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Perception of Tactile Attributes of Colored Texture Images

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Abstract

Understanding multimodal interaction and its effects on user experience and behavior is becoming increasingly important with the rapid development of immersive mixed-reality applications. While significant attention has been devoted to enabling haptic feedback in multisensory extended reality systems, research on how the visual and tactile properties of materials and objects interact is still limited. This study investigates how the color appearance of texture images affects observers' judgments of different tactile attributes. For this purpose, we captured images of different texture samples and manipulated the color of the images based on the previously reported consistent mapping of tactile descriptors onto color space. The observers were asked to rate these textures on different haptic properties to test the effects of color on their perception of materials. We found that the effect of changing color is most significant for the perception of heaviness, warmness, and naturalness of textures. For these attributes, a strong correlation between ratings of textures and ratings of uniform color patches of similar colors was also observed, while other attributes, such as hardness, dryness, or pleasantness, showed low or no correlation. The results can increase our understanding of the role of color as a visual cue in estimating material properties of visual textures and for designing and rendering surface properties of objects in 3D printing and virtual and augmented reality applications, including online shopping and gaming.

Keywords*: multi-sensory, material properties, color perception, visual textures*

Introduction

Transferring the sense of touching a surface is a desirable and valuable technology that is not yet adequately possible despite recent advances in the development of haptic devices. To capture and realistically simulate the surface properties of objects, we need to characterize and classify different textures and relate them to human perception. Several studies have focused on characterizing the perceptual tactile dimensions of a surface by touching surfaces and describing or rating their tactile properties.

Multidimensional scaling analysis showed that tactile judgments of textured surfaces can be represented in a perceptual space with two identifiable dimensions: smoothness-roughness and softness-hardness [1]. Further studies added the third dimension of coldness-warmness [2] and expanded the haptic perceptual space to be four-dimensional [3].

In other experiments, researchers asked blindfolded subjects to touch a surface and describe it using terms that express tactile sensations [4] [5] or permitted subjects to see the surfaces while they touched them [6]. These studies revealed a close correspondence between visual and tactile assessment of materials, thus concluding that by only looking at a texture, our visual system can predict the tactile properties of the surfaces with considerable accuracy [7] [8] [9].

At the same time, color information can influence the visual identification of materials, reducing the correct recognition rate when color information is removed, and images are converted to grayscale [10]. In studying the relationship between colors and haptic adjectives, systematic associations of brightness and chroma with haptic terms were also found [11]. Consistent mapping of tactile adjectives onto color space identified in [12], when participants described Munsell color samples by choosing the most suitable haptic terms from the list, further suggests the existence of sensory and semantic associations between visual evaluations of color and texture properties.

Although the above experiments indicate a potential interaction between the perception of color and texture, the effects of color perception on the perception of texture materials have not been systematically investigated.

To test if the association between tactile terms and visually presented colors goes beyond lexical and conceptual only, in the present experiment, we investigated the effects of color on visual perception of tactile attributes of texture images rendered using different color targets by asking observers to rate visual stimuli along ten scales previously shown to be relevant to the perception of touch. We addressed the following research question: Will using colors with known tactile associations significantly affect perception of touch-related attributes for visually presented texture stimuli?

Method

In the present study, observers had to rank order and arrange texture images using ten attribute scales.

These attributes were chosen based on previous research conducted in this field [1] [2] [3]. Roughness and hardness, followed by warmness, are usually mentioned as the most important and consistently identifiable dimensions of tactile perception of textures. In addition to those, other haptic and aesthetic characteristics related to touch were included. The pairs of opponent attributes used in the experiment as bipolar scales are listed in Table 1.

Table 1: Ten opponent paired tactile attributes

Pleasant	Unpleasant
Rough	Smooth
Hard	Soft
Warm	Cold
Moist	Dry
Heavy	Light
Natural	Unnatural
Regular	Irregular
Elegant	Inelegant
Calming	Exciting

For the present study, the attributes were defined as follows:
Pleasantness: The quality of a texture to be pleasant to touch.
Roughness: The quality of a texture to feel rough or smooth to the touch.
Hardness: The quality of a texture to feel hard or soft to touch.
Warmness: The characteristic of a texture related to the perception of the temperature of it.
Dryness: The quality of a texture to feel dry or moist to the touch.
Heaviness: The quality of a texture to feel associated with a heavy or light object when touched.
Naturalness: the attribute of a texture to look like a real texture that you would see in a natural environment.
Regularity: the characteristic of a texture to have a predictable repeated pattern when touched.
Elegance: the quality of a texture to feel premium to the touch.
Calming-exciting: the quality of a texture to feel relaxing or exciting to touch.

