On Uniform Resampling and Gaze Analysis of Bidirectional Texture Functions

JIŘÍ FILIP
Heriot-Watt University and Institute of Information Theory and Automation of the AS CR
MICHAEL J. CHANTLER
Heriot-Watt University
and
MICHAL HAINDL
Institute of Information Theory and Automation of the AS CR

The use of illumination and view-dependent texture information is recently the best way to capture the appearance of real-world materials accurately. One example is the Bidirectional Texture Function. The main disadvantage of these data is their massive size. In this article, we employ perceptually-based methods to allow more efficient handling of these data. In the first step, we analyse different uniform resampling by means of a psychophysical study with 11 subjects, comparing original data with rendering of a uniformly resampled version over the hemisphere of illumination and view-dependent textural measurements. We have found that down-sampling in view and illumination azimuthal angles is less apparent than in elevation angles and that illumination directions can be down-sampled more than view directions without loss of visual accuracy. In the second step, we analyzed subjects gaze fixation during the experiment. The gaze analysis confirmed results from the experiment and revealed that subjects were fixating at locations aligned with direction of main gradient in rendered stimuli. As this gradient was mostly aligned with illumination gradient, we conclude that subjects were observing materials mainly in direction of illumination gradient. Our results provide interesting insights in human perception of real materials and show promising consequences for development of more efficient compression and rendering algorithms using these kind of massive data.

Categories and Subject Descriptors: I.3.7 [**Three-Dimensional Graphics and Realism**]: Color, shading, shadowing, and texture; I.4.7 [**Image Processing and Computer Vision**]: Feature Measurement-Texture; J.4 [**Social and Behavioral Sciences**]: Psychology

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Additional Key Words and Phrases: BTF, uniform resampling, visual degradation, phychophysical experiment, texture compression, eye tracking

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Author's addresses: J. Filip, Heriot-Watt University and Institute of Information Theory and Automation of the AS CR; email: filipj@utia.cas.cz; M. J. Chantler, Heriot-Watt University; M. Haindl, Institute of Information Theory and Automation of the AS CR.

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1. INTRODUCTION

In many industrial sectors, demand is currently increasing for accurate virtual representation of real-world materials. Important application areas include, among others, safety simulations and computer-aided design. In the former area, the main concern is choosing the right material to fulfill given safety limits of reflectance, while in the latter, the aim is to avoid costly and time-consuming design cycles of material selection, solid model production and visual evaluation. These tasks, among others, require accurate photo-realistic representations of real material samples dependent on different illumination and viewing conditions.

One such representation is the bidirectional reflectance distribution function [Nicodemus et al. 1977] (BRDF). The BRDF is defined as ratio of radiance reflected from the material (outgoing) to the illuminating radiance (incoming) for all possible pairs of incoming $\omega_i(\theta_i, \phi_i)$ and outgoing $\omega_v(\theta_v, \phi_v)$ directions (see Figure 1). This ratio is spectral dependent (d spectral channel) and results in a five-dimensional multispectral function $BRDF_d(\theta_i, \phi_i, \theta_v, \phi_v)$. This function possesses two important properties: energy conservation and reciprocity of incoming and outgoing directions. As the BRDF captures the reflectance of only a small or averaged portion of the material surface, it is most applicable to surfaces without texture, such as paints and similar finishes. Although spatially varying BRDFs can be used to describe textured materials [Pellacini and Lawrence 2007], it is limited by its properties to smooth and opaque surfaces. The first real illumination-/view-dependent surface texture representation was the Bidirectional Texture Function (BTF), introduced in Dana et al. [1999]. A BTF is a six-dimensional function representing the appearance of a sample surface for variable illumination and view directions. Compared to a five-dimensional BRDF, a BTF depends on two additional spatial parameters, a planar position (x, y) over a material surface, resulting in seven-dimensional multispectral function $BTF_d(x, y, \theta_i, \phi_i, \theta_v, \phi_v)$.

The BTF represents such effects as masking, shadowing, interreflections, and subsurface scattering. During recent years, different BTF measurement systems have appeared based on different principles each offering different advantages and disadvantages. Although material visualization using BTFs provide superb visual quality, even an average BTF sample (e.g., 256×256) often reaches gigabytes in size. This data size can be edited almost interactively by careful data management and empirical editing operators [Kautz et al. 2007]. However, it is still beyond the real-time rendering capabilities of current graphics hardware, so there have been many recent research attempts to develop an efficient compression techniques that allow computationally cheap reconstruction and visualization of BTFs [Müller et al. 2005; Filip and Haindl 2009]. All such methods compress a full BTF sample, which often leads to extreme computational and excessive storage demands.

In this article, we aim to analyze the impact of several uniform resampling schemes on visual quality of images rendered from resampled BTF data. The visual quality is being assessed by human observers. To achieve this, we propose a psychophysical study of various uniform BTF resampling schemes performed on eight datasets. This article starts with recapitulation of published work in this research area in Section 2. Section 3 describes the experimental dataset and proposes several resampling schemes applied on these data. The design of the proposed psychological experiment is in Section 4. A discussion of the obtained results from the subjects' responses and their gaze fixation analysis are provided in Section 5. Section 6 summarizes and concludes the article.

