Cross-modal Correspondence between Vibrations and Colors

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Abstract— **Participants matched a color to a vibrotactile stimulus of 1 s duration on the palm of the hand. Stimuli were combinations of one of six frequencies (10-200 Hz) and four amplitudes (10-40 dB SL). Color choices were converted to lightness, chroma, and hue angle values defined in the CIELAB color space. Results showed that the color chroma increases with the increase in vibratory amplitude, with no effect of vibration frequency. Lightness was not significantly modulated by the vibratory variables. Histograms of color hue showed three main peaks (violet, red and green) in participants' responses. The pattern was for low-frequency vibrations (10-35 Hz) to evoke the violet color hue at low amplitudes and the red color hue at high amplitudes, whereas high-frequency vibrations (60-200 Hz) evoked the green color hue with some trace of the red color hue at high amplitudes. The results are discussed for designing *colorful* experiences using vibrotactile feedback.**

I. Introduction

Do we feel colors? Visual perception is the key to creating realism and surrounding environments in virtual and mixed reality settings. While spatiotemporal features are rendered to create logical and coherent flow of information to immerse the users, colors are often used to enhance experience, not only consciouskly but also without invoking awareness [1]. Our perception of color is inherently a visual process that associates light wavelengths with rich and evocative sensations. We use colors to differentiate objects, structure them, and make aesthetic choices. Natural color-to-object correspondences exist, such as the blue of a gas flame or the red of a robin's breast. Artificially colored objects surround us and embellish our experiences, as shown in Figure 1. There are well-established color conventions, such as the use of red to indicate danger or affection.

While not as widely acknowledged, vibrotactile experience is also a part of the everyday sensory world. There are natural associations of objects to vibrations, such as the texture we feel when stroking fur. There are also fabricated vibratory signals like the cellphone alert. In this paper, we explore the existence of cross-modal correlation between colors viewed through the eyes and vibrations felt on the skin, as evidenced by common patterns of association across individuals.

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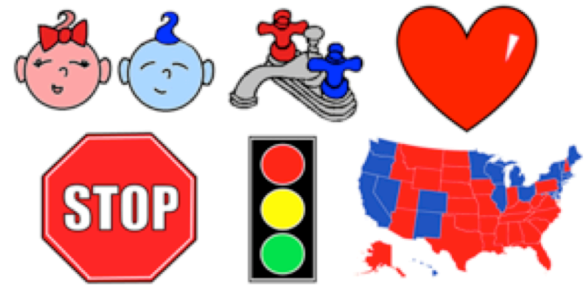

Fig. 1. Use of color in symbols.

There are no direct physiological connections between the sensory basis of colors, arising from the cone system in the retina, and vibrotactile sensations triggered by mechanoreceptors within the skin. This peripheral separation does not, however, preclude the formation of color-to-haptic associations at more central levels. Mechanisms for such associations have been demonstrated in the forms of crossmodal correspondence [2, 3] and synesthesia [4, 5]. Crossmodal correspondence is defined as a tendency to make associations between sensory features in two modalities, for example, pitch height with retinal height [6]. Cross-modal correspondences may occur at a cognitive level and even exist when stimli are merely imagined. Synesthesia, in contrast, is an automatic perceptual response linking two channels within or across sensory modalities, such as an association between grapheme form and color (its most common form) [7, 8].

Recent investigations have looked into whether, by such mechanisms, colors could represent haptic features including the compliance and texture of objects, force feedback, temperature, and electric stimulation [3, 4, 5]. In this paper, we present a study to explore the crossmodal correspondence between colors and vibrations across a broad vibrotactile range: 10-200 Hz and 10-40 dB SL (sensation level). Participants felt a vibration through their hand and paired it with a color by specifying lightness, saturation and hue. Our goal is to determine whether there are regularities between the physical features of colors and the composition of vibrations, in an effort to extend the use of vibrations in multisensory settings. Establishing such correlations would allow designers to select vibrations that are naturally and closely related to the colorful experiences in multisensory settings.

The organization of the paper is as follows: In the next section, we discuss color perception and previous work in crossmodal correspondence between color and haptics. This is followed by presentation and discussion of an experiment in which participants felt vibrations and matched them with a color's lightness, saturation and hue. Finally, the paper concludes with discussion and future work.