Participants

Fifteen observers participated in the experiment: 12 women and three men. 13 participants were in the 25-30 age range, and 2 participants were in the 40-50 age range. All participants had normal or corrected to normal visual acuity and normal color vision. They were paid $20 for participating in the experiment after completing the study.

Experimental setup

The experiment took place in a darkened room dimly illuminated with a D65 light source. For the stimulus presentation, we used a high-resolution EIZO CG319X monitor. The monitor has a resolution of 4096 x 2160 and was calibrated for Adobe RGB 1998 color space with a D65 white point and a 120 cd/m^2 luminance level. The observers were seated 85 cm from the monitor.

Procedure

The experiment consisted of three sessions conducted on different days to minimize fatigue and session interaction. In the first session, experimental participants scaled ten textures on ten attribute scales in 100 trials. In a single trial, they saw ten versions of the same initial texture image rendered using ten target colors, including gray, and were asked to arrange the samples along one of the scales. The observers could freely move the samples around to position them according to the perceived strength of the attribute characteristic using the scale presented at the bottom of the screen (Figure 1). Before each trial, a description of the attribute in question was displayed.

The observers were divided into two groups, each completing the session for half of the scales to minimize fatigue and obtain more reliable results. Since roughness-smoothness and hardness-softness represent the most robust tactile dimensions, they were included in the attribute list for all the observers to evaluate.

The second and third experimental sessions utilized a similar evaluation procedure. In the second session, however, grayscale images of textures were used as stimuli with the color information removed, while the stimuli in the third session had texture information removed. This was done to selectively observe the effects of texture and color on the attribute judgments.

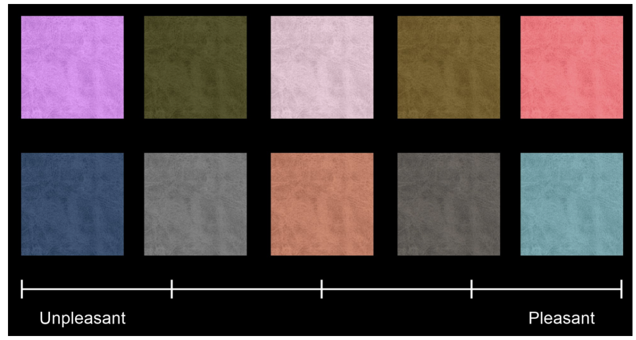

Figure 1: User interface for presenting and rating colored textures in the experiment for Unpleasant-Pleasant scale as an example.

Stimuli

The stimuli consisted of 10 texture samples cut in 10*10 cm squares and attached to the same-size cardboard backing. These samples represented materials typically found in everyday life, such as carpet, sandpaper, wood, glass, vinyl, and plastic.

Texture samples were photographed using a Canon EOS 60D DSLR camera in a viewing booth under standard D65 lighting conditions (Figure 2). High-resolution images were cropped to 640x640 pixels, which subtends 7.4 x 7.4 degrees of visual angle. The image resolution, size, and monitor settings enabled sufficiently visible texture elements to the observers.

Figure 2: Images of the labeled texture samples in their original colors.

The images were mapped to the target colors to study the effects of different colors on tactile attributes. To this end, we first converted the images defined in Adobe RGB 1998 color space to CIELAB color space with D65 white point and then to grayscale images. In that process, the pixel values of a* and b* channels were set to 0, achieving a grayscale image for every texture.

Secondly, to systematically map the gray textures to colored textures, we modified the images by assigning them an identical average L* lightness of 50 while maintaining the standard deviation in the L* channel to preserve the texture. For this, we calculated the mean L* for all pixels in each texture image and subtracted the mean from 50; afterward, we added the difference to all L* values. Thus, the mean value of L* in all textures became 50, while the original standard deviation of the pixels' intensity was intact.

