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Analysis of Sharpness Increase by Image Noise

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Abstract. *In this study, the authors investigated how noise affects sharpness perception. The authors probed the sharpness of black-and-white tree bark images with various noise levels. Overall, the sharpness decreased as the noise amount increased, while some observers seemed to perceive more sharpness. The authors next used one- and two-dimensional unifrequency patterns as stimuli in an attempt to reduce such variability in the judgment. The result showed that sharpness of higher-frequency stimuli decreased with increased noise, while that of lower-frequency stimuli increased at certain levels. From this result, the authors thought that noise reduces the sharpness at edges, but can sharpen the lower-frequency component or texture of the image. To prove this prediction, the authors experimented again with the image used in the first experiment. The perceived sharpness only decreased when noise was added to the edge regions, whereas it improved when noise was applied to texture. The authors consider that the interaction between noise and texture increases the perception of image sharpness. © 2011 Society for Imaging Science and Technology.*
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INTRODUCTION

Widespread digital imaging technology has brought us smooth low-noise images and allowed us to shoot images under low-light situations. This is thanks to a number of sophisticated denoising algorithms developed so far. Application of such algorithms is based on the notion that noise in a digital image is a hindrance to and only degrades image quality. There are, however, some indications that image noise is able to improve image quality. One such example is reduced banding or contouring.[1,2] Banding is an artifact that is most visible in smoothly transitioning areas in an image such as clear sky or metal. This is due to the limited bit depth of common digital image formats and is sometimes due to excessive image processing. Adding noise to these areas makes the artifact invisible or less noticeable by the masking effect. (This is similar to the concept of dithering in that applying fluctuation makes the image richer in tone.) Another advantage of applying noise to a digital image is a better preference judgment by human observers. Kashibuchi et al. studied whether preference judgment of black-and-white (black-and-white) digital photographic prints could be improved by the addition of noise.[3] They asked observers which of the images with various noise levels was most preferable and concluded that certain kinds of subjects were preferred when noise was applied. They also inquired about the reasons for the observers' choice and reported that the improved preference was mainly due to the enhanced perception of texture by the subjects.

In addition, some studies exist that deal with the effect of noise on the perceived sharpness and report that image noise can enhance sharpness. In their work on investigating the effect of various image quality parameters (resolution, noise, contrast, and sharpening) on the perceived sharpness, Johnson and Fairchild[4] reported, among interesting results, that an appropriate amount of additive noise could enhance sharpness. Kayargadde and Martens examined the interaction between noise level and blur (what they call "noisiness" and "unsharpness," respectively) in their work of multidimensional scaling of perceptual image quality.[5] Although they showed that these two attributes interacted only weakly, they also observed that unsharpness is dependent on the noise level: Applying noise to a sharp image makes it appear blurred, whereas noise addition to very blurred image makes it appear slightly less blurred.

The objective of the present study is to analyze the effect of noise on the perceived sharpness and to investigate under what condition noise is able to enhance the image sharpness. Although some sharpness metrics have been proposed, they are usually based on the modulation transfer function of the imaging system to be measured. They assume that the system is not so noisy, which means that they cannot measure the change in sharpness by (large amount of) image noise. Therefore, in this study, we examine the effect of noise by subjective experiments. If the effect could be quantified, we think that it will provide another strategy for the development of novel denoising algorithms: By leaving some of the noise, not simply removing all noise, we will be able to preserve sharpness and fine details in digital images, which are inevitably lost by excessive denoising.

PRELIMINARY EXPERIMENT

Stimuli

In this preliminary experiment, we used black-and-white natural images as stimuli and examined whether adding noise to the entire image can improve sharpness.[6] A black-and-white image of tree bark, shown in Figure 1, was used as the original image. The reason for using an achromatic image is that we do not have to consider the color component. We added achromatic white Gaussian noise, which is one of

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Figure 1. Original black-and-white image of tree bark used in the preliminary subjective experiment.

