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Interactive Technology for People with Colour Vision Deficiency

Translating Colours into Haptic Feedback

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Abstract

Interactive Technology for People with Colour Vision Deficiency – Translating Colours into Haptic Feedback

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Ten percent of all males live with a colour vision deficiency, meaning their visual perception of colour is limited or absent, causing challenges in their daily lives. To find out how, and to which extent, haptic feedback can be utilised to communicate information about colour variations while achieving a high accuracy, an iterative interaction design cycle was applied, a functional physical prototype was developed further, five interviews and three user studies were conducted. Translating colours into haptic feedback, the wearable, a wristband, can automatically present a colour's hue and saturation to the user. An evaluation with eight colour-vision deficient users found that for some users both hue and saturation are relevant, while for others one parameter is sufficient. Hence, the user should be given the option to switch between different settings.

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– Alexandra Kandler, May 2018

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List of Acronyms and Abbreviations

AI	Artificial Intelligence
CIE	International Commission on Illumination (Commission Internationale de L'Éclairages)
CMYK	Cyan, Magenta, Yellow, and Key (Black)
CVD	Colour Vision Deficiency
HCI	Human-Computer Interaction
HSB	Hue, Saturation, and Brightness
HSL	Hue, Saturation, and Lightness
HSV	Hue, Saturation, and Value
IDE	Integrated Development Environment
IT	Information Technology
LED	Light-Emitting Diode
NASA TLX	National Aeronautics and Space Administration's Task Load Index
PACT	People, Activity, Context, Technology
RGB	Red, Green, and Blue
RYB	Red, Yellow, and Blue
SD	Standard Deviation
SUS	System Usability Scale
TUL	Łódź University of Technology
UX	User Experience

1 Introduction

A Rubik's cube, traffic lights, clothes, and bananas. One might wonder why this thesis starts off with a list of items that, on a first glance, do not appear related. The connection is the fact that colour is crucial to understanding all of them. While this does not necessarily represent a problem in itself, it may create challenges for those who have a limited visual sense. Being more prevalent among men, about one in ten males lives with a colour vision deficiency (CVD), often referred to as "colour-blindness". Comprising several forms, CVD can range from full monochromacy to colour vision with limited ability of colour discrimination.

CVD may impact people in different ways, but generally affects them in situations where colours are important or convey information. Solving a Rubik's cube, knowing which signal a traffic light gives, which clothes to select or combine, or when a banana is ripe can be more challenging when colour perception is limited or absent. Workarounds and techniques, such as learning the attributed meanings of a traffic light by remembering the order of lights instead of their colour, or memorizing colours of items are common and can help in everyday life. In some situations, such as shopping, supportive tools and applications for CVD may also be useful.

Aiming to provide a supportive tool for people with CVD, this thesis builds upon the research of Woźniak et al. [1] and Carcedo et al. [2], [3] who developed physical prototypes in the form of a glove and a wristband using vibrotactile sensations to translate colours from one sense to another (see Chapter 2.2). With the sense of touch being perceived twenty times faster than vision [4, p. 2], the wearables can support users in colour identification and comparison tasks by using haptic feedback. Their final prototype, a wristband named *HaptiColor,* made use of interpolation between three motors encoding twelve positions circularly mapped around the user's wrist, with each of them representing one hue of a colour wheel. However, it did not consider other parameters of an object's colour than the hue. In addition, neither Woźniak et al.'s [1] nor Carcedo et al.'s [2], [3] prototypes were tested in a real-world scenario such as shopping.

Therefore, the goal of this thesis was to firstly investigate user needs in the context of realistic fields of application. Interviewing five individuals with CVD (see Chapter 5.1) and conducting an initial pilot study (see Chapter 5.6) helped gain insights into the usage of the *HaptiColor* prototype, and led to the following research question this Master thesis aimed to answer:

> *How and to which extent can haptic feedback be utilised to communicate information about colour variations presented to people with CVD while achieving a high accuracy?*

Overall, the thesis project aimed to contribute the following:

1. Understanding
   - Thorough understanding of the problems and needs that colour-vision deficient people might face in their daily lives
   - Investigating how the prototype could help them in the identified needs and problems
   - Reviewing the current state of research on supportive tools for CVD

2. Prototyping
   - Making the prototype more stable and reliable
   - Adding a colour sensor to the prototype, making it more automated and less depended on Wizard of Oz techniques

3. Design Alternatives and User Testing
   - Based on user feedback, generating different design alternatives representing saturation and testing them with users to narrow down the design
   - Testing the enhanced prototype (with its colour sensor and the proposed design representing saturation) in a real-world scenario, ideally in the field, with individuals with CVD, aiming to evaluate the usefulness of the design

2 Background

The general field of this thesis project spans over the research area of *Human-Computer Interaction* (HCI), more particularly the areas of *User Experience* (UX) and *Interaction Design* are relevant. It is further connected to the field of *Universal Design* as the tool in question can be considered an assistive or enabling technology [5, p. 310] belonging to the area of *Wearable Computing* [6, p. 450].

2.1 Related Work

2.1.1 Mobile Applications for CVD and Other Visual Impairments

The variety of mobile applications supporting people with visual impairments is large. As the scope of this thesis does not focus on mobile applications, only a small selection of applications is presented in this chapter. The selection, however, is not limited to CVD only, but also looks into other visual impairments such as vision loss, as the target groups of some applications overlap and identified functions might be of relevance for this thesis project. Appendix A presents a more detailed overview of all the examined applications, their functions, and their availability for different operating systems.

To gather information about a user's environment, all of the selected applications use the smartphone's camera. Some of them provide instant feedback *(Chromatic Glass, Color Inspector, NowYouSee, Seeing AI)*, whereas others require the user to take a photo or record a video first, before information is processed and presented *(Eye of Providence, TapTapSee).*

Assisting people with CVD, several apps provide filters making colours more easily distinguishable *(Chromatic, Color Binoculars, NowYouSee).* Other approaches include replacing red and / or green parts of colours with differently striped patterns *(Red Stripes),* or highlighting confusing colours through blinking areas *(Chromatic Glass).* Instead of changing the look of colours, applications can also display their names *(Colour Inspector, Eye of Providence, NowYouSee, SeeingAI, TapTapSee)*. Additionally, some apps offer filters for people with normal vision simulating how people with CVD perceive colours *(Chromatic Glass, Sim Daltonism).*

For people with loss of vision, text-to-speech functions are available and / or objects in the environment can be identified *(Eye of Providence, Seeing AI, TapTapSee).* Sonification, the conversion of visual information into sound, is used by the applications *Seeing AI* and *Eye Music.* The latter provides training material and games to support the learning process of decoding the soundscapes. A crowd-based approach is implemented in *Be My Eyes* connecting visually impaired people and sighted volunteers via live video calls when assistance is requested.

All of these applications require interaction with a smartphone. Remaining with the sense of vision, many of them use visual data as way of communicating information to the user, while some make use of sound.

2.1.2 Computer-Based Applications for CVD

Of the aforementioned mobile applications *Sim Daltonism* and *Red Stripes* are also available for macOS, and *ChromaticGlass* can be used with a browser. Similarly to filters added to screen recordings in some of the mobile applications *(Chromatic, Chromatic Glass, Color Binoculars, NowYouSee, Red Stripes),* research has been done on using visual clues to encode information about colours on computer screens. Sajadi et al. [7] use patterns to encode colour information, while Jefferson [8] developed an algorithm allowing colour-deficient users to change colour representation with an application that can run as an extra layer above other screen content. Unlike other programs, Flatla et al. [9] present an highly individualized model supporting people with CVD in colour differentiation. Through calibration, the model can adapt a particular display to the user in a specific environment.

Different visual clues are examined by Flatla et al. [10]. Adding pop-out effects and clustering through patterns are found to provide the best results in colour identification tasks for people with CVD. For pop-out effects, users select one out of ten colours, and all pixels that do not include this particular colour are then reduced in brightness and chroma, whereas the selected colour remains the same and hence stands out. Clustering through patterns resembles a visual representation of a gauge through lines added above a colour – colour properties are mapped to properties of the lines (hue: angle; chroma: length). The techniques are tested on mobile devices and desktop computers, but the authors report that they could also be applied in other applications, such as glasses.

Computer-based applications can be of help for any screen-related tasks. Yet, they are not useful in everyday life away from the computer screen, such as being in a store.

2.1.3 Sonification of Visual Information

Sonification, "the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" [11], can be used to convert visual information to non-speech audio.

By mapping a 3D colour space to a 3D sound space, *SoundView* helps explore colours through sound and touch [12]. Sonification in *See ColOr* uses the hue, saturation, lightness (HSL) colour system to replace colour through various music instruments (hue: instrument timbre; saturation: sound pitch, luminosity: bass for dark and singing voice for bright), and explores mapping of spatial depth with rhythm [13]. The *KromoPhone* translates colour pixels detected on a screen or through a head-mounted camera to sound, making use of three selectable modes (red, green, blue (RGB); HSL; or red, green, blue, yellow, white (RGBYW)) [14]. Research conducted by Okunaka and Tonomura [15] looks into mapping visual to auditory features in *Eyeke* (hue: frequency / sound pitch; area size: loudness; shape: instrument; texture: noise; position: stereo balance; brightness: octave level). Cavaco et al. [16] developed a software to sonify images and videos making use of the hue, saturation, value (HSV) system (hue: pitch; saturation: timbre; value: loudness). In addition to colour, their system conveys information about shapes and objects, such as the number of objects, their location, geometry, and movement, as well as the location of light sources.

Examples of mobile applications making use of sonification by converting live camera recordings into soundscapes are *Seeing AI* and *Eye Music* (see Appendix A). *EyeMusic* converts shapes and colours of objects to different music instruments and different notes, while *SeeingAI* sonifies only the brightness of the environment to non-text audio and describes colours through speech output.

A rather extreme example is the monochromatic cyborg Neil Harbisson who has a permanent antenna with a colour sensor mounted to the front of his head to enable him to hear colours [17], [18]. A colour's frequency is converted into waves of musical notes, which are then transmitted through bone conduction by a chip connected to his auditory system via an implant at the back of his head.

Similar projects include *CitiesUnlocked, SoundScape,* and *CityScribe* which present sound making use of a wearable bone conducting headset, but instead of focusing on colour, 3D soundscapes are created, both verbally and no-verbally, for people with vision loss [19]. *EyeWear* looks into sonification of the spatial location of 3D objects within a distance of an arm length away from the user [20]. Using a head-worn sensor, objects on planar surfaces are detected, and audible information is presented through headphones. The prototype is aimed for people with vision loss and does not include information about colours. Unlike other projects, *The Oregon Project* does not create audio to directly map visual features, instead it is an interactive audio visual installation for people to experience landscape art enhanced with sounds based on their proxemics [21].

While sonification is an interesting approach as visual information is made audible and thereby communicated through another sense, it also remains to be investigated whether this fits the needs of user with CVD.

2.1.4 Glasses

2.1.4.1 Colour Correction Glasses for CVD

Currently, there are two leading firms offering colour correcting glasses for red-green CVD. Using so-called multinotch filtering in their lenses, *Enchroma* glasses filter out "sharp wavelengths of light to enhance specific colors[, and] separate the overlapping red and green cones" [22]. The glasses are offered as indoor or outdoor model for people with deuteranomaly or protanomaly, and can additionally be provided with lens strengths for both single and progressive lenses [23]. *Vino* offers multi-purpose glasses for people with CVD, but also protective eyewear for medical context enhancing the visibility of veins and blood oxygenation [24].

Scientific evidence on the effectiveness of colour correcting glasses is still scarce, but first results report no significant effects of *Enchroma glasses* tested with digital Ishihara plates [25]. The study does not, however, specify in detail which forms of CVD their participants had. Stating that "six severe deutans, two moderate deutans and two severe protans" [25] are tested does not take into account that the terms deutan and protan refer to all four forms of red-green CVD (see Chapter 3.2.3), while *Enchroma* glasses are labelled to function particularly for deuteranomaly and protanomaly. Another study looks into *Vino's O2Amp* glasses and *Enchroma* glasses [26]. Among 27 participants (10 deuteranopic, 8 deuteranomalous, and 9 protanopic), *O2Amp* improves colour discrimination for both deutan forms but not for protans, while *Enchroma* does not improve colour discrimination for any of them. The study does, however, not specify which model of *O2Amp* glasses they used. As stated by the manufacturer, the applied technology is called *O2Amp*, but from their selection of models only *Oxy-Iso* is suitable for people with CVD, while all others are not [24].