In the next step, we selected a set of target colors that showed association with the tactile attributes using previously reported data [12]. We converted the provided Munsell color system coordinates for these colors to their respective CIELAB values with the D65 white point. Subsequently, the values of a* and b* channels for all pixels in each image were changed to the a* and b* values of these specific colors to generate the experimental color texture stimuli. The target colors named by the associated tactile attributes with the corresponding Munsell color system coordinates and L*a*b* values are shown in Table 2.

Table 2: Target colors in Munsell Color System and CIELAB

Target color	Hue	Value	Chroma	L*	a*	b*
Cold	2.5B	6	6	62.26	-26.88	-11.77
Humid	2.5PB	3	6	31.25	-4.34	-24.47
Smooth	2.5R	7	16	71.96	65.32	28.33
Light	2.5RP	8	6	81.63	18.62	-0.95
Soft	7.5P	7	16	71.77	53.31	-33.31
Warm	7.5R	6	10	62.24	36.84	31.99
Hard,Dry ,Rough	7.5Y	3	4	31.43	-4.95	28.89
Heavy	10YR	4	6	41.95	-6.88	45.59

In the second session, we used the grayscale images to avoid the effects of color by nullifying a* and b* channels in the images as described above. The grayscale images are shown in Figure 3.

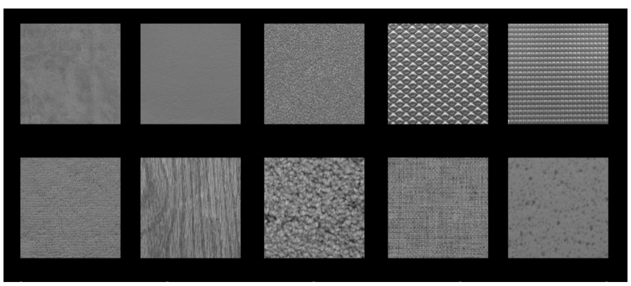

Figure 3: *Grayscale images of the texture samples used in the second experiment.*

In the third session, we used ten plain color patches the same size as the textures with the CIELAB color values from Table 2. These stimuli sets enabled us to observe the effects of texture without color and color without texture.

Results and Discussion

Effect of color on the visual perception of textures

The scale values for each stimulus, participant, and session were recorded for further analysis. To compare the attribute scores of different textures to each other, we normalized the scores of all colored textures according to the results from the gray textures experiment in the second session. For this, we shifted the scores assigned to the gray textures presented among colored textures in the first experiment for each observer and every attribute to their scores for that same gray texture in the gray texture experiment (second session). Then, we adjusted all the other scores for the colored textures accordingly, assuming that this allows us to compare the obtained normalized scores of all colored textures to each other.

To test if the color of the textures significantly affects the perception of tactile attributes, we performed a one-way ANOVA on the results of the first experiment for all the textures and participants separately for every attribute, where the perceived attribute value was the dependent variable, and color was an independent variable.

The results of the ANOVA showed that color has a significant effect on the perception of tactile properties for all attributes. On average, the observers perceived the textured stimuli rendered using specific colors to have systematically and significantly different scores compared to other colors for every attribute. For example, the textures rendered with the brownish-greenish "swamp" color (L*=31.43; a*=-4.95; b*=28.89) were found to be the roughest, hardest, and heaviest; the pale pink color (L*=81.63; a*=18.62; b*=-0.95) made the textures appear the smoothest, softest and lightest; gray textures were assessed as the most natural, pleasant, elegant and the most calming, while the textures with the reddish "peach" color (L*=71.96; a*=65.32; b*=28.33) on average were judged as the most unnatural, unpleasant, and warm. Blue color, on the other hand, tended to make textures appear moist and cold.

Since the observers could freely arrange the samples on the scales, we can analyze the data to assess the extent of spread among the samples on each scale. To assess this parameter, first, we calculated the mean scale value across all participants for every attribute. Then, we assessed Cohen's d, which indicates the effect size of color on the perception of each attribute for the textures with that color [13]. Cohen's d is calculated for each pair of samples with different colors on each attribute scale. Then, we averaged the Cohen's d calculated for all pairs of colors separately for every attribute. This average value elucidates the influence of color on the perception of the attributes, highlighting, thus, the extent to which the attributes are more perceptually affected by the changes in the texture color. The results of this analysis are shown in Table 3.