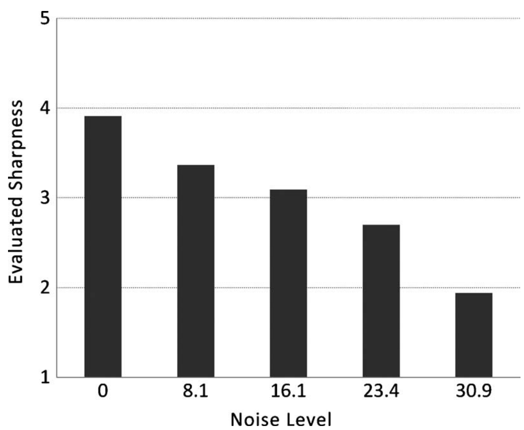

Figure 2. The result of the preliminary experiment. Overall, evaluated sharpness decreases as the noise amount increases.

the most common forms of noise found in the image processing literature, to the original image. The mean of noise distribution was zero. The noise level was defined by the standard deviation of the distribution and was varied to five different levels: 0 (original), 8.1, 16.1, 23.4, and 30.9. The images were then printed on an Epson glossy photographic paper with an Epson PX-5500 ink jet printer at 360 ppi. The resultant images were $16 \times 16\ \mathrm{cm}^2$ in size.

Method

We asked 19 human observers to arrange the five images with different noise levels in order of the perceived sharpness. Images were viewed under about 700 lx fluorescent illumination. The viewing time and distance were not restricted so that the observers could look at the stimulus images freely. We then analyzed the collected data by a rank order method to derive a sharpness scale.[7]

Results and Discussion

Figure 2 shows the result of the preliminary experiment. The larger the evaluated sharpness score, the higher is the perceived sharpness. Although the overall result indicates that the perceived sharpness decreases as the noise amount increases, there exists large variability in the evaluated sharpness. It seems that the observers can be classified into two types: those who perceived more sharpness as the noise amount increases and those who perceived less sharpness. Out of the 19 participants, five seemed to belong to the former group, and the rest belong to the latter. Figure 3 shows the evaluated sharpness after the classification. Even three of those who generally perceived less sharpness with increasing noise (observers 2, 7, and 17) judged noisy images as having the highest sharpness. We think that this discrepancy in the response may be associated with different interpretations of sharpness; interestingly, those who perceive more sharpness with increasing noise answered in the introspective report that they made the judgment based on a "more focused appearance" due to noise. On the other hand, some of those who perceived less sharpness reported that the "no clean-cut appearance of edges interfered with by noise" was the reason for this choice. Taking into consideration the observation by Kashibuchi et al. that adding noise mainly enhances texture of the subject,[3] we think that the reported "more focused" appearance by noise is probably due to the enhanced texture in the image. We also think that the difference in responses among the observers could be attributed to a difference in the part in the image at which they were looking during evaluation, because natural images generally contain both edge and texture, and hence is complex. However, from this experiment alone, there is no way of knowing which is the main reason.

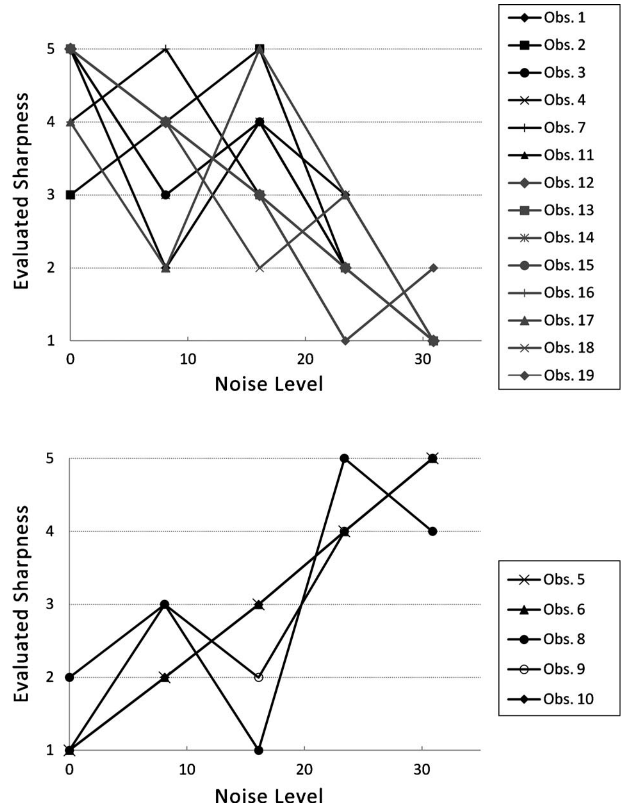

Figure 3. Classification of the observers. Top: those observers who perceive less sharpness with increasing noise ($N=14$). Bottom: those who perceive more sharpness ($N=5$).