Tanuwidjaja et al. [27] developed an augmented reality application to be used with *Google Glass* to support people with CVD when distinguishing colours. The user can choose between four different modes to change the presentation of the real-time stream on the glasses' display: highlighting selectable colours, comparing two colours through increased contrasts, changing colour presentation through filters, and outlining of similarly coloured areas.

Making use of stereoscopic 3D glasses and an extensive setup, Hau Chua et al. [28] investigate augmenting vision for people with CVD through binocular luster effects. Both a pattern- and colour-based approach applied to stereo images with a luster effect are reported to be faster and to require a lower cognitive load than recolouring and pattern techniques, such as presented by Sajadi et al. [7]. The examined luster effect can be created with 3D glasses [28], but also with head-mounted displays or autostereoscopic displays.

All in all, CVD correction glasses such as *Enchroma* or *Vino* are only of help for users with certain forms of CVD, and scientific proof of their functionality is scarce. Other research required large setups or augmented reality glasses.

2.1.4.2 Multi-Function AI Glasses

The following commercial glasses make use of Artificial Intelligence (AI), and convey more functionality than 'just' colour as they are intended to be supportive tools for people with partial or full vision loss.

Microsoft's aforementioned mobile application *Seeing AI* can also be used with *Pivothead SMART* glasses which are equipped with a camera in the glasses' bridge [29]. By swiping the touch panel on the side of the glasses a photo of the surrounding scene is taken, then analysed, and the information is audibly read out to the user through the glasses [30].

OrCam MyEye, a small camera system that can be attached to any pair of glasses, works similarly and presents detected information audibly [31]. The camera, however, is gesture-based. By pointing on objects with a finger, it can detect colours, money notes, and product barcodes. Additionally, texts can be read out, and pre-stored faces are recognized. Time and date are announced by turning the wrist.

While these kinds of glasses offer large potential for users with visual impairments, they might have too much functionality for people with CVD who do not need support in all seeing-related tasks.

2.1.5 Haptic Feedback

2.1.5.1 Wristbands and Other Wearables with Tactile Displays

Tactile displays function similarly to common screens, but instead of visual output they give tactile feedback, and user input is done via touch. One possible output is vibrotactile feedback, which is differently perceived depending on the frequency, duration, intensity, and locus of a stimulation [32].

Jones and Sarter [33] report that users react slower to notifications on their mobile phone whilst being visually distracted, but not to alerts from a wristband with a tactile display. Out of 24 different vibration patterns, temporal patterns are found to be the easiest, and intensity-based ones the most difficult.

Investigating the ideal positioning of actuators, some researchers position vibrating motors on the volar or dorsal side of the wrist [33], [34], while Matscheko et al. [35] found that motors distributed circularly around the wristband perform better. The number of motors placed on wristbands varies for different studies, but Hong et al. [36] report that four circularly placed motors are preferred over eight. Despite the fact that eight motors result in a slightly higher accuracy than four in a study about directional guidance of the hand conducted by Hong et al. [37], the authors recommend a number of four motors considering the additional cost and weight of more motors. To represent more loci than only the ones of the motors, *phantom sensations* [38] can be created through interpolated vibrations [34], [36], [39].

While a lot of research is done on haptic wristbands with vibrotactile feedback [33]–[36], [40], few investigate approaches such as squeezing sensations generated with a spring [39]. *MagTics* is a rather flexible device that can be worn as a wristband, but also on other body parts or objects [41].

Other than focusing on the output given by a device, Gupta et al. [39] examine the potential of direct user manipulation. Users can interact with the tactile screen being placed circularly around the wrist by performing gestures with their second hand.

Overall, tactile displays provide the potential of communicating through tactile feedback without requiring visual or audible information to be presented through a wristband. Moreover, they can be utilized for user input and manipulation. Phantom sensations and interpolation allow to show more loci than actually exist.

2.1.5.2 Perceiving Colours Haptically

In 1998, one of the first devices presenting colours through haptic feedback is developed as part of the *VIDET* project [42]. Some other early interfaces make use of vibrotactile and force feedback on a joystick called *PHANToM* [43], [44]. Later, a variety of wearable colour detection gloves with haptic feedback are applied. Meers and Ward [45] present information about depth and colour through gloves worn on both hands. With electric pulses, blind users are supported in navigation tasks and colour detection. In addition to gloves, their prototype include rather bulky head-mounted goggles with several sensors. Using colour sensors mounted to the fingertips of a glove, Tapson et al. [46] communicate information about colour through haptic feedback on a torso-worn belt. Their prototype represents only four colours, users require a long time to decode vibration, and find it tiring. Later, they the positioning of the actuators is moved to the arm by adding a tactile display to the user's wrist [47].

Shrinking the size of prior gloves to a finger-mounted colour sensor with actuators Burch and Pawluk [48] aim for a more portable and affordable device, which is, however, not evaluated with users. The *HandSight* project look into wearable micro-cameras placed on the finger to support people with vision loss [49]–[51]. Their prototype has been evaluated in reading tasks, but the authors plan to extend it for other non-tactile information, such as colour and visual patterns. Both haptic and audible feedback are reported to perform similarly well, but audio supports the tracing of text lines better. Haptic feedback is given in the form of two vibration motors mounted to the upper and lower part of the index finger which is moved to 'sense' text. Similarly, Medeiros et al. [52] experiment with finger-mounted cameras equipped with a light-emitting diode (LED) allowing to identify the colour of clothes and visual textures.

Haptic feedback offers a large potential when it comes to communicating information about colours for people with CVD. Having started about 20 years ago, research is still relevant today. With the size of devices having decreased over time, today's wearables, being small in size and portable, can be at-hand whenever needed. While finger-mounted devices and gloves might attract attention and, therefore, give rise to stigmatisation, wristbands can be more unobtrusive. It is, however, important to have a simple and logical system as users might be exhausted when decoding demands high concentration, such as in Tapson et al.'s [46] work.

2.2 Previous Projects – *ChromaGlove* and *HaptiColor*

The thesis project builds upon previous work on supporting individuals with CVD using interactive technologies. In particular, the project expands on the work presented by Woźniak et al. [1], and Carcedo et al. [2], [3].

Woźniak et al.'s [1] research includs a prototype in the form of a glove *(ChromaGlove)* supporting people with CVD with the identification of colour. Using a sensor to identify the colour in question, its hue is converted to haptic feedback by means of different pulse widths. The glove is further equipped with a display mounted to the top of the glove providing the colour's name and debugging information.

As this does not allow for comparing different colours, a second prototype in the form of a wristband *(HaptiColor)* with vibrotactile feedback was developed by Carcedo et al. [2], [3]. Conducting several studies, they report that, for colour comparison tasks, the wristband being placed on the participants' dominant hand works best with *three motors* achieving an accuracy of 94.9 %. As their aim is to represent more than just primary and secondary colours, they investigate how to represent interpolated points, which are imaginary points between two physical locations, showing positions on the wristband that do not have a motor. Out of four different dimensions (intensity, duration, number of pulses) and two different temporalities (simultaneous, sequential) a combination of *duration* and *sequential temporality* is found to have the highest accuracy for such interpolation. Therefore, twelve positions on the wristband, each of them presenting one hue, are encoded by three motors. For this, an RGB colour wheel is mapped onto the wristband. The prototype consists of an *Arduino Genuino UNO* connected to a breadboard as well as a Velcro wristband. Figure 1 shows the *HaptiColor* prototype, which, along with its Arduino code, was available for the thesis start to evaluate and research further.

Limitations of the two prototypes include that neither *ChromaGlove* nor *HaptiColor* are tested in a real-world scenario. Also, *HaptiColor* does not have a colour sensor, but makes use of Wizard of Oz-techniques, meaning that the colour input has to be simulated by entering data through the *Arduino Desktop Integrated Development Environment*'s (IDE) serial monitor. Thus, the prototype needs to be connected to a computer to be able to receive haptic feedback. As listed as one of their limitations, the motors are directly placed on the skin, which is an unlikely solution for a final product [2]. Moreover, the scope of colours that can be communicated is limited to twelve hues.

Figure 1 – HaptiColor Prototype [2]

3 Theory

3.1 Colour

3.1.1 Definition of Colour and its Properties

Generally speaking, light is electromagnetic radiation of which a small part lies within the range of the visible spectrum [53, p. 4]. The definition of colour depends on its context. According to Shevell [54, p. 151] it can generally be differentiated between *related colours* and *unrelated colours.* Related colours refer to one single light or colour seen in isolation [54, p. 151], [55, p. 163], while unrelated colours mean light or colour seen in relation to other colours or lights [54, p. 151], [55, p. 129]. A single isolated light, however, only appears in laboratory settings, and not in the real world. Further, the International Commission on Illumination (CIE) defines that a perceived colour "depends on the spectral distribution of the colour stimulus, on the size, shape, structure and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situations of observation" [55, p. 28].

Three different modes of colour appearance can be described for the perceived colour of an object [54, pp. 151 – 152], [55, p. 28]. Firstly, *illuminant mode* means colour is visible due to light being directly emitted from a light source; this relates to unrelated colours only. Secondly, *surface mode* describes when the colour of an object becomes visible through light being reflected by a surface. Thirdly, *object mode* describes the colour of an object. Both, illuminant and object mode can be associated with related colours.

The properties of the appearance of unrelated colours include *hue*, *saturation*, and *brightness* [54, p. 151]. Additionally, *lightness* and *chroma* are relevant to describe related colours [54, p. 162]. Table 1 presents an overview of these properties, Figure 2 to Figure 6 show examples of them.

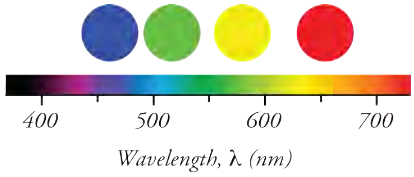
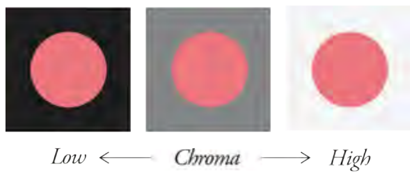
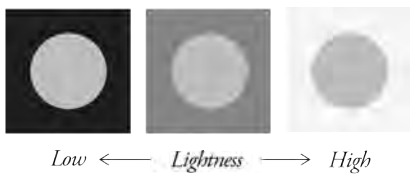
	Property	Definition	Example
Unrelated Colours	*Hue*	"Hue is the aspect of the percept that differentiates it from white" [54, p. 151]. It can be interpreted as the different parts of the visible spectrum [56, p. 235]. All possible hue percepts can be described through the four unique hues or combinations of them [54, p. 153], [55, p. 163]. The unique hues (also called unitary hues), red, green, yellow, and blue, represent a minimal set of hues. None of them can be described through the others, which makes them unique [54, p. 153], [55, p. 163]. On the visible spectrum, red can usually be found around 640 nm – 700 nm, yellow near 580 nm, green near 500 nm, and blue near 470 nm [54, p. 152].	 *Figure 2 – Visible Spectrum and Unique Hues*
	Saturation	Saturation can be described as "the perceived difference between a color and white" [54, p. 153]. The CIE frames it as "colourfulness of an area judged in proportion to its brightness" [55, p. 136]. On the visible spectrum, yellow is perceived as least saturated due to the fact that "long-wavelength lights and short-wavelength lights are perceived as more saturated than wave-lengths near 580 nm" [54, p. 153]. The more saturated a hue, the more intense and vivid it appears; the less saturated a hue the more grey and dull it is perceived [56, p. 240], [57, p. 12].	 *Figure 3 – Example of Saturation*
	Brightness	For unrelated colours, brightness defines the "perceived level of light emitted by the source" [54, p. 154]. For related colours, it refers also to the "attribute of a visual perception according to which an area appears to emit, or reflect, more or less light" [55, p. 15]. It can range from "dim to dazzling" [54, p. 151].	 *Figure 4 – Example of Brightness*
Related Colours	*Chroma*	Chroma is similar to saturation but differs in the way that "saturation [...] is the perceived difference between a color and white, regardless of lightness (or brightness)" [54, p. 162], while chroma is a relative value depending "on a reference color that varies according to the lightness of the stimulus under consideration. The reference color is often a gray" [54, p. 162].	 *Figure 5 – Example of Chroma (identical circles, but differently perceived chroma depending on reference colour)*
	Lightness	Lightness is similar to brightness, but as it refers to related colours, it is the "brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting" [55, p. 82]. Also, in nature, lightness tends to be more salient than brightness [54, p. 162]. Lightness is also named value [57, p. 14].	 *Figure 6 – Example of Lightness (identical circles, but differently perceived lightness depending on reference colour)*

Table 1 – Properties of Related and Unrelated Colours

3.1.2 Naming and Organisation of Colours

Most visualisations of colour relationships are presented in the form of colour wheels including a set of twelve hues [56, p. 235], [58, p. 79]. "On a color wheel, colors are not shown at the same value. Each color is shown unmixed and pure" [56, p. 235]. *Primary colours* are the three basic colours of such a model, for instance Red, Green, and Blue for RGB (see solid lines on left side of Figure 7), Cyan, Magenta, and Yellow for CMYK, or Red, Yellow, and Blue for RYB [56, p. 235], [57, p. 19] (see solid lines on right side of Figure 7). By mixing primary colours, three *secondary colours* are created [56, p. 235] (see dashed lines in Figure 7). Mixing primary and secondary colours results in a total of six *tertiary colours* [56, p. 235], [57, p. 19] (see dotted lines in Figure 7).

