Evaluating the Material Appearance of Objects Under Different Lighting Distributions Against Natural Illumination

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Abstract. The recent development of new solid-state lamps including OLED lighting offered a wide variety of lighting conditions through controlling the spectral power distribution and the spatial distribution of light. The appearance of an object surface is largely influenced by lighting conditions and object materials. Variable control of lighting condition would be useful to offer an optimal material impression. We have investigated the possibility whether the subjective evaluation, comparing material appearance under different lighting distribution with that under natural illumination, is able to determine a lighting condition for an appropriate material appearance. We tested viewing condition consisted of three spotlight sizes and three illuminance levels. Participants chose one viewing condition in which the material appearance of fruits and vegetable food samples was closest to those impression learned from observing and holding freely in a reference natural illumination. In addition, they evaluated impressions of stimuli in each condition by the twelve questionnaires of seven-point scales. The result showed higher tendencies to select the wide spotlight size condition with higher diffuseness of illumination rather than narrower spotlight conditions, suggesting that diffuseness of illumination influences object material appearance. Results of seven-point scales showed differences between samples, but little differences among lighting distribution. It was thus suggested the possibility to provide an optimal lighting condition to offer material appearance similar to material impression learned with visual and tactile information in natural illumination.

Keywords: Material perception · Material appearance · Lighting distribution · Illumination diffuseness

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1 Introduction

The recent development of new solid-state lamps including OLED lighting offered a wide variety of lighting conditions through controlling the spectral power distribution and the spatial distribution of light. Especially, OLED lighting would give a surface light source with strong diffuseness. There are also other various ways of changing lighting distributions such as spotlights, which change the size of a lighting area through the changing the distance of a lens and a lamp. This kind of variation in lighting distribution also give rise to the changes of the lighting conditions such as the state of shadow and diffuseness.

The appearance of an object surface is mainly influenced by lighting conditions and object materials. Considerable amounts of researches have been done on the color rendering of lighting and the influence of lighting on color appearance. The technical Report on new color fidelity index for accurate scientific use" has been published recently and other evaluation methods are also under consideration in the CIE [1]. It has, however, not been systematically studied how the diffuseness of lighting influences material appearance.

The material and texture of objects is one of the major information to determine object impression. Material perception can be mainly classified into the visual and the tactile sensation. The object impression is consisted of the combination of these information. Besides, we normally have quite good material perception through visual observation without touching. However, this perception is not perfect and could vary under different lighting conditions. It is important to offer desirable material impression under artificial lighting. One important citation to give desirable material impression would be the fidelity of material appearance which is similar to color fidelity, namely the evaluation of color appearance under artificial lighting to give close enough to that under natural illumination. Variable control of lighting condition would be useful to offer an optimal material appearance.

The perception of an object surface is influenced by color (including hue, value, and chroma), material properties (including diffuse and specular reflection, scattering, and transparency) and the surface roughness of the object [2]. The random subsurface scattering of light and the emerging light rays distributed in a wide range of directions, give the surface a matte appearance [3]. The previous study of computer-generated graphics clarified that appearances depend on a viewpoint, illumination and a scale at which the texture is observed [4]. It suggests illumination, viewpoint and surface condition are important factors for material perception. It was shown that both lightness and glossiness ratings were well correlated with the skewness of the luminance histogram. It indicates optical conditions are corresponding surface physical properties [5]. The histogram of gloss surface has a positive skewness, while that of matte surface has a negative skewness. There are interactions between illumination and material perception [6]. In the cases where the correct perception of the light field is important, more emphasis should be put on the realism of the global properties of the light field such as direction and diffuseness. In the perception of computer-generated graphics, the global properties of the light field such as the mean direction and directedness (or diffuseness) would be the most important for light field perception [6]. The texture perception of roughness or smoothness is correlated with the global properties of the light field. It was also reported that the diffusivity of lighting influenced the appearance of an object surface such as glossiness and roughness [7], but the color appearance was stable [8]. These researches suggest that the distribution and diffuseness of lighting can be a strong factor of material perception. It was reported that an effect of material constancy appeared among different distribution of specular and diffuse reflection, but no obvious gloss constancy when observing only the distribution of specular reflection since the shape and size of light source give a great influence to the gloss perception in the research using printed paper object [9]. Previous research suggests that texture perception is generated by the interaction between the optical condition of an object surface and a lighting environment. However, it was suggested that the estimation of surface reflectance does not require the knowledge of the specific conditions of illumination [10]. Thus, the influence of illumination would be one of the key factors of material perception and the appearance of objects should be investigated further. However, it is not clear what kind of lighting conditions are adequate to realize the appropriate appearance reproduction of materials.