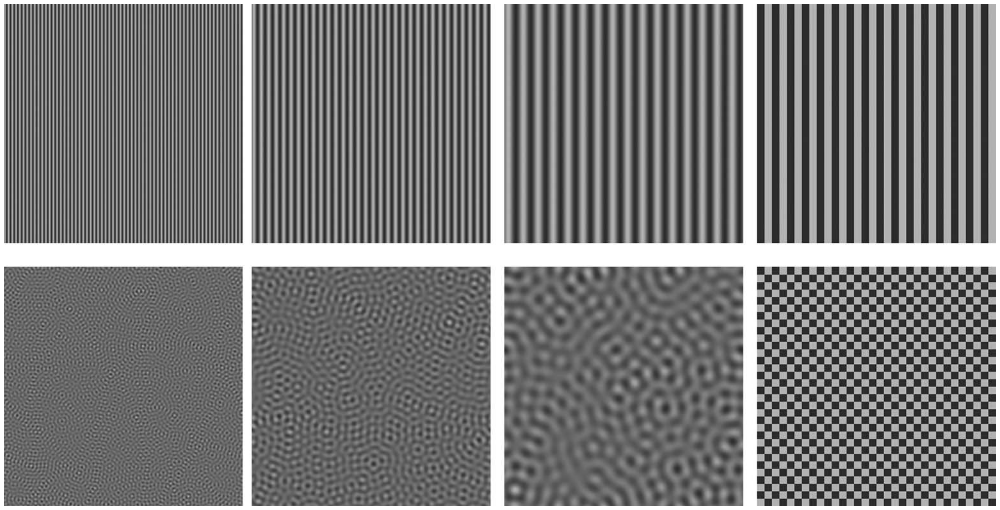

Figure 4. Some of the stimuli (without noise) used in experiment 1. Upper row: 1D unifrequency patterns [from left to right, three sinusoidal gratings (7.4, 3.7, and 1.9 cpd) and a rectangular grating]. Lower row: 2D unifrequency patterns [from left to right, three unifrequency patterns (7.4, 3.7, and 1.9 cpd) and a checkerboard pattern].

EXPERIMENT 1: EXPERIMENT USING UNIFREQUENCY PATTERNS

The result of the preliminary experiment implied that perception of sharpness by noise differs from observer to observer. We thought that this discrepancy might be due to the difference in the place in the image the observers were paying attention to during judgment. From the introspective reports by some observers, we also thought that the discrepancy might be due to the difference in what they interpreted as sharpness. From the preliminary experiment alone, however, we could not know which was the actual reason. Then, in this experiment, we tried to reduce to such variability by devising artificial stimuli that were simple and homogeneous over the entire area. We thought that this approach would also serve to avoid the difficulty in characterizing ordinary natural images, because even a simple one contains very fine texture and edges. Experimenting under a more restricted condition was another objective of this experiment.

Stimuli

In this experiment, we used black-and-white images that contain only one frequency component or unifrequency patterns. All images were 512×512 pixels in size and had the same contrast (maximum and minimum pixel values of 64 and 192, respectively). One-dimensional (1D) versions of unifrequency patterns included sinusoidal gratings with frequencies of 128/512, 64/512, 32/512, and 16/512 [1/pixel]. For comparison, a rectangular grating pattern with a period of 32 pixels was prepared as stimulus that is exclusively composed of sharp edges. Two-dimensional (2D) versions of stimuli, which had only one frequency component at all directions, were obtained by filtering 2D white Gaussian noise at frequencies of 128/512, 64/512, 32/512, and 16/512 [1/pixel]. In addition, a checkerboard pattern whose individual square was 16×16 pixels was prepared as a 2D version of rectangular grating. Figure 4 shows some of these original stimuli. (The stimuli with highest frequencies are not shown here because we think that they might be too fine to be reproduced.) Added to each original stimulus were five different levels of grayscale white Gaussian noise with a mean of zero and amounts (defined by the standard deviation of pixel values, σ) of 0.0 (original), 5.0, 10.0, 15.0, and 20.0. Figure 5 shows enlarged portions of these noisy stimuli.