2. PRIOR WORK

2.1 Psychovisual Analysis

To the best of our knowledge, there are few publications on psychophysical analysis of view- and illumination-dependent texture data. Several articles investigate influences of light position, material

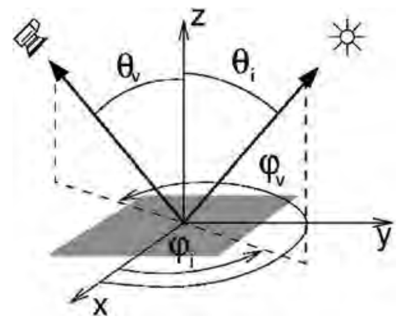


Fig. 1. Relationship between illumination and viewing angles within texture coordinate space.

reflectance, view position, or surface shape [Fleming et al. 2003; Lawson et al. 2003; te Pas and Pont 2005a, 2005b; Ramanarayanan et al. 2007]. Pellacini et al. [2000] derived a psychophysically based model of light reflection with two perceptually meaningful uniform dimensions. Matusik et al. [2003] performed psychophysical tests showing consistent transitions in perceived properties between different BRDFs. Meseth et al. [2006] shows a study comparing performance of material photographs, BTF rendering, and flat textures modulated by BRDFs for the same illumination condition. Different BTF compression and modeling methods are perceptually compared in a recent survey [Filip and Haindl 2009]. The methods mentioned earlier investigate influences of light, view, material reflectance, or shape. The only method dealing with optimal sparse sampling of view-/illumination-dependent textural data was introduced in Filip et al. [2008]. This method is based on a psychophysical study and enables significant reduction of BTF images while still providing the same visual quality. In comparison with the previous research, this article psychophysically assesses different uniform resampling of BTF data.

2.2 Eye-Gaze Analysis

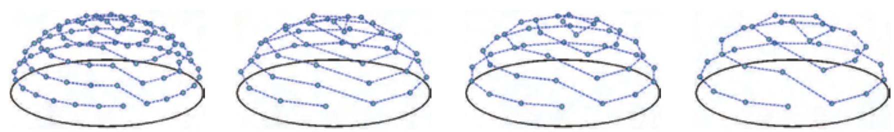
Eye tracking methods have been an important source of information about human visual perception. Their typical application is visual search where a subject's task is to identify presence or magnitude of specific features in stimulus image [Pomplun 2006; Over et al. 2007]. Gaze analysis has allowed the development of many applications [Duchowski 2002], for example, gaze-contingent displays [Duchowski et al. 2004], methods for eye-motion synthesis [Lee et al. 2002; Deng et al. 2005] or for prediction of fixation behavior in computer games [Sundstedt et al. 2008]. Although Elhelw et al. [2008] used eye tracking to analyze visual realism in simulated medical scenes, we are not aware of any relevant research analyzing human gaze behavior for stimuli representing realistic materials' properties captured by bidirectional texture functions.

3. PROPOSED DATA RESAMPLING

In this article, we have chosen BTF data as a typical example of simultaneous illumination and view dependent data. We have used the datasets from the Bonn BTF database.[1] For reduction of the size of processed datasets and simultaneously for enabling seamless covering of the test object, a BTF data-tiling approach was applied. We have chosen BTF datasets corresponding to distinct types of real-world materials. Thus, the following six different BTF datasets formed the subject of our experiment: aluminum profile (*alu*), corduroy fabric (*corduroy*), dark cushion fabric (*fabric*), artificial dark leather (*leather d.*), artificial light leather (*leather l.*), glazed tile with white pointing (*impalla*), lacquered wood

[1] http://btf.cs.uni-bonn.de/.

Fig. 2. Examples of used BTF samples illuminated by point-light and environment illumination.



Original BTF sampling	Scheme **A** down-sampling	μ^{ς} Scheme **B** down-sampling	μ^{ς} Scheme **C** down-sampling
81 samples	41 samples	41 samples	31 samples
$\mu = 0^o : \# = 1$	$\mu = 0^o : \# = 1$	$\mu = 0^o : \# = 1$	$\mu = 0^o : \# = 1$
$\mu = 15^o : \# = 6$	$\mu = 15^o : \# = 3$	$\mu = 18\triangleright 75^o : \# = 5$	$\mu = 25^o : \# = 6$
$\mu = 30^o : \# = 12$	$\mu = 30^o : \# = 6$	$\mu = 37\triangleright 5^o : \# = 9$	$\mu = 50^o : \# = 11$
$\mu = 45^o : \# = 18$	$\mu = 45^o : \# = 9$	$\mu = 56\triangleright 25^o : \# = 12$	$\mu = 75^o : \# = 13$
$\mu = 60^o : \# = 20$	$\mu = 60^o : \# = 10$	$\mu = 75^o : \# = 14$	
$\mu = 75^o : \# = 24$	$\mu = 75^o : \# = 12$		

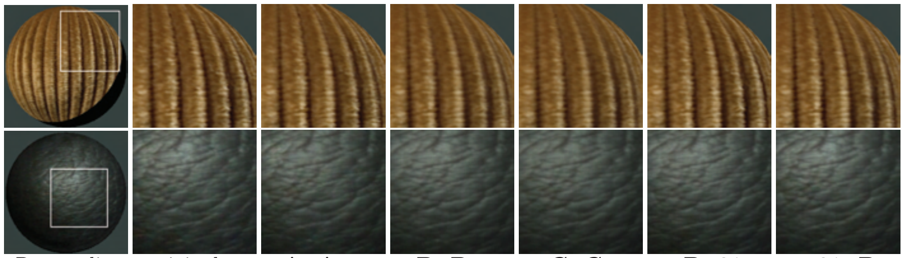
Fig. 3. Sampling of original BTF measurements (left) compared with its three tested resampled schemes: A—along azimuth θ, B,C—along azimuth θ and elevation ϕ angles. At the bottom are numbers of azimuthal samples for each elevation level.

(*wood*), and knitted wool (*wool*). Examples of these materials for both tested illumination environments are shown in Figure 2. The original datasets have an angular resolution of illumination and viewing angles of $n_i \times n_v = 81 \times 81$ (see Figure 3 (left)).