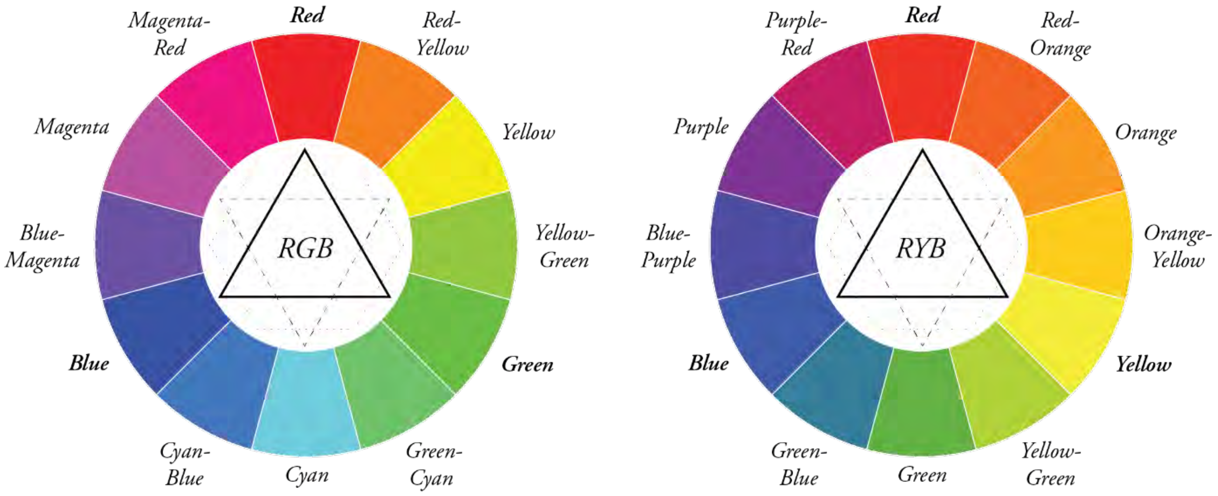


Figure 7 – RGB and RYB Colour Wheel with Three Primary Colours (Solid Lines), Three Secondary Colours (Dashed Lines), and Six Tertiary Colours (Dotted Lines) each; Colour Values Based on w3schools.com [59].

One of the fundamental studies on naming of colours in various languages was conducted by Berlin and Kay [60] in 1969. Examining 98 languages, they found that most languages comprise a set of up to eleven *basic colour terms*. As shown in Figure 8, they report that black and white are always part of these basic colour terms; when a language consists of three terms, it includes red; languages with a fourth term include either green or yellow; a fifth term means they use both green and yellow; a sixth term is used for blue; the seventh term is brown; and languages with eight or more terms include purple, pink, orange, grey, or combinations of them [60]. Building upon this cross-linguistic study, Boynton and Olson [61] examined the use of these terms in English confirming that, despite linguistic richness, the eleven basic colour terms are used in more than two thirds of all their conducted tests.

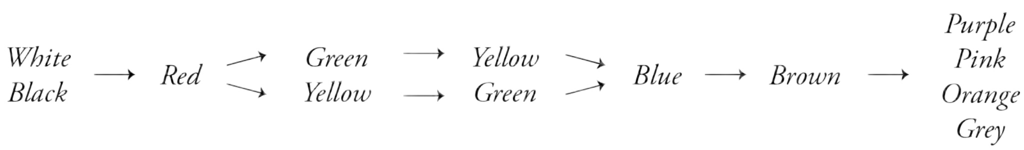


Figure 8 – Seven Stages of Basic Colour Terms [60, p. 4]

3.1.3 Additive and Subtractive Colour Systems

Generally, colour is based on two different systems, namely *additive* and *subtractive system*, depending on the source of light. The additive system, presented on the left in Figure 9, is commonly called *light colours* and refers to colours being created from a direct light source, such as a screen [56, p. 232]. No light means black; the more light added, the brighter the result; mixing all primary colours of an additive system (red, green, and blue) results in white [56, p. 232]

In the subtractive system objects neither illuminate nor do they have a colour on their own, instead what is perceived as their colour is based on reflected and absorbed light. While white reflects all light, black absorbs it all. By adding 'colour' to a white surface, the wavelengths of this colour are reflected, while all other colours are absorbed; only the colour that is not absorbed is perceived. The more colours are added, the darker the result [56, p. 232]. Common subtractive colour models are RYB used in painting, and CMYK in printing [56, p. 232], [58, p. 7] (see right side of Figure 9).

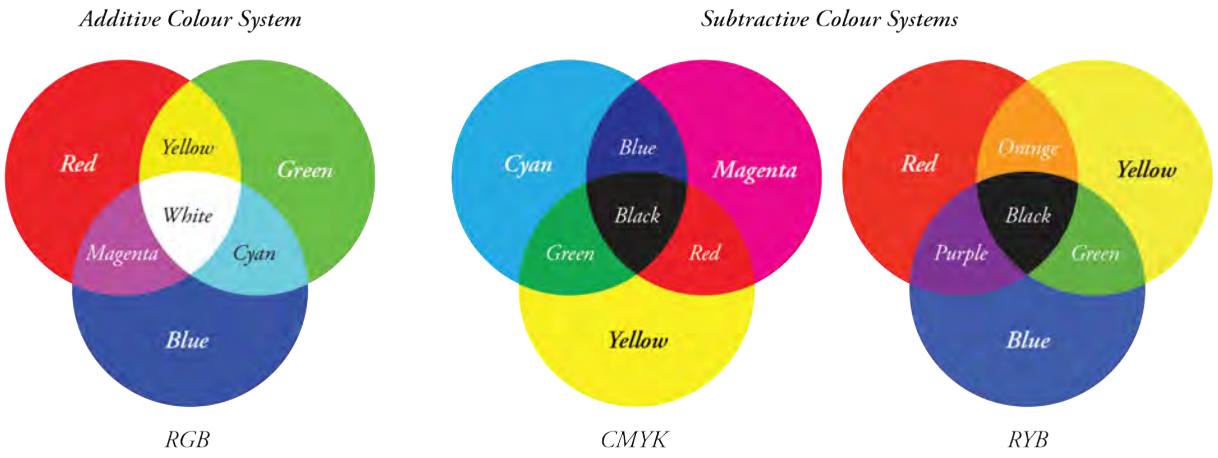


Figure 9 – Additive and Subtractive Colour Systems

3.1.4 HSL and HSV / HSB Colour Space

The RGB colour model can be represented three-dimensionally through the colour spaces *HSL* or *HSV* (sometimes also referred to as hue, saturation, brightness *(HSB)*) [58, p. 58]. As shown in Figure 10, they are akin, but differ in their shape – HSV is a (hex-)cone, while HSL is shaped as double (hex-)cone [58, p. 60]. Both the HSL and HSV colour space have a centred vertical axis that reaches from black at the bottom to white at the top – for HSL this axis represents lightness, for HSV value [58, p. 63]. Both axes start at the bottom of the shape, but for HSV it ends in the centre of the colour wheel, giving it the shape of a cone, while it reaches above the colour wheel resulting in a double coned shape for HSL [58, p. 62]. Value is used to describe the brightness, and it ranges from 0 % (black) to 100 % (centre of the colour wheel) [58, p. 62]. Lightness describes the level of illumination, and spans from 0 % (black, no illumination) to 100 % (white, full illumination) cutting through the colour wheel at 50 % [58, pp. 62 – 63].

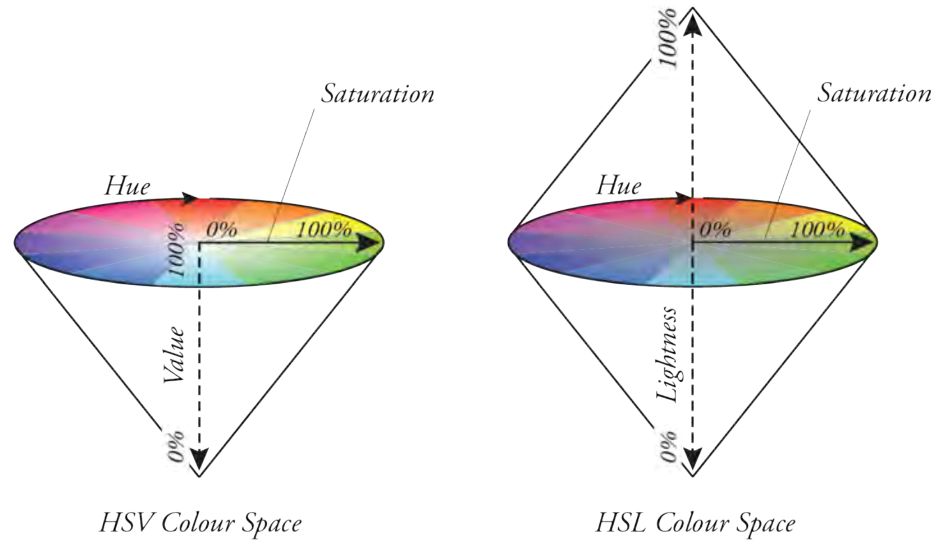


Figure 10 – HSV / HSB and HSL Colour Space (based on Rhyne [58, pp. 61 – 64]); For Value and Lightness 0 % Means Black, while 100 % Means White

For both, hues are represented circularly with 0° / 360° for red, 60° for yellow, 120° for green, 180° for cyan, 240° for blue, and 300° for magenta [58, p. 61]. As illustrated in Figure 11, the saturation is indicated from 0 % for desaturated and 100 % for fully saturated colours – the further inside the colour wheel the less saturated, the further out the more saturated. For HSV 0 % saturation means 100 % value, hence, white. For HSL, on the contrary, 0 % saturation means 50 % lightness, hence neutral grey [58, p. 61], [62].

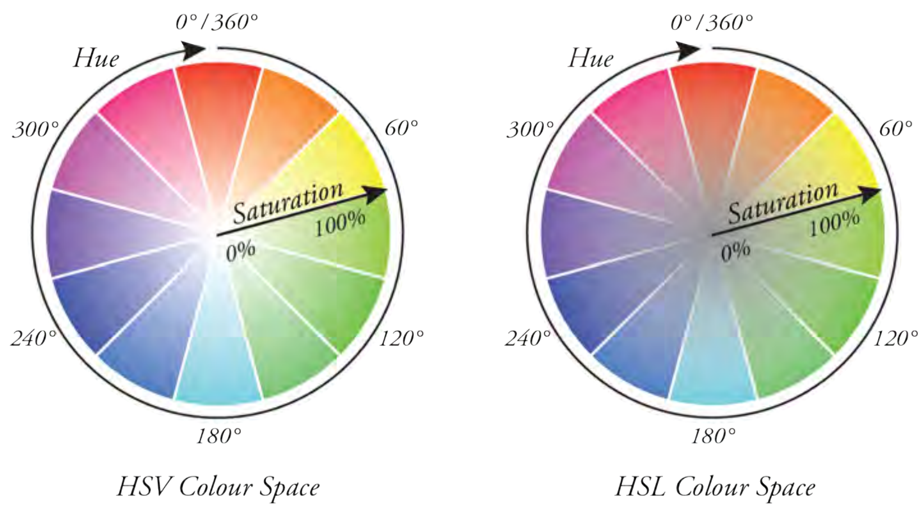


Figure 11 – HSV / HSB and HSL Colour Space: Hue and Saturation in Aerial Perspective

Neither HSL nor HSV are absolute colour spaces [58, p. 64]. HSV is conceptually simpler than HSL [58, p. 64], but mixing a pure colour with white inevitably results in a desaturation, while mixing it with black does not affect the saturation [58, p. 63]. On the contrary, for HSL a colour's saturation is not affected when mixed with black or white [58, p. 64], instead it "is symmetrical to lightness and darkness (which is not the case with HSV […])" [62]. For the scope of this project, HSL is selected as colour space owing to the fact that it is simpler to grasp than RGB, but also because hue and saturation are not affected by lightness.