Method

We used the paired comparison method in the subjective experiment. Two stimuli with different noise levels were pre-

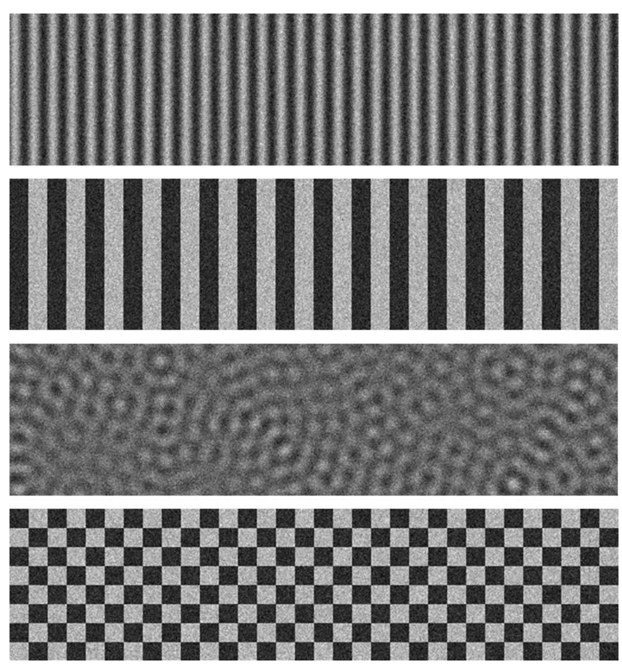

Figure 5. Enlarged portions of noisy stimuli. (From top to bottom: sinusoidal grating of 3.7 cpd, 1D grating, 2D unifrequency pattern of 3.7 cpd, and checkerboard pattern.) Noise amount is 15.0.

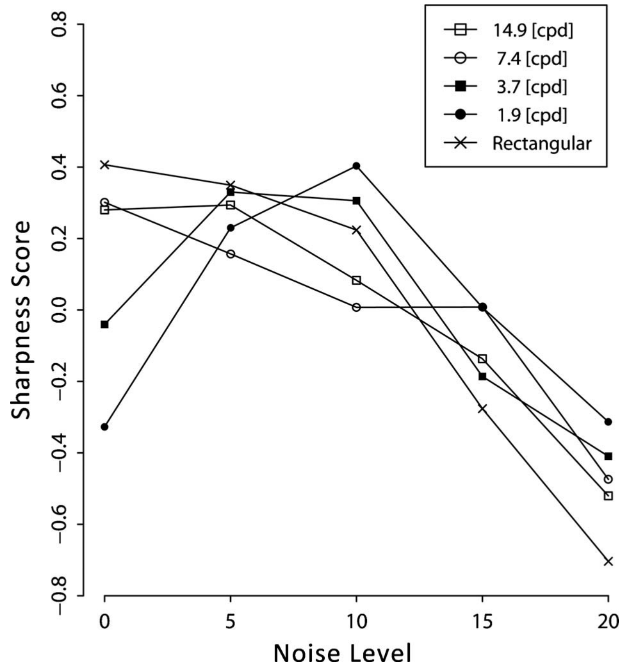

Figure 6. Result for 1D grating patterns plotted against noise level (standard deviation). Sharpness depends both on noise level and on frequency of the original stimuli. In this experiment, 95% CI of score difference is 0.24.

