materials, such as velvety and glittery materials. In the current paper we studied how lighting influences material perception. In order to systematically address this question in a generic sense, we approach "lighting" and "material" via a representation in canonical modes. Canonical modes refer to standard or archetypal components that are essential ingredients to mix into generic representations.

In 2012, Pont et al. showed that optical mixtures[1] of canonical BRDF modes (such as matte, velvety and specular) can be used to systematically vary visual material qualities of real objects in a real setup and on a computer screen[2, 3]. On the basis of this study, we developed a novel material probe by optically mixing four materials that have clear features representing diffuse, asperity, forward and micro facet scattering modes. We selected these four canonical reflectance modes because they together span a large part of the BRDF space. The BRDF is a function that represents the amount of light scattered in every direction as a function of the amount of light arriving from every direction. Generally, if the main directions of the BRDF lobes are different, the main image features will appear in different locations on the object too. For instance, forward scattering will cause highlights at specular attitudes while asperity scattering causes bright contours. Thus, we propose to take the BRDFs as the criteria, and believe that when the BRDFs span the whole BRDF space, the image features will also span the whole space of possible visual appearances[4].

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Photographs of the probe were made under generic office lighting. In order to test the probe, we integrated it into an interface and performed matching experiments[5]. The stimuli in the interface were also created by optically mixing images of the four materials. However, in order to systematically study the influence of lighting on material perception, the photographs for the stimuli were taken using three canonical modes of lighting. We chose so-called ambient lighting, focus lighting and brilliance lighting since these are commonly applied in lighting design and architecture for building up lighting plans[6]. Moreover, these modes were proven to be basic components of physical decompositions of the light field[7, 8], and it has been shown that human observers are sensitive to these modes[7, 9]. Ambient lighting is represented by a uniform light distribution illuminating an object in it equally intense from all directions. A combination of snow and fog is an example of a condition in which ambient lighting can be encountered in nature. Focus lighting can be created by a single collimated light source that produces hard shadows, like the sun. Brilliance lighting is represented by the higher order statistics of the light field or, in other words, high angular frequencies of the light. In real scenes, the local light field is normally a combination of the canonical lighting modes in various ratios. However, in this study we will test the influence of the canonical lightings in isolation.

2. METHODS

2.1 Basis images

In order to systematically vary the visual perception of material qualities in the stimuli, a series of basis images was created from photos of four bird-shaped objects. First, the objects were finished with matte, velvety, glossy and glittery materials to represent the four canonical reflectance modes, which were diffuse, asperity, forward and micro facet scattering, respectively. Second, we took photos of the objects under different lighting conditions by using the equipment shown in Figure 2. The camera and one of four objects were fixed on a frame, which was attached to a tripod standing on a cart. We then rolled the whole setup between three canonical lighting setups, namely ambient lighting (by using a white photo tent as shown in Figure 2 – which was almost closed at the front side during the photography but left open for visualization purposes for this figure), focus lighting (by using a spot light from the left side of the object), and brilliance lighting (by hanging a LED-strip containing 150 small sources around the object). In order to align the bird images, we had to make sure each object was placed in exactly the same position and orientation on the frame and in the lighting setups. Their shadows and base outline on their grounding were drawn as references in order to align the imagery, and the cart positions were marked on the floor.

Figure 1. The setup for the photography of the object under different lighting conditions. Left: The object and the camera were fixed onto a frame attached to a tripod and placed on a small trolley. This setup could be rolled into the three canonical lighting setups of which one is shown on the right. The ambient lighting scene was created using a white photo tent – which was almost closed during the photography.

Next, we edited the photos to find the shared contour, and made the backgrounds outside the contour black for all images. To avoid color interactions the images were processed in MATLAB to set the hue values to 0.33 (green) – which only had a minor influence on the images since the birds were pure green. In addition we photometrically calibrated the luminances, to arrive at a linearly calibrated optical mixing system. The resulting basis images are shown in Figure 2.

