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ORIGINAL ARTICLE

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Quantification of visual inducement of knots by eye-tracking

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Abstract Knots have been considered an undesirable visual feature of lumber. To clarify the essence of this visual undesirability, eye-tracking data from 20 subjects, who freely observed 55 images of wood wall panels, were recorded and distribution maps of eye-fixation pauses were composed. These maps were compared with the arrangement of knots on each knotty wall panel image and the visual inducement of knots was evaluated using a new numerical index of pausing probability. The present study is the first to objectively quantify the visual inducement of knots. In addition, the subjective noticeability of knots and ten visual impressions of each wood panel image were investigated by a sensory evaluation. There was a very clear linear relationship between the visual inducement of knots and the subjective noticeability of knots. A correlation analysis suggested that many visual impressions of wood wall panels were influenced by a complementary effect between the subjective noticeability of knots and the visual inducement of knots. The visual impact of knots was masked to some extent by special visual stimuli such as deep red grooves on the wood wall panels.

Key words Knot · Visual inducement · Masking effect · Eye mark · Sugi

Introduction

Knots are the remains of branches in a tree trunk and are evidence that the wood came from a living tree; however, they reduce the mechanical properties of lumber and have been considered an undesirable visual feature. Therefore, lumber with few knots is traded at higher prices in the market than lumber with many knots. Recently, the number of consumers who do not object to knots has increased, and interior designs featuring wood with many knots have become more common due to the boom in the use of natural building materials. However, knots are a conspicuous feature of wood, and may not always be desirable.

Masuda and Nakamura reported that wall panels with knots evoked "natural" impressions very well, but "agreeable" impressions declined as the number of knots increased.[1,2] Broman[3–5] mentioned that many people in Northern Europe also tend to prefer knot-free lumber over knotty lumber.

Sakuragawa et al.[6] carried out a sensory evaluation with continuous measurement of blood pressure using the visual stimuli of a knotty hinoki board and a white painted steel board. In this experiment, visual stimulation from the hinoki wood board reduced feelings of depression and made a natural impression on the subjects. Blood pressure decreased significantly in subjects who liked them; however, there was no significant increase in blood pressure in those who disliked the hinoki wood board. In another study of the relationship between human physiology and wood, Tsunetsugu et al.[7] recently reported that the amount of wood used for a room influenced human physiological responses, blood pressure, and brain activity.

Nakamura and Kondo[8] extracted eye-fixation pauses (steadily gazed points) from 20 subjects who freely observed various knotty wood panel images, and characterized the distribution patterns of eye-fixation pauses using two numerical indices. Although the studies above suggest that all sorts of visual characteristics of wood, including knots, influence humans psychologically and physiologically in many ways, they do not address the reason why knots are perceived to be a poor visual characteristic of the lumber surface. To answer this question, the visual impact of knots should be evaluated by appropriate methods.

The purpose of the present study was to determine the visual inducement of knots (VIK), and to clarify the relationship between VIK and the subjective noticeability of

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This study was presented at the 56th and 57th Annual Meetings of the Japan Wood Research Society, Akita and Hiroshima, August 2006 and August 2007, respectively knots (SNK). Eye-tracking data from 20 subjects who freely observed 55 wood wall panel images were recorded using an eye tracker. Distribution maps of eye-fixation pauses were composed from these data, and the distributions were compared with the arrangement of knots to evaluate VIK. In addition, visual impressions and SNK of each wood panel image were investigated using sensory evaluation.

Methods and materials

Visual stimuli

Many flat-sawn boards of Japanese cedar (*Cryptomeria japonica*; sugi, from the Yoshino area of Nara Prefecture, Japan), with dimensions of 1000 mm in the longitudinal direction, 110 mm in the tangential direction, and 12 mm in the radial direction, were sorted based on the size of knots. Photographs of the boards were taken using a digital still camera (Nikon D1x, Nikkor 50 mm f/1.4D lens). After the photo-retouching process, these images were arranged as wall panel images using 1280 × 768 pixel composition on a computer screen. These wall panel images were classified into three types based on the diameters of knots specified in Japan Agriculture Standards (JAS) for timber; those with knots 20 mm or more in diameter were the large knot type, knots less than 20 mm in diameter were the small knot type, and those with only a few pin-knots were the clear type. In addition to these categories, some wall panel images with a combination of the above three types were made.