Table 3: Effect of color on tactile attributes. One-Way ANOVA: p-values and effect sizes

Attribute	p-value	effect size (Cohen's d)
Heaviness	$<.0001$	0.83
Warmness	$<.0001$	0.81
Naturalness	$<.0001$	0.73
Elegance	$<.0001$	0.53
Roughness	$<.0001$	0.51
Pleasantness	$<.0001$	0.36
Hardness	$<.0001$	0.34
Dryness	$<.0001$	0.32
Exciting	$<.0001$	0.31

As shown in Table 3, concerning the impact of color, there is a noticeable difference among the attributes regarding the effect size. This result suggests that when comparing similar textures with different colors, the perception of the textures' heaviness, warmness, and naturalness are the most strongly affected by the color, followed by elegance and roughness. In contrast, the perception of textures as exciting - calming, and dry-moist is least affected by the colors we used.

It is important to note that a more significant effect size results from the more considerable difference in the position of the texture stimuli on each scale. For example, the average heaviness score for all the textures rendered using "heavy" color (10YR V4 C6; L*=41.95; a*=-6.88; b*=45.59) equals 40.6, while the mean heaviness score for the textures with the "light" color (2.5RP V8 C6; L*=81.63; a*=18.62; b*=-0.95) is - 40.25, indicating an extensive range of perceived differences for this attribute.

On the contrary, for the moistness, most of the scores are very close to each other, with the largest difference between the gray-colored textures (L*=50, a*=0, b*=0) and the "soft"-colored textures (7.5P V7 C16; L*=71.77; a*=53.31; b*=-33.31), having -67.49 and -33.92 average scores. The maximum range of variation here is only 33.57 units compared to 80.85 for heaviness.

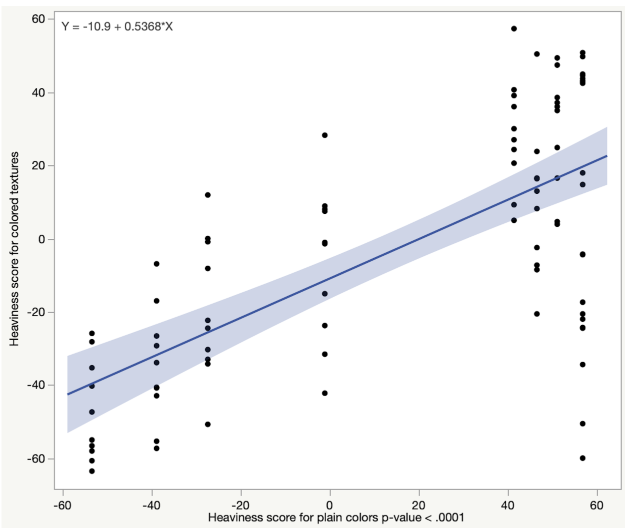

Figure 4: *Heaviness attribute scores for colored textures vs. plain color patches. The slope of the fitted line indicates the degree of correlation between textures and patches of the same color.*

Colored textures vs plain colors

The data from the third experiment with the plain colors were used to evaluate if the impact of color on the perception of textures aligns with the trend observed for the color patches. If we can identify consistent relationships between color samples and similarly colored textures for specific tactile attributes, we can extend these correlations to other textures featuring those colors.

To address this question, we plotted the average scores of the texture stimuli of a given color against the scores for that color without the texture (plain color patches) for every attribute. The slope of the fitted line in such a plot indicates the degree of the linear correlation between these stimuli and reveals the overall influence of color on the perception of the attribute across all textures.

Figure 4 demonstrates a high correlation (correlation coefficient = 0.72) between textures and plain patches of the same color for the heaviness attribute. The slopes of the fitted lines for all attributes are listed in Table 4.

