HaptiColor: Interpolating Color Information as Haptic Feedback to Assist the Colorblind

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ABSTRACT
Most existing colorblind aids help their users to distinguish and recognize colors but not compare them. We present HaptiColor, an assistive wristband that encodes discrete color information into spatiotemporal vibrations to support colorblind users to recognize and compare colors. We ran three experiments: the first found the optimal number and placement of motors around the wrist-worn prototype, and the second tested the optimal way to represent discrete points between the vibration motors. Results suggested that using three vibration motors and pulses of varying duration to encode proximity information in spatiotemporal patterns is the optimal solution. Finally, we evaluated the HaptiColor prototype and encodings with six colorblind participants. Our results show that the participants were able to easily understand the encodings and perform color comparison tasks accurately (94.4% to 100%).

Author Keywords
Color blindness; wearable computing; vibration; spatiotemporal vibrotactile pattern; wristband.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces – Haptic I/O.

INTRODUCTION
Color blindness, or partial color vision, affects a person's ability to perceive colors. It affects up to 8% of men and 0.5% of women among those with a northern European background [5], contributing to difficulties in everyday life and at work [2]. The tasks colorblind users have difficulty with in their daily lives can be roughly categorized into three types.

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The first type, *distinction,* refers to the ability to distinguish one color from another when presented simultaneously. Since different colors are often used to represent different information, being able to distinguish colors from each other is critical for colorblind people to extract the information they represent. The second type of task is *recognition*, where colorblind people need to be able to determine which class of colors a particular instance belongs to, in addition to distinguishing it from other colors. Color recognition is very important and useful in everyday life, as colors are frequently used as identifiers in daily conversations, e.g.: "Look at that guy in the red shirt." However, color recognition is not always enough. Some daily tasks also require understanding the relationship between colors so that meaningful comparisons can be made. Color *comparison* is the third kind of task. An example of such task is "Can you find me a shirt that goes well with the color of these pants?" Many colorblind aids are currently available [7,18,21], but most existing solutions are designed to help with only the first two types of tasks. We are not aware of any solutions that address all three tasks.

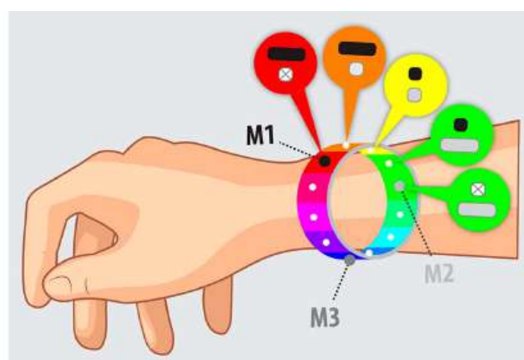

Figure 1. HaptiColor is a wristband that encodes color into spatiotemporal vibrotactile patterns, and embeds three vibration motors (M1, M2, M3). Colors are encoded using their proximity to the nearest vibration motors. Examples of patterns for five colors are shown (red to green)

This motivates us to investigate an easily accessible haptic wristband that can help colorblind people (including one of our co-authors) to perform all three types of color recognition tasks. We chose to focus on a wearable vibrotactile solution over other alternatives based on the feedback we receive from informal interviews with four colorblind participants. According to them, existing colorblind aids are often inconvenient because they require additional interactions with another device that can interrupt their activity. This suggests that an easily accessible, wearable solution is more desirable. When discussing potential wearable solutions, colorblind participants expressed preference for a haptic wristband due to its non-intrusive, private, and familiar nature over alternative solutions such as Google glass, which may give some users *"the impression of wearing a prosthetic"*. Their preference is consistent with results of the 2014 Forrester's Consumer Technology Surveys[1] for North America and Europe, where the wrist is identified as the preferred location for wearable devices.

To support all three types of tasks with haptic feedback, we developed a general strategy to represent interval relationships among multiple data points by encoding spatiotemporal vibrotactile patterns on vibration motors. Using this strategy, we developed HaptiColor (Figure 1), a wristband encoding color information over three evenly-spaced vibration motors. It enables colorblind users to perform distinction, recognition and color comparison tasks involving up to 12 colors. HaptiColor facilitates color comparison by enabling colorblind users to understand the relative relationship between color pairs. This is achieved by encoding the distance of color pairs on a color wheel as distinct vibrational patterns. This feature is particularly useful for matching colors between multiple items, such as when choosing the right color combination of clothes, paint, and onscreen elements.

To assess the effectiveness of our haptic solution, we performed three experiments. The first determined the maximum number and optimal placement of motors. Our results show that users' ability to locate vibration positions decreases if there are more than four motors around the wrist. The second investigated the effectiveness of different strategies to represent distance-aware encoding of points on a circle using vibration. The most accurate solution (97% accuracy) uses only sequential short or long vibration pulses on two motors. The third experiment was an ecological validity study of our spatiotemporal encodings and prototype from the two previous experiments. Six colorblind participants performed color comparison tasks, and results showed that our encoding can achieve between 94.4% and 100% accuracy.

This paper makes the following contributions:

- Spatiotemporal vibrotactile encodings that allow clear recognition of individual points and understanding of spatial relationships among multiple points on a line or a circle. This vibrotactile encoding can be applied to recognize and compare colors on a color wheel, and other types of information, such as direction and time.
- A working prototype of an assistive wearable wristband that provides haptic feedback and implements spatiotemporal encodings that represent color information to colorblind users. Like the encodings, the device can also be adapted for presenting other types of information.
- An empirical validation of our prototype and encodings, including an ecological validity study with six colorblind participants performing color comparison tasks.