In the present study, we have investigated the possibility whether the subjective evaluation, comparing material appearance under different lighting distribution with that under natural illumination, is able to determine a lighting condition for an appropriate material appearance by comparing subjective evaluations under different lighting distribution with those under natural illumination. There are varieties of lighting conditions changing light field and diffuseness. Thus, it is difficult to test all conditions. Here, we focus on the effect of lighting with the different size of spotlights for the appearance of vegetable and fruits. We often encounter these kinds of lighting conditions in shops, home and restaurants in our daily life, and their appearances and impression are sometimes not identical or quite different from what we expect or prefer. It would be useful to examine whether we actually can evaluate the difference in naturalness or impression of objects under those lighting and decide a preferable lighting condition giving the natural appearance.

2 Experiment

Spot light size and intensity were controlled by an LED lighting system. It was constructed for evaluating the influence of lighting distribution to material appearance. We tested how the appearance of fruit and vegetable food samples under different lighting conditions was close to the impression of those objects constructed by viewing and touching under natural light. In a reference phase, participants held and observed stimulus objects under natural illumination and evaluated the impression of objects' appearance. Then, the participants evaluated the appearance of objects under nine viewing conditions (three spotlight conditions and three illuminance conditions) against the material impression of the objects under natural illumination.

2.1 Apparatus and Stimuli

A viewing booth was placed in a dark room. An LED lighting control system was set on the ceiling of the viewing booth as shown in Fig. 1. A participant viewed food samples in the booth through a window and observed only illuminated stimulus. An LED lighting system blind from participant.

The LED lighting control system consisted of an LED bulb, a Fresnel lens, diaphragm rings, slide rails, and a flexible duct. An LED bulb (Panasonic LDA7DHEW2, 6500 K, Ra 80) used as a light source. Fresnel lens and slide rail were used for spotlight control. The four slide rails guided the Fresnel lens to move up and down. The slide rails were able to change the distance between the Fresnel lens and the LED bulb. The spotlight size was controlled by changing their distance. The diaphragm rings managed illuminance.

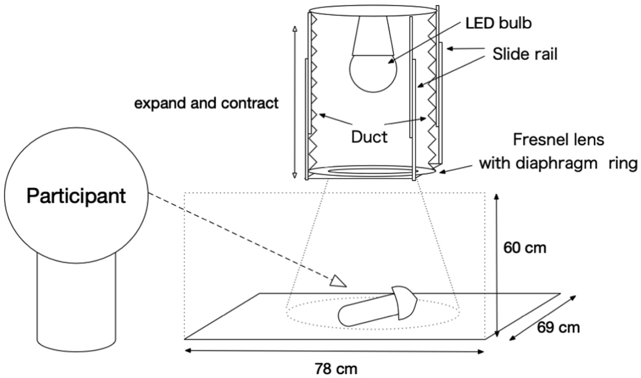

Fig. 1. Arrangement of an experimental booth with an LED lighting system and a stimulus.

We tested three levels of spotlight size; narrow, middle, and wide. The change of spotlight size corresponded to the change in the diffuseness of lighting. Thus, we measured the diffuseness of the illumination at the position of a stimulus was measured by a cubic illuminance measurement [11]. The illuminance of six directions (tilt angle +35° with rotate angle 0° ($E_{(\mathrm{u}+)}$), 120° ($E_{(v+)}$), 240° ($E_{(w+)}$) and tilt angle −35° with rotate angle 60° ($E_{(w-)}$), 180° ($E_{(u-)}$), 300° ($E_{(v-)}$) were measured to calculate cylindrical illuminance (E_{cl}) and horizontal working plane illuminance (E_{wp}). Diffuseness (E_{cl}/E_{wp}) can be specified from cylindrical illuminance and working plane illuminance. The diffuseness was 0.16 for wide spot, 0.12 for middle spot, and 0.06 for narrow spot size condition as shown in Table 1. The relation between spotlight size and the skewness of luminance histogram are shown in Fig. 2.

