International Journal of Innovative Computing, Information and Control
Volume **11**, Number **1**, February **2015**

ICIC International ©2015 ISSN 1349-4198
pp. 77–86

A THERMAL TACTILE DISPLAY FOR PROVIDING THE BLIND WITH COLOR PERCEPTION

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Received March 2014; revised July 2014

Abstract. *This paper proposes a thermal tactile display to provide color perception for the blind people. The color space transformation from* $\{R, G, B\}$ *to* $\{H, S, I\}$ *is studied, and the mapping between color and temperature is established on the basis of hue values. The display mainly consists of a serial communication and program download circuit, an MCU control circuit, and a Peltier driving circuit and its driving signal selection circuit, as well as a temperature measuring circuit. And the Peltier module is especially designed to convey different thermal sensation to the human finger. Two experiments are performed to evaluate the performance of the display: color identification and discrimination. The experiment results indicate that there is no significant difference in simulated color identification, and color information of the captured images can be reliably discriminated by using this proposed thermal tactile display.*
Keywords: Tactile displays, Color space, Hue values, Thermal stimulation

1. Introduction.

According to estimates from the World Health Organization, the number of the visually impaired worldwide is around 285 million, of which 39 million are blind and 246 million have low vision. However, about 20% of all visual impairment cannot be avoided or cured. Therefore, care should be taken to design effective user interfaces for this important population. For instance, visually impaired and blind computer users have significant difficulties in accessing computer-based data. Tactile displays can offer an alternative channel to present information if other senses are overloaded or impaired. For some visually impaired users, the tactile modality can become the primary or only input for the information reception. It is the visually impaired who is the largest and earliest target population for tactile displays.

Tactile information is personal and quiet, so it will not disturb anyone else. The tactile sensory system can receive the external information at any time, as it does not require the equivalent of eye movements. It is also easy to integrate tactile displays with controls, like joysticks or mice, allowing for a close relationship between perception and action [1]. To explore a larger tactile image with a device limited to the size of one or two fingertips, some researchers have succeeded in mounting a tactile display on a computer input device. Souza and Pawluk investigated the use of a haptic matrix-like display that can produce multiple amplitude levels and multiple frequencies, presenting contour information to the individuals who are blind or visually impaired [2]. Kim et al. proposed a racing game prototype with haptic and graphic feedback, and the haptic mouse system conveyed vibrotactile and thermal sensation to the players according to the users' interaction with graphic environment [3]. Kushiyama et al. designed a video game interaction system, and their game controller could offer temperature sensation to users dynamically according to game situations [4]. Rastogi and Pawluk proposed an "intuitive" zooming algorithm to provide visual graphics for the visually impaired, and the algorithm was tested using a small, "mouse-like" display with tactile feedback [5]. In case of thermal displays, there are only a few studies on using temperature to associate with color. Shinoda et al. proposed a vision-based thermal sensor using thermo-sensitive paint and a CCD camera for telexistence, and the thermo-sensitive paint was employed to measure thermal information on the basis of its color, which changes according to its temperature [6]. Hribar and Pawluk focused on the portrayal of painting through refreshable haptic displays from their digital representations, and their haptic display included a thermal display on which the warm-cold spectrum of colors was mapped [7].

In this paper, a thermal tactile display is designed to provide color perception based on hue values of the captured color image. Both the color space transformation and the mapping relationship between color and temperature are explored to clarify the design principle. Two psychophysical experiments are implemented to evaluate the performance of the display in providing color perception. Experimental results indicate that the proposed tactile display plays a good role in discriminating color information of the captured images.