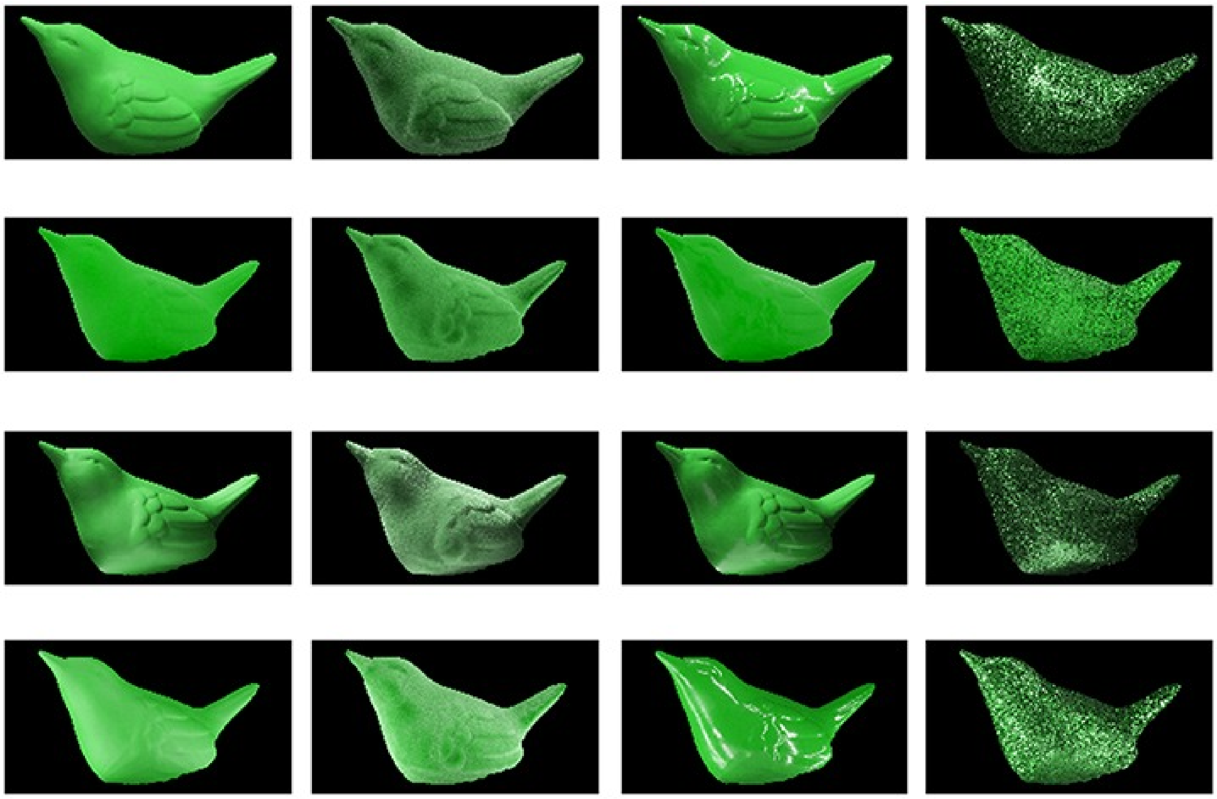

Figure 2. Basis images. From left to right each column shows a canonical reflectance mode, namely diffuse, asperity, forward and micro facet scattering, represented by matte, velvety, specular and glittery materials, respectively; From top to bottom the first row shows the probe basis images which were shot under generic office lighting, below which each row shows stimulus basis images for a canonical lighting mode, namely ambient lighting, focus lighting and brilliance lighting (from second to fourth row, respectively).

2.2 The stimuli and the probe

The stimuli were linearly superimposed optical mixing results of the basis images taken under any of the three canonical lighting conditions. We made 15 weight combinations of four canonical reflectance modes as shown in Table 1. The mixing was done per lighting mode and can be illustrated by equation (1)

$$I_{stimulus} = w_m \cdot I_m + w_v \cdot I_v + w_s \cdot I_s + w_g \cdot I_g \qquad (1)$$

where subscripts {m, v, s, g} denote matte, velvety, specular and glittery, representing the four canonical reflectance modes (diffuse, asperity, forward and micro facet scattering); $\{w_m, w_v, w_s, w_g\}$ are the weights of the reflectance modes (Table 1); $\{I_m, I_v, I_s, I_g\}$ are the processed basis images of the different materials (Row 2 to row 4 in Figure 3). As a result, 15 mixed images for each lighting mode were created. In combination with the three lighting conditions this makes 45 stimuli in total, as shown in Figure 4.