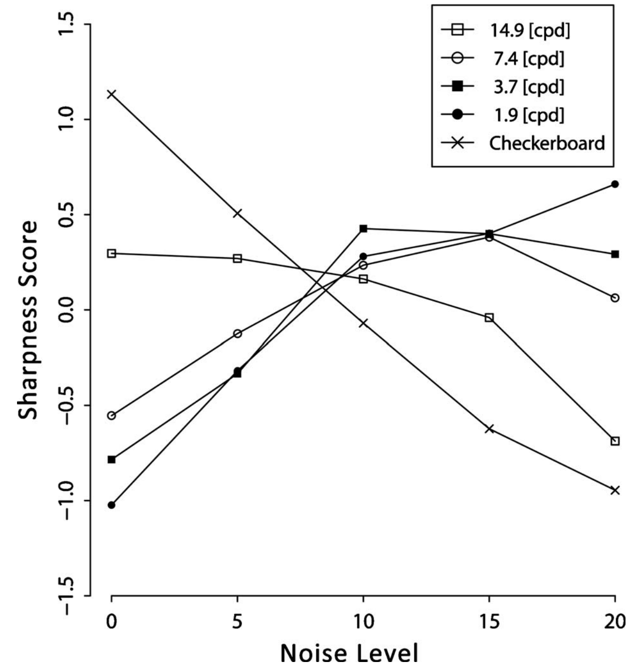

Figure 7. Result of the experiment using 2D unifrequency patterns. Sharpness depends on noise level and frequency of original patterns. In this case, 95% CI of score difference is 0.25.

sented on a middle gray background on an EIZO L568 liquid crystal display (17.0 in. in size and with a resolution of 1280×1024 pixels). The order of presentation was randomized and the left-right positions of two stimuli were interchanged; an observer completed $5 \times (5-1) = 20$ comparisons for a set of five stimuli derived from an original image. The observers' task was to indicate which one of the two images had the higher sharpness. They were allowed to look at the stimuli as long as they wanted. Thirteen observers participated in the experiment using the 1D grating patterns and 12 in the experiment using 2D unifrequency patterns. All of them had normal or corrected-to-normal vision. The experiment was conducted in a darkroom to avoid viewing glare. The viewing distance was 90 cm, which means that stimuli frequencies of 128/512, 64/512, 32/512, and 16/512 [1/pixel] correspond to visual angles of 14.9, 7.4, 3.7, and 1.9 cycles/degree (cpd), respectively. The collected data were converted to an interval scale under the assumption of Thurstone's case V.[7]

Results

Figure 6 plots the result of the experiment using 1D grating stimuli against the noise amount added. The larger is the score, the higher is the perceived sharpness. The 95% confidence interval (CI) of score difference is 0.24. The figure clearly shows that sharpness is dependent on both noise level and frequency of stimuli. For sinusoidal gratings of 14.9 and 7.4 cpd, noise addition only reduces sharpness. In contrast, the sharpness of lower-frequency patterns (with frequencies of 3.7 and 1.9 cpd, shown by filled squares and filled circles) is enhanced as the noise level increases and then decreases. The rectangular grating loses sharpness most dramatically.

The results of the experiment using 2D unifrequency patterns are plotted in Figure 7. The 95% CI is 0.25 in this experiment. The sharpness score of the highest-frequency pattern gradually decreases, while that of lower-frequency patterns increases as the noise amount increases. In addition, the lower the frequency of pattern is, the more sharpness the stimuli gains. The sharpness of the checkerboard pattern decreases most drastically as was the case with the rectangular grating pattern.

Discussion

From Fig. 6, it is clear that sharpness perception of grating patterns strongly depends both on the noise amount added and on the frequency of stimuli. The noise amount between 10 and 15 seems to give higher sharpness to the stimuli with frequencies of 3.7 and 1.9 cpd than the original, while the sharpness of other stimuli is reduced with increasing noise level. This means the existence of an optimal noise level for the sharpness of lower-frequency patterns. On the contrary, the sharpness of higher-frequency patterns is reduced by noise as is evidenced by the result for the rectangular grating. In other words, adding noise to edge, which contains a high-frequency component, makes it appear less sharp. We think that this is related to the introspective report in the preliminary experiment by some observers that they evaluated less noisy images as sharper because of the no clean-cut appearance of edges interfered with by noise.