Three illuminance levels (800 lx, 600 lx, and 400 lx) were tested also to examine the influence of the overall lighting level to the material impression of objects. We used the appearance of stimuli under natural illumination as a reference in fidelity evaluation, but our lighting system was difficult to realize such a high illuminance environment (>1990 lx). We tested three illuminance levels to examine the influence of illuminance on the fidelity evaluation and to confirm that the result was not determined solely by illuminance difference between the test and reference environments.

Four kinds of food samples included Orange, Apple, Eryngii, and Paprika were used for stimuli. These stimuli were selected by the combination of matte-gloss (micro texture) and smooth-rough (macro texture) surface. Orange had gloss and rough surface. Apple had a matte and smooth surface. Eryngii had a matte and rough surface. Paprika had a gloss and smooth surface. Stimuli under the different size of spotlight were shown in Fig. 3. Three spotlight sizes and three illuminances conditions were combined to establish nine viewing conditions.

Natural illumination condition (Fig. 4) was used for a reference phase to establish the criterion of the objects' material appearance. Any standard illumination condition for material evaluation has not been established like the color fidelity evaluation using blackbody and daylight color as references. Therefore, we decided to use a condition with free observation under natural illumination from a north window as a reference since we normally use visual factors and tactile sensation to establish a solid impression for materials and natural illumination would be natural and easy to recognize objects in the same way as color evaluation. We chose natural illumination condition which illuminance and geometry largely change since we usually establish "stable and acculate object recognition" not by observing in one particular viewing condition but by observing and touching under the variation of viewing conditions. Participants were able to hold and rotate food samples to see them from different angles. The diffuseness (E_{cl}/E_{wp}) of natural illumination varied from 0.542 to 0.674 which are relatively high diffuseness and the illuminance varied from 1990 lx to 7010 lx. Natural illumination illuminance was fluctuated by weather at observation with tac-tile. However, in present study, no significant difference was detected in subjective evaluation results under natural illumination (P > .05).

Table 1. Viewing conditions of illuminance, spotlight size and diffuseness.

Illuminance (lx)	800	600	400	800	600	400	800	600	400
Spotlight size	Wide	Wide	Wide	Middle	Middle	Middle	Narrow	Narrow	Narrow
Diffuseness (E_{cl}/E_{wp})	0.166	0.163	0.168	0.119	0.118	0.119	0.057	0.054	0.055

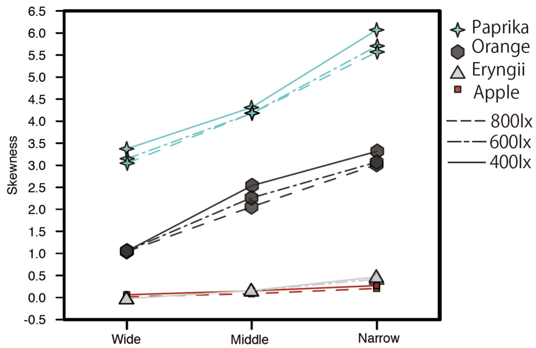

Fig. 2. Relation of skewness and spotlight size.

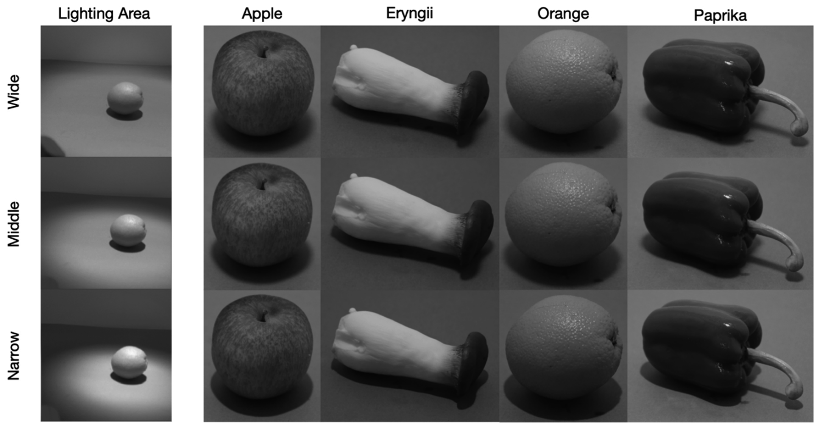

Fig. 3. Spotlight size and each stimulus.