3.2 Visual Perception

As humans commonly perceive colours through their visual sense, this chapter first outlines the basic functioning of trichromatic colour vision, photoreceptors found in the human eye, and parameters of the visible spectrum (see Chapter 3.2.1). Further, a theoretical framework is presented according to which our colour perception is grounded on three channels (see Chapter 3.2.2). Building upon this, it is described how and why for some people colour vision is limited or absent, which forms of CVD are known, and who is predominantly affected (see Chapter 3.2.3).

3.2.1 Basic Principles of Human Colour Vision

As light stimuli fall into the human eye in the form of radiation, visual sensations are created [63, p. 42]. In the retina four photoreceptors, three cone receptors and one rod receptor, can be found [64, p. 309], [65, p. 66]. While cone receptors enable vision during daylight (photopic vision), the more sensible rods are specialised for vision at night (scotopic vision) and operate for monochromatic vision only [64, p. 308], [66, p. 66], [67], [68]. The three cone receptors are called *L-, M-, and S-cones*; L-cones are predominantly sensitive to long wavelengths (red), M-cones to middle wavelengths (green), and S-cones to short wavelengths (blue) [64, pp. 308 – 309], [66, pp. 66 – 67], [69, p. 5]. As human colour vision is based on these three receptors in normal light conditions, it is considered three-dimensional and trichromatic [70, p. 98].

According to the CIE, "there are no precise limits for the spectral range of visible radiation since they depend upon the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 nm and 400 nm and the upper limit between 760 nm and 830 nm" [55, p. 166]. As presented in Figure 12, the spectral sensitivity of S-cones peaks around 420 nm, M-cones around 534 nm, and L-cones around 564 nm [64, p. 309], [71, p. 505], [72, p. 34].

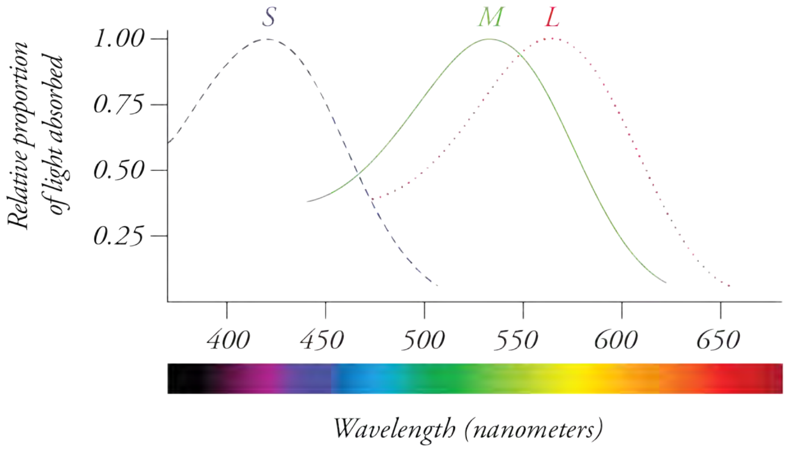


Figure 12 – Spectral Cone Sensitivity [64, p. 309], [71, p. 505], [72, p. 34]

3.2.2 Colour Opponent Process Theory

According to the colour opponent process theory visual perception is based on three different main channels, more precisely one luminance channel, and two chromatic channels [65, pp. 68 – 69], [70, pp. 110 – 111]. These channels are based on the aforementioned S-, M-, and L-receptors.

The *luminance channel* (also called brightness channel) represents the total energy of brightness and can be seen as black-white channel. Including information about the brightness differences of different colours, this channel obeys more details than the two chromatic channels. It "combines the outputs of long- and middle-wavelength-sensitive cones" [65, p. 68] and can be summed up as $M + L$ (see dashed lines in Figure 13).

The two *chromatic channels* are the red-green opponent channel (c1; see solid lines in Figure 13), and the blue-yellow opponent channel (c2; see dotted lines in Figure 13). The former represents "the difference between the signal from the middle- and long-wavelength sensitive cones" [65, p. 68], and can be calculated with $c1 = M – L$. The latter relates to $c2 = S – (M + L)$.

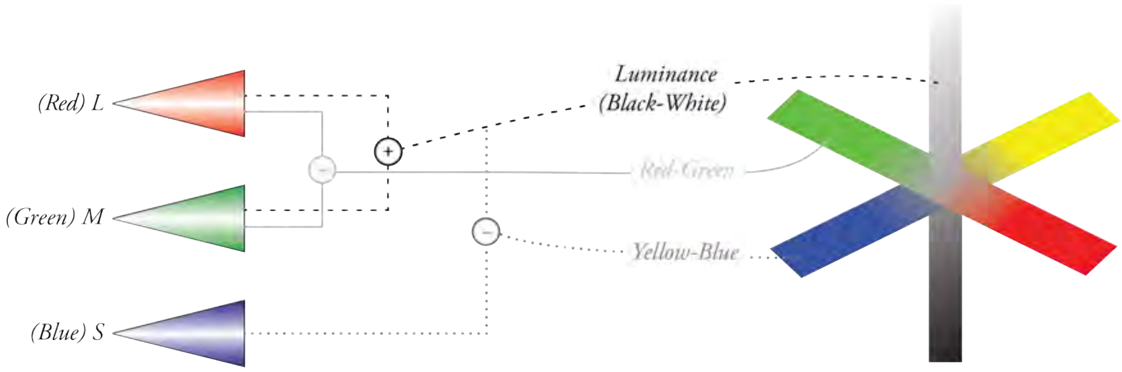


Figure 13 – Colour Opponent Process Model based on [70, p. 111]

3.2.3 Colour Vision Deficiency

Vision is *trichromatic* when all photoreceptors function, dichromatic when two cones work, and *monochromatic* when only one receptor operates [64, pp. 308, 316], [66, p. 66]. While trichromacy is generally referred to as "normal human color vision" [73, p. 104], dichromacy, monochromacy, as well as anomalous trichromacy are considered to be a CVD, often referred to as "colour-blindness" in everyday language. The CIE defines CVD as "anomaly of vision in which there is a reduced ability to discriminate between some or all colours" [55, p. 39].

In total, "about 10 % of the male population and about 1 % of the female population have some form of color vision deficiency" [70, p. 99]. Being most prevalent among Caucasian, the most common form is a red-green deficiency (protan and deutan) with approximately 8 % of men and 0.5 % of women [64, p. 315], [69, p. 22].

CVD can be acquired through damages caused to the eye, optic nerve, or brain [58, p. 28] "owing to ocular diseases (such as glaucoma), or to systemic conditions that affect the eye and optic pathways (such as diabetes and multiple sclerosis), or to strokes, cerebral inflammations, and head injuries" [69, p. 25], but is most commonly genetically inherited [64, p. 314]. Lost, non-functional, or altered genes, as well as gene mutations [64, pp. 314 – 315] lead to "changes in the properties of L, M and S cones, which cause specific patterns of colour discrimination loss" [74, p. 35]. Other visual functions, such as visual acuity are, however, not affected [74, p. 35].

For *deutans* the M-cone is absent or altered, while for *protans* the L-cone is missing or limited in its functions. For both of them the red-green channel of the colour opponent process model (see Chapter 3.2.2) is affected. *Tritans'* S-cone is either lacking or distorted, which impacts the yellow-blue channel. Table 2 presents an overview of the variations of CVD that can be distinguished.

	Form of CVD	**Absent Contribution**	**Effect on Colour Vision**
Monochromacy	*Rod Monochromacy (Achromatopsia)*	All three cones absent	*No colour vision.* Only brightness differences distinguishable. Sensitive to bright light as only rods function.
	Cone Monochromacy	Two cones absent	*No colour vision.* Only brightness differences distinguishable. Different variations: S cone always absent or inactive; can have M or L cone, but not both.
Dichromacy	*Deuteranopia*	M-cone absent	No discrimination of *red and green* parts of colours.
	Protanopia	L-cone absent	No discrimination of *red and green* parts of colours. Reddish colours appear abnormally dim.
	Tritanopia	S-cone absent	No discrimination of *blue and yellow,* or *blue and green* parts of colours.
Anomalous Trichromatism	*Deuteranomaly*	M-cone weak or altered	Reduced discrimination of *red and green* parts of colours.
	Protanomaly	L-cone weak or altered	Reduced discrimination of *red and green* parts of colours. Reddish colours appear abnormally dim.
	Tritanomaly	S-cone weak or altered	Reduced discrimination of *blue and yellow,* or *blue and green* parts of colours.

Table 2 – Forms of CVD [55, pp. 39 – 40], [58, pp. 28 – 31], [64, pp. 314 – 321], [74, pp. 35 – 45], [75, pp. 32 – 36]

While the majority of people with acquired CVD are tritans (yellow-blue deficient) [64, p. 318], inherited CVD is more common among protans and deutans (red-green deficient) [64, p. 315]. For the latter men are more likely to be colour deficient due to genetic reasons, more precisely due to disturbances of an opsin gene on the X-chromosome [64, p. 315], [76]. Women have two X-chromosomes, whereas men have one X- and one Y-chromosome. When a man's single X-chromosome is affected, he has a CVD. A woman, on the contrary, is only impacted when both of her X-chromosomes are affected; if just one of them is, she is considered a carrier potentially passing it on to her children, but not being colour-vision deficient herself – or at least not noticeably due to a process called X-inactivation [76].

It is possible to diagnose CVD in various ways, for instance through an optical device called anomaloscope [69, p. 33]. Especially for red-green deficiencies colour confusion charts such as pseudoisochromatic Ishihara plates [64, p. 315], [69, p. 33], or other diagnostic tools such as "hue discrimination or arrangement tasks […], and lantern tests" [64, p. 315] can be used.

3.3 Wearables and Haptic Technology

For wearable computing six key attributes can be identified [6, p. 453], [77]:

1. *Unrestrictive:* User can interact with wearable or do other things while wearing and moving with it.
2. *Unmonopolizing:* User is not cut out from outside world and can pay attention to other tasks while wearing wearable. Ideally, sensory capabilities are enhanced.
3. *Observable:* The wearable is continuously perceptible by the user.
4. *Controllable:* User is in control of wearable at any time.
5. *Attentive to environment:* Increased environmental and situational awareness for the user. Often use of multimodality and multisensory.
6. *Communicative to others:* Wearable can serve as communication medium.

The term *haptic* refers to "the science of applying tactile, kinesthetic, or both sensations to human-computer interactions" [4, p. 5]. While *kinesthetic perception* is connected to the feeling of motion and the positioning of our joints, muscles, and tendons, *tactile perception* is related to sensations on the skin [4, pp. 5, 9]. The human skin can distinguish four modes of sensation, namely touch, cold, heat, and pain [4, p. 2], but *tactile* commonly relates to "pressure rather than temperature or pain" [4, p. 5]. To enable interaction, haptic devices are equipped with sensors as input, and / or actuators as output [4, pp. 5 – 6]. Haptic interfaces can generally be distinguished in *tactile devices*, and devices using *force feedback* [4, p. 10]. The former use vibration, temperature, or pressure, whereas the latter utilize resistive force, friction, or roughness [4, p. 10]. Compared to human visual perception, touch is perceived twenty times faster [4, p. 2], and can therefore be considered an efficient way of augmenting or communicating information to users.

3.4 Usability and User Experience

According to ISO 9241-210, the international standard for ergonomics of human-system interaction, *usability* is defined as "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [78]. The characteristics of high usability are often extended as to being easy to learn, being safe to use, and having a high utility [6, p. 81].

Usability is also related to the People, Activity, Context, Technology (PACT) framework which describes the aim of balancing out four factors: "People[,] Activities people want to undertake[,] Contexts in which the interaction takes place[, and] Technologies (hardware and software)" [6, p. 82].

Taking this a step further, Morville's [79] honeycomb of UX includes seven dimensions as a framework of UX. While a product does not only need to be useable to have a good UX, it also needs to fulfil several other qualities such as being accessible, credible, desirable, findable, useful, and valuable [79]. Hence, UX goes beyond designing usable products by designing a positive experience [6, p. 94] that yields pleasure [6, pp. 99 – 100] and is aesthetically appealing [6, p. 102].

To evaluate usability different methods can be applied, such as usability testing, A / B testing, and surveys [80, pp. 10 – 17]. A common approach is also the usage of standardized questionnaires which are "designed for repeated use, typically with a specific set of questions presented in a specified order using a specified format, with specific rules for producing metrics based on the answers of respondents" [80, p. 85]. Different standardized questionnaires are available for different purposes, such as the two utilised for this research project, namely the System Usability Scale (SUS) to evaluate the usability of a product or system [80, pp. 198 – 211], [81], and the National Aeronautics and Space Administration's Task Load Index (NASA TLX) to assess the perceived workload of a system or tool [6, p. 480], [82].