Fig. 7 indicates that the sharpness of 2D unifrequency stimuli is dependent both on stimuli frequency and on noise amount, too. Although the unifrequency pattern with the highest frequency and the checkerboard pattern lose sharpness as the noise amount increases, the other patterns gained sharpness. These results are consistent with the observation

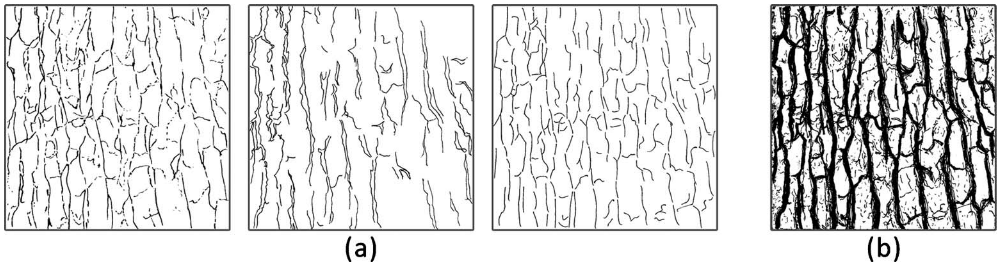

Figure 8. The results of edge detection (tracing) by human observers. (a) Results by three of the participants and (b) after the integration of the results by all the participants (final mask image).

by Kayargadde and Martens that noise improves the sharpness of blurry images, which have more low-frequency components, while decreasing the sharpness of originally sharp images, which contain more high-frequency components.[5]

Comparing the result of 2D unifrequency patterns to that of 1D gratings of the same frequency, we can see that sharpness perception of 1D patterns is different from that of 2D patterns. For example, the 2D pattern with a frequency of 7.4 cpd is sharpest at a noise level of 15, while the 1D pattern with the same frequency has the highest sharpness score at a noise level of zero (original).

One possible explanation of these results may be visual masking and facilitation, where adding a "masker" to "signal" raises (masking) or lowers (facilitation) the signal detection threshold. Blackwell examined the effect of noise on the detection thresholds of sinusoidal gratings and showed that low-contrast white noise facilitates the detection of middle-frequency sinusoidal gratings.[8] Masking theory, however, does not seem to account directly for the result of sharpness perception because the sinusoidal grating was clearly visible in our experiment but almost invisible in Blackwell's experiment, although the result by Blackwell is in qualitative agreement with ours.

Although the difference in sharpness perception between 1D gratings and 2D unifrequency patterns is also yet to be investigated, we think that the discrepancy in judgments found in the preliminary experiment is associated with this different perception of 1D and 2D patterns. That is, those observers who perceived less sharpness with increasing noise have looked mainly at sharp 1D components (edge) during judgment, whereas those who perceived more sharpness have concentrated on 2D lower-frequency components of the image (texture) in addition to edge. We also consider that sharpness perception could be enhanced by adding noise only to the texture components of image, not to edges.

EXPERIMENT 2: EXPERIMENT USING A NATURAL IMAGE

Stimuli

To confirm the prediction in experiment 1 that adding noise only to the texture part of image improves the perceived sharpness, we conducted subjective evaluation of image sharpness again using the tree bark image employed in the preliminary experiment. The stimulus image was the tree bark image used in the preliminary experiment (Fig. 1). Usually, to detect and separate the edge part of an image from the rest (texture), an edge detection algorithm has to be applied. However, the parameter setting for the edge detection algorithm (and threshold for binarization) is inevitably arbitrary. Therefore, instead of using computer algorithms, we tried to use human observers as edge detectors.

Edge/Texture Separation

We printed the tree bark image onto a paper and asked 16 participants to trace the part of the image they regarded as edge. Figure 8(a) shows some of the results. We then scanned the images and integrated them into one binary mask image, regarding the part traced at least by one participant as the edge. The resultant mask image is shown in Fig. 8(b). (As individual participants traced slightly different parts, all the lines are not necessarily of the same width.)

Stimuli Preparation

Five different levels of grayscale white Gaussian noise, whose standard deviations were 0, 5.0, 10.0, 15.0, and 20.0, were added to the tree bark image. Using the mask image obtained in the tracing experiment, we applied the noise to the edge part of the bark image [indicated as black in Fig. 8(b)], which we will refer to as the edge condition. We also prepared texture condition stimuli, which were made by adding noise to the texture area [indicated as white in Fig. 8(b)]. Figure 9 shows top halves of the stimuli of both conditions with noise amount of 15 applied.