Fig. 4. Natural illumination condition (by a north window).

2.2 Subjective Evaluation

Participants answered a viewing condition which the material appearance of a stimulus was the closest to the reference condition from nine viewing conditions. The evaluation for the impression of the stimuli was also conducted in each viewing condition including the reference condition with natural illumination. Participants answered twelve questionnaires using a seven-point scale (Fig. 5). The questionnaires included following items; bright-dark (brightness), vivid-dull (chroma), gloss-matte (glossiness), smooth-rough (smoothness), transparent-opaque (transparency), fresh-bad (freshness), delicious-awful (taste), sharp-blunt (sharpness), light-heavy (weight), distinct-indistinct (distinction), hard-soft (stiffness) and natural-unnatural (naturalness) [7, 12]. After finishing all trials, we took participant's direct reports and their implications.

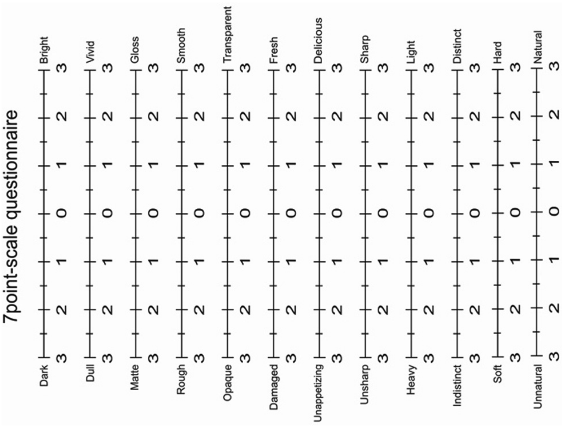

Fig. 5. Twelve questionnaires of seven-point scale evaluation sheet.

2.3 Procedure

First, a participant held and observed stimulus under natural illumination condition for 10 min in a reference phase. The participant observed stimuli from various angles by rotating them by their hands with memorized the material appearance of stimulus. After the observation, participant evaluated the impressions of stimulus using a seven-point scale. A rest time was set for making form a firm object impression, and the test phase started 30 min after the reference phase. The participant sat in front of the viewing booth. Viewing distance to a stimulus was about 60 cm. The participant observed the stimulus and evaluated its impressions by seven-point scale questionnaires in one of nine viewing conditions. Then participant repeated evaluations for nine viewing conditions in random order. After nine trials finished, participants selected a condition which the appearance of a stimulus was closest to that in the reference condition. One session consisted by the evaluation of impression in nine conditions and the fidelity judgment. Three sessions were executed for each of four stimuli and twelve sessions were executed in total. Participant gave direct reports and their implications after all sessions finished.

2.4 Participant

Two males and four females participated. The range of their age was 22 to 25 years old (the average was 23.0 years old). All participants had normal visual acuity (binocular vision was 1.0 or better) either naturally or with correction and normal color vision which was confirmed by Ishihara color vision test plate and Anomaloscope (OT-II, Neitz). A thorough explanation regarding the purpose and the method of experiment was provided to participants, and their consents were obtained before the experiment.

2.5 Analysis

Two-way ANOVA was used to compare the average frequency of fidelity selection as well as the reference condition and test conditions on seven-scale questionnaires. Multiple comparisons of the Tukey-Kramer test were used to compare each factor of spot light size, illuminance, stimulus and participant. Two-way ANOVA compared the differences between the reference condition and test conditions on seven-point scale questionnaires.