II. Background

A. Colors and Color Perception

Cones within the retina of the human eye are the sensory basis for color vision. The length, amplitude, and separation between light waves give rise to a color's perceived *hue*, *lightness* and *chroma*, respectively [9]. However, color perception is well known to be under-determined by elementary cone mechanisms [10]. The phenomenon of metamers, for example, shows that the same perceptual response can be elicited with different wavelengths as inputs. Perceptual responses such as discrimination and categorization are affected by learning and context. Recent work supports the longstanding hypothesis of "cultural relativism," namely, that linguistic color categories influence how colors are discriminated and remembered [11]. Context effects take different forms including the phenomena of color contrast (influence across opponent colors in neighboring regions) and color assimilation (adjacent colors bleeding, or sharing chromatic values). Contextual effects at the object level were demonstrated by a clever illusion designed by Adelson [12]: When a cylinder casts a shadow on a checkerboard, there is a tendency to perceive the gray square under the cylinder shadow as lighter, the result of attributing its color to the shadow. (The trick also relies on regularities in the board and local contrast.)

The discovery of such high-level influences on color perception have been the foundation for exploration of multi-modal correspondence between color and emotion, memory, smell, taste, sound, and most recently touch. If humans' perception of color is based on their experiences with the world around them in addition to visual input itself, there may arise associations between color perception and other senses, such as touch. This possibility is reviewed in the next section.

B. Color and Haptics Crossmodal Correspondence

Crossmodal correspondences between color perception and sound, taste, emotion, and object shape have been previously examined. Spence et al. determined that food color influences flavor identification [13]. In one study, when participants were asked to list a perceived flavor of a drink based on the drink's color, they tended to choose a particular color and flavor combination, such as orange flavor with an orange colored drink [14]. When the effects of pale and vivid red, blue, and yellow colors on students' emotion, concentration and heart rate were studied by AL-Ayash, et al., the color red was found to be associated with frustration/distraction and blue with calm concentration [15]. Spector and Maurer explored the crossmodal effect of color on shape perception by asking participants to associate various letters (differing shapes) with different colors, They found that participants had a tendency to associate I, O and letters with soft curves with a white color, and letters with sharp edges and harsh angles such as X and Z with black. This color association was not limited to achromatic colors, since the letter C corresponded to a yellow color [16].

Haptic feedback creates a means of experiencing varying textures and objects virtually, while still maintaining a realistic touch experience. Crossmodal correspondence between tactile sensation and color was investigated by Slobodenyuk, et al. [3]. Participants were asked to use colors to describe vibrotactile stimuli of varying frequencies and intensities simulating variations in roughness-smoothness, heaviness-lightness, elasticity-inelasticity, and adhesiveness-non-adhesiveness. Analysis of the hue, chroma, and brightness of the chosen colors showed a bias towards the red, violet and blue spectra of hue for the highest-intensity haptic stimuli, and toward yellow and green for the lowest-intensity, for which green colors were chosen the least. The least intense stimuli also had the lowest level of chroma and highest level of brightness, whereas the opposite was true for the most intense stimuli [3]. Furthermore, in a study by Elliot and Arts [17], participants were asked to pinch a small metal clasp open with their hands after seeing a paper depicting either a red, blue or gray color. Overall, the force and velocity of the pinches by those who were exposed to the color red were the highest, showing again that the perception of color red was closely linked with higher intensity. An additional study by Kahol, et al. [18] has shown that color perception through haptic feedback can allow individuals with visual impairment to recreate a color space, solely using tactile sensations.

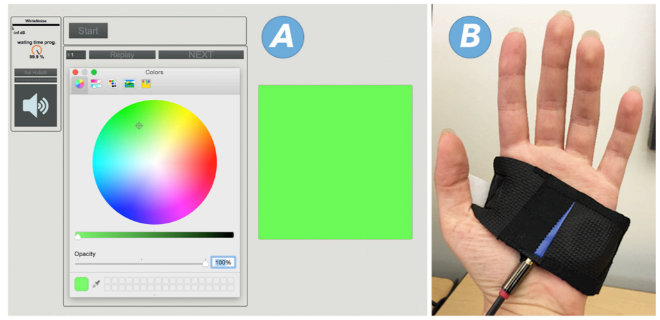

Fig. 2 A: Experimental Computer Display; B: Haptic Device

While previous studies have indicated that there is a crossmodal correlation between color and touch, this paper aims to better understand the color mapping through systematic vibrations of varying amplitude and frequency. The goal is to devise a color map of vibrotactile space, within the range of our display.