Method

The stimuli were presented in the same way as in experiment 1. Twelve out of the 16 participants in the tracing experiment took part in the experiment. They had normal or corrected-to-normal vision. Each observer completed $5\times(5-1)=20$ comparisons for each condition. The collected data were converted to an interval sharpness scale under the assumption of Thurstone's case V.

Results

Figure 10 plots the evaluated sharpness against the noise level, which is again defined by the standard deviation of pixel value. For the edge condition, the sharpness score monotonically decreases with increasing noise, as was observed with the rectangular grating and the checkerboard patterns in experiment 1. For the texture condition, it increases with the noise level up to 15 and then decreases. As

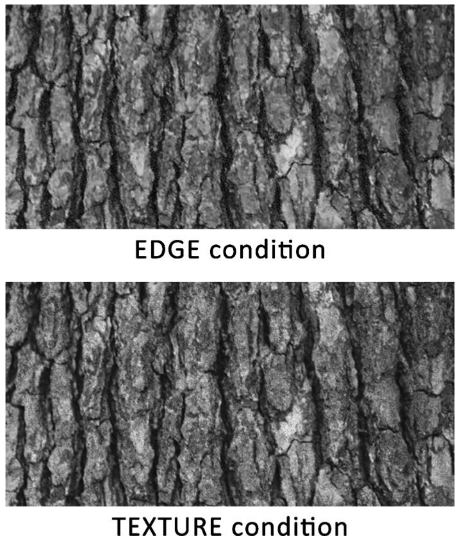

Figure 9. Top halves of noisy stimuli used in experiment 2. Noise level added is 15. (Top: edge condition; bottom: texture condition.)

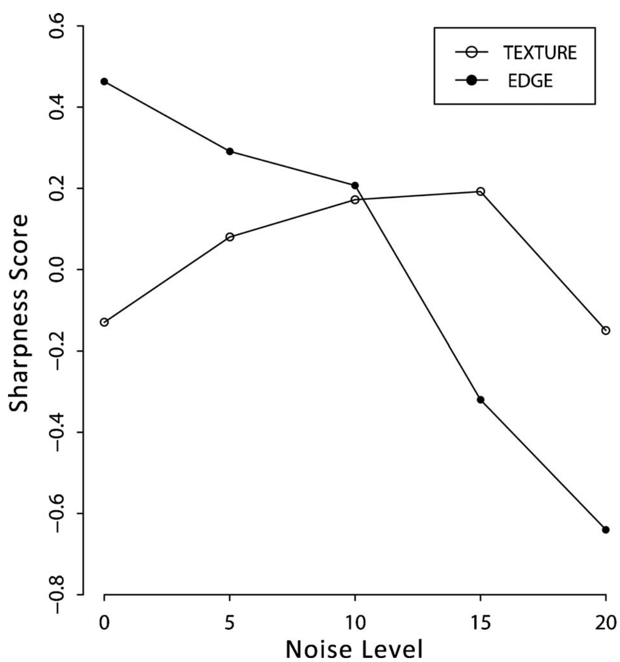

Figure 10. Result of experiment 2. Sharpness of edge condition stimuli monotonically decreases with increasing noise. On the other hand, for texture condition, sharpness at noise levels of 10 and 15 is significantly higher than the original. In this experiment, 95% CI of score difference is 0.25.

95% CI of difference is 0.25, there is a significant difference between noise levels of 0, 5, and 20 and the other noise levels (10 and 15).

Discussion

Fig. 10 shows that, for the edge condition, adding noise only reduces sharpness. In contrast, for the texture condition, the perceived sharpness at noise levels of 10 and 15 is significantly higher than for the original image or for the noisiest one. Thus, we conclude that noise is capable of sharpening a natural image, but only when added to texture in the image, not to edges.