3 Result

The result of the fidelity selection is shown in Fig. 6. The selection of a stimulus closest to the appearance of the reference is examined. The horizontal axis represents nine viewing conditions and the vertical axis represents a frequency that each condition was chosen. Each bar corresponds to the average value of all participants and food samples. Error bars show the standard deviations. The wide spotlight condition at 800 lx was chosen most frequently, followed by those at 600 lx and 400 lx, the middle size spotlight condition at 800 lx, 600 lx and 400 lx, then the narrow spotlight condition at 800 lx, 600 lx and 400 lx. Significant differences are detected between the wide and narrow spotlight conditions ($p < .001$), and between wide and middle condition ($p < .001$) ($F = 16.61$). There are also significant differences between wide and narrow ($p < .05$) spotlight conditions at 800 lx, wide and narrow ($p < .001$), wide and middle ($p < .05$) at 600 lx, wide and narrow ($p < .001$), at 400 lx. No significant differences were detected between illuminance levels ($F = 0.439$). These results suggested that the illuminance levels does not influence the material appearance, but a large impact was observed on spotlight size causing the light with different diffuseness.

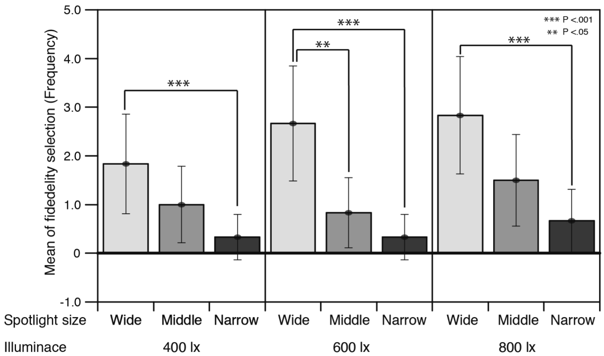

Fig. 6. Result of the fidelity selection of each diffuseness and illuminance conditions.

We compared the results of food sample stimuli (Fig. 7). The horizontal axis represents spotlight size conditions for each stimulus and the vertical axis represents the frequency of fidelity selection. Each bar corresponds to the average of all participants and all illuminance levels. Error bars show the standard deviations. The wide spotlight conditions are chosen more frequently than the narrow spotlight conditions for Apple ($p < .05$), Orange ($p < .001$), and Paprika ($p < .001$). There is also a significant difference between middle and narrow condition ($p < .05$) for Paprika. No significant differences were detected for Eryngii.

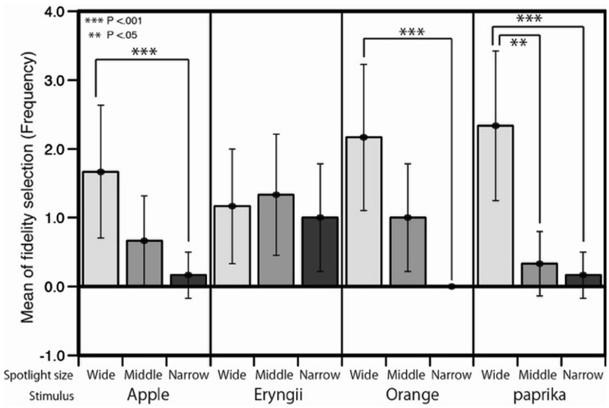

Fig. 7. Result of fidelity selection for each stimulus.

Next, we compared the results of the individual participant (Fig. 8). The horizontal axis represents spotlight size conditions for each participant and the vertical axis represents the frequency of fidelity selection. Each bar corresponds to the average of all stimuli and all illuminance levels. All participants chose the wide spotlight condition the most. There were significant differences between the wide and narrow conditions for participant B, D, E, and F ($p < .05$), and between wide and middle conditions for participant C and F ($p < .05$).

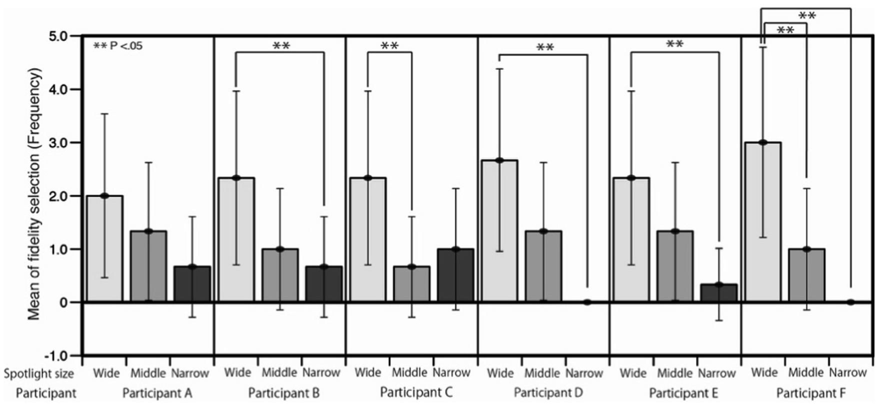

Fig. 8. Result of fidelity selection for each participant.