In order to obtain considerable reduction of BTF dataset size we adopted three different BTF sampling schemes denoted as A, B, and C in Figure 3. Each of the schemes is designed to fulfill uniform sampling in azimuthal angle ϕ. While scheme A preserves original sampling of elevation angle θ but reduces the number of azimuthal samples along angle ϕ, schemes B and C reduce sampling for both angles. While schemes A and B produce the same number of samples, that is, 41, scheme C reduces the number of samples even more aggressively yielding only 31 samples. Numbers of samples for individual levels of elevation angle θ for individual resampling schemes are given at the bottom of Figure 3. Note that the view and illumination-dependent data, that is, BTF, require directional sampling of both illumination $\omega_i(\theta_v, \phi_v)$ and view directions $\omega_v(\theta_v, \phi_v)$. However, in these two directions, we can adopt different sampling schemes without limiting practical usage of the data. Thus, we decided to resample the original BTF datasets in five different test sets. The first three are straightforward and resample both $\omega_i \times \omega_v$ directions in the same way, using a combination of the same schemes A × A, B × B, and C × C. The last two, used resample scheme B on either ω_i or on ω_v. This resulted in resampling patterns of B × 81 and 81 × B. Consequently, the resampled datasets use the following numbers of BTF images:

A × A	1,681 images (26%)	B × 81	3,321 images (51%)
B × B	1,681 images (26%)	81 × B	3,321 images (51%) .
C × C	961 images (15%)		

Note that the original number of images in each dataset is 6,561. To avoid introduction of local errors into the original data by means of their down-sampling using local interpolation, we used a two-step



Resampling:	original	**A A**	**B B**	**C C**	**B 81**	**81 B**
(I V)	**81 81**	(41 41)	(41 41)	(31 31)	(41 81)	(81 41)
Images:	6,561	1,681	1,681	961	3,321	3,321

Fig. 4. Examples of *corduroy* and *leather d.* BTF samples with illumination/view directions uniformly resampled in the five proposed ways.

global interpolation scheme based on radial-basis functions [Carr et al. 2001]. In the first step, the data for all illumination directions ω_i for fixed viewing direction ω_v are interpolated into a new illumination discretization scheme and these interpolated values for all combinations of θ_i and ϕ_i angles are further interpolated into a new viewing direction discretization scheme. Finally, all eight datasets were resampled in the five proposed ways (see Figure 4) and together with the original datasets used in the following psychophysical experiment.

4. PSYCHOPHYSICAL EXPERIMENT

The goal of the experiment was to analyze the influence of different illumination and view direction resampling schemes on the final appearance of rendered images.

Experimental Stimuli. As experimental stimuli, we have used pairs of static images of size 800×800, representing a material BTF rendered on a 3D object. Each pair consisted of a rendering using the full original dataset and one using one of the five resampled datasets. Pairs of images were displayed simultaneously, side-by-side. A sphere was used as a test object rendered for point-light and grace[2] illumination environments. The point-light was positioned on the top left from a viewing position consistent with the surrounding physical illumination. The environment maps were approximated by a set of 144 discrete point-lights [Havran et al. 2005]. The background of the point-light illuminated stimuli, and the remaining space on the screen, was set to dark gray. Example stimuli are shown in Figure 5(a). Given eight material BTFs, five different resampling schemes proposed in Section 3 and two different illumination types, the total number of stimuli was 80.

Participants. Eleven paid observers (six males, five females) participated in the experiments. All were students or university employees working in different fields, were younger than 35 years of age, and had normal or corrected to normal vision. All were naive with respect to the purpose and design of the experiment.

Experimental Procedure. The participants were shown the 80 stimuli in a random order and asked a yes-no question: *"Can you detect any differences in the material covering the two spheres?"*. There was a pause of 2 seconds between stimuli presentations, and participants took on average less than 40 minutes to perform the whole experiment. All stimuli were presented on a calibrated 20.1" NEC2090UXi LCD display (60Hz, resolution 1,600 × 1,200, color temperature 6,500K, gamma 2.2, luminance 120cd/m^2).

[2]http://www.debevec.org

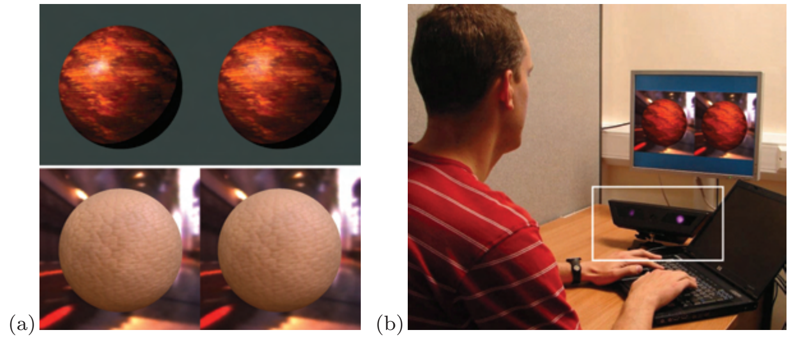


Fig. 5. Examples of two stimuli (a) and experimental setup (b) with the eye-tracker highlighted.