2. Theoretical Background.

2.1. Color space transformation. Generally, a specific recombination of red (R), green (G) and blue (B) can create any color. By using the common color cameras, what is provided directly at the camera interface is often the analog RGB-signal. When the incoming analog signals are digitized by 8 bit A/D-converters, the R, G and B values will vary in the range between 0 and 255. After obtaining the digital information of such color images, we are able to construct a color vector Q(R, G, B) in the psychophysical color space. In order to convert color to temperature, we choose to utilize the hue of the captured image. Previous research [8] has suggested that, the hue change could correspond to the thermal change. Therefore, we perform a color space transformation from $\{R, G, B\}$ to the psychological $\{H, S, I\}$. This conversion was implemented by the following formulas [9]:

$$H = \begin{cases} \xi & \text{if } G \geq B \\ \pi + \xi & \text{elsewhere} \end{cases} \tag{1}$$

$$S = 1 - \frac{3\min(R, G, B)}{R + G + B} \tag{2}$$

$$I = \frac{R + G + B}{3} \tag{3}$$

where ξ is expressed as

$$\xi = \frac{\pi}{2} - \arctan\frac{2R - G - B}{\sqrt{3}(G - B)} \tag{4}$$

2.2. Mapping between hue and temperature. From the color space transformation, H can be interpreted as an angle in the color circle, with each color having a relevant angle range. Different from visual and auditory channels, tactile perception has limited spatial and temporal resolution, so that the blind cannot identify every color in the form of temperature. In general environmental conditions, the human skin rests in a narrow 'neutral' zone, ranging from ~28°C up to ~40°C [10]. However, heat/cold-pain will arise at specific temperatures for individual differences, which have been identified at around 11-15°C for cold pain and 45°C for warm pain [11,12]. In everyday usage scenarios, thermal feedback that is painful to receive is unlikely to be accepted by users. Therefore, thermal feedback needs to avoid stimuli that would cause pain, and so it is important to use temperatures away from the pain thresholds, within the range of approximately 20-40°C [13].

The hue value from 0° to 360° can be separated into seven colors, which are red, orange, yellow, green, cyan, blue, and purple respectively. Due to the lower resolution of tactile channel, we compress these seven colors to four in color similarity, with Red, Yellow, Green and Blue (left). The compression can be demonstrated from the following equation. Furthermore, taking warm and cold colors into consideration, we correlate four different temperature levels with these colors from high to low. The size of this neutral zone is relatively constant across individuals at around 6-8°C, and outside of this range a constant sensation of warmth (above) or cold (below) will be perceived [14,15]. Therefore, to make thermal stimulation both salient and comfortable, we choose the temperature range between 18°C and 42°C to represent these colors, with the neighboring interval 8°C. Figure 1 shows the mapping between the hue of color images and the temperature levels. In order to eliminate the individual differences, the initial skin temperature is adapted to 28°C, approximately the ambient temperature.

$$H = \begin{cases} purple\ [272^\circ, 330^\circ) \\ blue\ [180^\circ, 272^\circ) \\ cyan\ [155^\circ, 180^\circ) \\ green\ [70^\circ, 155^\circ) \\ yellow\ [45^\circ, 70^\circ) \\ orange\ [22^\circ, 45^\circ) \\ red\ [-30^\circ, 22^\circ) \end{cases} \Rightarrow H' = \begin{cases} Blue\ [180^\circ, 330^\circ) \\ Green\ [70^\circ, 180^\circ) \\ Yellow\ [22^\circ, 70^\circ) \\ Red\ [-30^\circ, 22^\circ) \end{cases} \tag{5}$$

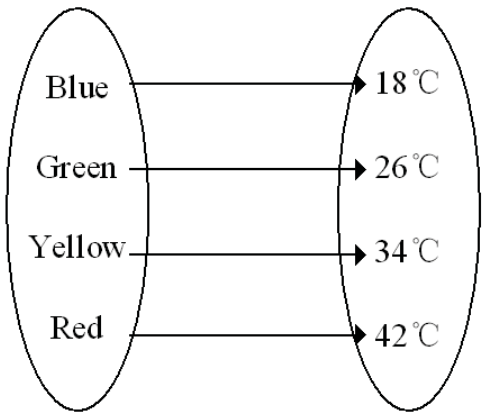

FIGURE 1. Mapping between hue values and temperature levels

In order to provide the relevant stimulation level to each color, the thermal tactile display will serve as a constant temperature source, maintaining the interface temperature. Based on the typical semi-infinite body model, the temperature profiles within the skin (for $x > 0$) can be solved as:

$$T_S(x,t) = T_P + (T_{S,0} - T_P) erf\left(\frac{x}{2\sqrt{\alpha_S t}}\right) \tag{6}$$

where T_P is the constant interface temperature, $T_{S,0}$ is the initial skin temperature, and α_S is the thermal diffusivity of the skin. The heat flux conducted out of the skin during contact can be derived from Equation (7):

$$q_S = \frac{\lambda_S (T_P - T_{S,0})}{\sqrt{\pi \alpha_S t}} \tag{7}$$

where q_S is the heat flux conducted out of the skin during contact, λ_S is the thermal conductivity of the skin, and t is time. With the same initial skin temperature and different interface temperatures, there will be different thermal changes generated within the skin. The resulting warm or cold sensation in the central nervous system can therefore be leveraged to identify and discriminate various colors.

3. System Construction Design.

3.1. Thermal tactile display. The hardware circuit of the thermal tactile display can be divided into three levels as shown in Figure 2, which are monitoring and operation level, temperature measurement level, and thermostatic control level. The display includes a serial communication and program download circuit, an MCU control circuit, and a Peltier driving circuit and its driving signal selection circuit, as well as a temperature measuring circuit. Color information of the hue image was captured through the position of the mouse pointer when clicking its left button. The serial communication circuit would transfer this information from the host PC to the microcontroller. Then the core controller would conduct different thermal feedback based on the results processed by the PC. In this course, the Peltier driving circuit and its driving signal selection circuit were also indispensable. Furthermore, the temperature measuring circuit was devised to realize the measurement in real time.

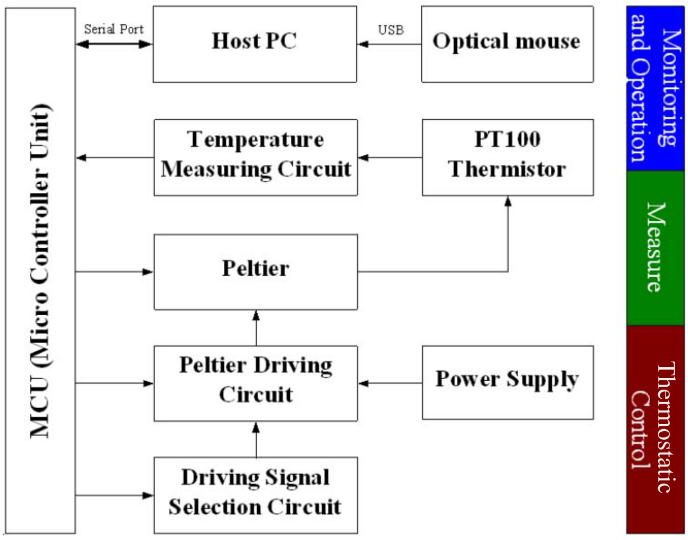

FIGURE 2. Design block diagram of thermal tactile display

The selected microcontroller had eight 10-bit AD converters, one of which was used to measure the temperature on the Peltier surface through the temperature measuring circuit. Two I/O ports selected the Peltier driving signal, and one PWM output port made a decision on the on-off of the driving circuit. As a result, the temperature control for the Peltier module was implemented. With respect to measuring temperature, thermistors are small, highly sensitive, low-price and robust, as well as they can contact with the Peltier directly. Therefore, the PT100 thermistor was voted to be the temperature measuring device, which was attached to the Peltier surface. The Peltier driving circuit and its driving signal selection circuit realized the switch between refrigeration and heating modes. As the tactile display is specially designed for the blind, the translational speed of the mouse should not be too fast.

