Colorful Tactile Stimuli. Association Between Colors and Tactile-Display Stimuli on Russell's Psychological Plane

Hikaru Hasegawa, Ken Itoh, Shogo Okamoto, Hatem Elfekey and Yoji Yamada

Abstract Supplementing the presentation of colors with tactile displays has yet to be developed. This study used Russell's affective plane to investigate the association between the rainbow colors and vibrotactile and variable-friction stimuli presented as tactile displays. A user study indicated that high-frequency and rhythmical tactile stimuli that were perceived as arousing were suitable for presenting the warm colors such as red, orange, and yellow. In contrast, low-frequency and slow tactile stimuli that were perceived as less arousing were suitable for the cold colors. Furthermore, unpleasant tactile stimuli that involved fine but strong frictional texture could be linked with purple and with unpleasant psychological images. Our findings indicate that tactile displays can be used to assist the user's perception of hue.

Keywords Hue · Vibrotactile · Friction · Electrostatic

1 Introduction

One of the roles of tactile displays is to compensate or complement visual information; however, the presentation of colors is challenging in this respect. The relationships between temperature stimuli and colors are well known [1–3]. Furthermore, Ludwig and Simner reported psychological relationships between the lightness, chroma, and surface roughness of materials [4]. However, the association between hue and vibrotactile and frictional stimuli has yet to be clarified. Our ultimate goal is to establish a stimulus set for expressing each of the rainbow colors. For this purpose, we associated the tactile-display stimuli with color hues. As described in Sect. 2, we first attempted find associations between color wave-length and the fineness of vibrotactile and frictional stimuli. However, we were unsuccessful because of the discrepancy between psychological images for colors and those for tactile stimuli. We then mapped hue and tactile stimuli via psychological images.

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2 Design Principles for Color-Tactile Association

2.1 Associations Based on Physical Color Elements

A color is typically decomposed into hue, luminance, and chroma. We considered association of each of these three types of color element with independent tactile stimuli. This idea is supported by a findings that texture roughness is correlated with the chroma of a color [4], and a vibrotactile texture display can present textures with various levels of roughness [5]. Furthermore, because hue depends on the frequency of light, intuitive color-tactile associations using vibrotactile stimuli with varying frequencies appear plausible. For example, low-frequency vibrotactile stimuli may correspond to colors such as red and yellow, and high-frequency stimuli may correspond to colors such as blue and purple. We tested such color-tactile associations based on frequency by using a vibrotactile display. Unfortunately, we failed to find frequency-based associations. This was because the impressions provided by colors and vibrotactile stimuli did not match. For example, our impression of warm colors, such as red, orange, and yellow, is energetic. In contrast, low-frequency vibrotactile stimuli that were potentially linked with the warm colors evoked impressions such as calmness and stillness. Hence, the psychological images associated with colors and vibrotactile stimuli are inconsistent, and hue-tactile associations based on frequency may be inconsistent with an intuitive user-experience.

2.2 Associations Based on Affective Responses

Colors can be associated with emotions [6]. Furthermore, vibrotactile stimuli can evoke affective responses [7]. These findings led us to use psychological images to connect tactile stimuli and colors. We adopted Russell's psychological plane [8], which is a two-dimensional plane composed of arousal and pleasantness axes. We designed nine tactile stimuli that mapped on Russell's psychological plane, using the vibrotactile and frictional stimuli to present stimuli that varied along arousal and pleasantness axes, respectively (Fig. 1).

Based on prior reports [7], we used attenuating sinusoidal vibrotactile stimuli, and generated different stimuli by changing the frequency of the sinusoidal wave and the tempo of additional signal periodicities, as shown in Fig. 1. High frequency and rhythmical vibrotactile stimuli were arousing, and low frequency and slow vibrotactile stimuli were sleepy. We used the electrostatic friction display to present stimuli that varied along the pleasant-unpleasant axis. We switched friction on and off with switching frequencies of 30–100 Hz, with larger magnitudes for the faster-switching frequencies. Strong and high-frequency friction stimuli were intended to evoke unpleasant user experiences, whereas weak and low-frequency stimuli were intended to be relatively pleasant.