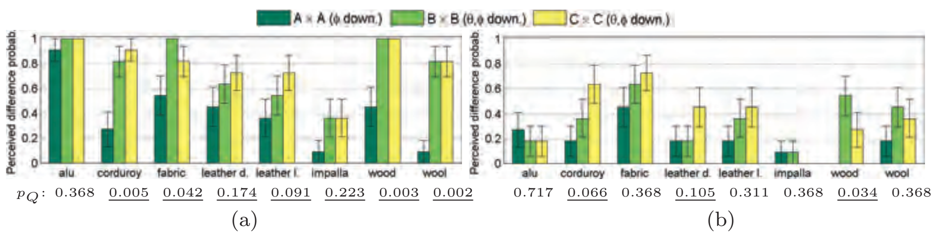


Fig. 6. Mean perceived difference for all tested resampling schemes A × A, B × B, and C × C for different datasets and (a) point-light, (b) grace illumination environment.

The experiment was performed under dim room lighting. Participants viewed the screen at a distance of 0.9m so that each sphere in a pair subtended approximately 9 degrees of visual angle.

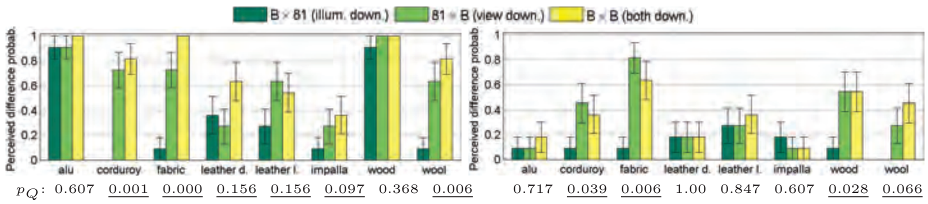
Observers gaze data were recorded using a Tobii x50 infrared-based binocular eye-tracking device as shown in Figure 5(b). The device was calibrated for each subject individually and provided the locations and durations of fixations at a speed 50 samples/s. Maximum error specified by manufacturer is approximately ±0.5 degrees of visual angle, which corresponds to ±32 pixels for our setup and stimuli resolution. The shortest fixation duration to be recorded was set to 100ms.

Experimental Results Analysis. When participants reported a difference between the rendered images, their response was assigned a value of 1, and otherwise 0. By averaging the responses of all participants, we obtained psychometric data for eight tested BTF samples, two different illumination schemes, and the five proposed resampling schemes. The following section analyzes and discusses the results of the experiment.

5. RESULTS AND DISCUSSION

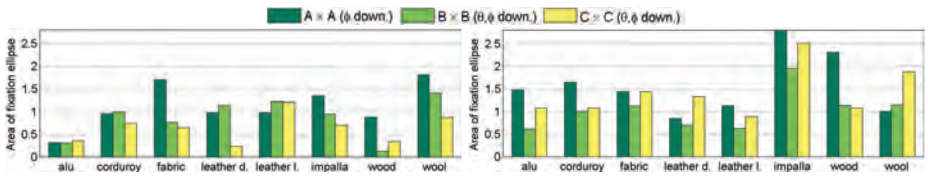
5.1 Subjects' Responses Analysis

Results of the experiment for all five test sets in are shown in Figure 6 and Figure 7. All graphs in the figures show perceptual values of observed differences between the renderings of original and resampled BTF data. Figure 6 shows average participants' responses for resampling schemes A × A, B × B, and C × C. Figure 7 illustrates responses for resampling schemes 81 × B, B × 81, and B × B. Both figures show results for point-light (a) and *grace* environment illumination (b). The graphs include error bars representing twice the standard error. Additionally, we performed Cochran Q-test [Cochran 1950] on the original dichotomous data obtained from the experiment. The obtained confidence intervals (p_Q)



(a) (b)

Fig. 7. Mean perceived difference for resampling of illumination/view/both respectively using the scheme B for different datasets and (a) point-light, (b) grace illumination environment.



(a) (b)

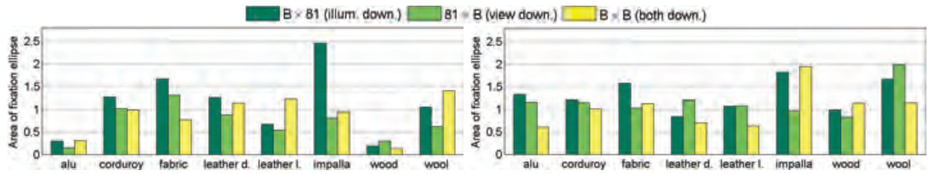
Fig. 8. Comparison of fixation areas for resampling schemes A × A, B × B, and C × C for different datasets and (a) point-light, (b) grace illumination environment.

corresponding to the tested datasets are shown below the individual graphs. Despite a relatively low number of tested subjects, we can see that for most of the datasets for point-light, we have got quite significant values (the values fulfilling 75% significance test are underlined). The least significant values ($p_Q > 0.2$) were estimated for specular samples (*alu* and *wood*), where most of the resampling schemes blure specular highlights. The p_Q values for *grace* environment are often less significant than for point-light, that is caused by less apparent differences between spheres in the stimuli.

In Figure 6, we can observe a significant increase in perceived difference when resampling scheme B × B is used comparing to the scheme A × A. This pattern was visible for both types of illumination. This means that the participants were much more sensitive to reduction of samples along elevation angle θ than to reduction of samples along azimuthal angle ϕ. More aggressive down-sampling C × C did not introduce much more difference. Similar behavior can be found in Figure 7, where resampling of view direction 81 × B introduces a significantly higher perceptual difference than resampling of illumination direction B × 81. When we compare resampling of view direction 81 × B with resampling of both direction B × B, we cannot observe any particular increase in the perceptual difference. While the datasets of highly structured fabrics samples *corduroy*, *fabric*, and *wool* comply the most with the described behavior, the datasets corresponding to altogether smoother and more specular materials *alu* and *wood* have similar performance for point-light illumination regardless of the resampling scheme used. Figure 6 suggests that using resampling based on scheme A can give even better visual performance, while using the same number of BTF images (3,321 for A × 81). This allows considerable reduction of original 6,561 BTF images, that are used as input data in many compression and modeling algorithms, without any particular perceptual error (see Figure 4). This conclusion holds mainly for environment illumination which is, however, the prevailing type of illumination used in contemporary rendering systems.