4 Project Procedure

4.1 Methodology

The overall methodological approach this thesis builds upon is an iterative interaction design cycle such as presented by Preece et al. [83, p. 332] and Benyon [6, p. 49]. As shown in Figure 14, there are four main activities, namely *Understanding* (alias *Requirements*), *Design Alternatives* (alias *Envisionment*), *Prototyping*, and *Evaluation*, but there is no given start of the cycle meaning that it can begin with any activity, nor is the order of activities predefined. Instead, quick iterations, early evaluation, and user engagement are incorporated. Being user-centred this approach focuses on users and their needs from an early stage of the design process.

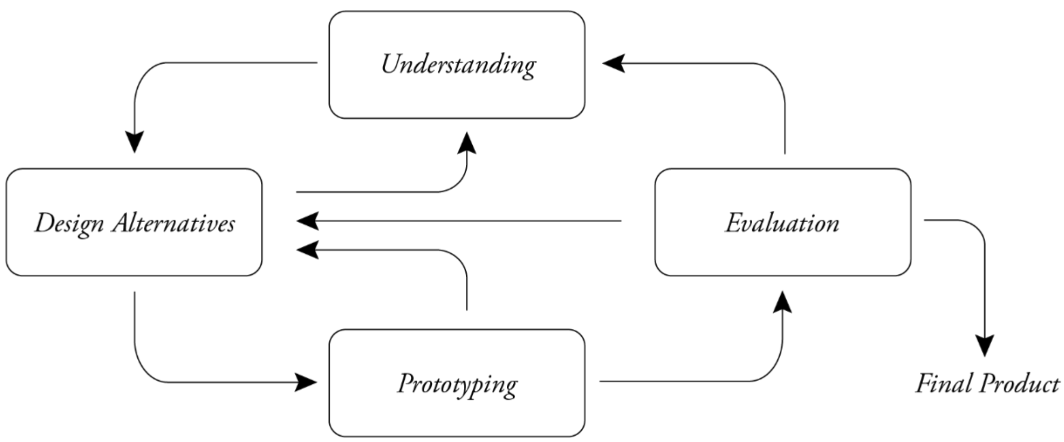


Figure 14 – Interaction Design Cycle based on Benyon [6, p. 49] and Preece et al. [83, p. 332]

4.1.1 Initial Understanding – Literature Review, Interviews, Pilot Study

Despite the fact that an evaluated prototype was available for the start of this project, requirements needed to be established and, as "requirements are essentially about understanding" [6, p. 50], a thorough understanding of CVD as well as the needs of people with CVD was crucial. They are commonly "generated through discussions and interactions with people who will use or be affected by the proposed system" [6, p. 50], such as users or other stakeholders. Engaging with them in the design process is often referred to as participative design and includes techniques such as focus groups, workshops, interviews, observations, and think-aloud [6, p. 141]. Being strongly interwoven with other phases of the aforementioned design cycle these techniques were likewise applied later on in the process, and a third of the project's time span was dedicated to an understanding phase. Together, the following three activities formed the project initiation of this thesis and helped define the research question (see Chapter 1).

Literature Review

Firstly, a literature review was conducted to see where the current state of research for supportive tools lied (see Chapter 2.1). In addition, the theoretical background of colours, colour vision, as well as CVD were investigated (see Chapter 3).

Semi-Structured Interviews

Secondly, five colour-vision deficient people were interviewed (see Chapter 5.1) to get a deeper insight of the needs and problems of people with CVD. The chosen method, semi-structured interviews, helped receive individual opinions as well as interesting insights on topics such as memorising colours and techniques used in their daily lives. Further, different themes related to problems emerging from CVD were identified, qualities of supportive tools were discussed, and the focus of the initial pilot study was formed. Compared to open and structured interviews, it was possible to have guiding themes and question, but still being responsive and open towards individual statements and thoughts.

Initial Pilot Study

Thirdly, an initial pilot study with six participants was conducted aiming to see how the prototype presented by Carcedo et al. [2], [3] was used (see Chapter 5.6). To receive a more comprehensive overview, qualitive and quantitative data were combined, including observations, think-aloud, and post-test interviews. A more detailed description of the study design and the applied methods can be found in Chapter 5.6.2.

4.1.2 Project Execution – Design Alternatives, Prototyping, Evaluation

User-Based Design Alternatives

Building upon the initial interviews and pilot study it was decided to take the design of the current prototype and expand it by introducing more information about colour. While users already received information about hues, the aim was to decode a colour's saturation. For this, it was decided to apply the colour space HSL. Based on user feedback different design alternatives were generated to represent the saturation (see Chapter 6.1). Additionally, a basic interaction model was outlined with two device settings.

Second Pilot Study

By means of a pilot study with six participants, three design alternatives for the haptic encodings of saturation were evaluated (see Chapter 6.2). Similarly to the initial pilot study, quantitative data helped gain insights on measurable factors such as performed accuracy, and perceived workload rated through a questionnaire, while being enriched with qualitative data letting people express their opinions through think-aloud and post-test interviews without being restricted to numbers only. A more detailed description of the study design, and the applied methods can be found in Chapter 6.2.2.

Prototyping

While Wizard of Oz techniques were applied to operate during the two pilot studies, the physical prototype was then improved to function more independently by equipping it with a colour sensor (see Chapter 6.3).

Final User Study

As all tests conducted during this research project, the final study was participant-based as opposed to expert-based [6, pp. 214 – 230]. The evaluation of the final design alternative took place by means of a user study with eight colour-vision deficient individuals (see Chapter 6.4). Comparing two conditions in a controlled laboratory environment [6, pp. 222 – 223], here, too, a combination of qualitative and quantitative data helped gain comprehensive insights, and gave insights from different perspectives with different data explaining saliences in other kinds of data. In terms of quantitative data, accuracy was measured, and usability and workload were ascertained through standardised questionnaires. Qualitative data included think-alouds, post-test interviews, as well as observations. A more detailed description of the study design, and the applied methods can be found in Chapter 6.4.2.

4.2 Time Plan

Allotting the time, about 20 weeks were available for both the practical implementation of the project and writing the thesis before defending the final draft. Overall, the thesis project can be divided into three phases as presented in Table 3.

As part of the thesis project, a two-months traineeship which included the *Execution Phase* was spent at *Łódź University of Technology (TUL)* in Poland under the Erasmus+ program. The main goal of the traineeship was to improve the thesis project by making use of the knowledge and skills of the *Institute of Applied Computer Science* at *TUL*, in particular their technical expertise in physical prototyping.

Phase	Duration (Weeks)	Methods and Action Steps	Chapters
Initiation	01 – 06	Literature Review	2 – 3
		Initial Interviews	5.1
		Initial Understanding of Prototype	5.2 – 5.4
		Initial Adjustments on Prototype	5.5
		Initial Pilot Study	5.6
		Definition of Research Question	1
Execution	07 – 16	Design Alternatives	6.1
		Evaluation of Design Alternatives (Second Pilot Study)	6.2
		Prototyping	6.3
		Evaluation of Final Design Alternative (Final User Study)	6.4
		Conclusion and Future Work	7
Documentation	17 – 20	Report Work (Revision, Proofreading, Formatting)	
		Thesis Presentation	

Table 3 – Phases of Thesis Project

Throughout the project an interactive Gantt chart was used to inform everyone involved about the recent state and the next steps, as well as to support time management. As shown in Appendix B it included both milestones (triangles at the top) and tasks (coloured bars below) to visualise next steps and deliverables. Being web-based the tool *Agantty* enabled easy updates and access to the latest version without the need of sharing updated files with everyone involved in the project.

5 Project Initiation

5.1 Initial Semi-Structured Interviews – Understanding User Needs

5.1.1 Objectives of Initial Interviews

The aim of these interviews was to get a deeper understanding of CVD and problems people with CVD might face in their daily lives. Additionally, it helped define the focus of the subsequent pilot study (see Chapter 5.6) which served as input for the next phases of this study.

5.1.2 Interview Design of Initial Interviews

5.1.2.1 Apparatus

One interview was conducted in person, and the other four via Skype as the interviewees lived in other countries. The informed consent forms shown in Appendix E were used.

5.1.2.2 Procedure

The interviews were divided in two groups; the first three interviews focused on deepening the understanding of CVD and problems related to it, while the last two additionally helped define the precise focus of the subsequent pilot study. Guiding questionnaires were prepared for all interviews (Appendix C for I1 – I3, Appendix D for I4 – I5). As the interviews were semi-structured, these questions were, however, not followed strictly, but rather served as guidance to steer the topics of the discussions.

5.1.2.3 Data Collection

The data gathered through semi-structured interviews was of qualitative nature. During the first three interviews notes were taken in English, while the last two were recorded after asking for participants' consent, and notes were transcribed afterwards as they had to be translated from German to English.

5.1.2.4 Participants

In total, five people (I1 – I5) with CVD were interviewed (see Table 4). They were males aged between 24 and 33. Two of them worked in HCI-related fields, one of them in Information Technology (IT), and two had a background in economics.

Interviewee	Gender	Age	Form of CVD	Confusing Colours	Professional Background
I1	Male	24	Deuteranopia	Red-Green	HCI
I2	Male	33	Unknown	Yellow-Green, Red-Brown	IT
I3	Male	29	Unknown	Red-Green	HCI
I4	Male	27	Unknown	Red-Green, Blue-Purple, Brown-Red	Industrial Management, Business Administration
I5	Male	24	Protan	Red-Green, Problems with Blue	Health and Economics
Total	**Female: 0** **Male: 5**	–	**CVD: 5** **No CVD: 0**	–	**Economics: 2** **HCI: 2** **IT: 1**
Mean	–	27.4	–	–	–

Table 4 – Initial Interviews: Demographic Data of Interviewees (I1 – I5)

5.1.3 Results of Initial Interviews

The following presents different themes that were identified in the initial interviews.

5.1.3.1 Problems Related to CVD

How much someone felt affected by their CVD in their daily life seemed to depend on the perceived severity of their CVD. As shown in Table 5, I1 – I4 stated not be impacted strongly, while I5 was stronger affected.

Perceived Severity of CVD	Quotes
Relatively Weak	*"You mainly notice that you are colour-blind when doing colour-blindness test." – I1* *"I am generally not affected much by it." – I2* *"I have a red-green weakness, but it is not very strong." – I3* *"It does not hinder me in my daily life." – I4*
Relatively Strong	*"I have a relatively severe red-green weakness." – I5*

Table 5 – Initial Interviews: Perceived Severity of Interviewees' CVD

Problems emerging from CVD included different topics that were structured and clustered into themes presented in Table 6. Generally, distinguishing certain colours seemed to become more difficult the worse the lighting conditions are (I2, I3, I5), but the difficulties also increased "for small things […] and for things that are further away" (I5).