The probe was a linearly optically mixed result of basis images taken under generic office lighting. Similarly to eq (1), the result can be described by equation (2)

$$I_{probe} = w'_m \cdot I'_m + w'_v \cdot I'_v + w'_s \cdot I'_s + w'_g \cdot I'_g \qquad (2)$$

where $\{w'_m, w'_v, w'_s, w'_g\}$ are the weight values corresponding to the positions of the slider bars in the corresponding sliders (for details, see Figure 4); $\{I'_m, I'_v, I'_s, I'_g\}$ are the processed basis images under office lighting (first row in Figure 3).

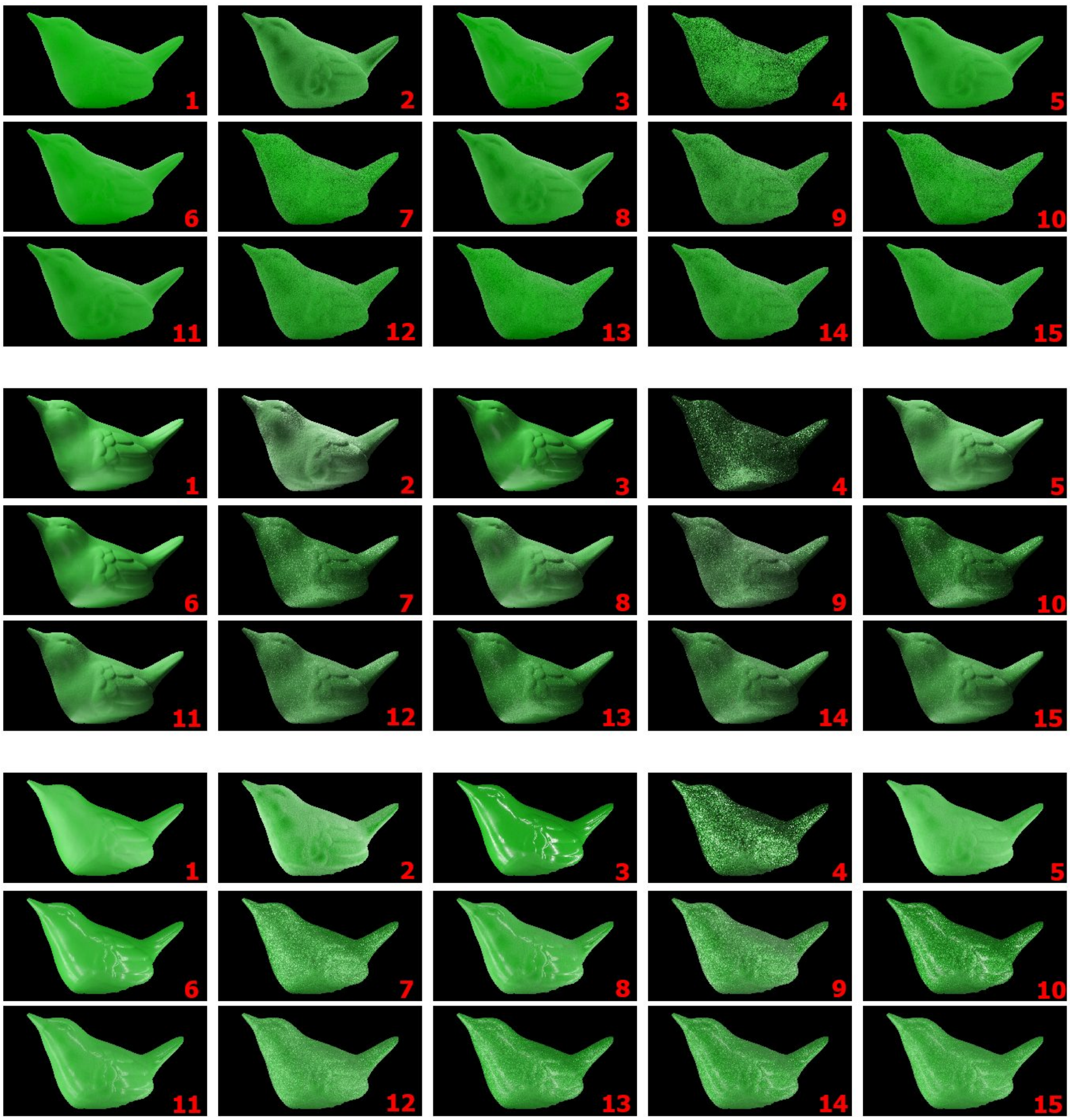

Figure 3. The stimuli. Rows 1, 2, 3 show the stimuli for ambient lighting; rows 4, 5, 6 show the stimuli for focus lighting; rows 7, 8, 9 show the stimuli for brilliance lighting. The number in each image corresponds to the weight combination number in Table 1.

Table 1. Weight combinations of the different reflectance modes for creating the stimuli. There are 15 combinations in total.

No.	w_m	w_v	w_s	w_g
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1
5	0.5	0.5	0	0
6	0.5	0	0.5	0
7	0.5	0	0	0.5
8	0	0.5	0.5	0
9	0	0.5	0	0.5
10	0	0	0.5	0.5
11	0.33	0.33	0.33	0
12	0.33	0.33	0	0.33
13	0.33	0	0.33	0.33
14	0	0.33	0.33	0.33
15	0.25	0.25	0.25	0.25

2.3 Procedure

An interface (Figure 4) containing two images and four sliders was shown to the observers. The task for the observers was to move the sliders to adjust the appearance of the bird in the top-right window (the probe) until it appeared to be made of the same material as the bird in the top-left window (the stimulus). In order to avoid the use of terms and provide purely visual information, we put a cropped image in front of each slider, representing one of the material components. The 45 stimuli were presented in a randomized order. In each trial, the positions of the sliders were randomly initialized as well. Once observers finished a trial, they pressed a button, after which only the stimulus image and the probe were presented on the screen, and they were asked to indicate on a scale how satisfied they were about the matching results. Five practice trials were performed before the experiment formally started. The interface was developed using Graphic User Interfaces (GUIs) in MATLAB R2014a, and presented to observers on a linearly calibrated Apple Inc. 15-inch Retina display.