5.2 Gaze Fixations Analysis

Although the subjects' responses are an important source of psychophysical data, they do not provide us with any spatial information concerning the underlying sample properties and their perception by the subjects. To overcome this, we recorded gaze fixations of all 11 subjects throughout the experiment.



(a) (b)

Fig. 9. Comparison of fixation areas for resampling of illumination/view/both respectively using the scheme B for different datasets and (a) point-light, (b) grace illumination environment.

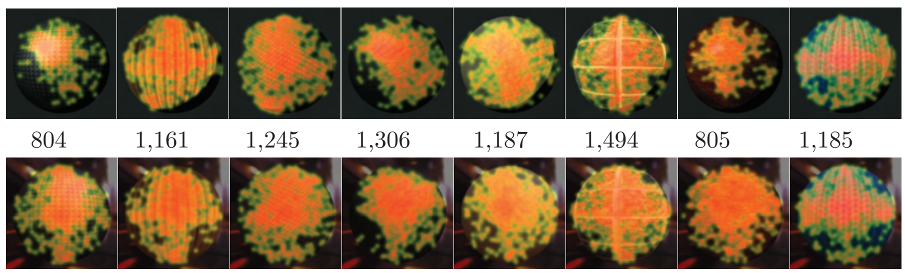


Fig. 10. BTF rendered spheres overlaid by all collected subjects fixations for point-light and *grace* illuminations. Numbers of fixations for individual samples and illuminations are shown below.

A rigorous analysis of such eye tracking data revealed interesting insights on how subjects observed different materials when assessing the performance of the five proposed resampling schemes.

During the experiment, subjects performed a visual search task, looking for differences in texture on the spheres and thus they were consequently comparing similar spatial locations on both spheres. One of the spheres was always rendered using the original data, while the other one was rendered using one of the proposed resampling schemes. In total, we recorded over 9,197 fixations for point light and 10,327 fixations for grace environment illumination. Only those fixations measured within the textured spheres were used in further analysis. Numbers of fixations and their spatial distribution for individual materials across all subjects for point-light and *grace* illumination environments are shown Figure 10. As the placement of the spheres was vertically symmetrical and the horizontal position of original and resampled rendering was random, we mirrored all fixations onto one sphere to ease further processing.

First, we analyzed fixation duration as a function of ordinal fixation number. Figure 11(left) shows that the average fixation duration was the lowest for the first three fixations and then increased almost linearly with trial duration. This behavior is similar to results in Over et al. [2007] and suggests that subjects applied a coarse-to-fine approach during visual search. The subjects notice within the first few fixations when the difference between spheres is more apparent, otherwise they spend more time by careful searching for a difference resulting in longer periods of fixations, which increased proportionally with total length of the search. Figure 11-right shows that the total number of fixations decreased almost exponentially and thus most responses to stimuli are given during the first 20 fixations. The decrease in number of fixations at the beginning of the trial was caused by subjects initially fixating on fixation cross in the middle of the screen before the stimulus appeared (Figure 5(a), that is, outside the textured spheres and thus those fixations were ignored. This helped us to avoid possible problems with central fixation bias Tatler [2007].

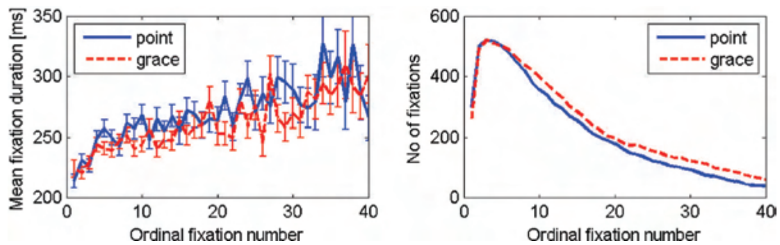


Fig. 11. Mean fixation duration (left) and number of fixations (right) as a function of ordinal fixation number for both illumination environments.

The next step was analysis of fixation locations. We employed PCA of x and y coordinates of selected fixations. As a result, we obtained two orthogonal principal directions (eigen-vectors) and corresponding data variances along these directions (eigen-values). We visualized these data as an ellipse shaped by the obtained variances with axes oriented in the principal directions. Such an ellipse clearly represents major properties of cloud of selected fixation points. In order to ease the comparison of results of individual materials and resampling schemes, we scaled the size of all ellipses using value of the largest recorded principal component. Results obtained results for both illuminations are shown in Figure 12. The estimated fixation ellipses (their centers shown as red crosses) are drawn against blue unit circles representing the textured sphere in experimental stimuli. Results for point-light illumination also show the location of the ideal specular reflection using a blue cross. The figure also shows marginal fixation ellipses computed for fixations across all materials (the last column) and across all schemes (the last row, respectively). The bottom-right ellipse then represents all fixations measured for a given illumination scheme.

In Figure 12, we can see that the size and slant of fixation ellipses strongly depends on the material and resampling scheme. For instance, for highly specular samples (i.e., alu, wood) is area of fixation ellipses very small, which is in contrast with more diffuse materials (i.e., corduroy, fabric, wool).