We think that this result accounts for the discrepancy in the judgment among observers and the introspective reports by some observers in the preliminary experiment: Those who perceived more sharpness with increasing noise might focused more on the enhanced texture of the subject, while those who perceived less sharpness have concentrated exclusively on the edges in the image. Although sharpness (and acutance) is usually judged from edges, focusing on texture in addition to edges may be reasonable because sharpness is about fine details or texture as well as edges.[9] Despite the differences in the characteristics of noise added (uniform versus Gaussian/chromatic versus achromatic), the existence of an optimal noise level for sharpening seems to be qualitatively in line with the observation by Johnson and Fairchild that an appropriate amount of noise enhances sharpness.[4]

GENERAL DISCUSSION AND CONCLUSIONS

We analyzed how white Gaussian noise affects sharpness perception. A preliminary experiment using a black-and-white natural image showed that adding noise to the whole image only degrades sharpness. However, there was a large variability in the response and there seemed to be two types of observers: those who perceived more sharpness with increasing noise and those who perceived less sharpness. From this experiment alone, however, we could not know whether this variability was because of the difference in the part of the image to which the observers were paying attention to during the evaluation process or because of a difference in their interpretations of sharpness.

In the next experiment (experiment 1), we used 1D and 2D artificial images that contain only one frequency component (gratings and unifrequency patterns) in an attempt to avoid the ambiguity in characterizing an ordinary natural image. We thought that this would also help keep experimental stimuli as homogeneous as possible and would make observers' judgment independent of their region of interest. The result showed that noise could enhance the sharpness of lower-frequency stimuli but reduce the sharpness of the higher-frequency stimuli and edge. At the same time, the result also demonstrated a difference in the perception of 1D gratings and 2D unifrequency patterns.

From the result of experiment 1, we thought that it might be possible to improve sharpness by applying noise only to the texture part of the image while leaving edges intact. To prove this prediction, in experiment 2, we used stimuli (1) to the edge part of which noise was added and (2) to the texture part of which noise was added, based on the result of an edge tracing experiment by human observers. The result showed that adding noise to edges monotonically reduced sharpness, whereas adding noise to texture enhanced sharpness at noise levels of $\sigma = 10$ and 15. We therefore conclude that noise can sharpen an image when applied to the texture component of the image, but not to edges or the entire image. We consider that the different introspective reports by some observers in the preliminary experiment can be attributed to this result; that is, those who perceived more sharpness with increasing noise might have concentrated more on the enhanced texture of the subject and perceived a more focused appearance, while those who perceived less sharpness might have focused mainly on edges interfered with by noise, and thus judged the image as less sharp. (In that sense, a term other than "sharpness" may more appropriately represent the images' appearance.)

We think that our results showed the need for considering behavior in textured areas in addition to edge and flat regions when evaluating the performance of denoising algorithms, which inevitably sacrifice fine details for smoothness. Our study also suggests that sharpness can be enhanced by intentionally leaving or making use of some noise.

REFERENCES

[1] B. W. Keelan, *Handbook of Image Quality: Characterization and Prediction* (Marcel Dekker, New York, 2002).
[2] J. P. Caponigro, "Use noise to reduce banding", http://www.johnpaulcaponigro.com/downloads/technique/documents/tech_using_noise.pdf (accessed December 2008).
[3] Y. Kashibuchi, N. Aoki, M. Inui, and H. Kobayashi, "Improvement of description in digital print by adding noise", J. Soc. Photogr. Sci. Technol. Jpn. **66**, 471–480 (2003) [in Japanese].
[4] G. M. Johnson and M. D. Fairchild, "Sharpness rules", *Proc. IS&T/SID Eighth Color Imaging Conference* (IS&T, Springfield, VA, 2000) pp. 24–30.
[5] V. Kayargadde and J.-B. Martens, "Perceptual characterization of images degraded by blur and noise: Experiments", J. Opt. Soc. Am. A **13**, 1166–1177 (1996).
[6] T. Kurihara, T. Tanaka, N. Aoki, and H. Kobayashi, "On sharpness increase by image noise", *Proc. Fall Meeting Soc. Photogr. Sci. Technol. Japan* (SPSTJ, Tokyo, 2007) [in Japanese] pp. 43–44.
[7] P. G. Engeldrum, *Psychometric Scaling: A Toolkit for Imaging Systems Development* (Imcotek, Winchester, MA, 2000).
[8] K. T. Blackwell, "The effect of white and filtered noise on contrast detection thresholds", Vision Res. **38**, 267–80 (1998).
[9] F. Cao, F. Guichard, and H. Hornung, "Measuring texture sharpness of a digital camera", Proc. SPIE **7250**, 72500H (2009).