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The effect of diffuseness and direction of light on perceived texture visibility

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Abstract

The diffuseness of light and its angle of incidence influence the way we perceive material properties like roughness and shininess, but whether it influences our ability to discriminate between differently textured materials is unclear. Therefore we examined the effect of diffuseness and direction of light on the perceived texture visibility of images of different materials. Images were made under strongly collimated or strongly diffuse lighting and superimposed to obtain mixed images with varying diffuseness levels. Participants rated texture visibility pairs of images using a 2-alternative forced choice task (AFC). We found that overall the perceived texture visibility was best for the most diffuse light source and worst for intermediate diffuseness levels. Texture visibility improved with angle of incidence for collimated lighting. The effect of the diffuseness level of the illuminant was strongly dependent the material. Our results confirm that the diffuseness of light is an important factor for discriminating textures of real materials.

Introduction

Modern LED luminaires allow much better control over the spectral composition and luminance distribution of light. One particular application is open wound surgery, where the composition of light may be modified to enhance the visibility of certain (diseased) tissues. In earlier work we showed that the spectral composition may be optimised to enhance colour contrast [14, 15, 16]. But apart from spectral composition the spatial arrangement of LEDs in the luminaire also influences the beam shape and the diffuseness of light. It is well-known that illuminating surfaces with three-dimensional textures with collimated light gives rise to cast shadows and shading patterns that can enhance visibility especially at grazing angles. Highly diffuse light on the other hand does not cast shadows, although light-dark variations arise due to vignetting. The lack of cast shadows is a big advantage for surgical applications as the surgeon needs to move the hands in and out of the luminaire's light beam. However, it is not clear whether the diffuseness of light also influences the discriminability of different tissues [13]. Therefore we investigated the effect of the diffuseness and angle of incidence on the perceived texture visibility for various materials with different three-dimensional textures.

There are many physical processes that give rise to texture variations. Rough surfaces give rise to cast shadows and shading patterns. Shiny materials materials reflect the light source directly giving rise to highlights, typically at strongly convex regions. Rough and shiny material show smeared out highlights [3]. Other physical processes like interreflections, scattering, (semi)transparency, refraction, absorption and emission further complicate the interaction with light. As a result the apparent visual texture is highly dependent on both the structure of the light field and the material properties [6]. The diffuseness of light mainly affects the shading patterns of rough surfaces and the highlights of shiny surfaces. According to the literature, the perceived roughness of materials depends on many visual cues like binocular disparity, motion parallax and other depth cues [7]. Ho and colleagues showed that perceived roughness strongly depends on the diffuseness of the light [2]. Diffuseness of light also influences other perceptual qualities of materials like specularity and ”velvitiness” [17]. Perceived roughness also depends on the angle of incidence of collimated light was perceived differently at different viewing angles [2, 5]. It is also possible to judge the direction of illumination for hemispherically diffuse and collimated lighting from the shading patterns [9].

Most research focuses on singular perceptual qualities like roughness, shininess, colour etc., but to distinguish real materials (e.g. distinguishing diseased tissues from healthy ones), one needs to judge differences on all relevant perceptual dimensions at once. This boils down to distinguishing between textures the perception of which is expected to depend on the illuminant. Fortunately, it appears that this so-called texture contrast is fairly predictable for a wide class of materials based on Lambertian shading [8]. In this study, we investigated whether people are able to judge texture visibility for a variety of real coloured materials with a strong three-dimensional structure. In particular, we investigated how variations of both diffuseness and direction of illumination affect perceived texture visibility. To do so we photographed ten different materials illuminated by strongly diffuse light and by a strongly collimated light at varying angles of incidence and mixed the images to create different levels of diffuseness. Participants then judged texture visibility between pairs of images of the same material. Based on earlier research we expected that edges of rough surfaces are better visible with collimated light at grazing angles of incidence. On the other hand, diffuse light is able to penetrate deeper into holes and cavities, which could also benefit texture visibility. The aim of the current study is to measure the effect of the diffuseness of the light and its dependence on the three-dimensional structure of the material.

Method

Participants and task

30 participants took part in the experiment: 10 female and 20 males. Mean age was 23 years; 3 participants were colourblind, but it was not necessary to exclude them. All participants had normal or corrected-to-normal visual acuity (mean visus of 1.7). The participants were recruited through the JSF participant database and received money for participating. The task of the participants was to indicate which out of a pair of images has more perceived texture visibility. The image pairs were always depicting the same material (see Figure 1), but under varying illumination conditions.