Measured gaze fixations in Figure 10 as well as the previous analysis in Figure 12 show that majority of fixations is concentrated near center of rendered sphere. One could wonder whether is this behavior typical and if it could be predicted automatically by some model of low-level human vision system. We used the visible difference predictor (VDP) [Daly 1993] to assess visual differences between the rendered spheres in all experimental stimuli. Results of VDP for all stimuli, that is, comprising different material and resampling schemes, and given the parameters of LCD screen used for psychophysical experiment, are shown in Figure 13. Intensity of responses obtained from VDP is generally low and the highest for fabrics materials *corduroy* and *fabric*. Although VDP predicted correctly as a main differences locations of specular highlights for shiny samples illuminated by point light, for the other materials it surprisingly found places with main visual differences near edges of the spheres, that is, for relatively high grazing angles. This is in contradiction with the measured fixations that are concentrated mostly on the center of sphere. From the results for individual resampling schemes, we can conclude that VPD can predict the visual degradation relatively correctly in accordance with the results obtained from the psychophysical experiment (the highest differences found for scheme C $\times$ C, the lowest response for scheme B $\times$ 81). On the other hand, it is quite difficult to assess visual differences between resampling schemes A $\times$ A, B $\times$ B, 81 $\times$ B.

If we analyze shapes of the fixation ellipses shown in Figure 12, more closely, we can spot several patterns. First is the typical slant and shape of ellipses that reflects the illumination gradient of the illumination (see Figure 14). This suggests that locations in material structure in the direction of the highest illumination gradient were the most important aspect for subject when assessing the similarity

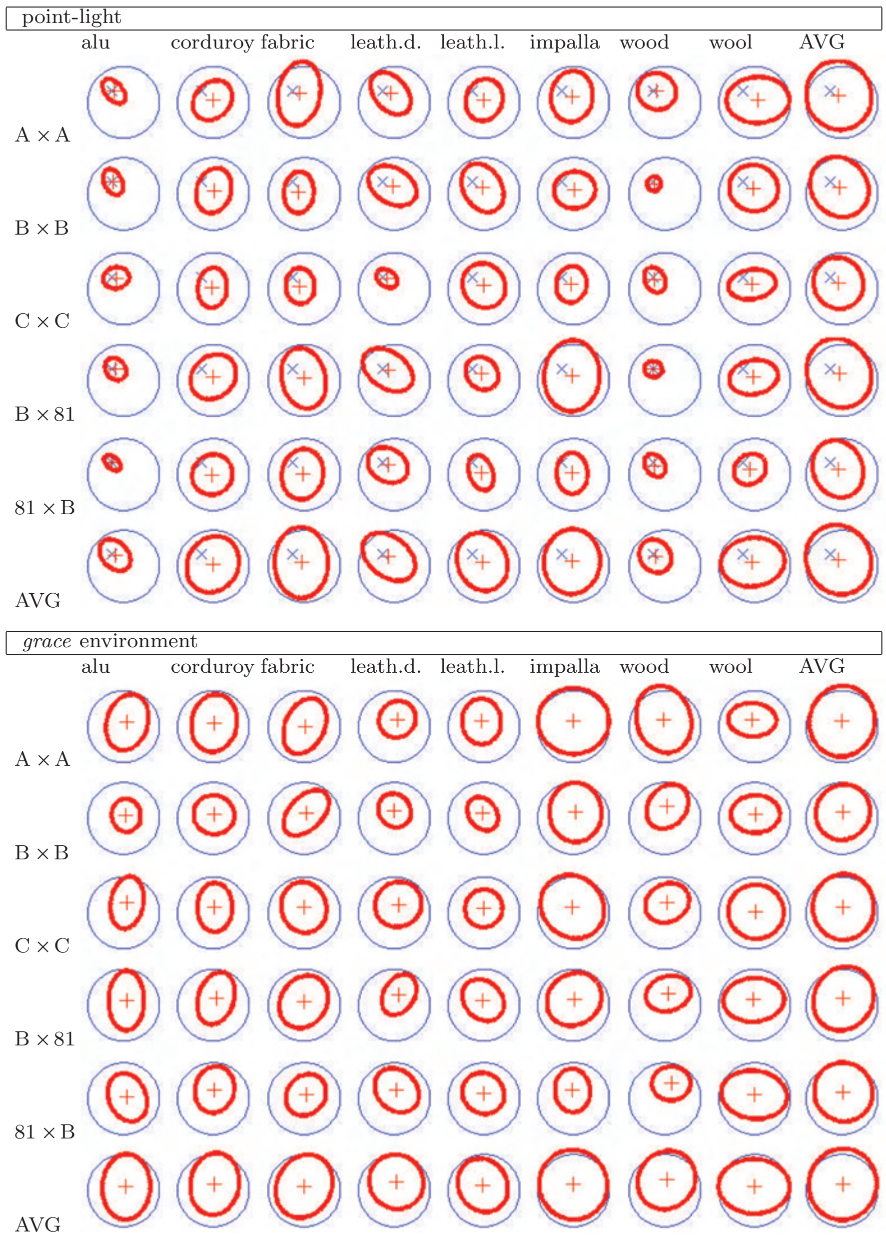


Fig. 12. Fixation ellipses for individual schemes (rows) and samples (columns) for point-light and *grace* environment.

of textures. To verify this hypothesis in Table I, we compared slants of the highest gradient in rendered images with estimated slants of fixation ellipses (see Figure 12) for all tested materials. To compute main gradient reliably, we used low-pass Gaussian filter to remove regular texture structures from the rendered images and used only the required overall reflectance characteristics of individual materials (resembling to material BRDF). The table also includes ratios of sizes of ellipse axes. The higher the ratio, the more directionally are fixations aligned and thus the estimated value of slant angle is more