To examine whether the visual inducement and impression of knots changed by the design of the wall, groove lines at the joints of the boards were drawn on the wall panel images as one of the design elements. The width and color of grooves varied in each wall panel image; six variations were selected for the width (0, 1.5, 3, 6, 12, and 24 mm) along with three variations in the color (light brown, dark brown, and deep red). To make the visual feel of the groove more natural, an uneven tone was added.

Finally, 55 wall panel images were generated using computer graphics and were used as visual stimuli in this study. The minimum, mean, and maximum numbers of knots in the wall panel images were 28, 61, and 142, respectively, and the total areas of knots were 1.3, 43.1, and 100.5 cm^2, respectively. Typical examples of the wall panel images are shown in Fig. 1a.

Free observation experiment

Fifty-five kinds of wall panel images were displayed in their actual size on a large liquid crystal display (LCD monitor; Sony, KDX-46Q005). The displayed size of the images was 950 × 570 mm, and the luminance of the monitor was approximately 57 $\mathrm{cd/m}^2$ when a neutral gray image was displayed.

Twenty healthy Japanese students (12 men and 8 women) participated in this experiment. After they were given suf-

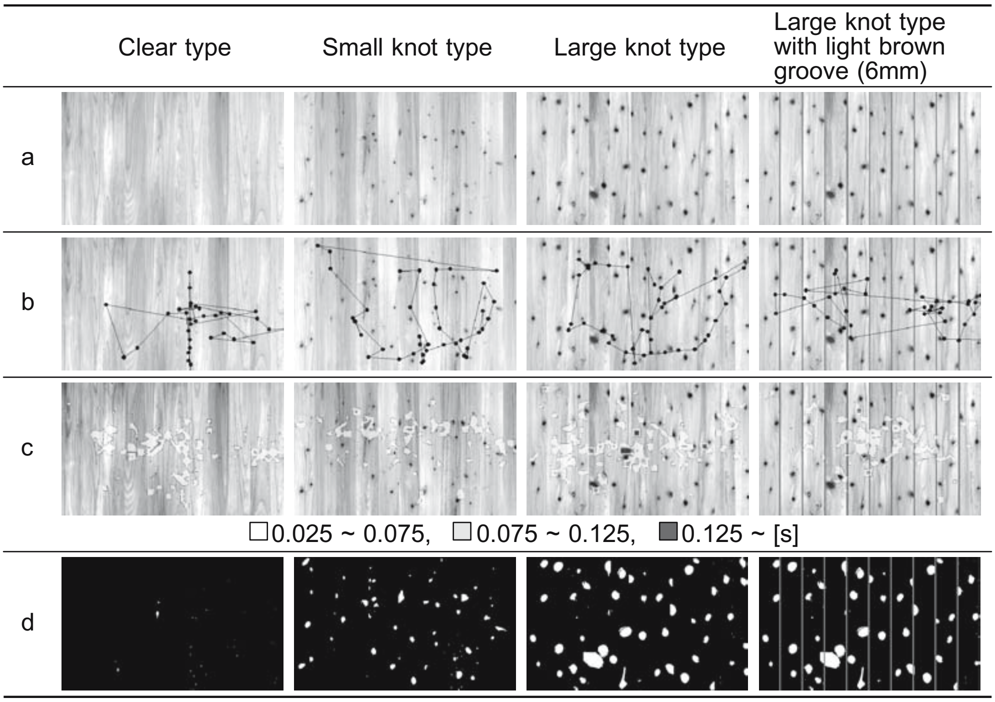

Fig. 1a–d. Examples of wall panel images, eye-fixation pauses, distribution maps of eye-fixation pauses, and binarized images. **a** Four examples of wall panel images used as visual stimuli. **b** Positions of eye-fixation pauses in three subjects: clear type, subject 6 (male); small and large knot type, subject 4 (female); large knot type with light brown groove, subject 1 (male). *Black dots* denote their eye-fixation pauses. Adjacent dots are tied in line with each other along the time sequence. **c** Distribution maps of eye-fixation pauses composed from 20 subjects' data. *Contour lines* and intensity of *shading* denote average pausing time. **d** Binarized wall panel images. Each knot (including very small pin-knots) was extracted as a knot region expressed in white. To reduce the threshold of judgment of whether an eye-fixation pause is on a knot, knot regions are dilated double to that of the real areas

ficient information and explanation about the objective and procedure of the experiment, written consent was obtained from each of them.