In this study, it is necessary to design the host PC software and the microcontroller software. The software designed for the host PC was built in the Visual C++ environment, and its major functions were capturing, displaying and processing the original image, as well as communicating with the slave computer. While the software designed for the microcontroller enabled the tactile display to receive the communication information. The extent of thermal change was directly affected by this information, so that different stimulation levels could be applied to the human finger.

3.2. **Closed-loop control system.** Besides the thermal tactile display, the entire system includes an image acquisition and processing unit. The USB camera was used to capture the object image. While the host PC could display the original image at its interface, and translate hue values into different thermal stimulation levels. With the aid of the optical mouse, the selected hue information was transferred to the microcontroller to modulate the tactile display, producing the relevant stimulation intensity. Furthermore, the temperature measuring unit could measure the temperature of the Peltier surface and deliver it to the microcontroller in real time. Eventually, a stable closed-loop control system was established to strictly control the thermal stimulation perceived by the human finger. Therefore, the blind could perceive color information of the target environment. Figure 3 presents a prototype of the thermal tactile display system.

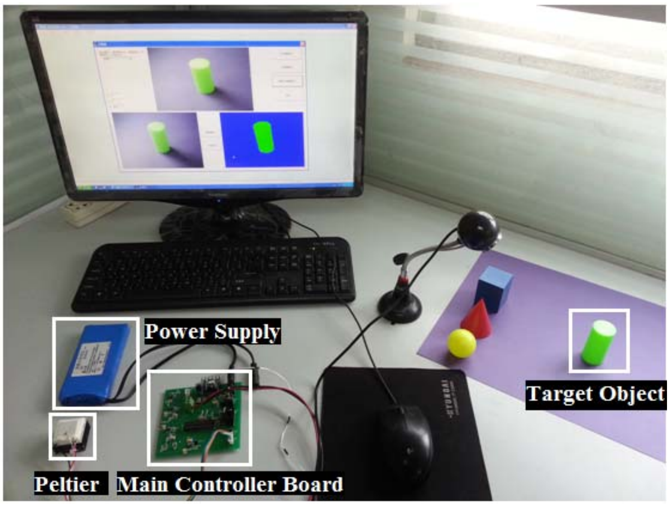

Figure 3. Prototype of thermal tactile display system

4. **Performance Evaluation.** With the purpose of presenting colors for the blind in the form of temperature, two psychophysical experiments was performed to evaluate the performance of the thermal tactile display, investigating subjects' ability to identify and discriminate between different colors when simulated by the proposed display.

4.1. **First experiment: color identification.**

4.1.1. *Experiment method.*

Subjects. There were ten normal healthy adults (eight men and two women) participating in this experiment. They were all students of Southeast University and were aged between 22 and 32 years (mean = 25), all reporting that they were right-handed.

Procedure. In this experiment, four monochromatic colors (i.e., blue, green, yellow and red) were selected as the test colors. Subjects were required to wash their hands with sanitizer before the experiment. Then they were trained to recognize these different colors. The mapping between color and temperature was explained, and these subjects were instructed to place their left hand on the hot-water bag [16]. The experiment began with adaptation of the subject's finger to 28°C, by resting on the hot-water bag for 1 minute. Subjects first completed a training session lasting 5-10 minutes where they could feel each color several times. During this time, four colors were shown on the PC screen corresponding to each of the four thermal stimulation levels. When pressing the left mouse button, the revelant thermal feedback would be produced in several seconds, and subjects needed to associate the sensation with the color. In each experiment, the Peltier kept the relevant temperature constant until the subject gave the judgment.

All four colors were repeated six times in a random order, giving each subject 24 trials. To imitate the blind, subjects were blindfolded to eliminate any visual cues. While the color was being presented, subjects needed to name the simulated color by their perceived thermal intensity. Once reporting the name of the color they thought, they moved their left hand back to the hot-water bag for 30 s, after which next random color was presented. Subjects' judgments were submitted into a Visual C++ program. No remarks were made on their performance during the experiment course.