RELATED WORK AND BACKGROUND

In this section, we first review facts about vision, color blindness, and color representation, before reviewing previously-developed colorblind aids and haptic wristbands.

Human Vision and Color Representation

The color we see is defined as a range on the electromagnetic spectrum—light reflected into our eyes. The spectrum visible to humans is from around 400nm (violet, short wavelength) to 700nm (red, long wavelength). Our color vision is stimulated when incoming light reacts with the retina at the back of our eye, where three separate kinds of *cone* cells react to short (blue), medium (green), and long (red) wavelengths [9].

Colorblind conditions

Humans can be affected by one of four challenges to their color vision, from mild to severe [3]. In total color blindness, *monochromacy*, two or three types of cone cells are missing or nonfunctional. This condition is rare (1 in 30-50,000 people) and results in severe visual impairment in some cases [12]. *Dichromacy* results when one of the color cones is missing, reducing vision to two dimensions. In *anomalous trichromacy*, one cone suffers from defects. This is the most common form of color blindness, where the patient experiences a slight to moderate compromise to his/her vision of one light wavelength. Depending on the cones affected, the patient experiences different kinds of difficulties, the most common being distinguishing red from green (red-green colorblindness), known as *deuteranomaly* and *protanomaly*. The set of colors that appear confusing to colorblind people depends on the particular condition they have. In order to help all colorblind people, assistive technologies should address all conditions.

Color models and color wheels

Color is often encoded using a three or four dimensional space, or a color *model*—a mathematical representation of color using three or four components representing primary colors. Each color is thus a combination of these primary colors. The most common models are Red Yellow Blue

[1] http://blogs.forrester.com/jp_gownder/14-12-09-the_data_digest_five_urgent_truths_about_wearables

(RYB) and Red Green Blue (RGB). In experiment 3, we use the RGB model commonly used for digital displays.

Color wheels are useful graphical representations of *hues*, which show relationships between colors, within a color model. Simple color wheels usually represent twelve different hues. Hue perception, or the degree to which a stimulus can be described as similar to or different from primary colors, is compromised in colorblind people. HaptiColor's vibrotactile feedback can interpolate any color in a color wheel via vibration patterns, allowing colorblind users to recognize colors they have difficulty with.

Colorblind aids

There are many colorblind aids available. These solutions convey information about confusing colors either using visual, audio, or haptic feedback.

Audio aids

SoundView [6] creates a direct mapping between color (hue, saturation, brightness) and sound components (frequency, width, gain) and uses auditory feedback. Mathematically, the mapping is simple, but it remains to be proven that users can easily learn and apply this mapping. Audio can also be hard to perceive in a noisy environment.

Visual aids

Visual aids either alter the colors of a scene/picture or overlay additional information to help users recognize a specific color. ColorID [7] displays the name of the color above the color itself. Sajadi et al. [18] use simple visual patterns instead of the name of the confusing color. ColorBless [4] leverages a binocular visual effect (luster) that produces an image with slightly different brightness components on each eye to distinguish confusing colors without altering the color of the image. All these solutions either require a complex apparatus [4] or a device with a large screen to be used as an extra layer between the real world and the user [7,10,18]. Chroma [21] uses Google Glass to alter the camera feed and help users recognize colors. In our classification of tasks, Chroma can help users to distinguish and recognize colors but cannot help users understand the relation between two specific colors.

There are also several interactive mobile apps that attempt to support color recognition and matching, but most require the user to look at the mobile screen.[2] Enchroma makes specially coated eyeglass lenses that filter and enhance the perception of certain colors. They are effective for red-green color blindness, but expensive.[3]

Haptic aids

Designing mobile or wearable aids based on haptic feedback has also been considered. Kahol et al. [11] proposed a mapping between an RGB color model (augmented with brightness) and force feedback via a Phantom Haptic Joystick that allows both sighted and blind participants to accurately recognize similar colors. Other works used multiple vibration motors on a wearable device as haptic aids. Gloves have been proposed as potential form factors [20,22], but the proposed prototypes have not been evaluated and the design of the color-vibration mapping is neither explained nor justified.

Haptic Wristbands

Spatiotemporal vibrotactile patterns have already been used on wristbands. Matscheko et al. [15] and Gupta et al. [8] used a similar spatial distribution around the wrist using four vibration motors. Our results confirm that four vibration motors can be seen as the optimal number of motors around the wrist. Other works, such as Lee et al. [13] and BuzzWear [14] rely on a 3×3 grid on either the dorsal or volar sides of the wrist, which we did not consider since we aim at mapping a color wheel around the wrist, which requires a circular configuration.

HARDWARE PROTOTYPE AND SHARED APPARATUS

We designed our hardware prototype using a Velcro wrist band. We used off-the-shelf vibration motors (coin-type Precision Microdrives, model 310-103, dia=9mm, h=3mm). The motors were affixed on the inner surface of the Velcro band. We followed Matscheko et al.'s [15] recommendation and distributed the motors evenly around the wrist. The prototype was worn on the dominant hand (Figure 2), which was the right hand for all our participants. Our hardware only provides vibrotactile feedback and does not scan color. Color scanning could be achieved through a RGB sensor or a camera located either under the wrist, or on the tip of a finger, as proposed in SmartFinger [17].

Figure 2. Hardware prototype of HaptiColor.