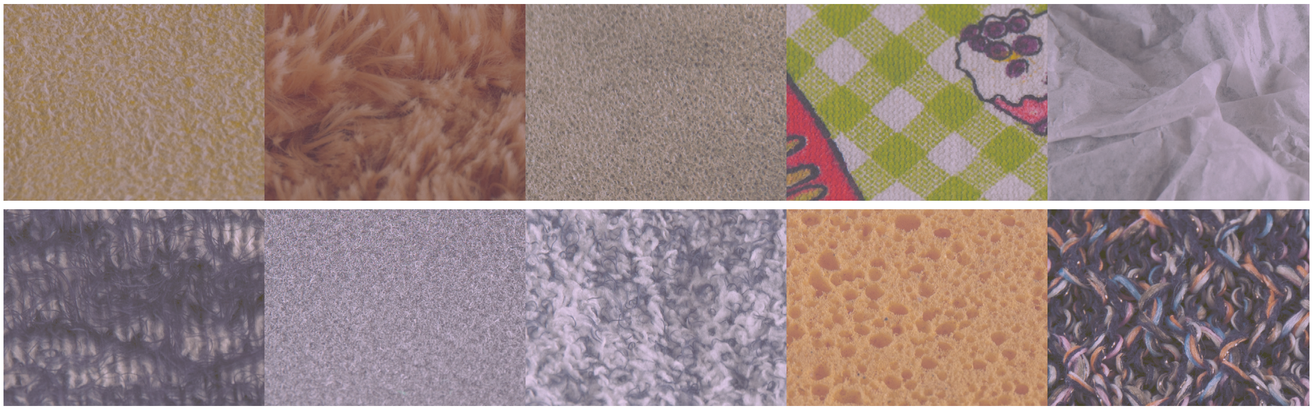


Figure 1. *Materials used in the experiment. From left to right, top to bottom: chamois leather, hand puppet, foam, placemat, wrinkled paper, scarf, camera protector cloth, sock, sponge, sweater.*

Figure 2. *Picture of the experimental set-up. The collimated light was positioned at a fixed distance from the centre of the table (d= 0.50 m). The angle of incidence was varied from directly above (0 deg) to 75 deg to the right.*

Experimental set-up

To create the images we placed various materials on a table that was either illuminated by halogen light source mounted within a light guide (see Figure 2) or two C Flash type 400 Professional lights, combined with white diffusers (umbrellas). The former light source is strongly collimated, whereas the latter is strongly diffuse.

The camera used was a NIKON D3100 with an AF-S DX VR Zoom-Nikkor 18-105mm f/3.5 – 5.6G ED lens. In order to make the displayed colour consistent with the visually perceived colours of the real object, the camera was colour calibrated with a Digital ColorChecker in order to map the camera RGB values to CIE XYZ values (see [4] for method). The camera was mounted on a tripod to fix its position. The camera was set on manual mode with focal length set at f=77 mm, white balance at Tungsten (2850 K) and F values at F=f/5.3. The exposure time is adjusted for each material to prevent over- and underexposure. All images are stored in Raw format, and then are saved as 8 bit tiff format using the Camera Raw® software plug-in for Adobe Photoshop CS6.

The stimuli were shown on a calibrated, 46 inch, NEC MultiSync P463, LCD monitor with a resolution of 1920x1080 pixels. The monitor was placed in a dark room so that the monitor was the only light source. The stimuli were presented on the monitor using MATLAB (The Mathworks, Inc.) in the centre of the screen against a medium grey background. An adjustable chair and chin rest were used to position the participants at 1m from the screen. The chin rest made sure the height of the participants' eyes were approximately equal to to the middle of the screen.

Stimuli

To create the stimuli 10 different materials from daily life were photographed using the diffuse light source and using the collimated light source. The materials used are shown in Figure 1. The materials were illuminated with the diffuse light source and the images were processed as explained below.

Luminance distribution rescaling

Before taking pictures of the various materials in a given lighting condition, a picture was made of matte white photography paper. As shown in Figure 3a, there is a clear luminance gradient on the image for the collimated light source. To remove the luminance gradient from the stimuli, the luminance values were rescaled in CIE XYZ space. The XYZ coordinates of the source image were multiplied by $w = 50/Y_{\text{background}}$ of the corresponding pixels of the neutral background, which removes the luminance gradient and equalises the average luminance level. The same procedure was applied to all lighting conditions. The effect of rescaling is shown for wrinkled paper in Figure 3b) and c). Some materials were not completely flat, which changed the exact shape of the light spot. In that case we used the average height to position the flat white paper, so as to reduce the overall gradient in the processed picture as much as possible. Only for the sponge, white photography paper was placed on top in order to compensate for the height difference.