4.1.2. *Result and discussion.* Subjects' responses when identifying four monochromatic colors are described in Figure 4. It can be seen that simulated colors corresponding to low temperature, such as blue and green, were identified more accurate than those corresponding to high temperature, such as yellow and red. That is, cold colors were a little easier to identify than warm colors, and the warmest color had the lowest discrimination accuracy. This is in line with the fact that cold receptors are much more than warm receptors in the human skin [14]. Furthermore, the color that subjects possibly confused with the target color was only its neighbor color(s).

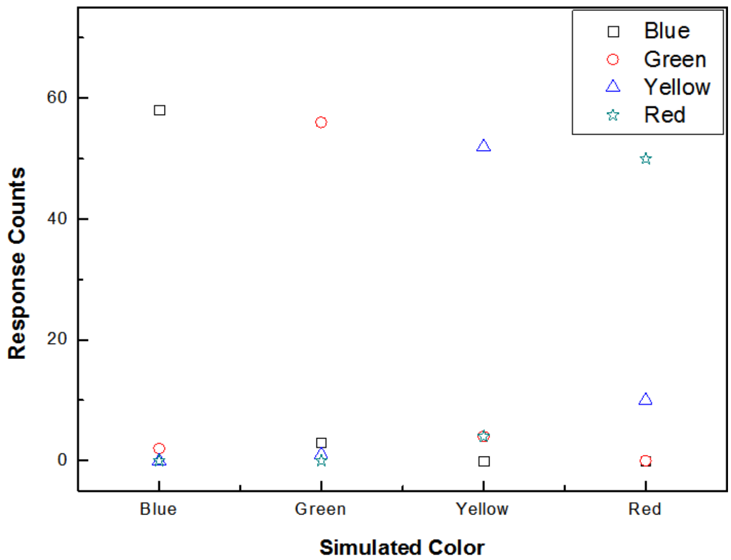

FIGURE 4. Subjects' responses in color identification experiment

In order to evaluate whether there was any response bias, the response counts for each color were calculated for each subject. A repeated-measures ANOVA was used to analyze the accuracy of the resulting data by using SPSS, with the simulated color as the within-subject factor and response counts as the dependent variable. The results indicated that there was no response bias for these four colors ($F(3,27) = 1.67$, $p = 0.196$). Figure 5 shows the proportions of correct responses for the color identification. Subjects' overall performance reached 90% correct for four colors (range: 83-97%). Because of

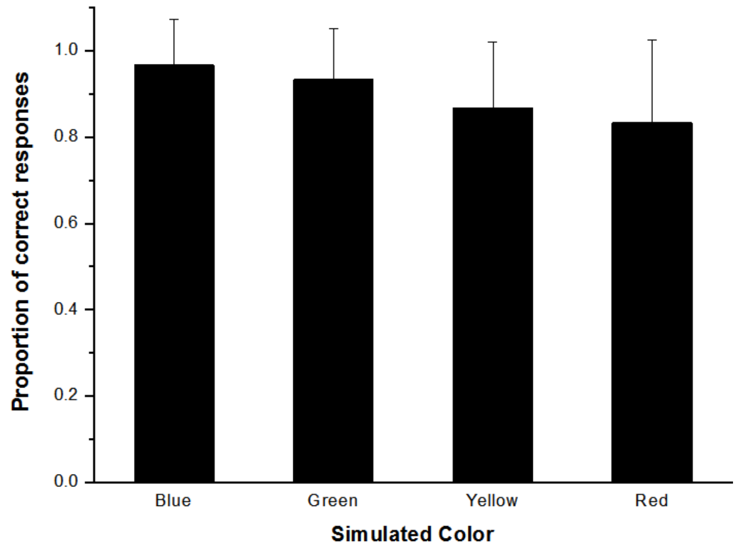

FIGURE 5. Group mean proportions of correct responses in color identification

four alternative colors, the chance level was 0.25 in each trial. One sample z-test for proportions indicated that at a 0.39 level of correct responses, subjects were able to identify the presented color reliably ($p < 0.01$). Note that there were no colors whose proportion of correct responses was below 0.39.