An Arduino board programmed to control the motors was connected to a Windows 8.1 ASUS laptop with a 2.4 GHz Intel Core 2 Quad Core CPU and 8 GB of RAM. The laptop was connected to an external 24" Dell Monitor. The experimental software, written in Java 8, was used to communicate vibration patterns to the prototype and to collect data.

[2] http://www.color-blindness.com/2010/12/13/20-iphone-apps-for-the-color-blind/

[3] http://www.enchroma.com

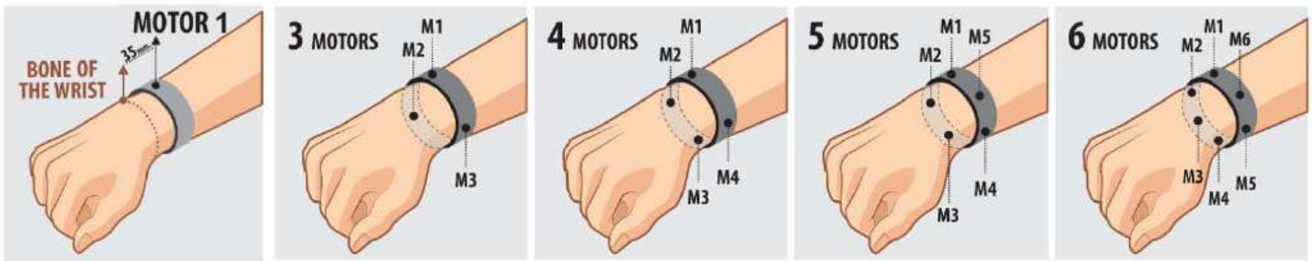

Figure 3. Localization of the reference motor on the wrist. Distribution of the vibration motors around the wrist.

EXPERIMENT 1: HAPTIC PERCEPTION - NUMBER OF MOTORS ON THE WRIST

Before determining the optimal spatial vibrotactile encodings for color, we tested the number of motors that can be reliably detected by users, and the effect of their spatial distribution on perception. We considered four conditions for the experiment: a wristband with three, four, five or six motors (see Figure 3 for each configuration).

Participants

Twelve normal color vision participants (7 females, all right-handed) ranging from 23 to 42 years old (*M*=28.1, *SD*=5.4) were recruited from within the university community. The average wrist size of the participants was 161.7 mm (*SD*=16.8), dividing them into two groups accordingly. The first group contained six participants (all female) with small wrists ranging 140-150 mm (*M*=145.8 mm, *SD*=3.76). The second group contained the six other participants (one female) with large wrists ranging 175-180 mm (*M*=177.5 mm, *SD*=2.7).

Tasks and Stimuli

During each trial, one of the vibration motors placed around the wrist would vibrate for 600 milliseconds as recommended by Saket et al [19]. The participant would then, without looking, have to select the correct position among all possible positions displayed on the experimental software interface. The motors were named M1, M2, M3, M4, M5, and M6, in a clockwise order from the anterior of the wrist, starting from a fixed position M1 described in Figure 3. A trial concludes after a user selects a position. There was a three second break between trials.

Procedure

Participants began the experiment by filling a pre-questionnaire with demographic information. Before starting the experiment, the experimenter measured the wrist of the participant and prepared the correct configuration, distributing the vibration motors equally around the wrist. For each motor configuration, we decided to have one of the motors (M1) at a fixed position: 35 mm from the most external center point of the ulna bone of the wrist in the direction of the elbow (Figure 3, left panel).

The experiment was divided into four sections for each motor condition. Each section started with a training block where each stimulus—the vibration of one of the motors—was played clockwise sequentially, starting from M1. This was repeated twice. After training, participants completed two test blocks of stimuli, presented in a random order. Each stimulus was repeated twice in each block. After completion, participants filled in a post-experimental questionnaire to measure the perceived difficulty of locating the patterns around their wrists.

Design

A within-subject design was used with only one independent variable with four levels: *number of motors {three, four, five, six}*. This variable was counterbalanced using a Latin Square. We measured accuracy, execution time and perceived difficulty as dependent variables. Participants could take voluntary breaks between blocks. Each participant performed the experiment in one sitting, including breaks, for around 30 minutes. The design included the following: 12 participants × 4 condition × [1 training block + 2 test blocks] × (3+4+5+6) stimuli × 2 repetitions per block = 2592 trials.

Results

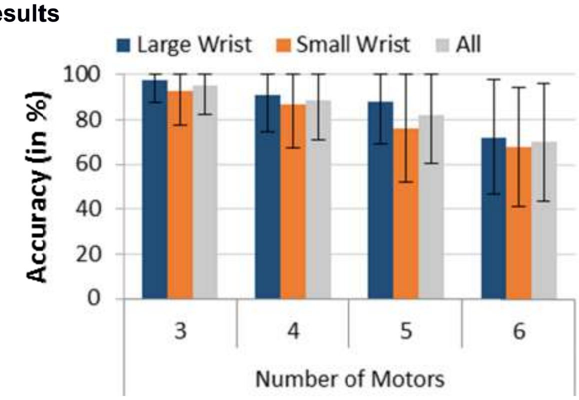

Figure 4. Accuracy rate depending on the number of motors. Errors bars are .95 confidence intervals.