Image superimposition and diffuseness level

All images are processed with Adobe Photoshop CS6® to adjust for the used white-balance 'Tungsten', to be able to check easily for differences in luminance and position and to crop each image at exactly the same image size. After rescaling the images of the collimated light and the diffuse light were super-imposed a)

b)

c)

Figure 3. *a) Luminance gradient on matte white photography paper under collimated lighting at 0 deg angle of incidence. b) Image before rescaling. c) Image after rescaling.*

with different mixing ratios. If, after the mixing, the image appeared blurred the cut-out position was shifted manually. Finally, the images were cropped to a 600 by 400 pixels, so that two images could fit side by side on the display without rescaling.

Cuttle [1] explains how the diffuseness of the light field can be assessed using a simple cubic illuminance measurement device. Basically, the illuminance difference on opposing faces of a cube is measured to determine the mean illuminance level and the illuminance gradient. The mean illuminance level obtained in this way was 55.66 for the collimated light and 1601.87 for diffuse light. The illuminance gradient for collimated light is (18.23, 45.82, 53.41) and for diffuse lighting (3757.09, 3587.32, 3716.37). The corresponding diffuseness level is 1.306 for the collimated light and 3.9873 for the diffuse light (see [1] for formula). To create intermediate diffuseness levels, we mixed the images after processing with 0%, 25%, 50%, 75% and 100% as mixing coefficients. Since the mean luminance was normalised, the mixing coefficients of the corresponding diffuseness levels are approximately the same: 1.3, 1.9, 2.6, 3.3 and 4.0.

Design

We used a 2-alternative forced choice task (2AFC) to let participants rate texture visibility. The dependent variable is the probability that participants chose the left (or right) image. Participants compared for each illumination direction and each material all possible combinations of the 5 diffuseness levels. There are (5*4)/2=10 possible pairs. This makes a total of 10 (materials) * 4 (angles of incidence) * 10 (possible pairs) = 400 pairs. Since this does not directly compare between different illumination directions, participants also had to compare all possible combinations of the four angles of incidence for the 0% diffuse (100% collimated) lighting condition. This was also done for all materials, which makes a total of 10 (materials) * 6 (combinations; (4*3)/2 pairs for 4 angles) = 60 pairs. So the total amount of choices participants had to make was 460. The image pairs were presented in random order. Note that there is no physical difference between the images for each angle for 100% diffuse lighting. This allowed us to compare between the different angles.

Procedure

Before entering the experiment room, participants signed an informed consent form and were tested on visual acuity using a Landolt C chart and on colour blindness using the Ishihara colour blindness test. The height of the chair was adjusted such that the chin rest was comfortable. This made sure that the participant was positioned at 1m from the screen with the eyes at the height of the middle of the screen. After explaining the task, they judged 460 pairs of images and selected the image with the highest perceived texture visibility by pressing ‘z’ for the left and ‘/’ for the right image. At the end of the experiment, participants were shortly de-briefed.

Data analysis

To analyse the 2AFC data we used Thurstone’s model [11]. This model assumes that the perceived texture visibility of a stimulus can be modelled by a Gaussian distribution, and that the choice between a pair of images depends only on the difference between the texture visibilities of each image of the pair. Since all distributions are Gaussian, this boils down to the statement that $z_{ij} = z_i - z_j$, where z_{ij} is the z-score of the cumulative normal probability distribution of choosing image i over image j, and z_i is the z-score that expresses the estimated absolute texture visibility of image i. Since we only measure relative differences between images, we need the Thurstone’s model to estimate the absolute values of perceived texture visibility. To do so, we first determined the frequency that the left image was chosen for each condition. The frequencies are transformed to probabilities and converted to a z-score resulting in a table of z_{ij} values. Taking the row average across j gives the estimated absolute z-value z_i up to an arbitrary constant. The resulting mean z-values are analysed using an analysis of (co)variance to test for significant effects. This procedure can be applied to the entire dataset or to subsets. For example, to study the effect of diffuseness the total number of choices per participant per pair of diffuseness levels was 10 (materials)*4 (angles) = 40. So if the left image was chosen 10 times for given pair of diffuseness levels, the corresponding probability would be 10/40=0.25.