Table 4: Correlation Coefficients for color patches vs. similarly colored textures for all attributes

Attribute	Correlation coefficient
Heaviness	0.72, high correlation
Warmness	0.57, moderate correlation
Naturalness	0.51, moderate correlation
Roughness	0.40, low correlation
Elegance	0.27, low correlation
Hardness	0.26, almost no correlation
Exciting	0.21, almost no correlation
Pleasantness	No correlation
Dryness	No correlation

Comparing Table 3 and Table 4 reveals that the attributes that exhibited the most significant effects of color in the first experiment, i.e., heaviness, warmness, and naturalness, also show the highest correlation of the scores between the textures and the plain patches of the same color. For several attributes, such as elegance and roughness, the effect of color on the textures is statistically significant, but the correlation with the plain patches is relatively low, while for other attributes, there is no correlation.

These results indicate that the association of color with tactile perception may change when colors are applied to textures, and this relationship is attribute- and texture-dependent. Figures 5 and 6 illustrate these findings.

In Figure 5, two sets of plain and textured samples are ordered based on the perception of their roughness. We can see that the order of colors has changed significantly. For example, the peach-colored vinyl sample (2.5R V7 C16; L*=71.96; a*=65.32; b*=28.33) was rated as the smoothest texture, while plain peach color was scored rougher than the other four colors.

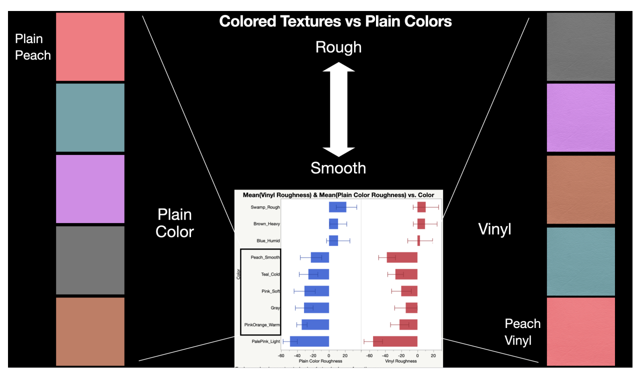

Figure 5: *Roughness perception of textures vs. plain colors. The order of colors (on the left) has changed when applied to the vinyl texture (on the right).*

Figure 6, in comparison, shows a highly similar arrangement along the perceived heaviness scale for the carpet texture stimuli and the patches of the same colors. These observations mean that we cannot simply define the effects of colors on visual perception of tactile properties of textures based on the association of the plain color patches with tactile attributes and have to consider specific visual properties of textures and their influence on perceived attributes.

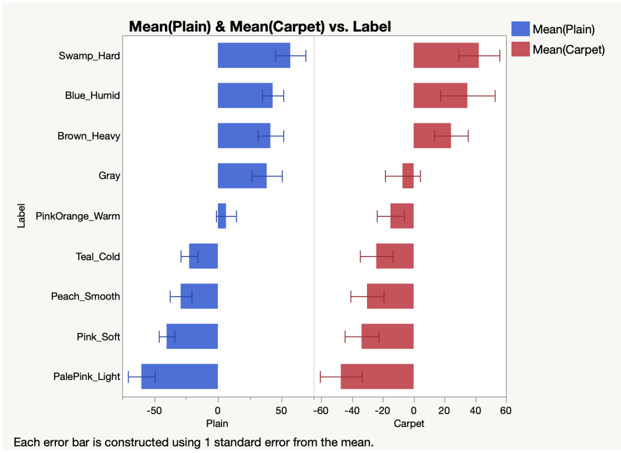

Figure 6: Heaviness perception of textures vs. plain colors. The order of colors (on the left) remained almost the same when applied to the carpet texture (on the right).

Conclusions

The results of this study demonstrated that color significantly affects the perception of haptic and aesthetic properties of visual textures. The size of the color effect varied for different attributes. Perceived heaviness, warmness, and naturalness of texture samples exhibited the strongest color influence among the attributes and, on average, showed similar patterns as the plain colors, while dryness and pleasantness did not reveal any systematic color-texture associations.

These findings imply the texture- and attribute dependencies of color effects on the visual perception of surface material properties and call for further investigation of these factors in greater detail. Future experiments should also consider multisensory assessment of color textures that include both vision and touch to reveal potential interactions between these modalities and evaluate the role of color. Virtual and extended reality environments, together with the systematic control of material properties using 3D rendered models and their 3D printed counterparts, can provide an effective experimental platform for these studies.

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