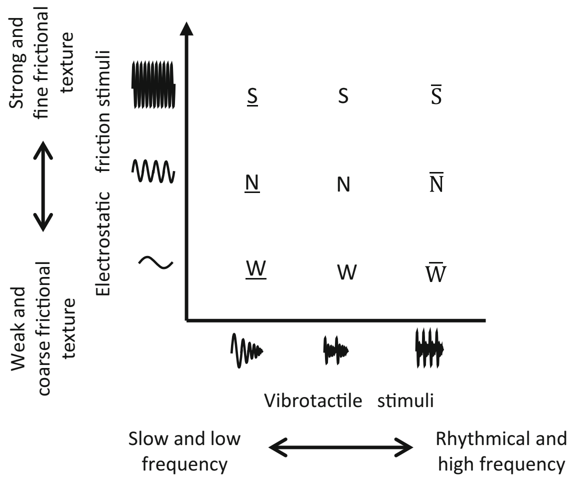

Fig. 1 Nine types of tactile stimuli using vibrotactile and electrostatic friction components. *S*, *N*, and *W* indicate the level of frictional stimuli. *Underline* and *overline* indicate the level of vibrotactile stimuli

3 Experimental System: Tactile Display for Vibrotactile and Electrostatic Frictional Stimuli

We used a tactile display that could present vibrotactile and variable-friction stimuli. The same equipment has been used in another study by the authors [9]. The whole system was computer-controlled at 1 kHz. As shown in Fig. 2, the vibrotactile stimuli were produced by four voice coil actuators (X-1741, Neomax Engineering Co. Ltd., Japan), each of which was located at each corner of the top panel. The four actuators were synchronously driven by a current amplifier (ADS 50/5, Maxon motor, Switzerland) and delivered mechanical vibratory stimuli to the finger pad on the top panel. The frictional stimuli were produced via the electrostatic force induced by the voltage between an aluminum pad and an ITO panel. An insulator (Kimotect PA8X, KIMOTO Co. Ltd., Japan) was located between the ITO panel and aluminum pad. The induced voltage was operated by a high-fidelity voltage amplifier (HJOPS-1B20, Matsusada Precision Inc., Japan).

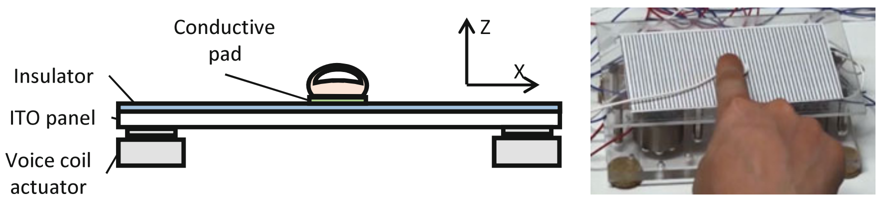

Fig. 2 Tactile texture display for the presentation of vibrotactile and variable-friction stimuli. *Left* Schematic side-view. *Right* Photo of apparatus

4 Experiment

We performed two experiments to investigate the association between colors and psychological images and between the tactile stimuli noted above and psychological images. Three student volunteers who were unaware of the objectives of the study participated in the two experiments in a counterbalanced manner.

In experiment 1, the participant experienced each of the nine types of tactile stimuli and mapped each stimulus on Russell's psychological plane which was drawn on a sheet of paper. The participant moved their finger on the panel and experienced the tactile stimulus as long as they wanted, but typically each trial lasted several seconds. From this experiment, we assessed whether the designed tactile stimuli were clearly located within Russell's psychological plane. The nine types of stimuli were presented in randomized order.

In experiment 2, the participants placed each of the rainbow colors, namely red, orange, yellow, green, blue, indigo, and purple, on Russell's psychological plane. Each color was tested only once for each participant. We did not show printed colors to the participant; he/she imagined each color.

5 Results

Figure 3 shows the results of experiment 1. The tactile stimuli generally differed in their psychological, affective components. Specifically, stimulus $\overline{\mathrm{S}}$ was perceived to be arousing, and stimulus $\underline{\mathrm{W}}$ was perceived to be less arousing for every participant. Meanwhile, the responses toward S, $\underline{\mathrm{S}}$, $\underline{\mathrm{N}}$, and $\overline{W}$ were inconsistent among the participants.