In this experiment, thermal cues were conveyed to subjects through their left index finger placed on the Peltier surface, and it is presumable that the local thermal transients during contact could be used to identify the relevant colors. Experiment results indicate that, subjects were able to reliably identify all colors simulated with the thermal tactile display, with their performance much higher than the threshold level. This is consistent with one earlier research on stimulus temperature discrimination, which showed that individuals can identify varying degrees of warmth [17]. Furthermore, an analysis of subjects' responses indicated that there was no response bias among the simulated colors. In other words, there was no tendency to take one color for another.

4.2. **Second experiment: color discrimination.** The first experiment results indicated that subjects could identify four different colors reliably by the perceived thermal stimulation intensity. The second experiment was therefore to investigate the ability of subjects to discriminate color information of the captured images with the thermal tactile display.

4.2.1. *Experimental method.*

Subjects. There were ten normal healthy adults (six men and four women) participating in this experiment. They were all students of Southeast University, aged between 22 and 29 years (mean = 24.7). None of the subjects had participated in the first experiment. They all reported that they were right-handed.

Procedure. In this experiment, all images were captured through a common USB camera, with one target in the background. The four selected objects were Cylinder, Sphere, Cube, and Cone, all having different color appearance, as shown in Figure 3. After being processed in color space, there were two colors left in each hue image, the background and the object colors. Each of the four colors was matched with each of other three colors, which gave a total of 12 different pairs. These 12 pairs were presented to subjects in a random order with four repetitions, giving a total of 48 trials. There was a 1-minute break between each block of 12 trials, during which subjects placed their left hand on the hot-water bag to recover the skin temperature.

Subjects needed to wash their hands with sanitizer before the experiment. Then they were trained to recognize different color pairs. During the training, twelve hue images were displayed on the PC screen corresponding to each of the 12 pairs. When moving the mouse slowly along one direction, subjects would perceive two different stimulation levels at their left index finger. When perceiving a thermal change, subjects could stop to associate the thermal feedback with the color. To figure out the color pair, subjects were encouraged to slide the mouse along another direction.

Subjects were blindfolded to imitate the blind people. While the hue image was being presented, subjects needed to name the simulated colors by their perceived thermal intensity. Once reporting the names of the background and the object colors they thought, they returned their left hand to the hot-water bag for 30 s, after which next random image was presented. Subjects' judgments were submitted into a Visual C++ program. No remarks were made on their performance during the experiment course.

4.2.2. *Results and discussion.* In this experiment, the responses for the trials involving different colors were analyzed in terms of the number of correct responses. The chance level in this experiment was 8%, and a threshold level of 20% correct was therefore chosen indicating that subjects could reliably discriminate the color pair. Figure 6 shows the proportion of correct responses for various color combinations. In this figure, the color presentation mode was divided into $B/O > 1$ and $B/O < 1$, where $B/O > 1$ denotes those trials in which the corresponding temperature of the background color was higher than that of the object color, and $B/O < 1$ refers to the opposite. It is clear that there were no color combinations whose proportions were below 20%. With presentation mode and color combination as within-subject factors and the proportion of correct responses as the dependent, a repeated-measures ANOVA indicated that there were significant differences between the two presentation modes ($F(1,9) = 7.55$, $p = 0.023$), and among the color combinations ($F(5,45) = 5.89$, $p < 0.001$). However, the interaction between presentation mode and color combination was not significant ($F(5,45) = 1.67$, $p = 0.160$). A further comparison found that in the color presentation mode of $B/O > 1$, subjects' performance in discriminating Blue and Green ($F(1,9) = 18.09$, $p = 0.002$) and Yellow and Red ($F(1,9) = 9.29$, $p = 0.014$) was significantly above the mean, and that their performance with Blue and Red ($F(1,9) = 11.13$, $p = 0.009$) and Green and Red ($F(1,9) = 8.98$, $p = 0.015$) was significantly below the mean; While in the color presentation mode of $B/O < 1$, subjects' performance in discriminating Blue and Green ($F(1,9) = 8.16$, $p = 0.019$) and Yellow and Red ($F(1,9) = 54.31$, $p < 0.001$) was also significantly above the mean [18].