Results

In order to investigate if the perceived texture visibility, the mean z-values for the different diffuseness levels are calculated from the observed frequencies of choices (see section). Since the absolute z-values have no meaning, the z-values for 100% diffuse light (level 5) were fixed at 0.

In Figure 4 the overall effect of diffuseness level on textures visibility is shown. It clearly shows a U-shaped pattern. If we fit a 2$^{\text{nd}}$ order polynomial $y = a_0 + a_2(x - a_1)^2$, we find $a_0 = -0.904 \pm 0.023$, $a_1 = 2.69 \pm 0.36$ and $a_2 = 0.166 \pm 0.009$, which are all significantly different from zero.

In Figure 5 the effect of both angle of incidence and diffusion level on the perceived texture visibility is shown. Again the absolute value for 100% diffuse lighting (level 5) is set to zero. This makes sense because for the 100% diffuse light condition there is

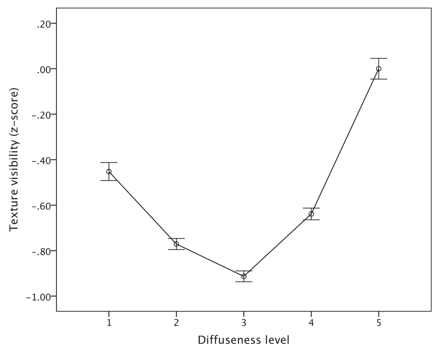
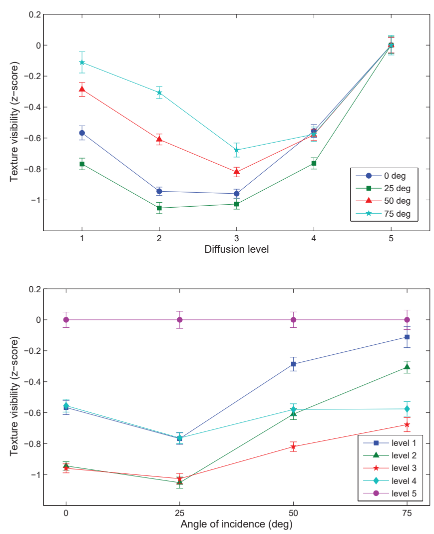


Figure 4. *Overall effect of diffuseness level on texture visibility. Error bars indicate SE.*



a)

b)

Figure 5. *Effect of diffuseness level on the perceived texture visibility for each inclination angle of the collimated light source. In panel a) diffuseness level is plotted on the x-axis and in panel b) the angle of incidence. Error bars denote SE.*

no angle of incidence making these conditions identical. For each angle of incidence the pattern is similar (Figure 5a), but where the angle of incidence does not affect texture visibility much for high diffuseness levels, it is rather pronounced for the lowest diffuseness levels. This is shown more clearly in Figure 5b, where the angle of incidence is plotted on the x-axis. For the diffuseness levels 1 and 2 texture visibility increases with angle of incidence, but it is more or less constant for diffuseness levels 3 and 4 (and by definition for level 5). Using a univariate ANOVA with texture visibility as dependent variable and angle of incidence and diffusion level as independent variables we found significant main effects of diffusion level ($F(4,580)$ =233.916, $p < 0.001$, $\eta^2 = 0.617$) and angle of incidence ($F(3,580) = 73.85$, $p < 0.001$, $\eta^2 = 0.276$), and a significant interaction effect ($F(12,580) = 11.6$, $p < 0.001$, $\eta^2 = 0.194$).

In Figure 6the effect of diffuseness on the perceived texture visibility is shown for each material separately. It is clear that the effect of the diffuseness of the incident light is qualitatively different between materials. In particular, the texture visibility for the scarf (circles) shows a decreasing trend , whereas that of the sponge (squares) shows an increasing trend. The texture visibility of the hand puppet (triangles) shows a V-shaped pattern. Most other materials also reveal an increasing trend. A univariate ANOVA with diffuseness level and material as independent variables confirms that there is a significant interaction effect between them ($F(36,150) = 9.363$, $p < 0.001$, $\eta^2 = 0.692$).