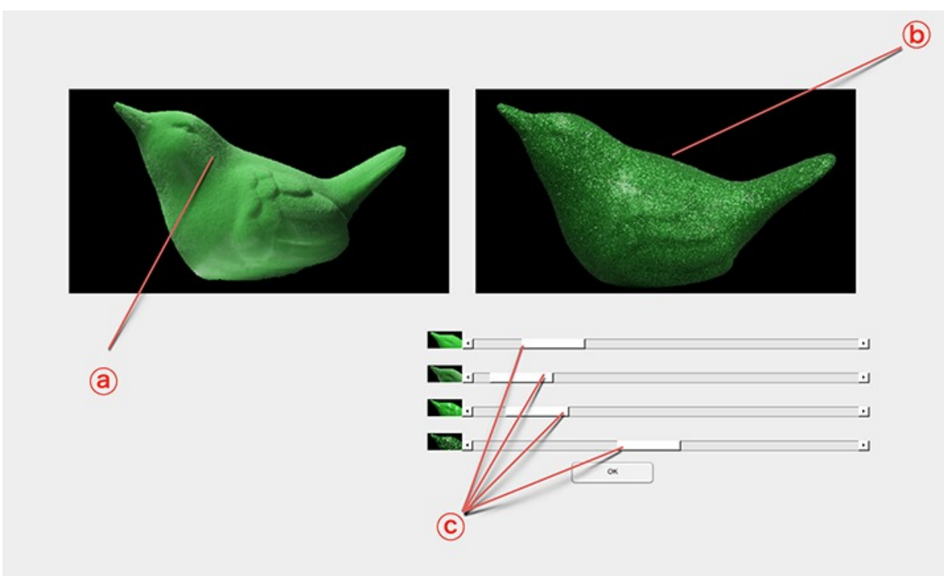

Figure 4. The interface. a): A stimulus image. b): The material probe. c): Four sliders. The position of each slider bar represents a weight corresponding to a reflectance mode, ranging from 0 to 1.2. The task of the observers was to match the materials of the probe and stimulus. Here, the two materials obviously do not match.

2.4 Observers

In total, 8 unpaid observers participated in the experiment (5 women and 3 men). They all have normal or corrected-to-normal vision. The study was approved by the TUDelft Human Research Ethics Committee. Before the experiment, we explained to observers that their participation was voluntary, and asked them to read and sign the consent form and introduction of the study.

3. RESULTS

The overall performance across all 8 observers per lighting mode was evaluated by solving the linear factor matrix A of equation (3)

$$[Y]_{4\times 120} = [A]_{4\times 4} \cdot [X]_{4\times 120} + [E]_{4\times 120} \tag{3}$$

where $[X] = \begin{bmatrix} w_m \\ w_v \\ w_s \\ w_g \end{bmatrix}$, $[Y] = \begin{bmatrix} w'_m \\ w'_v \\ w'_s \\ w'_g \end{bmatrix}$, and the residuals $[E] = \begin{bmatrix} e_m \\ e_v \\ e_s \\ e_g \end{bmatrix}$

Each column in Matrix X contains weights of 4 reflectance modes that define a stimulus image in one trial. The 4 values in Matrix Y in the corresponding column record the probing results. For each lighting mode, there are 15 weight combinations, which makes 15 trials * 8 observers = 120 datapoints in total per lighting mode. We solved the matrix A (a 4 by 4 matrix) using a least squares method (in MATLAB). If all observers would have matched the material mixtures perfectly, i.e. moved the sliders to exactly those positions that would have made matrix Y to be equal to matrix X, we would have gotten a 4 by 4 identity matrix for matrix A and a zero matrix for the residual matrix E. In the limiting case in which observers would have randomly adjusted the sliders according to some uniform distribution, all 16 elements in matrix A would be of equal value, with the value being dependent on the boundary conditions (e.g. for the sum of the weights, which is related to the overall brightness). In our analysis we will address the results for matrix A and not for matrix E, since we found that the residuals were negligible.

As shown in Table 2, for the ambient lighting mode we find dramatic influences, as matrix A deviates from an identity matrix to a great extent. Specifically, the diagonal elements of the matrix are 0.86 for matte, 0.50 for velvety, only 0.26 for specular, and 0.93 for glittery. For the focus lighting mode, the element in the diagonal that represents the specular component is also small (0.51), while the elements for the matte, velvety and glittery components remain around 1. For the brilliance lighting mode, the matrix is close to an identity matrix.

Besides the diagonal elements in matrix A, which show the overall matching results of all observers for each canonical lighting mode, we are also interested in the perceptual interactions between reflectance and lighting modes. If we compare the diagonal elements between the three matrices we can see that the diagonal elements for velvetiness in the matrices can be sorted in the following ascending order: ambient lighting (0.50) – brilliance lighting (0.84) – focus lighting (1.19), while for specularity, the order changed to ambient lighting (0.26) – focus lighting (0.51) – brilliance lighting (1.17).

In Figure 5 we plotted the bi-variations of the matching results per material combination (in the rows) and lighting mode (represented by the drawn, dashed and dotted lines in each graph). The crosses depict the stimulus weights combinations. The bi-variate normal distribution of the sets of individual datapoints was shown as ellipse with one standard deviation. We can easily see that in the stimuli containing a glittery component, very few interactions are found as the ellipses' centers deviate very little from the stimulus positions (the crosses) when glittery is involved. In contradistinction to the glittery component, the matte, velvety and specular components systematically interact with each other.