Accuracy

The overall accuracy was 81.6% and varied as a function of the number of motors (Figure 4). A mixed ANOVA with one within-subject independent variable (number of motor) and one between-subject independent variable (wrist size) showed a significant main effect of *number of motors* on accuracy ($F_{3,33}$=14.7; p<.0001). Participants had no difficulty locating vibrations on the 3 motors condition (*M*=94.9%), with performance slowly decreasing with 4 motors (*M*=88.9%), 5 motors (*M*=81.9%) and dropping dramatically with 6 motors (*M*=69.9%). Pairwise t-tests with Bonferroni correction showed significant difference between 3 motors and 5 motors (p<.01), 3 motors and 6 motors ($p<.001$) as well as between four motors and six motors ($p<.01$). Our results showed that accuracy drops as we increase the number of motors, which is not surprising. Based on the required error tolerance, these accuracy results can be useful for deciding the number of vibration motors to use in a wearable wristband.

There seems to be a trend in which participants with larger wrists tend to achieve better overall accuracy (84.9% compared to 78.4% for the small wrist group, Figure 4), but the difference is not significant (p=.073). This indicates that the ability to distinguish the location of vibration decreases with wrist size, which is an important design consideration.

Response Time

Response time is measured from the time the stimulus administration ends to the time the user finishes the trial, including the reaction time and the time to select an answer.

The average response time was 2.56s (Figure 5). ANOVA showed a significant main effect of number of motors on response time ($F_{3,33}=8.50$; $p<.001$). Overall, the total time increased from 2.02s (3 motors) to 2.23s (4 motors), 2.75s (5 motors) and 3.01s (6 motors). Pairwise t-tests with Bonferroni correction showed significant differences between 3 and 6 motors ($p<.05$) and between 4 and 6 motors ($p<.001$). As expected, our results indicate that as the number of motors increase, a longer processing time is needed to make a decision.

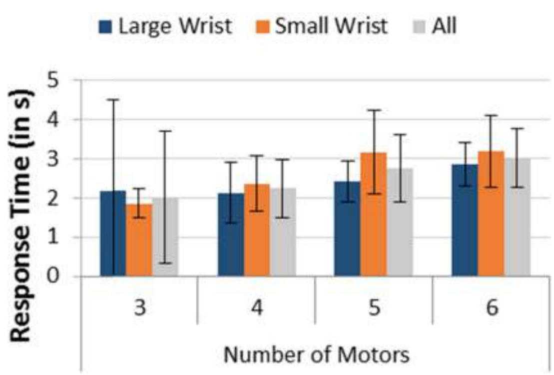

Figure 5. Response time depending on the number of motors. Errors bars are .95 confidence intervals.

No significant main effect of wrist size was observed on response time ($p=.35$), with both populations achieving comparable execution times (Figure 5). This also implies that the processing time needed to make a decision is not affected by the wrist size.

Perceived Difficulty

In the post-experimental questionnaire, we asked our participants to rate the difficulty of properly locating vibrations for each configuration on a 7-point Likert scale. Consistent with the quantitative results, perceived difficulty increased with the number of motors, with the 3 motor condition deemed very easy (median=2), 4 motors slightly harder (median=2.5), 5 motors was judged neutral to difficult (median=4) and 6 motors the hardest (median=5.5). A Friedman test showed significant main effect of the number of motors on perceived difficulty ($\chi^2(3)=27.08$; $p<.0001$). Pairwise Wilcoxon tests with Bonferroni corrections showed that 3 motors was judged significantly easier than both 5 motor and 6 motor condition (all $p<.05$); and 4 motors was seen as significantly easier than 6 motors ($p<.05$).

Discussion

The results of this study allow us to determine the maximum number of motors that can be placed around a wrist-worn device. Both quantitative and qualitative results suggest that vibrations occurring on three or four motors can be reliably and easily detected. In particular, using only three motors ensures high accuracy (94.9%), while the four motor condition remains reliable (88.9%).

Interestingly, people with larger wrists can still locate five motors with an accuracy of 87.8%, while people with smaller wrists have more difficulty, achieving an accuracy of 76.1%, suggesting two different, wrist-size optima for the number of motors. However, the observed difference is not significant and based on small samples. A more thorough follow-up study is required to investigate this aspect systematically.

Our study results can be generally applied to design vibrotactile feedback on smart watches and smart bands. While the accuracy may have been influenced by the size and quality of the motors used, our accuracy evaluation was obtained using cheap off-the-shelf motors, and might be improved using better quality motors. Recognizing a motor from up to four motors was proven to be relatively easy and reliable. This particular configuration could be used for navigation applications, where each motor could represent one direction (front, left, right, back).

Since our main interest is to convey information about color to colorblind people, the results we obtained suggest that we can use a color model based on three or four components. The most common color models, such as RGB or RYB have three components, used to represent 12 colors, and are thus good candidates, especially given user familiarity with these models. This raises a new question: how can we convey more precise information representing all 12 colors on fewer motors?

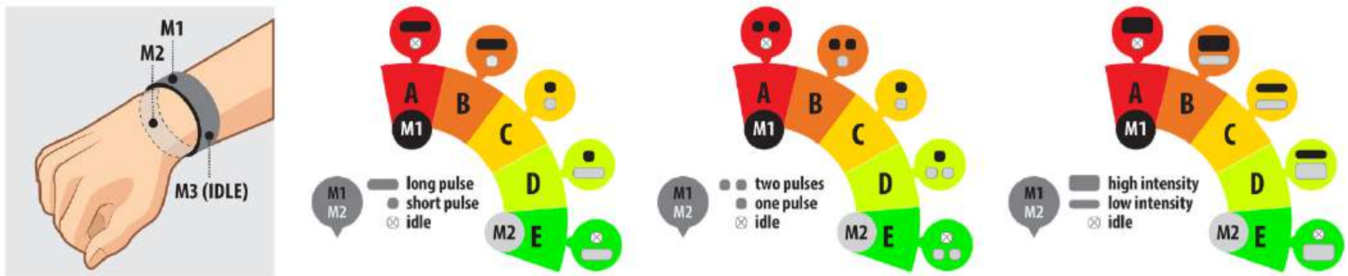

Figure 6. From left to right: Vibration motor configuration for Experiment 2. M3 was not used during the experiment. Examples of patterns to encode five points (A to E), using duration (long/short pulse), number of pulses (two/one) and intensity (high/low). A (resp. E) is physically collocated with M1 (resp. M2). The black component (resp. light grey) of a pattern shows the pulse(s) as they are played on M1 (resp. M2).