A subject sat on a chair in front of the LCD monitor. A cap with an eye camera (NAC, eye mark recorder EMR-8) was placed on the subject's head. The subject's chin was gently fixed to a stand to prevent any head movement. The observation distance was 1850mm and the visual angle of the image at this position was about 29 degrees in the horizontal direction. A small white cross was displayed on the center position of the LCD monitor with the neutral gray background for the initial 1-s period. The subject first gazed at the cross. After the cross faded out and a wall panel image faded in, the subject freely observed the image for 18s. This short observation time was defined to prevent the subject from becoming bored and to record sufficient eye-mark data for the analysis. The 55 wall panel images were switched automatically. To display the wall panel images, two sets of presentation order were defined based on random numbers and were assigned to the subjects randomly. The total observation time was about 30min, including a rest period of 10min at the midpoint of the session. The eye camera detected the subject's eye movement as a series of eye marks during the session. These eye marks were recorded on videotapes.

Sensory evaluation

After the free observation experiment, a sensory evaluation concerning the visual impression of the wall panel images was performed under the same conditions. A questionnaire was distributed by the semantic differential method using the following ten adjective pairs; "showy–sober," "novel–common," "natural–unnatural," "neat–disordered," "expensive–cheap," "agreeable–disagreeable," "calm–restless," "elegant–vulgar," "beautiful–ugly," "pleasant–unpleasant." All words were written correspondingly in Japanese on the questionnaire form. The 20 subjects in the free observation experiment and another 4 subjects (1 male and 3 female students), for a total of 24 subjects, participated in the questionnaire. The results of the questionnaire were totaled and converted to statistical indices based on the psychological scaling method using the averaged standard deviation.[9]

In addition to the questionnaire, "subjective noticeability of knots" (SNK) was evaluated by using a monopolar scale graduated with six notches from 0 (inconspicuous) to 5 (extremely noticeable). An arithmetic mean of the evaluation by 24 subjects was calculated as the index of SNK of each wall panel image.

Results and discussion

Distribution map of eye-fixation pauses

Eye mark time and coordinate data were extracted from the videotape every one thirtieth of a second. The dataset was then summarized to a smaller dataset of eye-fixation pauses (steadily gazed points). In this study, if eye marks stayed on a region less than 2.0 degrees in diameter for 0.1s or more, the center of that region was considered a point of eye-fixation pause. A position of eye-fixation pause was considered a point that contains visual information for the subject. Thus, if the knot is one of the eye-catching features of the lumber, the positions of the knots and the eye-fixation pauses must correspond.

Figure 1b shows typical distribution of eye-fixation pauses in three subjects. Adjacent eye-fixation pauses (black dots in Fig. 1b) are linked to each other with a line along the time sequence. This linear chart closely corresponds to tracking the eye movement of the subject. In the case of the clear type image, subject 6 (male) moved his eyes crosswise only around the center of the image, because there was no visually noticeable feature on this image. However, in the small and large knot type images, subject 4 (female) moved her eyes vertically in one lamina and hopped horizontally to another lamina while searching for the knots. Moreover, subject 1 (male) looked not only at knots but also at grooves for a short time in the large knot type image.

To examine the average observation behavior of all subjects, a distribution map of the eye-fixation pauses was composed for each wall panel image. A wall panel image was divided into 51 × 31 cells (each cell measured about 19 × 19mm), the durations of all subjects' eye-fixation pauses were accumulated in every cell, and the average pausing time of each cell was calculated. Finally, an average distribution map was constructed as a contour map as shown in Fig. 1c. In the clear type image, subjects' eyes wandered crosswise in the vicinity of the center. In the small and large knot types, however, many subjects tended to look at the knots and their surroundings for a longer time (or more frequently) as the amount of knots increased.

Pausing probability of knot regions and groove regions

The above distribution maps graphically demonstrate a degree of the qualitative visual inducement of knots. To quantify the visual inducement of knots, every knot in a wall panel image was extracted into knot regions using image binarization (Fig. 1d), and a pausing probability of the knot regions, R_K, was calculated as follows;

$$R_K = \frac{1}{N}\sum_{i=1}^{N}\frac{K_i}{T_i}, \tag{1}$$

where N is the number of subjects, i is the subject number, K is the total pausing time in knot regions, and T is the total pausing time in a whole image.

K in Eq. 1 was calculated by using an image analysis as follows. Knot regions in a wood wall panel image were first extracted as shown in Fig. 1d. Next, points of eye-fixation pauses were verified as to whether their coordinates were contained in the knot regions (white regions). In this study, a knot region was expanded to double that of the real area of a knot in order to reduce the threshold of judgment of whether an eye-fixation pause was on the knot. Finally, the pausing times in the knot regions were accumulated to derive the total pausing time at these regions, K. R_K was relatively simply calculated, but it was a good numerical index to evaluate the visual inducement of the knot (VIK) for reasons to be given later.