Table 2. The linear factor matrices of the model (the matrix A in Eq. 3). These matrices represent the perceptual relations between the weight combinations in the stimuli and the probing results. In this model, the relations between the weights of the same material component in both the stimuli and the probe, i.e. the perceptual relations between each material in one of the canonical lightings and the office lighting, are shown in the diagonal elements. For example, 86% of the matte component in the ambient lighting was matched with the matte component in the office lighting, while only 26% of the specular component in the ambient lighting was matched with the specular component in the office lighting. The perceptual relations between the weights of different material components in the stimuli and the probe are shown in the off-diagonal elements. E.g., 76% of the specular component in the ambient lighting was matched with the matte component in the office lighting. Each row represents the weights of the four material components in the probe relative to their contributions in the stimuli. For example, the weight of the matte component perceived in the probe (w'_m) in the office lighting can be predicted by the sum $w'_m = 0.86 \cdot w_m + 0.49 \cdot w_v + 0.76 \cdot w_s + 0.07 \cdot w_g + e_m$, when being matched to the stimuli in the ambient lighting.

Ambient Lighting	w_m	w_v	w_s	w_g
w'_m	**0.86**	0.49	0.76	0.07
w'_v	0.21	**0.50**	0.13	0.33
w'_s	0.13	0.01	**0.26**	0.18
w'_g	0.00	-0.01	0.02	**0.93**

Focus Lighting	w_m	w_v	w_s	w_g
w'_m	**0.81**	0.08	0.43	-0.08
w'_v	0.20	**1.19**	0.08	0.21
w'_s	0.09	-0.03	**0.51**	0.03
w'_g	-0.01	0.07	0.01	**0.96**

Brilliance Lighting	w_m	w_v	w_s	w_g
w'_m	**0.88**	0.42	0.10	-0.01
w'_v	0.15	**0.84**	-0.07	0.20
w'_s	0.24	0.13	**1.17**	0.00
w'_g	0.02	0.09	0.01	**1.17**