INTERPOLATING VALUES BETWEEN TWO VIBRATION MOTORS

We decided to use three vibration motors for our device, based on accuracy considerations and one-to-one mapping with the three primary colors of the RGB and RYB color models. Given that our system needs to be able to differentiate and convey information about more than just the primary colors, we decided to use vibration patterns to encode information about up to a total of 12 colors.

Design Rationale

To represent an interpolated point, we use proximity information with respect to the actual physical position of the vibration motors to encode non-primary colors. This proximity information is in turn encoded with vibrotactile patterns. A vibrotactile pattern is characterized by the *intensity* and the *duration* of the vibration, so we considered varying levels of these dimensions as potential candidates to encode proximity. We also considered an alternative where one motor delivers multiple pulses. Based on our requirements (three intermediary values across two motors), each of these dimensions is expressed as a value at one of the three levels: strong, medium, or none.

Dimensions and Levels

Three dimensions of vibration communicate information about the proximity between points: duration, intensity, and number of pulses. To encode the three value levels for the dimension of duration, we followed Saket et al's recommendation [19] for using a strong (or long) value of 600 milliseconds, and a medium (short) value of 200 milliseconds.

Intensity is communicated using Pulse Width Modulation (PWM), which produces a basic digital waveform, i.e. cycle. A cycle is thus a fixed percentage of time where 5V are sent to the component, followed by 0V. We decided to encode the “strong” value as a PWM cycle where 5V are sent 100% of the time, and the “medium” value rapidly alternates between 5V and 0V equally (50%-50%).

We decided to use number of pulses as a dimension because prior research suggests that counting pulses is an easy task for the user and thus an effective way to communicate [1,16]. The strong value for number of pulses was set as two successive pulses with a 200 ms delay between pulses, and the medium value as one pulse.

Pattern	Intensity	Duration	Pulses	Notes
A	(100%, 0%)	(600, 0)	(2,0)	Physical point on motor 1
B	(100%, 50%)	(600, 200)	(2,1)	
C	(50%, 50%)	(200, 200)	(1,1)	Equal proximity to both motors
D	(50%, 100%)	(200, 600)	(1,2)	
E	(0%, 100%)	(0, 600)	(0,2)	Physical point on motor 2

Table 1 Summary of the patterns generated. The first value (resp. second) within parenthesis is the value of the considered dimension on motor 1 (resp. motor 2).

Patterns

Let us consider two vibration motors placed around the wrist and imagine a color wheel around. Five points, representing colors, can be coded as vibration patterns with two motors (Figure 6). The first point would be encoded by expressing a strong value on the first motor, M1 and a value of none on the second motor, M2.

The second color, in a clockwise direction around the color wheel, would then be represented as a strong value on M1 and a medium value on M2. This pairing of strong and medium values suggests that this color is “closer” to the M2 than M1, with respect to our imagined color wheel. The third color would be equidistant (or in between) from both vibration motors and thus would be encoded by a medium value on each motor, denoting equal distance. Following this logic, the fourth color is still closer to M2, and would thus be encoded with a medium value on M1 and a strong value on M2. Ultimately, the last color happens to be exactly located at the second vibration motor and is thus encoded with a value of none on M1 and a strong value on M2. These point encodings are abstract and can be applied to represent any kind of data.

Temporality

A pattern can be conveyed by either vibrating both motors at the desired values simultaneously or using sequentially vibration. While simultaneously vibrations convey information faster, there is a risk of making the information harder to decode.

We decided on three sets of patterns, one for each dimension. Patterns within each set can be played simultaneously or sequentially. In the case they are played sequentially, the motors are activated in a clockwise direction with a 200-millisecond delay between vibrations. Table 1 summarizes the design rationale for two vibration motors.

EXPERIMENT 2: INTERPOLATED POINTS

We evaluated the set of patterns designed to represent *interpolated* points—i.e. points not located directly on a physical vibration motor. Since our goal is to represent a total of 12 points (or colors), we decided to test our patterns in a three motor configuration. However, in order to gather enough data and to optimize the duration of the experiment, we only tested the patterns using two vibration motors, for a total of 5 patterns within each set (Table 1).

The two motors used in this experiment are motor M1, which is our point of reference for distributing the motors around the wrist, and motor M2, which in a clockwise direction is immediately next to it (Figure 6, left panel). We evaluated six sets of patterns (3 *dimensions* × 2 *temporalities*).

Participants

Eighteen normal color vision participants (9 females, all right-handed) ranging from 19 to 34 years old (M=25.2, SD=3.9) were recruited from the university community. The average wrist size of participants was 159.2 mm (SD=15.8). As in Experiment 1, we grouped participants according to their wrist size. The first group comprised nine participants (all females) with a wrist size ranging 140-150 mm (M=147.2 mm, SD=3.3), while the second group comprised the other nine participants (all males) with a wrist size ranging 165-180 mm (M=174.4 mm, SD=5.3). The participants were asked to listen to pink noise while performing the experiment to mask audible cues.