In the same way, the pausing probability of the groove regions in a wall panel image, R_G, was defined by Eq. 2:

$$R_G = \frac{1}{N}\sum_{i=1}^{N}\frac{G_i}{T_i}, \tag{2}$$

where G is the total pausing time of the groove regions.

In addition to R_K and R_G, area fractions of knots, A_K, and of grooves, A_G, were also calculated. A_K and A_G are simple ratios between the area of a whole wall panel image and the area of knots or of grooves, respectively. As the number of knots on the wall panel image increases, it is natural that the value of A_K increases.

Relationships between A_K and R_K are shown in Fig. 2. If the subjects did not care about knots and they observed wall panel images randomly, R_K should be statistically equal to A_K. This ideal linear relationship is shown as a broken line in Fig. 2. Although R_K increases linearly with increasing A_K, R_K values are considerably larger than A_K values. This means that the subjects' eyes were obviously induced to the knots. R_K is a good index to evaluate VIK.

On the other hand, the relationships between A_G and R_G are shown in Fig. 3. Many of the dots in these scatter diagrams are distributed along the ideal line regardless of the knot sizes and groove colors. The fact that A_G and R_G were approximately equal suggests that the grooves lack visual inducement compared with the knots.

Masking effect of grooves for knots

Some grooves affected the subjects' observation behavior with respect to the knots. As seen from the R_K–R_G relations in Fig. 4, light brown and dark brown grooves have little effect on the pausing probabilities to the knot regions (R_K) even if R_G increases. Deep red grooves, however, tend to decrease R_K with an increase in R_G. As a strong visual stimulus, the wider and deep red grooves mask or reduce the visual inducement of knots, although whether a wall panel with such grooves looks good or not must be examined separately. This result also demonstrates the possibility that the visual impact of knots may be controlled by an appropriate wall design.

Visual impressions of knotty wall panel

Figure 5 shows the relationship between R_K and the subjective noticeability of knots (SNK). Note that the horizontal axis of this scatter diagram is logarithmic, and data of clear type walls are excluded. A very clear linear relationship between R_K and SNK is shown in Fig. 5. As mentioned in the previous section, R_K is a good index of VIK, and the linear relationship between R_K and SNK suggests that VIK and SNK are closely related. VIK and SNK are probably

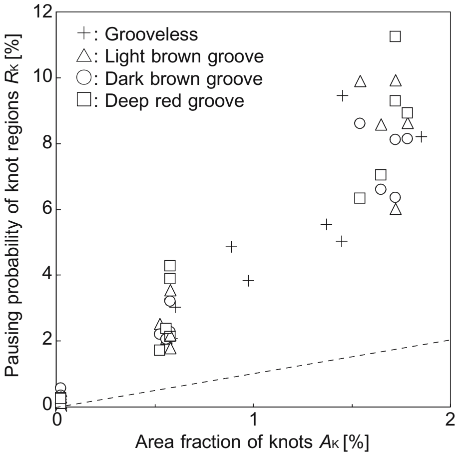

Fig. 2. Relationships between area fraction of knots (A_K) and pausing probability of knot regions (R_K). The *broken line* represents an ideal linear relationship when subjects did not care about knots