III. Method

A. Apparatus: Color Display and Haptic Stimulator

A small vibrotactile stimulator (or *tactor*, model: TEAX19C01-8, Tectonic Elements Ltd., UK) was placed inside the pocket of a custom hand strap. The strap was extended with a use of Velcro strips, so it could be donned on the participant's left hand (Figure 2a). The tactor stimulated the (glabrous) skin of the thenar eminence, while the participant's right hand was free to move the mouse. Sinusoidal waveforms were created in a computer and passed through the audio port of a typical PC. The audio signal was powered using a 1-Watt audio amplifier.

A 15.4" computer screen (MacBook Pro, OS Yosemite, resolution 2880 x 1800) displayed a user-interface that included click buttons for user's response and an HSV color wheel with a lightness slider as shown in Figure 2b). Having both the color wheel and lightness slider allowed participants to control two components of their color choice that could

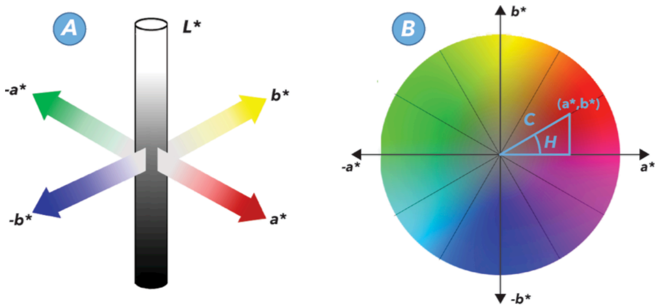

Fig. 3 A: Three-dimensional CIELAB color space where the L* axis represents the color's lightness; B: Two-dimensional CIELAB a*b* plane where C represents chroma and H represents hue.

later be used to define the chroma, hue and lightness of each color. The cursor position on the color wheel and lightness slider was varied in each trial of the experiment to prevent participant bias. A rectangular display directly to the right of the color wheel was used as a color preview space that displayed the participant's color choice. Participants could hit a "replay" button to replay a vibration that was previously felt and a "next" button to save their chosen color and proceed to the next vibration in the experiment.

B. *Participants*

Thirteen participants (6 males, average age = 26 years) took part in the study. All participants reported no sensory impairments. Participants signed a consent form approved by our internal IRB (Internal Review Board) and were compensated for their time.

C. *Experimental Procedure*

Each participant was seated in front of the computer screen at a distance of approximately 40 cm. Participants wore headphones with white noise that eliminated any resulting sound from vibrations that could be heard. Participants were exposed to a series of vibrations representing combinations of four amplitudes (10, 20, 30, 40 dB SL) and six frequencies (10, 20, 35, 60, 120, 200 Hz) and, for each stimulus, were asked to choose a color that best described the vibrating sensation that they were experiencing. Vibration duration was set at 1 second. Participants were specifically instructed not to associate the colors with objects, rather than thinking of only the colors themselves or associated objects. (For example, "Do not think of a red apple, think of the color red.")

Each participant completed 120 trials (4 amplitude × 6 frequency × 5 repetitions) presented in a random order, and received a rest period after every 30 trials. When the rest period came, a text box was presented to the participants and they could click OK when they received adequate rest time. Prior to full experimentation, a short training period was provided to users to familiarize them with the system. No data from the training module were recorded.

D. *Data Analysis*

Munsell recognized colors as comprising a 3-D space with dimensions of hue, value and saturation [9]. In 1976, the Commission Internationale de l'Eclairage (International Commission on Illumination), revealed the CIELAB color space which served as an additional way to define a color's hue, saturation using three alternate dimensions: L*, a* and b* [19]. L*, lightness, is a scale of how dark or light the color is, ranging from black to white. a* and b* represent the scales of the two-dimensional hue circle. The a* axis ranges from -a*, green, to a*, red. The b* axis ranges from -b*, blue, to b*, yellow [20]. Hue and chroma can be derived from a* and b* (Figure 3). The CIELAB space forms the basis for the present analysis.

The independent variables, frequency and amplitude, were recorded for each trial and the participants' color selections (dependent variable) were recorded using both CIELAB and RGB coordinates. Data were analyzed using the *lightness*, *chroma* and *hue* values corresponding to the CIELAB values chosen by participants. Equation (1) was used to calculate chroma and Equation (2) was used to calculate hue. Lightness was taken directly from the participants' chosen L* values (see [3, 9] and Figure 2).

$$Chroma = \sqrt{\boldsymbol{a}^{*2} + \boldsymbol{b}^{*2}} \quad (1)$$

$$Hue = \tan^{-1}({\boldsymbol{b}^*}/{\boldsymbol{a}^*}) \quad (2)$$

The average chroma and lightness values for each participant for the 24 combinations of frequency and amplitude were computed and submitted to separate repeated measures Analysis of Variance (ANOVA). Frequency and amplitude are within-subject factors; Greenhouse-Geisser (GG) degrees of freedom were used to test statistical significance.