Tasks and Stimuli

In this experiment, we evaluated the six sets of patterns described in the previous section. Thus, for each trial, one of the five patterns within each set would be played as a stimulus and users had to select the correct position among the five possible positions on the experimental software interface. Each position was named using a capital letter (A, B, C, D, E) with A corresponding to the point directly on the first vibration motor and E the point directly on the second motor (Figure 6). A 3 second break was taken between trials.

Procedure

Participants began the experiment with a questionnaire, providing demographic information and wrist size. The experimenter assisted participants to put the prototype on their wrist and to adjust the position of each of the three vibration motors. The motor configuration can be seen in Figure 6. In this experiment vibrations would only appear on motors M1 and M2. The experiment was divided into three sections, one for each dimension considered (intensity, duration, and number of pulses). In each sequence, both temporalities were tested, with the order of temporality being fully counterbalanced. The first block of each specific *dimension* × *temporality* combination was for training, with each pattern being played in the same order as presented in Table 1. After training, there were three blocks of tests with randomized order of stimuli. Two repetitions of each stimulus were done for each block. After the experiment, participants completed a post-experimental questionnaire to evaluate the perceived difficulty of understanding the patterns for each *dimension* × *temporality* combination.

Design

A 3×2 within-subject design was used with two independent variables: *dimension* {*intensity, duration, number of pulses*} and *temporality* {*simultaneous, sequential*}. Dimension was counterbalanced using the Latin Square design, and temporality was fully counterbalanced. Patterns were randomized within blocks for test blocks, but played sequentially during training blocks. We measured accuracy, execution time and perceived difficulty as dependent variables. Each participant performed the experiment in one sitting, including breaks, over approximately 40 minutes. In summary, the design of the experiment was 18 participants × 3 dimensions × 2 temporalities × 5 stimuli × (1 training block + 3 test blocks) × 2 repetitions = 4320 trials.

Results

We ran three-way mixed ANOVAs with two within subject factors (dimension and temporality) and one between-subject factor (wrist size) on both accuracy and execution time. We applied Greenhouse-Geisser sphericity correction when needed, which corrects both p-values and the reported degrees of freedom.

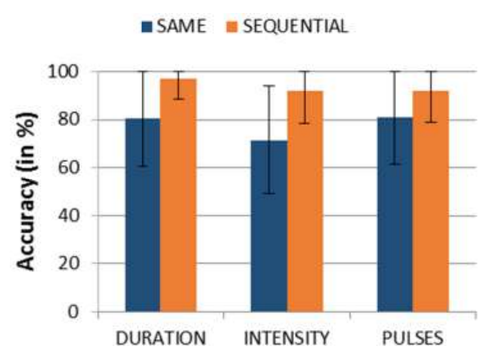

Figure 7. Accuracy rate for each temporality × dimension combination. Error bars represent .95 confidence intervals.

Accuracy

The average accuracy was 85.7% (Figure 7). There were significant main effects of both *dimension* ($F_{1.46,24.87}$=3.89; p=.045) and *temporality* ($F_{1,17}$=84.18; p<.0001) on accuracy. Participants were more accurate when patterns were played sequentially (93.7% vs. 77.7%). Paired sample t-tests with Bonferroni correction showed that *duration* is the most accurate (88.7%), significantly better than *intensity* (81.7%, p<.01), and slightly but not significantly more accurate than *number of pulses* (86.7%, p=.91). Participants were more accurate when the patterns were played sequentially (93.7% vs. 77.7%). There was not *dimension* × *temporality* interaction (p=.059). The best combination was *duration* as a dimension and *sequential* for temporality (97%) followed by *pulses* × *sequential* (92.2%) and *intensity* × *sequential* (91.9%). Wrist size did not have a significant effect on accuracy (p=.94) with 85.8% for the group with large wrist and 85.6% for the one with small wrist.

Response Time

The average response time was 3.57s (Figure 8). There was a significant main effect of temporality on execution time ($F_{1,17}$=12.39, p<.01). Response time was thus significantly shorter for the *sequential* temporality (3.29s) than for the *simultaneous* temporality (3.91s). No significant effects were found for *dimension* or *dimension* x *temporality*. Overall, *duration* seems to be slightly faster (3.34s) than *intensity* (3.62s) and *pulses* (3.76s) although no significant difference was found (all p> .05). *Wrist size* did not have an effect on execution time (p=.17).

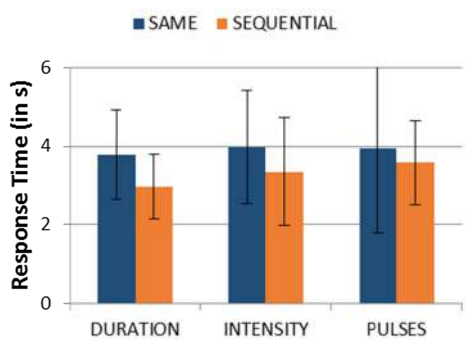

Figure 8. Response time for each temporality × dimension combination. Error bars represent .95 confidence intervals.

Perceived Difficulty

The perceived difficulty once again reflects the quantitative results. Overall, the perceived difficulty is deemed low to moderate for the sequential temporality, and high for the simultaneous temporality. A Friedman test showed significant main effect of the different combinations on perceived difficulty ($\chi^2(5)$= 49.64, p<.00001).