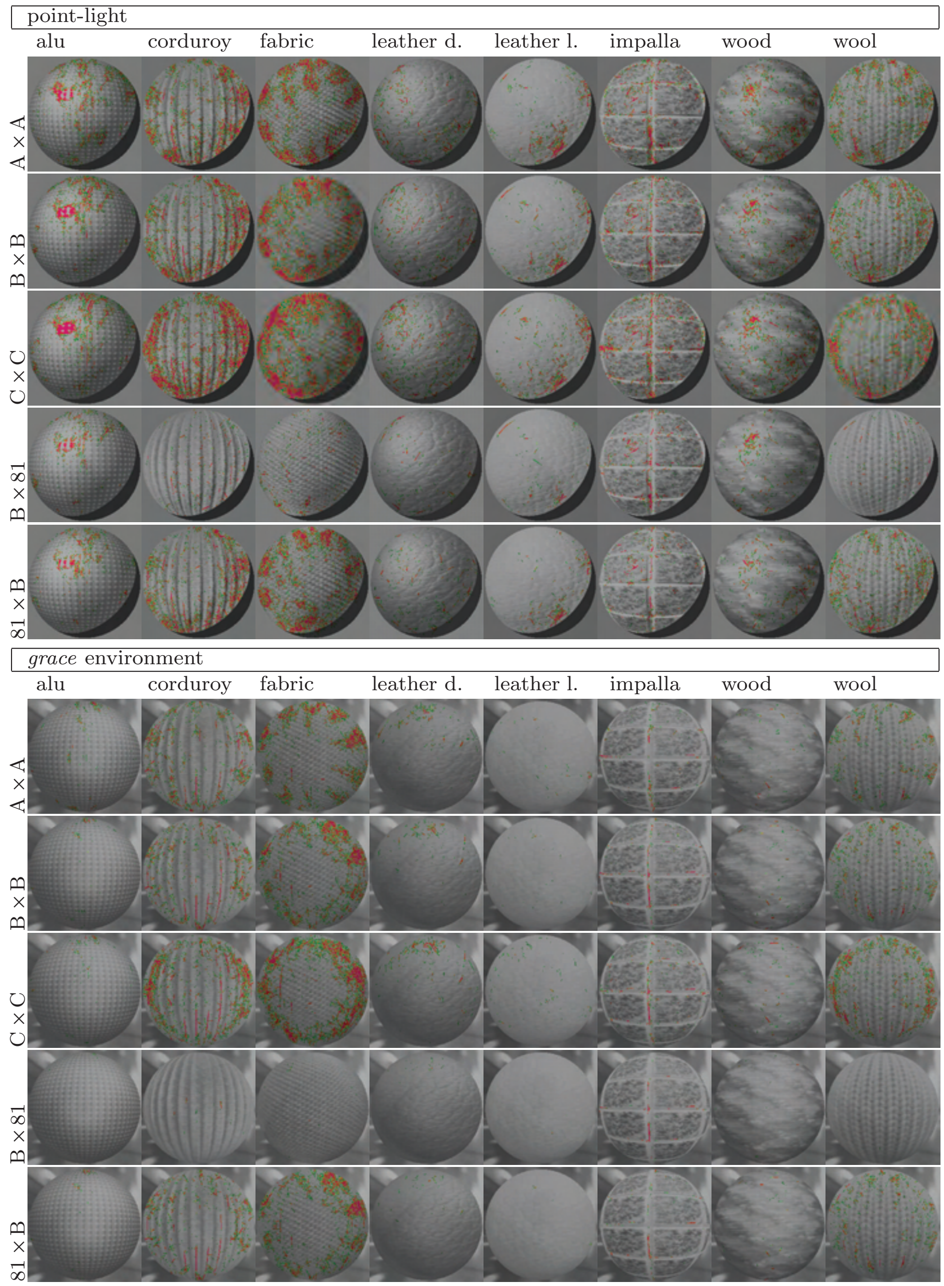


Fig. 13. Responses of visible difference predictor for tested materials and resampling schemes in point-light and grace illumination.

significant. A reflectance data are not always consistent with computed illumination gradient. This is often the case for the anisotropic samples *corduroy, fabric, impalla*. However, when we computed correlation coefficient between both sets of slants for all materials, we obtained quite significant values: $R = 0.808$ for point-light and $R = 0.865$ for *grace* environment. This result suggests that direction of

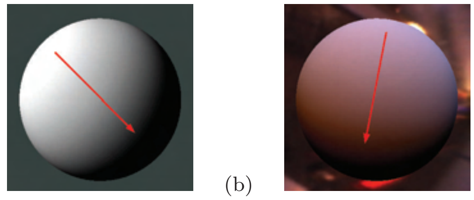


Fig. 14. Major illumination gradients for the used illumination environments: point-light and grace.

Table I. Correlation of Main Gradient Slant in Rendered Images (the Second and Fifth Columns) Compared with Estimated Slant of Fixation Ellipse (the Third and Sixth Columns) and Ratio of Ellipses Axes Sizes (the Fourth and Seventh Columns)

	Point-Light			*Grace* Environment		
	Gradient	Fixation Ellipse		Gradient	Fixation Ellipse	
Material	Slant	Slant	Ratio	Slant	Slant	Ratio
alu	137	139	2.0	72	87	1.8
corduroy	135	59	1.3	28	81	1.6
fabric	134	92	1.8	24	63	1.4
foil01	132	142	2.2	29	37	1.1
foil02	127	113	1.4	70	123	1.3
impalla	108	85	1.3	84	117	1.1
wood	138	130	1.4	22	46	1.2
wool	−10	7	1.7	10	−2	1.7
mean	113	96	1.6	42	69	1.4

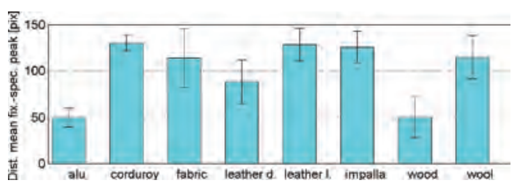


Fig. 15. Distance between specular peak and average fixation for different samples and point-light illumination.

main gradient in rendered images can effectively predict main direction of fixation cloud and thus the most probable locations of observer's fixations. As the main gradient is mainly caused by illumination gradient, we can extend the previous conclusion to illumination gradient at least for majority of the tested materials.