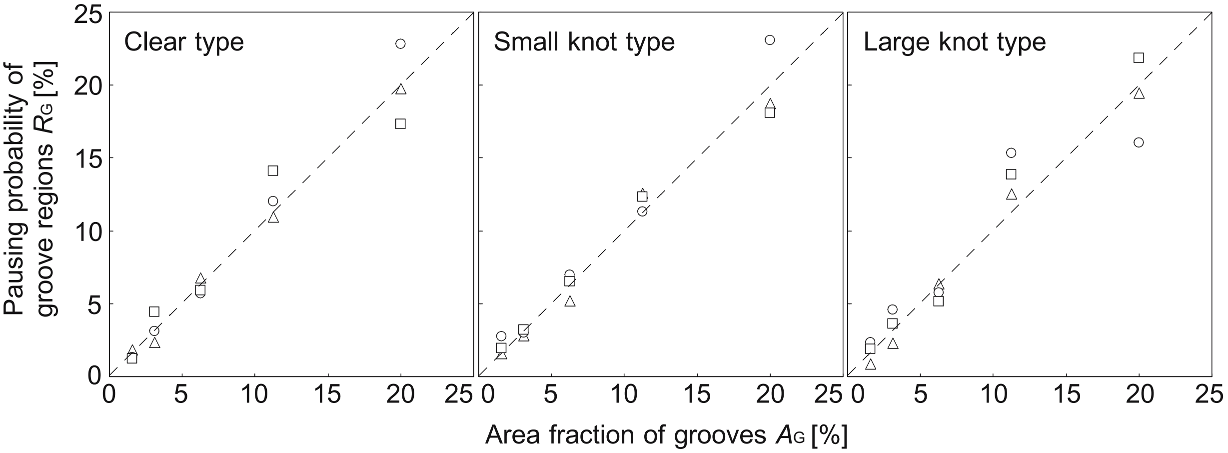

Fig. 3. Relationships between area fraction of grooves (A_G) and pausing probability of groove regions (R_G). *Triangles*, light brown groove; *circles*, dark brown groove, *squares*, deep red groove. *Broken lines* represent ideal linear relationships when subjects did not care about grooves

Table 1. Single correlation coefficient matrix of subjective noticeability of knots and paired adjectives used in questionnaire

		SNK	1	2	3	4	5	6	7	8	9	10
	SNK	–										
1	Showy–sober	–0.416	–									
2	Novel–common	–0.148	0.866	–								
3	Natural–unnatural	–0.274	0.852	0.931	–							
4	Neat–disordered[a]	–0.879	0.677	0.487	0.628	–						
5	Expensive–cheap	–0.745	0.470	0.403	0.587	0.874	–					
6	Agreeable–disagreeable	–0.568	0.818	0.761	0.888	0.839	0.823	–				
7	Calm–restless	–0.614	0.891	0.790	0.871	0.861	0.756	0.954	–			
8	Elegant–vulgar	–0.682	0.767	0.706	0.831	0.894	0.884	0.951	0.943	–		
9	Beautiful–ugly	–0.722	0.710	0.629	0.782	0.913	0.918	0.944	0.917	0.975	–	
10	Pleasant–unpleasant	–0.528	0.713	0.696	0.845	0.784	0.833	0.951	0.893	0.930	0.935	–

SNK, Subjective noticeability of knots

[a] The minus correlation coefficient to SNK means that the more knots are noticeable, the more "disordered" impression a wall panel image gives

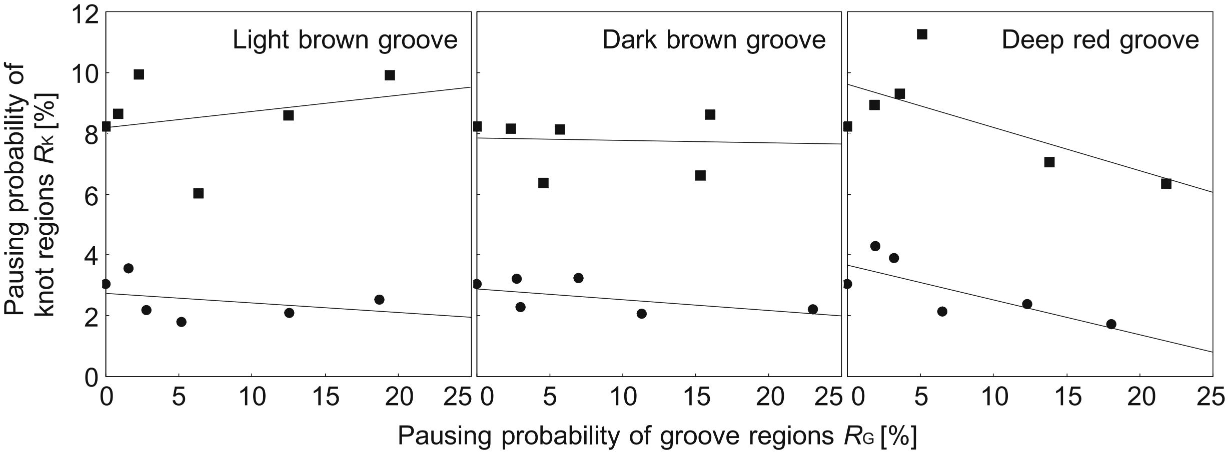

Fig. 4. Relationships between pausing probability of knot regions (R_K) and pausing probability of groove regions (R_G). *Circles*, small knot type, *squares*, large knot type. *Solid lines* are regression lines of the data