We now focus the pairwise analysis on the two most promising candidates, namely duration-sequential and pulse-sequential. Pairwise Wilcoxon tests with Bonferroni corrections showed significant differences between *duration* × *sequential* (median=2) and every other configuration (all p<.05) except for *pulses* × *sequential* (median=1.5, p=.9). The same trend was found for *pulses* × *sequential*, with significant differences observed for every other combination but *duration* × *sequential* and *intensity* × *sequential* (median=3, p=.42).

Discussion

In this experiment, we evaluated six different ways of interpolating points between two vibration motors. Interestingly, the sequential temporality turned out to be the most accurate method without causing an extremely significant delay between the time required to play the stimulus and for the user to execute the task: we found an overall total time of 4.17s for sequential temporality (3.29s of execution and 0.87s of stimulus playback time), which is faster than the 4.45s observed for the simultaneous temporality (3.91s + 0.55s). It is thus more accurate, faster, and also easier as perceived by the users to convey the patterns using a sequential temporality.

We noted an overall lower accuracy of *intensity* as a dimension. After discussing with our participants, they stated that they had trouble identifying the level of intensity depending on which motor was activated. M1 was located near a bone, and thus intensity differences were strongly felt by users. M2, on the other hand was located on a fleshy area, where the vibration signal gets diffused, altering the vibration perception. For this reason, intensity does not seem to be a reliable way to convey proximity.

While this experiment shows promising results, we did not evaluate it using the actual design derived from experiment 1, which uses three instead of two motors. In the three-motor form, our system can represent up to 12 points. We could also imagine a four-motor design capable of representing up to 16 points, for precise navigation purpose or to estimate angles.

The most important result of this experiment is that among our six designs, two of them appear to be strong candidates for encoding proximity: *duration* × *sequential* (97% accuracy) and *number of pulses* × *sequential* (92.2%). Even if the difference is not significant, we would advocate the use of the *duration* × *sequential* design in the future.

EXPERIMENT 3: ECOLOGICAL VALIDITY

In Experiment 3, we asked colorblind participants to perform color comparison tasks using the HaptiColor prototype with three vibration motors, allowing us to represent a total of 12 colors using the *duration* × *sequential* combination for generating patterns.

Participants

Six colorblind participants (all males and right-handed) ranging from 24 to 30 years old (M=27, SD=1.9) were recruited from within the university community. The average wrist size ranged from 160 to 200 mm (M=173.3 mm, SD=14). Five of the participants had deuteranopia and one had protanopia.

Tasks

We decided to simulate an online shopping task, which can be challenging for colorblind people [21]. During a trial, our experimental software would display a shirt of a specific color and our participants would need to select a shirt to match it according to an instruction. We asked the participants to perform three different tasks corresponding to three different instructions:

Same color. From a selection of seven shirts, participants had to find a shirt of the exact same color as the stimulus.

Close color. In this task, participants needed to find the shirt with the closest but different color, i.e. one of the two colors immediately next to the position of the stimulus on the color wheel.

Opposite color. Finally, we asked our participants to find the color opposite to the stimulus, i.e. the most distant point from the stimulus in the color wheel. Note that the concept of "opposite color" depends on the way colors are represented and what color wheel is chosen. Since this experiment is performed on a calibrated computer screen, we decided to use the RGB color wheel, as seen in Figure 9.

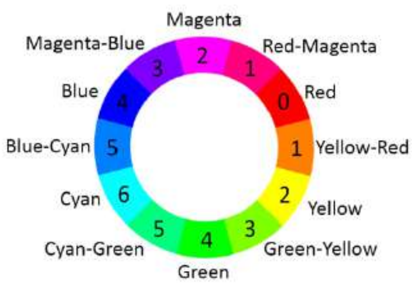

Figure 9. Color wheel used during the experiment, annotated with color names. The number in each cell is the distance of the indicated color from red. Cyan has the maximum distance as it is the opposite color of red on this color wheel.

Stimuli

For each trial, a shirt of one of the 12 colors of the RGB wheel was chosen as a stimulus. The experimental software (Figure 10) also selected 6 or 7 possible combinations based on colors with varying distance from colors to the stimulus. Thus, one of the two possible colors with a distance of 1 to 5 points was selected (Figure 9), plus the opposite color and the same color. For the *close color* task, the same color as the stimulus was excluded from the sets of possible answers.

To make the tasks harder, we added random noise to each color (stimulus or answers) by adding or subtracting up to 10 from each RGB component value making up each color. Adding this random noise also made the task more realistic, since it is very unlikely to find two items with the exact same perceived color, as the perceived color varies depending on the ambient light and/or on the calibration of the screen.

Procedure

Participants start the experiment by filling a pre-experimental questionnaire with demographic information and wrist size. The type of their color blindness was assessed using HRR pseudoisochromatic plates. The experimenter conducted a training session on color representation and the RGB color wheel with each participant. During training, participants were allowed to take notes and keep them throughout the whole experiment as an aid. The experimenter would also present the HaptiColor prototype and describe how each color is represented with vibrotactile patterns. The training session took between 20 and 42 minutes (*M*=30.3, *SD*=9).

The experiment itself was divided into two sections: one section where the participants perform the three presented tasks while wearing the HaptiColor prototype and another where they rely on their vision (i.e. without HaptiColor). At the beginning of each trial, the stimulus was displayed on the experimental software, along with the 6 or 7 possible answers. In the *HaptiColor* condition, the user could click on the stimulus and the possible answers to have their vibrotactile pattern played. The user would then select an answer and go to the next trial by clicking on a large OK button. Trials are separated by 3 second pauses.