Another typical feature is size of fixation ellipses. We have found that the area of the ellipses strongly correlates with the ease of finding a difference between textures. In other words, the less apparent the difference, the wider the search and hence more fixations were needed. If we translate this fact into the proposed comparison of different resampling schemes, those that large fixation ellipses should be the best. Similarly, a differences in materials having the largest fixation area are hard to distinguish (e.g., *impalla*). On the other hand, materials with a salient specular highlight have small fixation areas and can be relatively easily distinguished regardless of the resampling scheme used (e.g., *alu, leather dark, wood*). For these materials, subjects made their decision comparing only the areas of specular highlights. This is confirmed in Figure 15 which shows the average Euclidean distance of the mean fixation from the location of the ideal specular reflection. Error bars represent twice the standard error across all resampling schemes.

We visualized data for different materials and resampling schemes in a similar manner to that described in Section 5.1. Figure 8 shows fixation areas for resampling schemes A × A, B × B, and C × C.

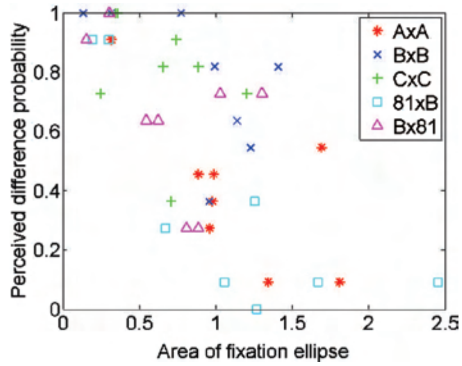


Fig. 16. Correlation of perceived difference probability and area of fixation ellipse.

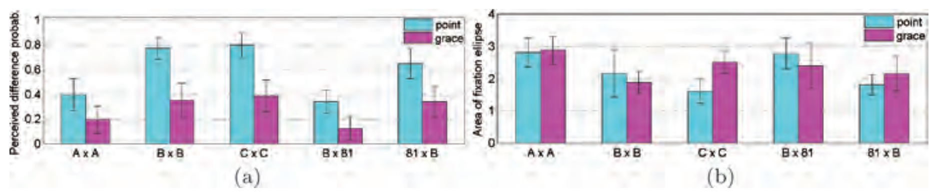


Fig. 17. Mean perceived differences (a) and fixation areas (b) for different resampling schemes.

Figure 9 illustrates fixation areas for resampling schemes 81 × B, B × 81, and B × B. Both figures show results for point-light and *grace* environment illumination. The similarity of the graphs for point-light with Figure 15 for different materials confirms our assumption that difference in specular highlights is the most salient feature influencing subjects' assessment. Results in the figures are inversely proportional to data in Figure 6 and Figure 7. Generally, the higher the perceived difference in the stimuli, the smaller is area of a corresponding fixation ellipse. This tendence is also apparent in Figure 16 which shows the correlation of perceived difference probability obtained from subject responses and the area of fixation ellipse obtained from the gaze data analysis.

To sum up this article, we have compared mean perceived differences of subjects from Section 5.1 in Figure 17(a) with areas of fixation ellipses in Figure 17(b) averaged across different materials. We can again observe that perceived difference is inversely related to area of fixation ellipse. Error bars in graphs represent twice the standard error across all materials. Additionally, the subjects' gaze fixation analysis supports our conclusion that resampling over azimuthal angle (and/or applied to illumination direction only) is the most convenient. The reason for this behavior might be that change of elevation angle has generally much higher impact on texture brightness that the same change in azimuthal angle. This may be intuitively explained by simple Lambertial model where the reflectance value depends only on elevation angle. So the closer is the material reflectance to Lambertian model, the smaller difference is between resampling schemes A and B. In Figure 6, we can see that materials with generally diffuse appearance *leather d., leather l.* have similar values for both schemes, which is not the case for other more anisotropic materials as fabrics and lacquered wood.

6. CONCLUSIONS

The main goal of this article was to determine the optimal uniform resampling of view and illumination data without significant loss of their visual quality. This was achieved by means of psychophysical experiments using several resampling strategies applied on eight bidirectional texture function datasets corresponding to several natural and manmade materials. An analysis of the subjects' responses and their gaze fixations showed that optimal resampling of these data should reduce the number of samples along azimuthal and preserve original elevation view/ illumination angles. Another important conclusion is that sampling of illumination direction can be significantly more sparse than sampling of view direction where the close-to-original sampling should be preserved to avoid significant blur in resampled data. Additionally, environment lighting is more convenient when resampled data are used, since the distortions introduced can be hidden by the convolution of the pixel with the underlying light pattern and low sampling is not so apparent to the observer. The gaze fixation analysis revealed that subjects prefered to observe materials in directions of illumination gradient when making their judgements.

In summary, our results have shown that even uniform resampling of view/illumination data can often significantly reduce the size of the required dataset without introducing significant perceptible differences. This simple result may benefit many compression, modeling, or rendering methods that use this type of massive reflectance data.

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