The performance of the thermal tactile display in simulating color information of the captured images was evaluated in this experiment. For trials involving different colors, it was predicted that the change in skin temperature elicited by the thermal stimulus, could be used to differentiate between different colors. Trials were divided into two presentation modes based on the corresponding temperatures of the background and the object colors, and six color combinations based on the four different colors. However, there were significant differences between the presentation modes and among the color combinations, while the interaction between presentation mode and color combination was not significant. For all the captured images, it was noted that the background color was different from the object color. The circumstance that the background and the object had the same color after being processed was excluded, as it had been explored in the first experiment. Based on different thermal stimulation levels, subjects' performance of discriminating the background and the object colors was well above the threshold level. This indicates that the

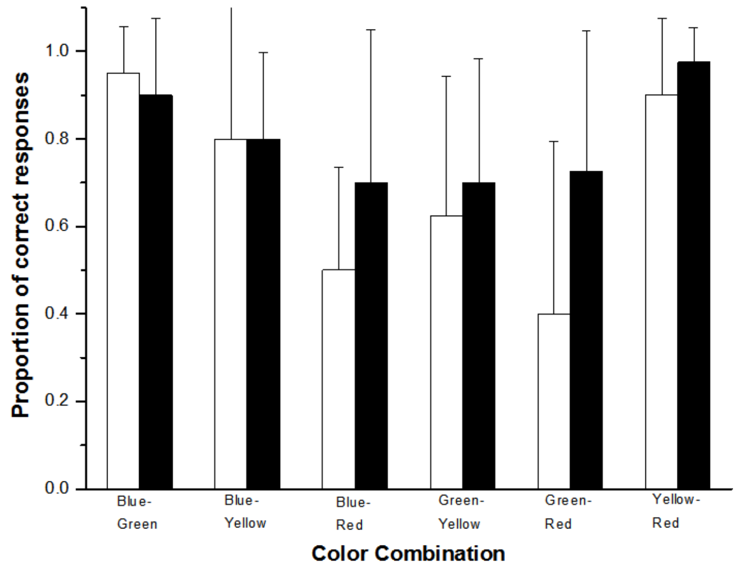

FIGURE 6. Group mean proportions of correct responses in color discrimination. Trials in which B/O > 1 are shown in white and those B/O < 1 are black.

thermal cues provided by the display were adequate to discriminate color information of the captured images.

5. **Conclusions.** In this paper, we study the color space transformation from the psychophysical $\{R, G, B\}$ to the psychological $\{H, S, I\}$. Based on hue values of the captured image, the mapping between color and temperature is established. Due to the limited spatial and temporal resolution of tactile channel, four different simulation levels are provided by the thermal tactile display for the blind. In order to evaluate the performance of the display, two psychophysical experiments are carried on. The first experiment examines the ability of subjects to identify various colors simulated with the display; the second experiment investigates the performance of subjects to discriminate color information of the captured images based on thermal cues. The results indicate that subjects are able to reliably differentiate the simulated colors from the captured images. Therefore, it is feasible to provide the blind people with color perception by using this proposed tactile display.

However, only four colors could not satisfy the needs of blind people to cognize the colorful world. In the future work, expanding more colors in terms of thermal feedback will be considered. As the extent of thermal change may not be a good stimulation parameter to present colors, the rate of thermal change will be an alternative. Although the finger is used for the thermal display because of its high sensitivity, other body locations may be more suitable, such as the thenar eminence or palm of the hand, especially when integrating the display into a computer mouse.