Figure 10. Software interface for Experiment 3. The right part of the shirts shows how a deutan perceives the color.

Design

A 2×3 within-subject design was used with two independent variables: *technique* {*baseline, HaptiColor*} and *task* {*same color, close color, opposite color*}. *Technique* was fully counterbalanced and *task* was counterbalanced using the Latin Square design. Within blocks, stimuli were randomized. We measured accuracy as a dependent variable. Each participant performed the experiment in one sitting over approximately one hour, including breaks. In summary, the experimental design included 6 participants × 2 techniques × 3 tasks × 12 stimuli × 1 block × 1 repetition = 432 trials.

Results

Contrary to Experiment 1 and 2, where we compared accuracy using ANOVA, in this experiment we will rely on non-parametric statistical tests since the homogeneity of variances between levels of our factors is different.

A Cochran Q's test showed a significant main effect of *Task* on accuracy ($\chi^2(2) = 5.98, p=.05$). The *same color* task was the easiest, with 100% accuracy achieved with HaptiColor and 94.4% without HaptiColor. The *close color* task was the second easies, with 97.2% vs 73.6% accuracy. The *Opposite color* task was the hardest, with 94.4% accuracy vs. 62.5% accuracy with and without HaptiColor.

A Chi Square also showed a significant main effect of *Technique* on accuracy ($\chi^2(1) = 37.94$, $p<.0001$). HaptiColor achieved an accuracy of 97.2%, while the *baseline* accuracy (without HaptiColor) was 76.9%.

While the accuracy may seem quite high even for the *baseline* technique (without HaptiColor), it is important to note that we consider all the twelve colors on the RGB color wheel and not only the ones that would be problematic for colorblind users. Furthermore, through the post-experiment feedback, the users indicated increased confidence in their decisions with HaptiColor, even if they might have done well on easier tasks without the device..

GENERAL DISCUSSION

In this project, our initial goal was to help colorblind people better understand the relationship between colors they may not be able to distinguish themselves. By using a color wheel, our problem is reduced to representing discrete points on a circle. However, the results from our experiments can also be used by any designer or researcher who wants to create a haptic wristband.

Number of Motors

In our first experiment, we found that users can reliably detect ($\geq$ 87% accuracy) up to four or five vibration motors around their wrist, depending on wrist size. A solution involving four vibration motors could for example allow eyes-free navigation.

Interpolating Points

In Experiment 2, we investigated how interpolated points can be represented between two physical points, i.e. vibration motors. We designed six sets of patterns that relied on encoding the proximity of an interpolated point to two neighboring vibration motors. Encodings were based on three dimensions and two levels of temporality. We found out that using sequential vibrations is more accurate and ultimately slightly faster, and that proximity can be conveyed by either varying vibration duration or the number of pulses. The set of patterns we tested allowed interpolating up to three points between two vibration motors, making it possible to represent up to 16 points using a prototype with four motors.

Real Life Applicability

Ultimately, we applied our findings to a more realistic scenario mimicking online shopping with colorblind users. HaptiColor led to 94.4% and 100% accuracy for color matching tasks. For real-life usage, the prototype could have an embedded RGB sensor and provide real time data. Since users usually touch objects they want to check and hold them with their dominant hand, the RGB sensor could simply scan color and provide feedback, without the need for an additional, explicit interaction with a device (e.g. getting phone out, or transferring the device to the non-dominant hand to scan the item). Apart from assisting colorblind users, our solution could be applied to navigation tasks, by representing precise directions or cardinal points; or to convey information about continuous one-dimensional values (volume, distance to an object, etc.).

Extensibility

Our current design only allows interpolating three points between two physical points. Since our final design incorporates vibration duration as a dimension to represent proximity, we could add additional levels. Adding a third level, e.g. 1000 ms, would allow us to interpolate two additional points. In terms of colors, we would thus be able to represent a total of 18 colors with three motors.

Limitations

Although the results of our experiments are promising, our current design has a few limitations. First, we used cheap off-the-shelf vibration motors, and using better quality motors could positively impact the results. The motors used were also directly in contact with the participant's skin. This may not be possible for a real product, where the motors would most likely be inside a wristband. Extra fabric could risk diffusing the vibration over a larger surface. This could be mitigated using specific casing, such as in T-Mobile [23].

CONCLUSION AND FUTURE WORK

In this paper, we presented HaptiColor, an assistive wristband technology that encodes colors using spatiotemporal vibrotactile patterns. This solution was designed according to the results of two experiments. Our results showed that users can reliably locate vibrations on three or four vibration motors around their wrist; and that encoding the proximity of interpolated points is more accurate and faster using patterns that rely on variation of duration of the vibration, with each vibration played sequentially. Finally, we validated our final design in an experiment with six colorblind users where we observed that our participants were able to perform color matching tasks with high accuracy (94.4% to 100%).

Our results are also generalizable for other researchers as they suggest that the maximum number of vibration motors which can be embedded on a wristband depends on wrist size: large size (standard size for males) and small size (standard for females). Our set of patterns can also be used to encode discretized one-dimensional information (angles, directions, etc.). In future studies, we would like to extend our set of patterns, as well as propose exclusively temporal solutions for smaller devices, such as smart rings on which a large number of vibration motors cannot be embedded.

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