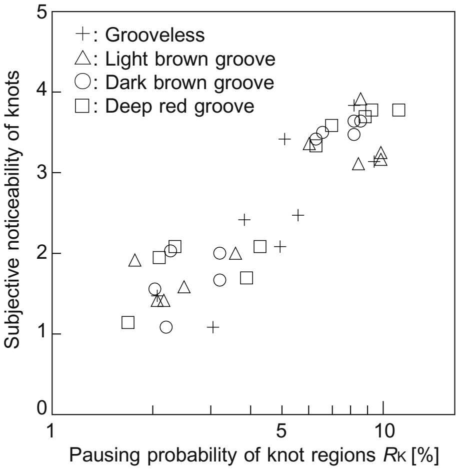

Fig. 5. Relationships between pausing probability of knot regions (R_K) and subjective noticeability of knots. Note that the data for the clear type walls are excluded because of the logarithmic scale of the horizontal axis

complementary and both affect the visual impression of wood wall panels.

A correlation analysis was made to detect simple relationships between SNK data and the questionnaire with ten paired impression adjectives. Table 1 is a single correlation coefficient matrix of the results. SNK shows an especially high correlation with a "neat–disordered" impression. In this case, the more subjectively noticeable that knots are, the more likely it is that a wall panel image will give an impression of being "disordered." Furthermore, the "neat–disordered" impression shows relatively high correlation with "expensive–cheap," "agreeable–disagreeable," "calm–restless," "elegant–vulgar," and "beautiful–ugly" impressions. Wood panel images with a "disordered" impression tend to give more "cheap," "disagreeable," "restless," "vulgar," and "ugly" visual impressions. These high correlations are evidence of the strong influence of SNK on the various visual impressions of the wood wall panels.

Conclusions

The results of this study are summarized in Fig. 6 as a schematic flowchart. The visual inducement of knots (VIK) was revealed by the analysis of eye-fixation pauses using an eye-tracking system. Subjects' eye-fixation pauses on the knotty wood wall panel images were demonstrated as distribution maps. To evaluate VIK numerically, the pausing

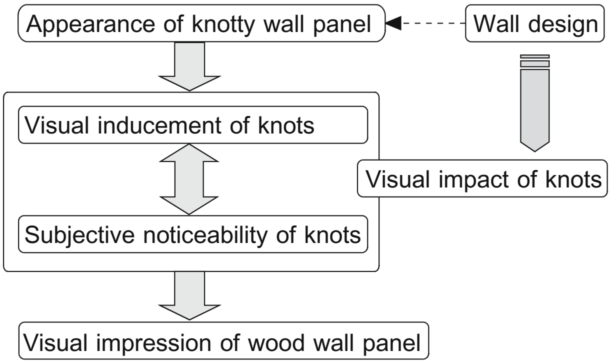

Fig. 6. A flowchart explaining the influence of visual inducement of knots on the various visual impressions

probability of knot regions was proposed as a new index. High VIK was demonstrated objectively for the first time in this study.

The subjective noticeability of knots (SNK) was also examined by sensory evaluation, and it had a high linear relationship with the pausing probability of knot regions. The correlation analysis suggested that many visual impressions of wood wall panels were also influenced by SNK.

VIK and SNK are probably complementary in their effect on these visual impressions. If VIK or SNK is effectively controlled, the visual impressions of knotty wall panels will be changed as per the designer's choice. As an example, the present study showed that the width and color of grooves on the knotty wall panels could influence the eye-fixation pauses of the knots. In other words, the visual impact of knots was masked to some extent by the design of the wood wall panel.

Some architects or designers intentionally use knotty lumber in their buildings. In such cases, however, the large knots are often screened out, and lumber with uniform small knots seems to be used frequently. According to the results of the present study, this design strategy aims to improve the visual impression of the knotty surface by reducing VIK or SNK with the small knots. If designers cannot use the "small knots strategy," they have difficulty in finding the optimum interior design that does not spoil the "natural" impression of the knotty lumber. In order to use a large quantity of knotty lumber in interior decoration, it is very important to control the visual impact of knots through effective design. Although only the masking effect of grooves is examined in this study, there must be many options to mask the visual impact of knots. The authors intend to explore other ways to mask the visual impact of knots and evaluate their effectiveness using image analysis. To promote efficient utilization of wood resources including knotty lumber, it is important to elucidate how effectively and why knots are masked by various wall designs.

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