The result of fidelity selection for each spotlight sizes is shown in Fig. 9. They are the average results of all illuminance levels, stimuli, and participants. There are some individual differences between participants. The appearance of material is closest to the reference condition in the wide spotlight size condition in general.

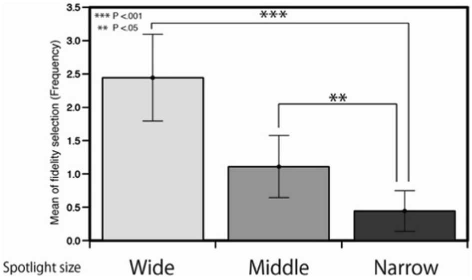

Fig. 9. Result of fidelity selection for each spotlight size conditions.

No significant differences were detected among spotlight size conditions on the result of seven-point scale questionnaires. Differences were observed among stimuli such as questionnaires of gloss-matte (glossiness), light-heavy (weight), and natural-unnatural (naturalness).

The score of glossiness is shown in Fig. 10. The vertical axis represents the difference of the score from that in a reference condition. Each bar corresponds to the average result of all participants and illuminance levels. Error bars show the standard deviations. Orange and Eryngii appeared glossier than Apple and Paprika ($p < .05$) in all spotlight conditions. The score for Eryngii was not stable and had large standard deviations. There are significant differences between glossiness for Eryngii and Paprika ($p < .001$), Orange and Paprika in wide ($p < .001$), Apple and Eryngii ($p < .001$), Eryngii and Paprika ($p < .001$), Orange and Paprika ($p < .05$) in middle, and Orange and Paprika in narrow ($p < .05$) spotlight conditions ($F = 14.53$).

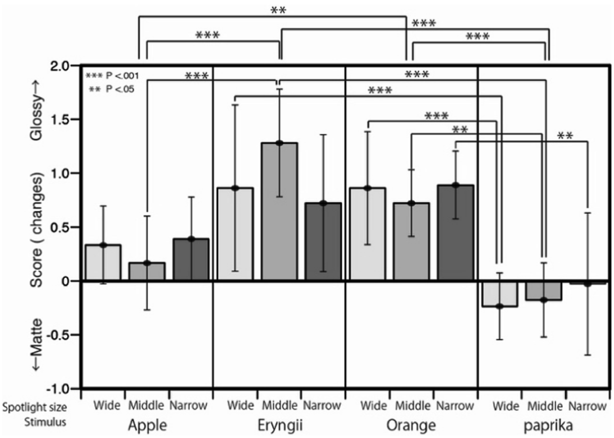

Fig. 10. Glossiness changes from that in the reference condition.

As shown in Fig. 11, Apple appeared heavier, and Eryngii, Orange and Paprika appeared lighter in all spotlight conditions. There are significant differences between weight score for Apple and Eryngii ($p < .001$), Apple and Orange ($p < .001$), Apple and Paprika ($p < .001$) in wide, Apple and Eryngii ($p < .05$), Apple and Orange ($p < .001$), Apple and Paprika ($p < .001$) in middle spotlight conditions ($F = 17.84$). Differences in score among stimuli become a little bit smaller in the narrow spotlight condition.

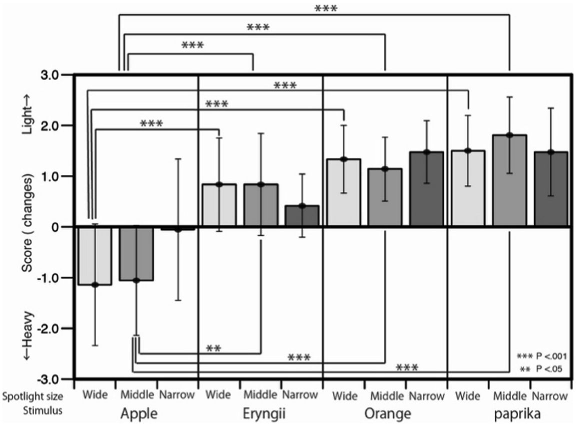

Fig. 11. Weight score changes from that in the reference condition.