For the hue analysis, the a* and b* coordinates of the CIELAB colors chosen by all participants across the 120 trials were presented in a scatter plot on the a*b* plane of the CIELAB color space. Histograms (15° bin size) of the hue values were overlaid on the a*b* plane and the mode of the hue values for each scatterplot was calculated.

IV. Results

A. *Lightness and Chroma*

The average lightness and chroma values corresponding to each test frequency are plotted as a function of vibration amplitude in Figure 4(a) and (b), respectively. Each data point shows the average matching response across the participants, and the error bars show standard errors of the means.

The measure of lightness showed a trend toward decreasing with vibratory amplitude and increasing with frequency. However, neither of these effects reached significance in the lightness ANOVA: amplitude [$F(1.2,14.4)=2.0$, $p=0.18$] and frequency [$F(1.4,16.6)=2.8$, $p=0.11$]; the amplitude by frequency interaction also did not approach significance ($p=0.57$). Closer examination of the data suggests that the frequency/lightness relationship may not be random, but rather that the direction of an underlying systematic relationship is under cognitive control: Whereas 8 of the 13 participants showed a strong positive correlation between frequency and lightness ($r >= .75$), two showed an equally strong negative correlation ($r > .80$). The dominance of one systematic trend is what produces the regularity apparent in Figure 4.

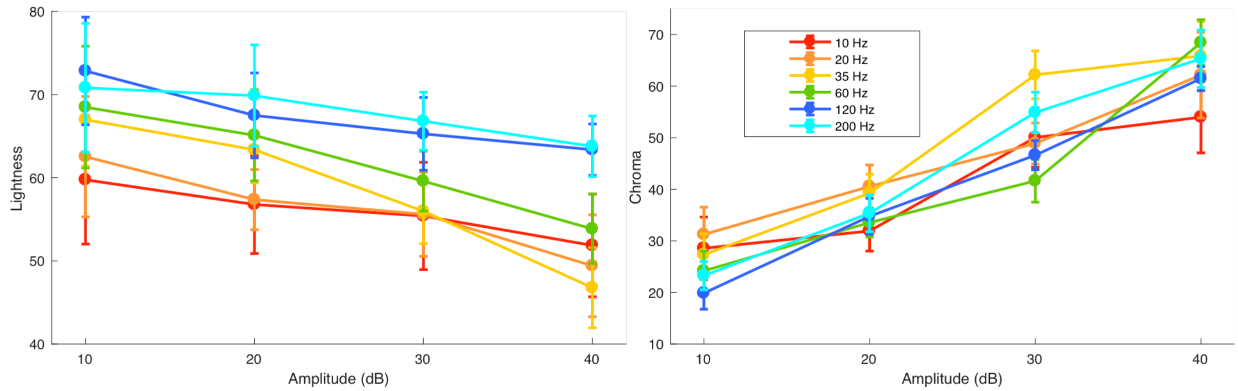

Fig. 4 Lightness (a) and Chroma (b) plotted as a function of stimulus amplitude (dB) at all test frequencies (Hz).

For the ANOVA on chroma, the amplitude effect was consistent and significant [$F(1.5,17.7)=29.0$, $p<0.001$]. Neither the effect of frequency ($p=0.26$) nor the amplitude by frequency interaction ($p=0.085$) were significant.

B. *Hue Histograms*

The raw a* and b* coordinates of all color choices are presented on scatterplots in the a*b* plane as black circles, and plotted for each amplitude and frequency in Figure 5. Dense clusters of black circles depict the colors that were most often chosen. The yellow (polar) histogram bars signifiy the number of hue occurrences within bin sizes of 15°. The largest bars within each scatterplot depict the bin containing the hue mode of a specific vibration stimulus.

Figure 6 shows the hue mode (binned value chosen by the greatest number of participants) as a function of vibration amplitude and frequency. Recall from Figure 3 that 0° lies at the red/violet boundary. We see a consistent pattern with low frequency vibrations, which converged from violet to red as the amplitude increased. The high frequency vibrations, in contrast, moved from green to red with increasing amplitude.