Theme	Quotes
Clothes	*"I never go shopping without friends, and I need to memorise which colours go well with each other. For borderline risks, like formal events, I text pictures to friends when I am unsure about my choice of clothes – but I don't not find this annoying as it is a good pre-test." – I3* *"When I go shopping I always take someone along to get a second opinion, such as my mother, sister, or girlfriend. So, it never was an issue, but I am also not the type of person who wears super bright colourful clothes." – I4* *"I always take someone with me when buying clothes to ask them what it fits well with, like my mother, sister, or girlfriend. I often ask people for advice to know if the colours of the clothes I picked fit together or not. […] I have never bought something without asking someone else for advice. […] If there was nobody around to ask I would never buy something because I would be unsure about the colour it has – in the end I might not wear it because I feel uncomfortable wearing it if it was for example light rose." – I5*
Distinguishing Colours (Sport Teams, Nature, Games, Transparencies)	*"I can see most colours but recognising and distinguishing them is difficult. […] When looking at a colour I often don't know what colour it is when nobody has told me the colour." – I4* *"In front of an autumn tree some leaves would be clearly green and other clearly red but many in between just blend or mix." – I4* *"When watching sports, it's hard to distinguish teams wearing colours that are similar for me." – I5* *"What is very problematic are cards [card games]. I need to hold them and change the angle so that light shines differently on them. […] Bad lighting conditions make it worse." – I5* *"It is much harder to see transparent colours. For warnings in the house saying that the water might be differently coloured in the next days, I would not be able to see when it actually does." – I1*
Food	*"It can be hard to know when food is starting to go bad, especially products like blue cheese, but usually you can just go for taste and smell instead." – I1* *"I would generally touch fruits and vegetables to see if they are ripe." – I3*
Light Conditions and Traffic Lights	*"The walking and standing figures used for some pedestrian lights are really good because shapes are better distinguishable than colours. I learned how to see which position is shining, but for the round lights I sometimes need to think about it for half a second." – I1* *"I have problems when my eyes are tired or when the light is bad." – I2* *"Traffic lights are not really problematic due to the different light intensities, but in the very moment the sun is setting it is difficult and extremely tiring for the eyes." – I3* *"When driving a car, it can be problematic in a city I don't know. When it is dark I might miss a street light, especially when there is a lot of disturbing stray light around." – I5*
Personal Acceptance	*"As a child I used to feel ashamed or depressed when people found out I am colour-blind. Nowadays I accepted that I can't do anything about it, and that it's not a shame, but I can imagine that there are many people who still feel ashamed in adulthood the way I did as a child, or who do not want to accept the fact that they are colour-blind." – I5*
Societal Awareness and Stigmatisation	*"It is more about people's reactions since many seem to be educated very badly. When someone hears that I am colour-blind they start quizzing me to see if am really colour-blind – as if I have to prove it." – I1* *"People are surprised when hearing about it the first time, and some feel like they need to test you." – I2* *"Many adults still have a hard time imaging it nowadays and are wondering if I cannot see colours at all – but I only have issues allocating them." – I4* *"In school classmates used to test me out and made me name plenty of colours. Nowadays, many adults still have a hard time imaging it and wonder if I cannot see colours at all, but I only have issues allocating them. […] When I was younger and wore a light blue shirt, I was told that it looks like baby blue – I avoided wearing this shirt ever since." – I5* *"In general, the government is trying to design for people with bad eyesight – so often elderly. I find it weird that often only colours are used to differentiate things. When looking at games, you often find colour-blind modes in the settings. Why do we have awareness for it in game design, but not for important things like governmental documents or applications?" – I1*

Table 6 – Initial Interviews: Identified Themes Related to Problems Emerging from CVD

5.1.3.2 Benefits Related to CVD

Two interviewees also saw benefits in having a CVD as it can serve as a conversation starter and be useful in design-related contexts.

> *"It can be a good conversation starter. It is fun to explain 'how it really is' and to see it as some sort of 'meta-topic' about the question whether we all perceive similarly or not. I can also give feedback to people, for instance when they are trying to create figures or graphics that should be colour-blindness-friendly." – I3*

> *"When I was choosing to become a designer, I was a bit worried, but nowadays I think that it actually is easy to work as a designer due to the tools available – I am working with a colour picker on my computer. Sometimes, I even think it is an advantage to be colour-blind, because my work has more contrast compared to others' work. Also, I learned a lot about colours (how they work, which harmonise well). However, working in print would probably be a lot more difficult." – I1*

5.1.3.3 Recognizing and Memorising Colours

Both I4 and I5 reported they can see most colours but recognising them can be challenging and requires a strong focus. Their brain often would not identify a colour with a name, for instance when looking at an object they could not put the object's colour into words, but as soon as someone else put it into words for them, it became easier, and they knew the colour themselves. When seeing the colour again at a later point they could relate back to it and recognising the colour became less difficult. Another described technique makes use of comparing an unknown colour to an already known colour.

> *"There are classical problems when I think it is red but then it's actually green, but I also sometimes look at a colour and just do not know what colour it is […] when nobody has told me which colour it is before." – I4*

> *"I compare colours with other colours I already know – for example that the sky is light blue – and then compare it to other colours. I always use banal things like grass, the bark of a tree, or similar for comparing it [a colour] to other things I have already learned before. […] When something 'feels' like red and then it's also likely to be red." – I5*

> *"It depends on the tone of the colour of an object, but sometimes they are hard to distinguish. For example, for someone with full colour vision a bright red dot would stand out in a big colourful image. I need to search for it instead and find the contrast. I can see the contrasts, but my brain doesn't make the red pop out as much. When focusing on it I could identify it as red but it's not as distinct." – I5*

5.1.3.4 Picking Colourful Clothing

I3 – I5 stated not to buy clothes without someone else's advice. While "picking clothes in the morning is a very conscious task" for I5, it is "not time-intensive" as he has "good knowledge about everything in [his] wardrobe". He stated to remember each colour that someone named earlier for all pieces of clothing he owns. Hence, he has to memorise a large amount of information about colours, which works well according to him.

> *"I know all colours from the clothes in my wardrobe – even if I don't see a colour, because I remember the colour." – I5*

> *"When a person tells me the colour of a piece of clothing, I need to remember this colour. So, whenever I buy something new I mentally store the information and the next time I pick something from my wardrobe I recall the colour." – I5*

When it comes to combining different colours, I5 knew exactly which of his clothes can be combined well and which not, but he had to learn certain rules, such as contrast being important, as well as which colour combinations harmonize well and which should be avoided.

> *"Basically, anything fits to black or blue jeans. I used to own a pair of beige-ochre pants – someone told me the colour – and then I learned not to wear light colours with it but something dark. I always try to have contrasting colours and combine dark with light, or light with dark. Of course, you could wear black with black, but it looks a bit dull. If you wear blue pants you could also combine it with a blue shirt, but it would be nicer to combine it with some light or dark colour […]. What is more complicated if I wear dark pants, but all my light shirts are in the laundry. I don't want to wear all-black, so I try to at least find a shirt that has something colourful printed on." – I5*

> *"I learned over time that you would not wear red with red because it does not fit together. That was weird for me because you could always combine a light blue shirt with dark blue jeans, so I thought it would work as well with dark and light red, but people told me it does not work with red." – I5*

> *"I have one very colourful shirt and try to avoid combining it with colourful pants but wear it with rather modest colours such as dark blue or black to avoid looking like a parrot." – I5*

> *"When I was younger I was told [by a fellow player in his sports team] that light blue looks like baby blue, so ever since I avoided wearing this shirt." – I5*

5.1.3.5 Supportive Tools for CVD

Asking them whether they would use supportive tools the interviewees had different opinions. While I1 would not want to test out glasses for CVD such as *Enchroma* due to the potential downsides of before and after comparisons, I2 and I3 were curious about such devices.

> *"I would not want to try them [glasses like Enchroma] because I do not want to know what I am missing." – I1*

> *"Would definitely try and benefit from it. I don't think it would affect me in a way that I am comparing before and after of using them, as I am not chasing to develop my brain with colours – but if there is a tool, I would use it." – I2*

> *"I could imagine using glasses such as Enchroma. I am already wearing glasses, so it would not be an extra thing. I would not mind using such CVD glasses." – I3*

I2 also imagined using tools "integrated in the phone and making use of the phone's camera, or maybe using it with Google glasses." Leading the questions towards a wristband, such as *HaptiColor*, the interviewees highlighted that it should be rather unobtrusive to avoid stigmatisation. Moreover, they pointed out to use it for rather specific applications, such as going shopping, but that most of them wouldn't wear it on a daily basis.

> *"I wouldn't just use the bracelet during the day […]. I would use it for shopping clothes." – I1*

> *"I would use this wristband for shopping clothes or for board games evenings. So, whenever I know colours would be relevant. I could imagine myself using it not only for shopping clothes, but also for other shopping situations such as regular groceries – for example to find out if an apple has a bright red or not – or when buying bed linen or sheets. I would even say such a wristband would not just be relevant, but strongly relevant for any situation related to shopping. I would definitely wear it all the time for shopping-related contexts as it would be very useful for me." – I5*

> *"Currently, I would rather not use it because my colour-blindness does not hinder me in my everyday life, but if the situation got worse, then I might because it would be a necessity like spectacles. Other than that, it would only be like a gimmick for me, but I also don't use other wearables like for example Fitbit. I think the main advantage of using a bracelet would be that you can use it secretly without anyone else noticing." – I4*

"I used to feel ashamed or depressed when I was a child and people found out I am colour-blind. Nowadays I accepted the fact that I can't do anything about it, and that it is not a shame, but I can imagine that there are enough people who still feel ashamed in adulthood just the way he felt ashamed as a child, or who do not want to accept the fact that they are colour-blind. […] Connecting this to psycho-social aspects it would be better to receive information 'clandestinely'." – I5

The look and feel of such a wristband played a big role. The interviewees listed some qualities and functions that they would expect from such a device.

"Please let it not be ugly. I would not use it if it is obvious that it is an assertive tool. Also, don't call it "bracelet", because that might stop some people from using it [referring to men who do not wear accessories]."

"Whether I would wear it, would depend on how it looks like. It should fit for all occasions. A semi-casual look would be good. I would also wear it as some kind of accessory as I am also wearing watches." – I2

"It should be pretty, small – so not too big –, and plain. I would not want to have another device that needs charging on a daily basis. It should be robust and not break easily. Up to a certain point it should be waterproof, for instance for taking a shower or not damaging it while washing your hands. It should also be comfortable to wear. Cheap plastic that you smell all the time should be avoided, and it should be intuitive to use. How would you solve that it is not turning around the wrist?" – I4

5.1.3.6 Extending *HaptiColor*

Asking them about extending *HaptiColor* with more information about colours, other than the twelve hues that are represented currently, I4 stated that for him only the hue would be relevant as that was the parameter that was hard for him to distinguish, whereas he could clearly see saturation or lightness of a colour. Similarly, I1 only had issues with different hues, but could imagine it to be relevant for people with stronger CVD. He suggested such a function to be a user setting. For I5, who stated to perceive his CVD as rather strong, receiving more information would be relevant. It would, however, depend on the situation and context – for his daily life the twelve hues would be sufficient, but in regards of psycho-social aspects it would be relevant to have more details about a colour.

"As far I know, just by experience, the big problem is the hue. So, it sounds great that it helps with that. Lightness and saturation are probably easier to see anyway, since, if I re-call correctly, colour-blindness mainly affects the hue. For example, I can see a light-coloured shirt but wonder if it is light blue or light purple. So, I think, at least for the initial phase to ease the learning curve, that the hue is the most important aspect. I can't recall having trouble with the lightness. It might be relevant for those who have a more severe CVD. It would probably be considered very 'high functioning' in that term. Ideally, maybe it could be a user setting?" – I1

"Saturation and lightness of a colour would not at all be relevant for me as that is what I can see. I only have issues with hues." – I4

"It mainly depends on the situation: for any kind of situation in my daily life the twelve colours would be sufficient, but in regards of psycho-social aspects it would be relevant to have more details about a colour. For instance, if my friends or colleagues talk about a specific colour and I only knows it's 'red' thanks to the wristband, I would still feel excluded as I could not discuss the details with them. So, if I would have more information about the colour I would feel more secure, better, and more integrated." – I5

For more information about colours, I5 could imagine some form of haptic feedback, but descriptive colour names such as "fire red", "wine red", or "bordeaux" would also be very helpful for him. He suggested adding a display to the wristband that gives such information in form of text. Using any kind of audible information would, however, be an absolute no-go for him as he used to be very ashamed for his colour-blindness as a child, and he could imagine other people with CVD still being ashamed in adulthood, so therefore the tool being "clandestine" was of high importance for him.

"It would be really bad if someone else could hear the wristband say a colour out loud. Connecting this to the aforementioned psycho-social aspect it would be better to receive the information 'clandestinely'." – I5

5.1.4 Limitations of Initial Interviews

The results of the initial interviews might be limited given that recruiting females with CVD for was particularly difficult due to the fact that CVD is more prevalent among men (see Chapter 3.2.3). In addition to that, none of the five interviewees tested the prototype themselves due to having been located in different countries. Hence, their feedback was based on verbal explanation of the prototype given to them, and not on own experience.

5.1.5 Discussion of Initial Interviews

It was found that although only one of the interviewees perceived his condition as rather strong (I5), with the rest stating not to be affected much, each of them had some problems related to colour in their daily life. In particular, selecting and purchasing colourful clothing was a reappearing theme.

Qualities and features of a supportive device were described by the interviewees, focusing primarily on the look and feel of such a tool. When designing a supportive tool for people with CVD, it is of high importance for it to be unobtrusive. In particular, making use of audible sound is to be avoided since participants highlighted the need for it to be clandestine. Interestingly enough, there is a large research field focusing on sonification of visual information, such as colour, despite the finding that people with CVD seemed to find it important not to use audible information. Similarly, for users with other visual impairments it might also interfere with their strong dependency on their sense of hearing. Therefore, it was implied not to apply sonification for the scope of this project.

For interviewees who perceived their CVD as rather weak, receiving information about the hue of confusing colours would be sufficient, while for one interviewee with a strong CVD more information would be relevant. This indicated different needs for different users, and required further investigation.