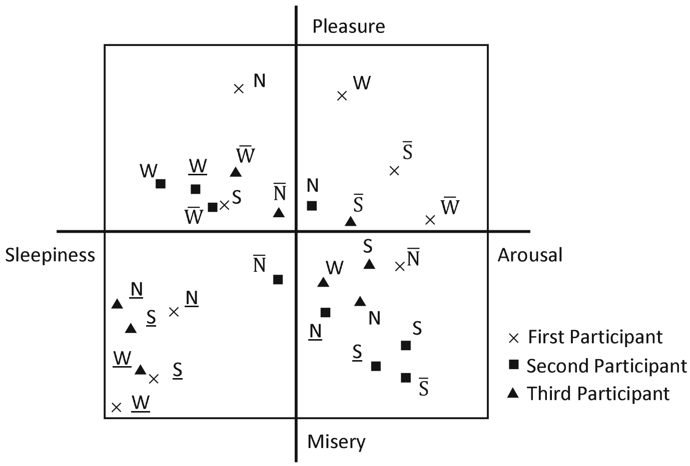

Fig. 3 Tactile stimuli placed on Russell's psychological plane

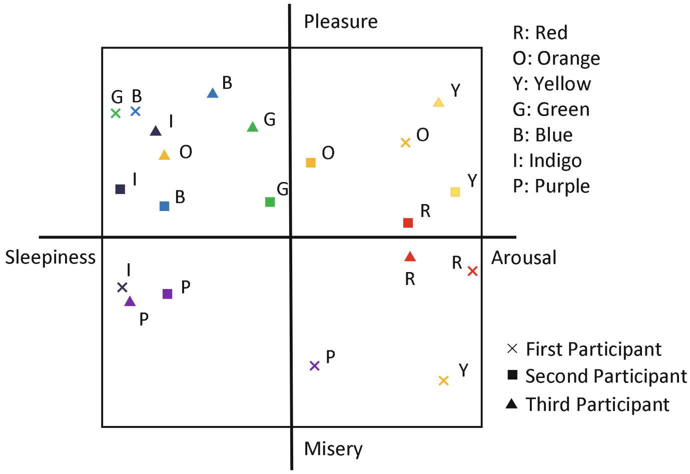

Fig. 4 Colors placed on Russell's psychological plane

Figure 4 shows the results of experiment 2. Note that locations of red, yellow, blue, and indigo only differed slightly among individuals along the arousal-sleepiness axis. Similarly, red, orange, green, and blue only differed slightly among individuals along the pleasure-misery axis. Moreover, most of the colors were assigned to the positive side of the pleasure-misery axis except for purple, which seems to be an unpleasant color. We also note that the warm colors were considered arousing, and the cold colors were placed in less arousing areas of the space.

6 Discussion and Conclusions

According to experiment 2, individual differences in the psychological associations of colors are small. This indicates that it is possible to present a hue supported by tactile sensory input if we control the arousal and pleasantness of the tactile stimuli. In particular, the warm colors are likely to be consistent with arousing stimuli, and the cold colors are likely to be presented by less arousing stimuli. Among the tactile stimuli tested above, $\overline{S}$ and $\underline{W}$ may be effective for pairing with the warm and cold colors, respectively.

We also note that changing the pleasantness of stimuli is not appropriate for presenting them in conjunction with colors. This is because all rainbow colors except for purple are associated with pleasant or neutral perceptions. Only purple has the possibility of being presented with unpleasant stimuli, such as $\underline{S}$ or $\underline{N}$ in our study.

To summarize, before the current study, no attempts had been made to find associations between the hue of colors and vibrotactile or variable-friction stimuli. We found that a frequency modulation approach, in which high-frequency tactile stimuli were matched with colors with short wave lengths, was not intuitive for users. Instead, we considered affective responses toward colors and tactile stimuli. Consequently, we found that warm colors can be linked with rhythmical and high-frequency tactile stimuli that evoke arousing responses. Furthermore, cold colors can be linked with slow and low-frequency stimuli that evoke less arousing responses. Since most of the rainbow colors mapped onto positive or neutral regions along the pleasure-misery axis, pleasantness may not be effectively used to classify the colors. Nonetheless, purple can be associated with unpleasant stimuli, namely strong and fine frictional stimuli such as S and N. Because the number of participants was small, we cannot conclusively propose associations between color and tactile stimuli; however, this study highlighted that such associations may exist.

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