V. Discussion

This paper explores crossmodal correspondence between vibrations and colors. Vibrations are specified in the ranges of 10-200 Hz and 10-40 dB SL, triggering both high-frequency (vibrational) and low-frequency (motional)

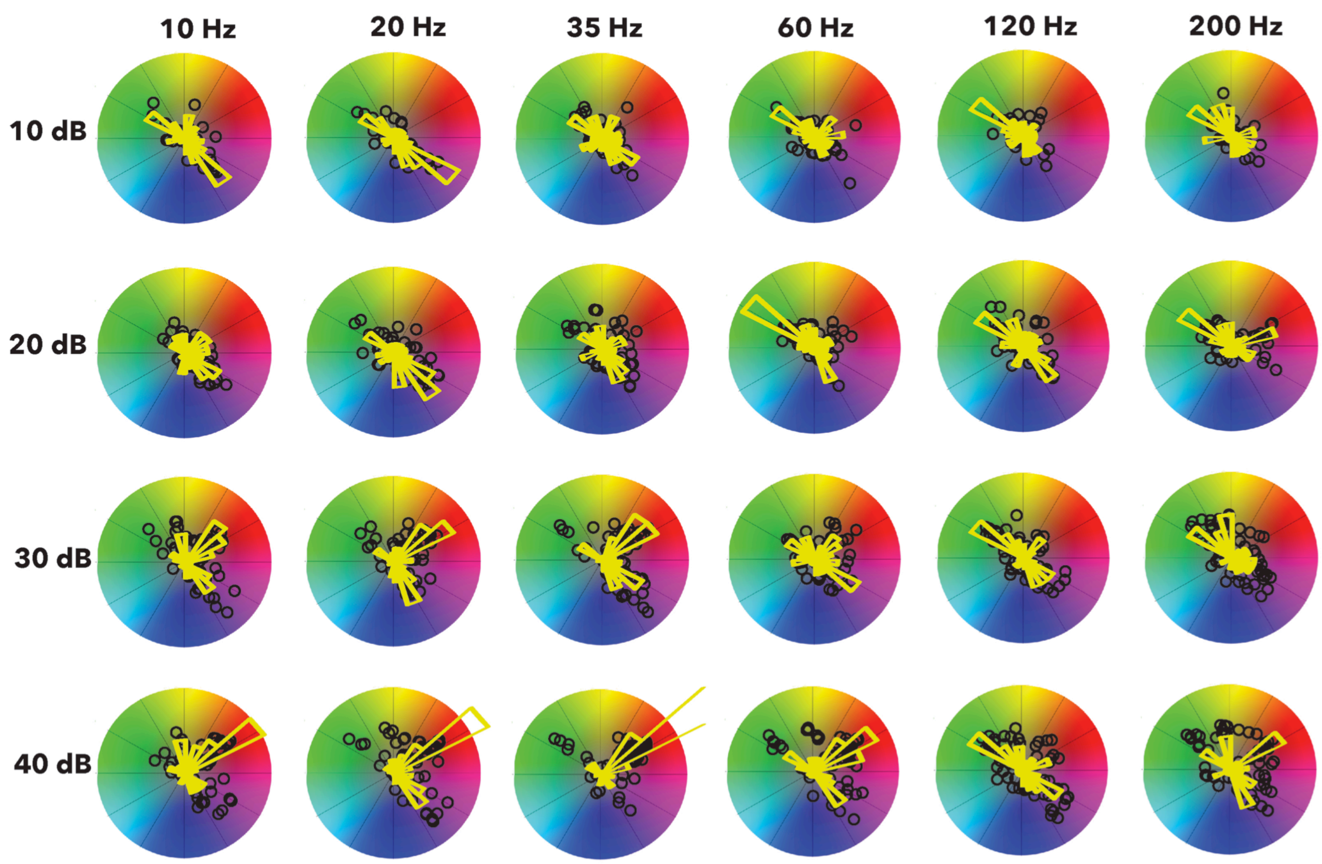

Fig. 5 Scatterplot of all participants' color choices with overlaid histogram of all participants' hue values (°). The black circles are the a*b* coordinates of the chosen colors. Yellow bars represent the histogram of hue angles.