5.2 Analysis of Colour Wheel Used in *HaptiColor*

In Carcedo's [3] second study conducted with twelve colour-blind people, the RYB colour wheel was found to be the most preferred colour model (55 %). Simultaneously, it was rated to be the easiest (83 %), and most accurate (73 %) out of four different models. Despite these results, the RGB colour wheel (see Figure 15) was applied for all their subsequent tests as they were conducted on a screen [2], [3]. Even though RYB seems to be a system well known by people, it was decided to keep RGB as mental model due to the fact that it resembles human colour vision more correctly for it is an additive system, while RYB is subtractive [57, pp. 10, 41], [58, pp. 6 – 7].

One motor each is placed on the three primary colours red, green, and blue (see Figure 15). To simplify refereeing to specific positions of the primary, secondary, and tertiary colours on the wristband, the wheel had a numbered position for each colour, counting from one to twelve starting under the first motor and then going clockwise. Lightness and saturation of a colour were not represented in these wheels, instead the hue was the single information conveyed.

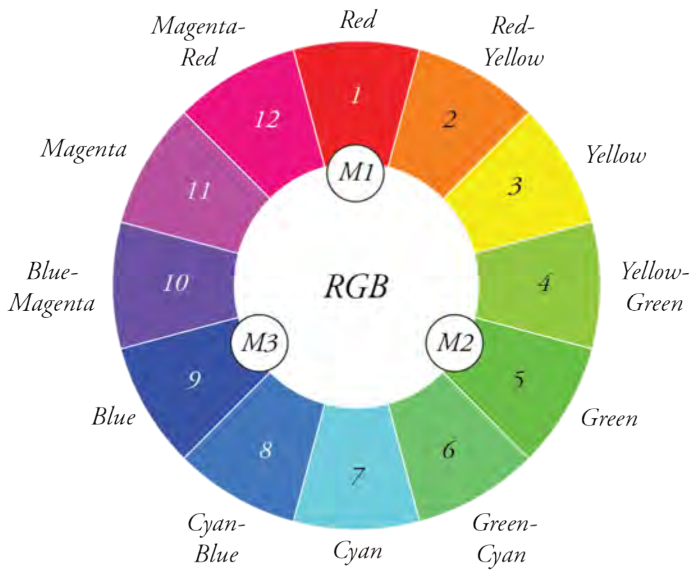


Figure 15 – RGB Colour Wheel with Numbered Hues (1 – 12) and Motors (M1 – M3)

5.3 Analysis of Vibration Codings used in *HaptiColor*

As found by Carcedo et al. [2], [3] sequential vibration patterns with differently long lasting vibrations performed best when representing interpolated points, imaginary points in between physical points. They differentiated between short vibrations lasting for 200 ms and long vibrations with 600 ms. To indicate a physical point located under a motor a long vibration was used on that motor. For interpolated points that were equally far away from two motors, both motors vibrated shortly after one another. For interpolated points that were closer to one motor and further away from another, the closer motor vibrated long, while the motor that was further away vibrated for a shorter time.

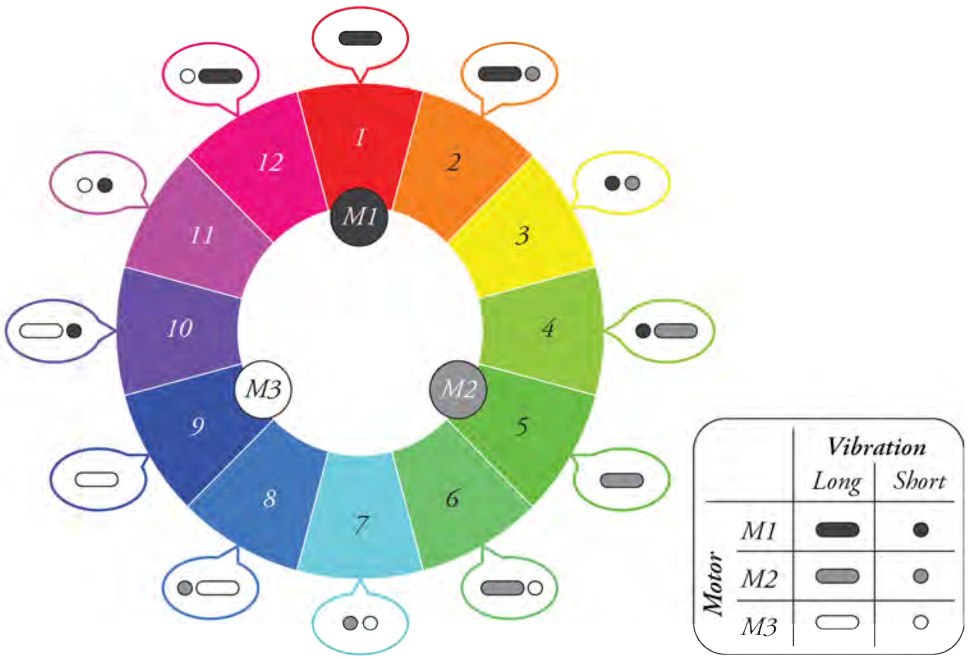


Figure 16 – Vibration Patterns and Interpolated Points Used in HaptiColor

Analysing the recently used vibration patters (Table 7), it was found that only twelve out of thirty possible vibration patterns were used to encode information. Possible vibration patterns included one vibration or a combination of two. The latter included either two short vibrations, or otherwise they always started with a long vibration. The following vibration encodings were not used:

– A pattern of two long vibrations sequentially.
– Only one motor vibrating shortly (was defined in the code but appeared not to have any functionality).
– More than two motors vibrating sequentially.
– All motors vibrating simultaneously.

	First Vibration	Second Vibration	Encoding
Two Motors Sequentially	M1-L	M2-S	Position 2
	M1-L	M2-L	
	M1-S	M2-S	Position 3
	M1-S	M2-L	Position 4
	M1-L	M3-S	
	M1-L	M3-L	
	M1-S	M3-S	
	M1-S	M3-L	
	M2-L	M3-S	Position 6
	M2-L	M3-L	
	M2-S	M3-S	Position 7
	M2-S	M3-L	Position 8
	M2-L	M1-S	
	M2-L	M1-L	
	M2-S	M1-S	
	M2-S	M1-L	
	M3-L	M2-S	
	M3-L	M2-L	
	M3-S	M2-S	
	M3-S	M2-L	
	M3-L	M1-S	Position 10
	M3-L	M1-L	
	M3-S	M1-S	Position 11
	M3-S	M1-L	Position 12
One Motor	M1-L		Position 1
	M2-L		Position 5
	M3-L		Position 9
	M1-S		Programmed, but no meaning
	M2-S		Programmed, but no meaning
	M3-S		Programmed, but no meaning

Table 7 – Vibration Patterns Used in HaptiColor (M = Motor, L = Long Vibration (600 ms), S = Short Vibration (200 ms); Positions Correspond to Figure 15)

5.4 Understanding the Arduino Code

Initially, small adjustments were made in the Arduino code, and it was annotated to help understand it read by anyone. The numbers of the positions of the twelve hues of the colour wheel were defined in decimals (see Figure 15 and Figure 16), whereas in the code, and therefore also the required input in the *Arduino Desktop IDE's* serial monitor, they were given in hexadecimals. This yielded the following relations to the connected vibration pattern as presented in Figure 17 required to operate the prototype with Wizard of Oz techniques.

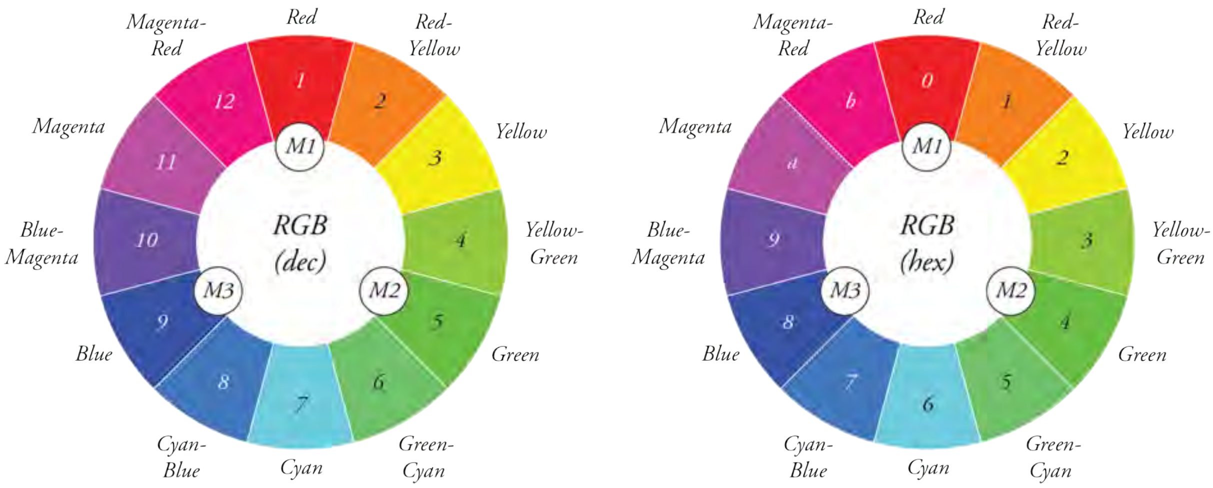


Figure 17 – Mapping of Hues and Positions on Colour Wheel in Decimal and Hexadecimal

5.5 Initial Adjustments of Physical Prototype

The final version of the physical prototype presented by Carcedo et al. [2], [3] (see Figure 18) was adjusted in the very beginning of this thesis project to ensure the same functionality, while decreasing its size and increasing its reliability (see Figure 19). Appendix F presents the circuit diagram created on the basis of the original *HaptiColor* prototype. Appendix G shows the circuit diagram with the adjustments taken.

Based on feedback from two technical experts, the following adjustments were coordinated and instructed to be implemented by an electrical engineer. An acrylic glass housing was mounted to the *Arduino Genuino Uno* as protection against electrostatic discharge. A new shield with soldered parts was produced, replacing the previous larger breadboard. The new shield was then placed on top of the Arduino and its new acrylic glass housing.

In the former wristband, motors were in direct contact to the skin as they were fixated to the Velcro wristband with transparent glue strips and Velcro patches. They were connected to the breadboard with several single wires. For better stability and higher mobility, a new wristband was prototyped using a 1.5-meter-long ribbon cable and two bands commonly used as antistatic grounding straps. On the ribbon cable three coin-type motors (VM-1002A3.0; diameter: 10 mm; height: 2 mm), similar to the ones used previously (Precision Microdrives 310-103; diameter: 9 mm; height: 3mm), were soldered and glued in equal distance to one another. The fabrics of the two bands were sewed together, leaving enough space to place the ribbon cable with the motors inside. Hence, the motors were not placed directly on the skin, instead vibrations were now played through a layer of fabric. The stretchable ends of the fabric band allowed varying the wristbands' perimeter from 155 mm to 190 mm fitting the group of people with larger wrists identified by Carcedo et al. [2] which ranged from 175 mm to 180 mm as well as some of the people with smaller wrists which ranged from 140 mm to 150 mm. A plastic clip attached to one end of the fabric was used to close it.

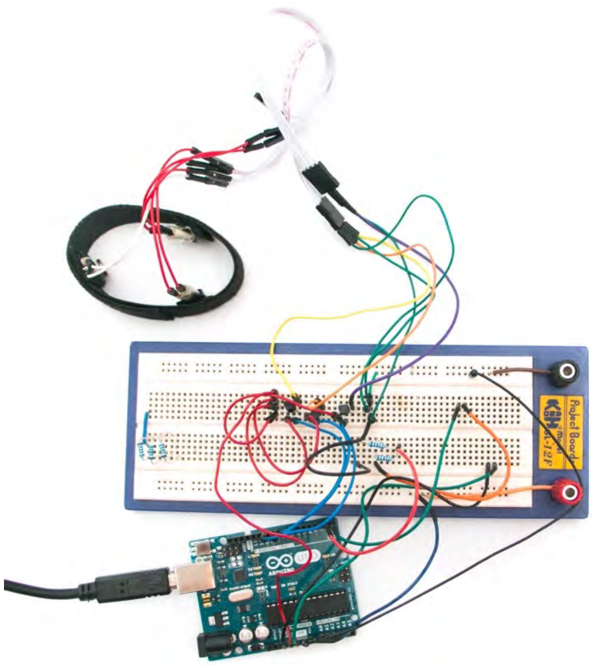


Figure 18 – Prototype: Before Adjustments

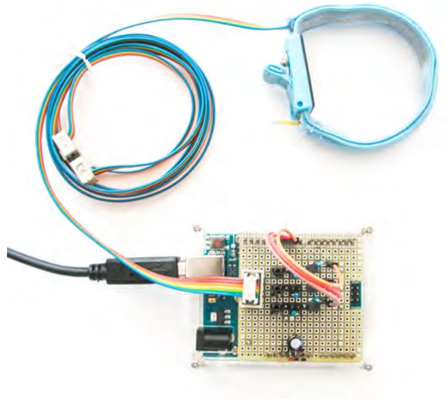


Figure 19 – Prototype: After Adjustments

5.6 Initial Pilot Study – Usage of *HaptiColor*

5.6.1 Objectives of Initial Pilot Study

The aim of the pilot study was to find out the following:

- *Usage:* How is the wristband used? Are there observable patterns in the usage?
- *Mapping:* Is the mapping between the colour wheel and the vibrations logical and understandable?
- *Information:* Is the information translated from the visual to the haptic sense sufficient to identify and represent different colours?