Acknowledgment. This research was supported by the Natural Support Program of China (2012BAI14B04), Natural Science Foundation of Jiangsu Province (BK2012560), and Research Fund for the Doctoral Program of Higher Education of China (20130092110 060).

REFERENCES

[1] H. A. H. C. Van Veen and J. B. F. van Erp, Tactile melodies in user interfaces, *Proc. of the Human Factors and Ergonomics Society Annual Meeting*, vol.47, pp.751-754, 2010.

[2] S. D. Souza and D. Pawluk, Comparison of methods presenting contour information to individuals who are blind or visually impaired, *Proc. of Assets' 10*, Orlando, FL, USA, pp.247-248, 2010.
[3] D. H. Kim and S. Y. Kim, Immersive game with vibrotactile and thermal feedback, *Proc. of the 5th International Conference on Computer Sciences and Convergence Information Technology*, Seoul, Korea, pp.903-906, 2010.
[4] T. Baba, K. Kushiyama and K. Doi, ThermoGame: Video game interaction system that offers dynamic temperature sensation to users, *Proc. of Siggraph 2010*, Los Angeles, CA, USA, 2010.
[5] R. Rastogi and D. Pawluk, Intuitive tactile zooming for graphics accessed by individuals who are blind and visually impaired, *IEEE Transactions on Neural Systems and Rehabilitaiton Engineering*, vol.21, no.4, pp.655-663, 2013.
[6] K. Sato, H. Shinoda and S. Tachi, Finger-shaped thermal sensor using thermo-sensitive paint and camera for telexistence, *Proc. of IEEE International Conference on Robotics and Automation*, Shanghai, China, pp.1120-1125, 2011.
[7] V. E. Hribar and D. Pawluk, A tactile-thermal display for haptic exploration of virtual paintings *Proc. of Assets' 11*, Dundee, Scotland, pp.221-222, 2011.
[8] M. Ozawa, U. Miller and L. Kimura, Flow and temperature measurement of natural convection in a hele-shaw cell using a thermo-sensitive liquid crystal, *Experiments in Fluids*, vol.12, pp.213-222, 1992.
[9] R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, Publishing House of Electronic Industry, Beijing, 2011.
[10] L. A. Jones and M. Berris, The psychophysics of temperature perception and thermal-interface design, *Proc. of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp.1-6, 2002.
[11] K. Johnson, I. D. Smith and C. L. Motte, Peripheral neural determinants of temperature discrimination in man: A correlative study of responses to cooling skin, *Journal of Neurophysiology*, vol.36, no.1, pp.24, 1973.
[12] J. C. Stevens, *Thermal Sensibility*, The Psychology of Touch, New Jersey, 1991.
[13] G. A. Wilson, *Using Pressure Input and Thermal Feedback to Broaden Haptic Interaction with Mobile Devices*, Ph.D. Thesis, School of Computing Science, University of Glasgow, 2013.
[14] L. A. Jones and M. Berris The psychophysics of temperature perception and thermal-interface design *Proc. of HAPTICS '02*, Orlando, FL, USA, 2002.
[15] D. Kenshalo and H. Scott, Temporal course of thermal adaptation, *Science*, vol.151, no.1, pp.2, 1966.
[16] C. Chen and S. Qiu, Influence of temperature profiles on thermal tactile sensation, *Advanced Robotics*, vol.28, no.1, pp.53-61, 2014.
[17] R. Wettach, C. Behrens and A. Danielsson, A thermal information display for mobile applications *Proc. of MobileHCI '07*, Singapore, 2007.
[18] H. N. Ho and L. A. Jones, Development and evaluation of a thermal display for material identification and discrimination, *ACM Transactions on Applied Presentation*, vol.4, no.2, pp.1-24, 2007.