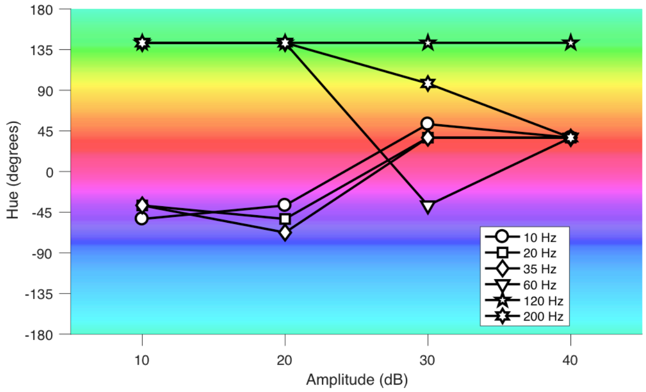

Figure 6. Trends of hue mode as a function of test frequency and amplitude.

sensations [21, 22]. Colors are defined in lightness, chroma and hue values (in the CIELAB space [9]), and are correlated with the vibration parameters. We discuss and highlight trends in following categories.

A. Lightness and Chroma

Although not significant, there was a trend toward a negative relation between the lightness of the chosen color and the vibration amplitude. Previous studies have similarly observed a negative trend between brightness and intensity levels of haptic roughness [3, 4]. Another trend was for lightness to increase with vibrotactile frequency. Although these effects might prove significant with increased power in the statistical design, they are sufficiently variable across participants that no general design principle is indicated.

Effects of chroma, in the form of an increase with vibratory amplitude, were robust in this experiment. A positive association between color and vibration amplitude was also observed in [3, 4]. Since chroma is the intensity or saturation of a color, it represents the vividness and vibrancy of the color perceived by the participant. Its association with the amplitude of vibration is likely to be mediated by an underlying intensity dimension common across modalities.

B. Hue

In general, we observed that the hue of the selected color varied with both vibration frequency and amplitude. Overall, the scatterplots depicted a lack of color choices in the deep blue area, with a focus of most choices along the green-violet complementary axis and in the red region. Figure 6 shows two distinct trends in the low and high frequency vibration range. At lower frequencies (10, 20, and 35 Hz) and low amplitudes (10 and 20 dB SL), most color choices and hue values were near the color violet (hue angle ≈ -50°). As the amplitude increased (30 and 40 dB SL) the chosen colors and hues shifted toward red (hue angle ≈ 50°). Higher frequency vibrations (60, 120 and 200 Hz) mostly evoked hue values within the green color range (hue angle ≈ 150°), and some traces of red at high amplitudes.

Two distinct patterns in the low and high frequencies could be due to two separate sensory systems activated by low and high frequency vibrations. Physiological data shown that the low-frequency vibrations activate Meissner corpuscles and high frequency vibrations stimulate Pacinian corpuscles [22]. Similarly, psychophysical data also shows distinct low- and high-frequency trends that became the basis of the dual-channel theory of vibrotaction [22, 23].

C. Implication of results and future directions

The present study reports what is to our knowledge the first demonstration of sensory crossmodal correspondence between colors and vibrations. The current data provide reference points to experience designers for selecting vibration levels to promote natural associations with colors. For example, intense low frequency vibrations (corresponding to the red hue) might be used to indicate approaching danger and/or extreme situations in video games, and high-frequency vibrations could promote the experience moving and flowing effects. Similarly, dark and dull environments can be supplemented with low frequency and low amplitude vibrations (low lightness and chroma), and bright and crisp ambience could use high amplitude and high frequency vibrations (high lightness and chroma). Character and object interactions can also be differentiated through vibrations based on colors associated with gender, warmth and emotions.

Overall, brief vibrations (1 second long) evoked colors in three specific hue regions, rather than the entire color spectrum (see Figure 6). The three primary regions indicated here (corresponding to red, green, violet) could be used to create complex vibrations corresponding to other color hues. One plausible use case could be a canvass of haptic colors in a painting application, where a user paints virtual objects and feels vibrations associated with their color.

One observation made from the present study is that associations to pure vibrations span a limited color range. Specifically, we have observed the lack of color selection in the blue hue range (between 180° and 270° hue angles). Other color ranges might be evoked with using complex vibrotactile stimuli that vary in rhythm, tempo and location. For example, Seifi and MacLean [24] showed synthetic vibrations varying in rhythm and frequency of modulation elicited a variety of affective responses in users' everyday tasks. Israr et al. [25] showed that moving vibrotactile stimuli yielded better information transfer (IT) and IT rates when compared to static stimulations on the back. We conjecture that moving and modulating vibrotactile patterns all around the body would trigger richer color correspondences, and these studies are left for future investigations.

VI. Conclusion

Our results demonstrate that brief vibrotactile stimulations reliably corresponded to selections on a palette of distinct colors. Specific associations depended on vibrotactile parameters, and low and high frequency vibrations evoked distinct color features. We offer these effects as a beginning for a haptic/color toolbox for immersive experiences in education and entertainment.

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