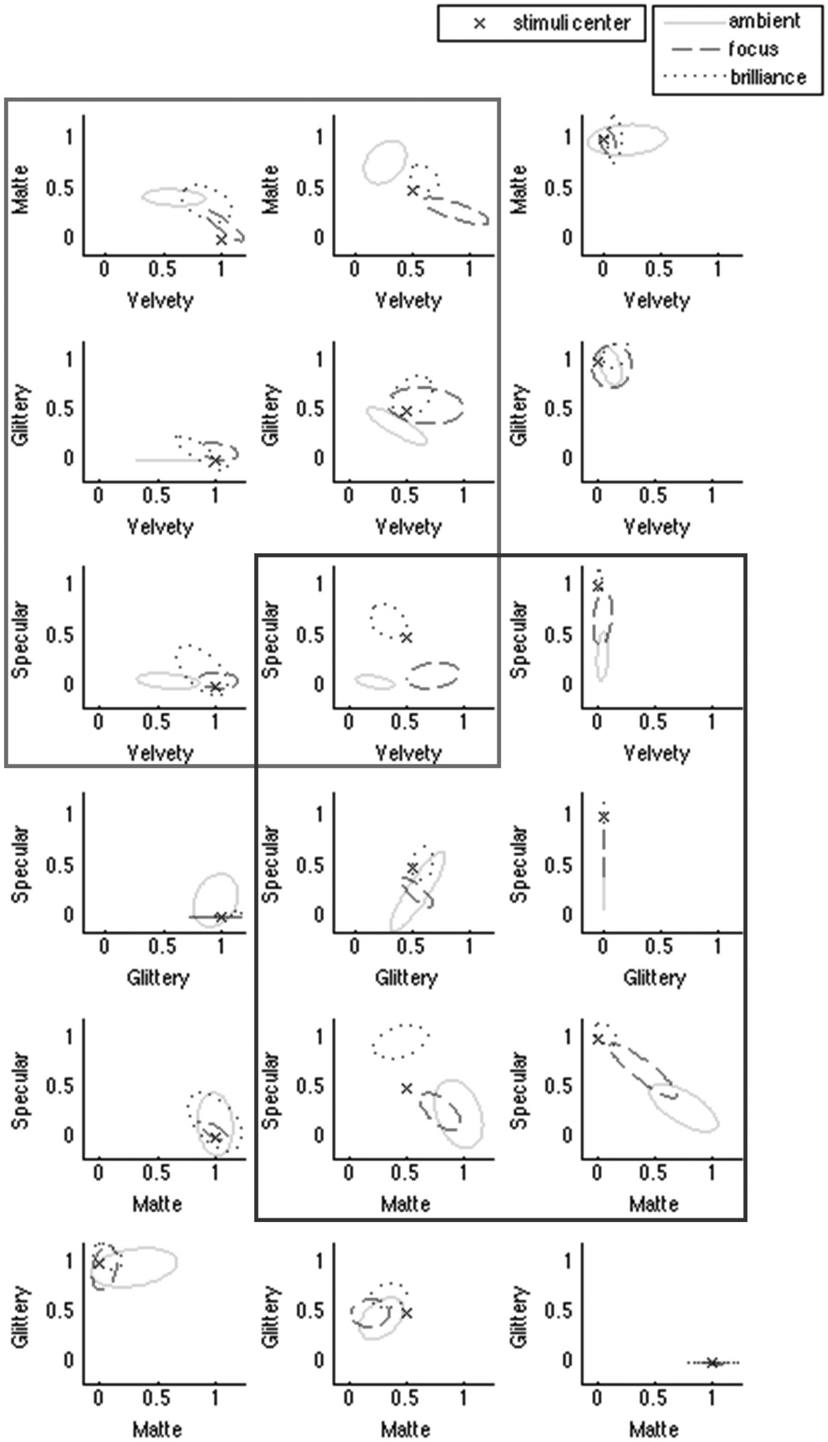

Figure 5. Interactions between each two of the reflectance modes. In each subplot, the matching results of 8 observers are fitted into one standard deviation bivariate ellipses. The black cross represents the weight combination of the stimulus in each subplot. In the top-left block of six subplots, perceived velvetiness of the stimuli in comparison with the probe under office lighting decreases as the lighting changes from focus lighting to brilliance lighting to ambient lighting. In the middle-right block of another six subplots, perceived specularity of the stimuli in comparison with our probe decreases as the lighting changes from brilliance lighting to focus lighting to ambient lighting.

4. CONCLUSION

Our results showed that the visual perception of materials was systematically (un-)affected by the canonical lighting modes, depending on the material mode. Firstly, the diagonal elements for matte and glittery components in all matrices remained at around approximately 0.9 and 1, respectively, which indicates that the matte and glittery components in our stimuli were perceived similarly to the matte and glittery components in the probe and hardly influenced by the lighting modes. Secondly, the magnitude of the deviations from veridical for the velvety and specular modes differed per lighting mode. The ambient lighting mode caused the largest influence on the perception of velvetiness and specularity. The focus lighting mode, surprisingly, caused almost half of the specular component in the stimuli being confused with the matte component in the probe. The brilliance lighting mode had the least influence on the perception of the four material modes. Finally, the diagonal elements in the matrices representing velvetiness increased as the lighting modes changed in the order ambient lighting - brilliance lighting - focus lighting, while for specularity, it increased according to the order ambient lighting – focus lighting – brilliance lighting. Thus, our brilliance lighting brought out the specularity most similarly to our office lighting, while our focus lighting brought out the velvetiness most similarly to the office lighting. Figure 6 illustrates this effect; it concerns stimulus 8 (weights of velvety and specular contributions both 0.5) that looks rather velvety under focus lighting (left image), while it looks rather specular under brilliance lighting (right image). This result indicates that specific, material-dependent lighting modes are required to bring out the characteristics of specific materials. Since our experiment only addressed relative judgments or comparisons we cannot draw conclusions about, for instance, which of our lightings brought out the glossiness or velvetiness best. This question we will address in future experiments.