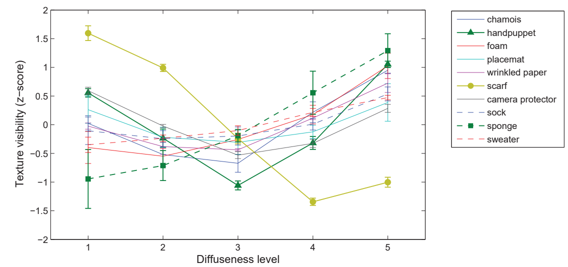


Figure 6. *Effect of diffuseness level on perceived texture visibility for each material.*

Discussion and conclusions

We investigated the effect of the diffuseness level on perceived texture visibility of three dimensional textures of various materials and for varying angles of incidence. Our participants were able to consistently judge texture visibility for a variety of materials. Overall we found a U-shaped dependence of texture visibility on the diffuseness level with the highest texture visibility for the most diffuse illumination. This would seem to suggest that the fact that diffuse light penetrates deeper in cavities in materials than collimated light, is most beneficial to the perceived texture visibility. Indeed some of our materials like the sweater, sponge and foam had a very open structure. So if light can enter more deeply, it makes the deeper pits and cavities more visible. For collimated lighting texture visibility was high for grazing angles of incidence and much lower for almost perpendicular angles of incidence. This confirms the idea that at grazing angles the shading and cast shadows create high luminance contrast edges, which enhance the visibility of the three-dimensional texture. This would especially be true for materials that are very smooth with some three-dimensional micro structure. Indeed, when comparing between the different materials we see that texture visibility under collimated lighting is relatively high compared to the most diffuse lighting for wrinkled paper, the finely woven camera protector, the placemat and chamois leather. This explanation does not work for the hand puppet and the scarf, which both have a very rough open structure. The dependence of the texture visibility on diffuseness level is V-shaped for the hand puppet and decreasing for the scarf.

To analyse our data we used Thurstone's model. In theory other functional relationships like $z_{ij} = f(z_i - z_j)$ might have produced even better results. The effect of such a function f is to make the underlying Gaussian distributions more or less heavy tailed and/or more asymmetric. Since there was no need to try other theoretical models, this suggest that Gaussian distribution assumption for the perceived texture visibility is not unreasonable.

To create the stimuli we rescaled the luminance distribution and mixed the resulting images to obtain intermediate diffusion levels. It would have been better to optically mix the light fields themselves. This was not possible with our set-up due to the huge intensity difference of the collimated and the diffuse light sources. However, superimposing images is approximately equivalent to optically mixing light fields [10]. Another problem of superimposing pictures is that if the camera or the sample material was moved in-between shots, the pictures would be slightly misaligned. This would result is slightly blurry pictures after superimposing them. When this happened the pictures were manually aligned. Still it may be the case that the mixed images have a somewhat lower texture visibility because they are slightly blurred compared to the unmixed pictures. However, raising the texture visibility for the intermediate diffuseness levels does not alter our conclusions. It may make the U-shaped dependence on diffuseness less pronounced, but we still get qualitatively different dependencies for different materials.

The luminance rescaling was also difficult to get right. We placed matte white photo paper on the table for a given lighting setup and then made pictures of all materials using the exact same set-up. But the surface of our material was not smooth and elevated above the plane of the table (although we compensated for this as much as possible). This means that the luminance distribution on the material could deviate slightly from that on the neutral background. This may have influenced the perceived texture visibility differently for different materials. However, since we never compared directly between different materials, it would hardly affect our results.

Before the making of the pictures, the feasibility of making High Dynamic Range (HDR) images was explored. Since our LCD screen cannot display HDR images, a method had to be chosen to compress the HDR to the luminance range of the image. We tried 5 different methods but they did not produce better images than the images obtained with automatic exposure time. However, for shiny materials containing highlights it may be necessary to use HDR images.

To summarise, we have shown that the diffuseness level of the illuminant affects the perceived texture visibility. The effect depended strongly on the material: for the sponge texture visibility increased with diffuseness level, for the scarf it decreased, and for the hand puppet it showed a V-shaped dependency. The texture visibility of open, very rough materials was mostly high for diffuse lighting, whereas the relatively smooth materials benefited from the additional shading information of collimated light at grazing angles. In open wound surgery, tissues smooth and shiny and inside a cavity. Diffuse lighting would penetrate deeper, prevent cast shadows from the surgeon's hands more and reduce specular reflections. Given our result we expect that the perceived texture visibility is also best for diffuse lighting.

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