As shown in Fig. 12, Orange and Paprika showed little changes their appearance of naturalness. On the other hand, Apple appeared more natural and Eryngii appeared less natural. There are significant differences between naturalness for Apple and Eryngii ($p < .001$), in wide ($p < .05$) and middle spotlight ($p < .05$) conditions ($F = 6.263$). Apple appeared most natural and Eryngii appeared most unnatural There are significant difference between Apple and Eryngii in wide ($p < .05$) and middle spotlight ($p < .05$) conditions ($F = 8.01$). However, differences in stimuli become smaller in the narrow spotlight condition. These trends imply that the impression of object material become similar in the narrow spotlight with low diffuseness.

As the results of direct reports, participants did not recognize the difference in illuminance conditions, but they were able to distinguish the change in spotlight size. All participants felt that narrow spotlight condition gave strong shade and shadow to the observed scene.

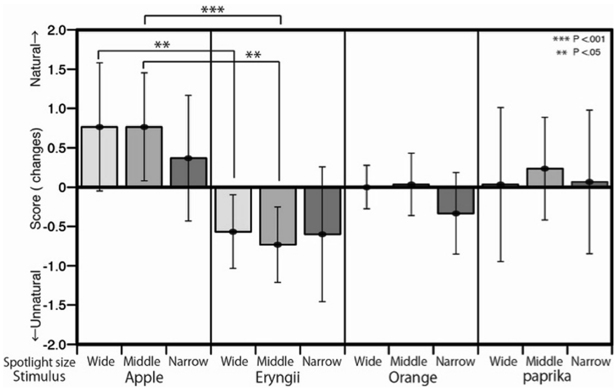

Fig. 12. Naturalness score changes from that in the reference condition.

4 Discussion

The present study examined the material perception under different lighting distributions. Results showed that the appearance under the wide spotlight was closest to that in a reference condition under natural illumination. The present results also suggest that change in the diffuseness of lighting due to the spotlight size influence a material perception. In addition, the frequency of fidelity selection is correlated with diffuseness at Pearson's rank correlation. (r = 0.577) (Fig. 13). Our results are consistent with previous studies which showed a relationship between object surface perception and diffuseness of illumination [6, 7]. Moreover, a material appearance would be more natural and appropriate under diffused light at least in the ranges we tested. It is interesting that the participant was able to do fidelity selection task even through the illuminance levels and various diffuseness of lighting in the viewing conditions we tested were far from those of reference illumination. The present results suggest a possibility to create an indoor lighting environment to offer an accurate reproduction of material appearance under natural illumination.

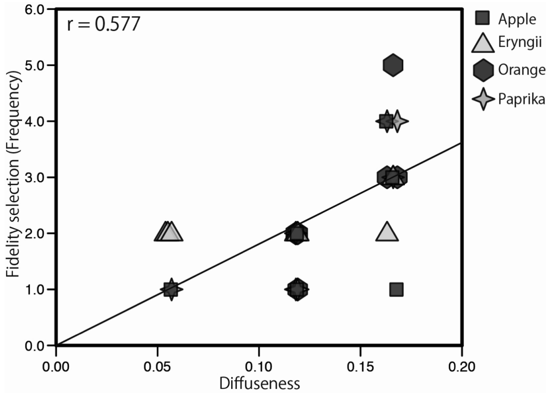

Fig. 13. Correlation of diffuseness and fidelity selection (each observed condition).

The results of illuminance level (Fig. 6) suggests that the material appearance is significantly influenced by the spot size and diffuseness of lighting, rather than illuminance. In the post interview, participants also reported that they barely noticed the illuminance difference. However, the higher frequency of fidelity selection in 800 lx would be because that condition was closer to the illuminance level of the reference illumination.