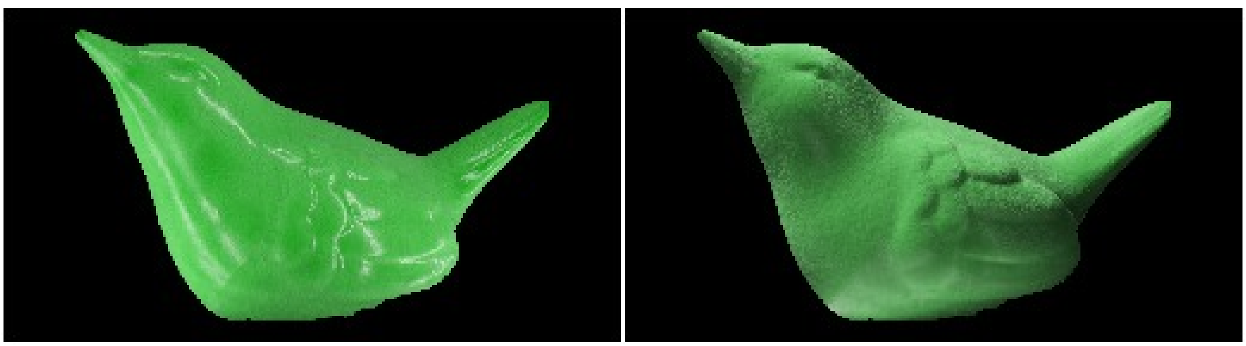

Figure 6. Stimulus 8, an optical mixture of velvety and specular materials, looks velvety under focus lighting (left image), while it looks specular under brilliance lighting (right image).

The phenomenon that glossy materials look like matte materials under ambient lighting has already been reported[10, 11, 12]. Here we found the same effect and presented it in a quantitative way, i.e. 0.76 of the specular component in the stimuli in our ambient lighting scene contributed to the perception of the matte component in the probe in the office lighting. In addition, we found that 0.49 of the velvety component in the ambient lighting contributed to the perception of the matte one in our office lighting and 0.33 of the glittery component in the ambient lighting contributed to the perception of the velvety one in our office lighting.

In our focus lighting scene, we also found a small decrease of the glossiness contribution. As shown in Table 2, 0.43 of the specular mode in the stimuli was confused with the matte component in the probe. When considering all elements in the first row for the focus lighting mode, we can find that the total amount of matte component in the matching results consisted of one third of the specular component and two thirds of the matte component in the stimuli. We believe this was due to the relative position of the light source and the object in the focus lighting scene, resulting in a less glossy appearance, compared to the probe which was taken in office lighting. In Figure 3 it can be seen that the number of high contrast highlights was much smaller in focus lighting and more comparable to the office lighting and brilliance lighting cases. Since highlight coverage, sharpness and contrast are the main cues for perceived glossiness in non-disparity conditions[13], this decrease of sharp, high contrast highlights probably explains our finding.

Comparing to the office lighting environment in the probe, our brilliance lighting mode is the most similar one among the three canonical lighting modes we implemented. Due to the limitations of the laboratory conditions, there were also a little focus lighting mode and ambient lighting mode present in the brilliance lighting mode. These altogether probably have led to the fact that the brilliance lighting caused the smallest effects.

In conclusion, a matching experiment was conducted in a quantitative and purely visual manner by using the material probe we previously developed. Three canonical lighting modes (ambient, focus and brilliance) and four canonical reflectance modes (matte, velvety, specular and glittery) were included. n. The ambient lighting had the largest impact in comparison to office lighting, especially on the perception of velvetiness and specularity. The focus lighting had a strong influence on the perception of specularity. The brilliance lighting had the least strong influence on the perceived reflectance modes. These findings suggest that due to complex material-lighting interactions, perceived material qualities will depend on both lighting and material. Thus, this means that in lighting design (for architecture, computer rendering, retail design, webshop photography, etc.) one needs to be aware of such interactions and explore per material which lighting will bring out the desired material qualities maximally or eliminate undesired material qualities.

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