We used different kind of fruit and vegetables to test the influence of stimuli surface; Apple with a matte and smooth surface, Eryngii with a matte and rough surface, Orange with a gloss and rough surface, and Paprika with a gloss and smooth surface. The influence of spotlight size is different in stimuli. For example, the glossiness score was higher than that in the reference condition for Orange, Apple, and Eryngii, which is expected because the diffuseness of spotlights was much higher than the reference illumination. However, there was no difference for Paprika. This result may suggest that the Paprika with gloss and smooth surface appeared glossy enough under natural illumination and its impression did not change by adding spotlight, but the glossiness of other stimuli was enhanced by the spotlights. The fidelity selection for Eryngii did not show systematic difference among spotlight size, but the results of impression score showed glossier, lighter, and less natural than the impression in the reference condition. This suggests that the appearance of Eryngii with a matte and rough surface is changed by spotlight in comparison with the reference condition, but the difference in spotlight size did not have a large influence. These differences in stimuli suggest that the influence of lighting distribution differ among object materials and surface properties, and thus we have to consider object property in cases that we need to choose an appropriate lighting condition.

We have found the influence of spotlight size for the fidelity selection in the present study. Participants successfully selected the viewing condition, in which the material perception closest to that in the reference condition. However, the results of seven-point scale questionnaires showed no difference in the present study. Seven- point scale questionnaires include twelve questionnaires, but they may not sensitive enough to show the difference in viewing conditions.

To see if any trends revealed by an analysis using the relationship between scores and image statistics, we took the Pearson's rank correlation of each score and the skewness of luminance histogram of stimuli. They suggest that skewness does not correlate with glossiness, weight or naturalness questionnaires (Figs. 14, 15 and 16). Stimuli were used the combination of matte-gloss (micro smoothness) and smooth-rough (macro smoothness).

In the present study, we have used the viewing conditions with the definite ranges of lighting distribution and diffuseness. Further studies will be necessary to use more wider range of lighting distribution and diffuseness to find a lighting condition for accurate material impression. The method of impression evaluation should be improved to be able to extract the differences among lighting conditions.

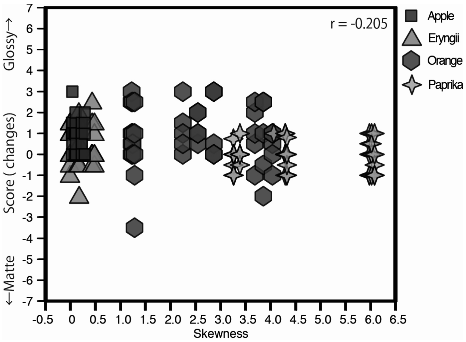

Fig. 14. The relationship between the skewness of luminance histogram and glossiness.

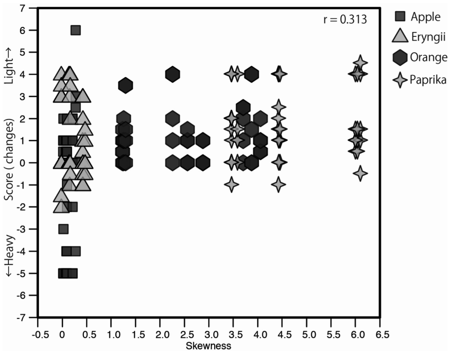

Fig. 15. The relationship between the skewness of luminance histogram and weight.

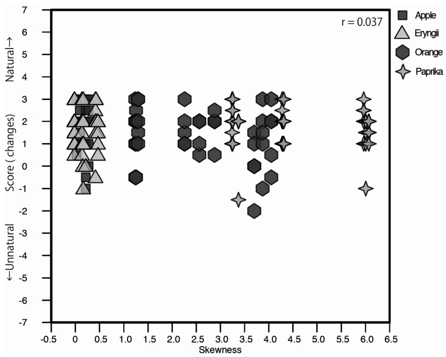

Fig. 16. The relationship between the skewness of luminance histogram and naturalness.

5 Conclusion

We investigated whether it is possible to determine a lighting condition to show an appropriate material appearance by comparing material appearance under different lighting distribution with that under natural illumination by subjective evaluation. We tested viewing condition consisting three spotlight sizes and three illuminance levels by the fidelity selection and the impression evaluations of stimuli. The result shows the wide spotlight size condition with higher diffuseness of lighting is more selected than narrower spotlight conditions. It suggests that the diffuseness of illumination influences object material appearance and a wider and more diffused spotlight would be more appropriate to show the impression under natural illumination. The results of seven-point scales show differences between samples, but little differences among lighting distribution. It was suggested that it would be possible to set a lighting condition to realize an appropriate material appearance.

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