5.6.2 Study Design of Initial Pilot Study

5.6.2.1 Apparatus

To ensure a quiet environment with no potential disturbances, a private study room was reserved for testing. The set-up of the room included a table on which a laptop was connected to the prototype which included the wristband and Arduino (see Figure 20). Each participant was seated in a way that they could be observed, but at the same time could not glance on the screen of the laptop. Further, a tablet was placed to the left of the participant showing different figures to the them. The wristband was placed on their dominant hand.

Each session of the pilot study involved two people at a time – one participant and one facilitator. The latter's roles included note-taking, observing, as well as operating the prototype, which required a Wizard of Oz technique. By entering a hexadecimal number (see Figure 17) in the *Arduino Desktop IDE's* serial monitor on the laptop, a specific vibration pattern was played for a specific hue. Participants conducted the test and were asked to think-aloud, giving insights to their methods of decoding vibration patterns, as well as problems or challenges they faced.

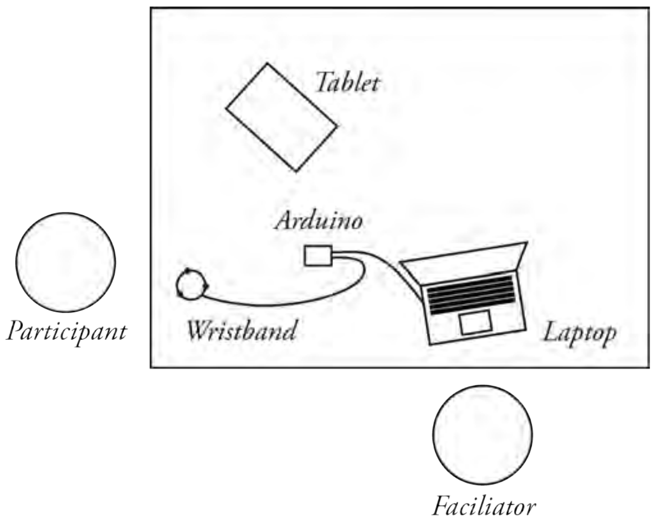


Figure 20 – Initial Pilot Study: Setup

5.6.2.2 Procedure

An outline of the pilot study was planned and tested beforehand with two participants to identify potential flaws or needs for improvement, as well as test the equipment. To ensure the same procedure was applied for each participant, the following outline (see Table 8) was present during the pilot study.

Phase	Procedure
(1) **Introduction**	Welcome participants and try to make them feel comfortable. Ask them to fill out the consent form (see Appendix H). Ask which hand is dominant and measure the wrist of dominant hand. Explain *HaptiColor* and its way of functioning. Show the colour wheel (left side in Figure 17) and explain mapping between positions on wrist, hue, and vibration pattern. Introduce participants to all vibration patterns by playing all twelve patterns in clockwise order (from red to red-magenta) while the colour wheel is visible for participants, and while naming the colour allocated to the respective position. Ask if the explanations were clear and if they have any questions.
(2) **Learning and Understanding**	Ask the participant to think-aloud during this phase to understand their way of interpreting the logic of the vibration patterns. Play two sets of the twelve vibration patterns (24 patterns in total) in a randomized, but pre-defined order that is the same for all participants while the colour wheel is displayed to them. Ask participants to name the colour belonging to each pattern played. Note both their answer and additional comments based on observing their reactions and usage behaviour.
(3) **Amount of Information**	Hide the colour wheel for this phase to get a first impression on the learning curve. Mimic a CVD by showing differently coloured squares that include the two confusing colours red and green as part of their colour with a colour filter added simulating protanopia (see Figure 21). Additionally, the squares vary in brightness and saturation, while the hue remains unaltered. Ask participants to figure out the actual colours of the different squares by naming one square at a time. Then play the respective vibration patterns and ask participants to state the hue.
(4) **Semi-Structured Post-Test Interview**	(a) "Was anything particularly difficult? If so, what?" (b) Display Figure 16. "Which of the vibration patterns were easy and which were harder?" (c) "Is the information about colour presented through the wristband sufficient? Should it be extended, and if so, in what way?" (d) Show squares from phase 3 without CVD filter (Figure 22) and let the participant compare the colours with and without filter (Figure 21). (e) Observe their reaction. "Seeing the difference between the colours, do you think it would be useful to receive further information, such as the saturation?" (f) "How could the wristband be improved?"

Table 8 – Initial Pilot Study: Outline of Procedure, Tasks, and Questions

During Phase (1) and (2) the colour wheel shown on the left in Figure 17 (decimal) was presented to the participant on the tablet, while the facilitator had the right colour wheel from Figure 17 at hand. The reason the participant and the facilitator did not use the same numbering for the positions of the colour wheel is due to the fact that not all participants might know the hexadecimal system, but at the same time it saved time and reduced errors for the facilitator not having to convert from decimal to hexadecimal.

For phase (3) the colour wheel was hidden and Figure 21 was shown to the participants instead. Simultaneously, the facilitator made use of Figure 22 which included additional information about the HSB values as well as the required hexadecimal input. Figure 21 showed the same squares as Figure 22, but a filter was added with the application *Sim Daltonism* to simulate a red-green weakness (protanopia).

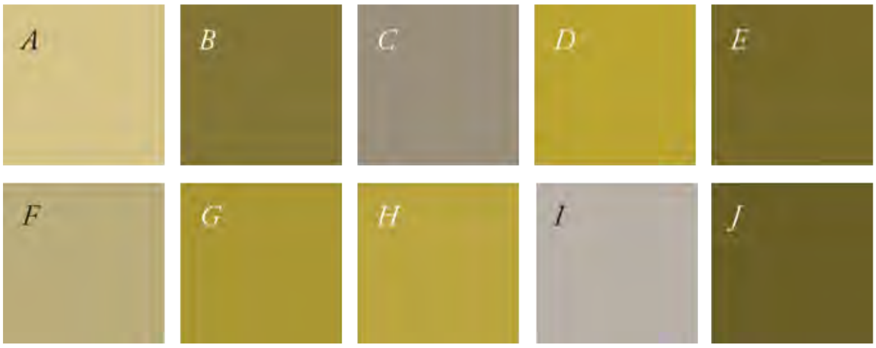


Figure 21 – Initial Pilot Study: Colours Simulating Protanopia for Participants in Phase 3; A – J correspond to Figure 22

Figure 22 – Initial Pilot Study: Colours Used in Phase 3 as Guideline for Facilitator Without CVD Filter; Additional Information: HSB Values and Required Hexadecimal Input; A – J correspond to Figure 21

The follow-up questions served as guideline but were not strictly followed, for instance when a question was already answered during the prior tests. For the second follow-up question Figure 16 was displayed to the participants so they could visually relate to all the different vibration patterns.

5.6.2.3 Data Collection

The pilot study included a mix of qualitative and quantitative data. During the introduction demographic data was gathered through a pre-test questionnaire (see Appendix H) during. In phase (2) and (3) quantitative data was collected in form of the accuracy of participants' answers given. At the same time, they were observed and asked to think-aloud. After conducting the test, a semi-structured post-test interview delivered qualitative data.

5.6.2.4 Participants

In total, eight participants were recruited all of whom stated to have no CVD (see Table 9). They were all recruited from within the university community. After contacting them via email or through an HCI students' Facebook group, they were asked to sign up in a Doodle list. None of the participants received any form of incentive. Each pilot study took approximately 30 minutes, and each participant was asked to sign an informed consent form (see Appendix H).

Participant	Gender	Age	Colour Vision	Professional Background	Handedness	Wrist Circumference
P1	Male	24	No CVD	Technical	Right	17.7 cm
P2	Male	21	No CVD	HCI	Mixed, mainly right	15.5 cm
P3	Male	27	No CVD	Technical	Right	16.3 cm
P4	Male	31	No CVD	HCI	Mixed, mainly right	17.0 cm
P5	Female	27	No CVD	HCI	Right	15.5 cm
P6	Female	26	No CVD	HCI	Right	14.5 cm
P7	Female	26	No CVD	HCI	Right	15.0 cm
P8	Male	25	No CVD	HCI	Left	17.5 cm
Total	**Female: 3** **Male: 5**	–	**CVD: 0** **No CVD: 8**	**Technical: 2** **HCI: 6**	**Left: 1** **Right: 7**	–
Mean	–	25.9	–	–	–	**Female: 15.0 cm** **Male: 16.8 cm** **All: 16.1 cm**

Table 9 – Initial Pilot Study: Demographic Data of Participants (P1 – P8)

5.6.3 Results of Initial Pilot Study

5.6.3.1 Learning and Understanding

In the second phase of the pilot study, which focused on people's understanding, learning, and usage of the prototype (see Table 8), taken as a whole, 192 vibration patterns were played – each of the twelve hues twice for each of the eight participants resulting in 24 patterns per participant, and 16 repetitions per hue.

Overall, the vibration patterns were accurately decoded in 87 % of the trials in Phase 2 (see Table 10). For six participants (P1, P3 – P5, P7, P8) their accuracy of given answers was above 95 %, while two participants ranked below 63 % (P2, P6) (see Table 10).

All three vibration patterns using only one motor achieved the highest accuracies with 100 % for red as well as green, and 93.8 % for blue (see Table 10). All interpolated points were detected less accurately ranging from 68.8 % for magenta-blue to 93.8 % for green-yellow and yellow (see Table 10). On average, participants were able to name the correct hue in 97.9 % of all patterns that used only one motor (mean of red, green, and blue). For interpolated points equally far away from both motors the mean of the accuracy lied at 85.4 % (mean of yellow, cyan, and magenta). With 82.3 % the lowest accuracy was achieved for interpolated points which were closer to one and further away from the other motor (mean of all yellow-red, green-yellow, cyan-green, blue-cyan, magenta-blue, and red-magenta).

		Participants								Accuracy per Hue		
		P1	P2	P3	P4	P5	P6	P7	P8	Total		Mean
Red		2	2	2	2	2	2	2	2	16	100.0 %	2.0
Yellow-Red		2	1	2	2	2	1	2	2	13	81.3 %	1.6
Yellow		2	2	2	2	2	1	2	2	15	93.8 %	1.9
Green-Yellow		2	2	2	2	2	1	2	2	15	93.8 %	1.9
Green		2	2	2	2	2	2	2	2	16	100.0 %	2.0
Cyan-Green		2	1	2	2	2	1	2	2	14	87.5 %	1.8
Cyan		2	2	2	2	2	0	2	2	14	87.5 %	1.8
Blue-Cyan		2	1	2	2	1	1	2	2	13	81.3 %	1.6
Blue		2	1	2	2	2	2	2	2	15	93.8 %	1.9
Magenta-Blue		2	0	2	2	2	0	2	1	11	68.8 %	1.4
Magenta		2	0	2	2	2	0	2	2	12	75.0 %	1.5
Red-Magenta		2	1	2	2	2	1	1	2	13	81.3 %	1.6
Accuracy per Participant	**Total**	24	15	24	24	23	11	23	23	167	–	–
		100 %	62.5 %	100 %	100 %	95.8 %	45.8 %	95.8 %	95.8 %	–	87.0 %	–
	Mean	2.0	1.3	2.0	2.0	1.9	0.9	1.9	1.9	–	–	1.7

Table 10 – Initial Pilot Study: Accuracy of Answers Given in Phase 2 (Learning and Understanding of Vibration Patterns)

5.6.3.2 Amount of Information

The third phase of the pilot study investigated whether the amount of information presented to the user is sufficient (see Table 8). For this end, a CVD was simulated for the participants (see Figure 21) as they did not have a CVD. They were allowed to pick the order of the vibrations patterns played for the colours shown in Figure 21.

Overall, the given tasks in Phase 3 seemed to be very easy for the participants as overall 95 % of their answers were correct. Five participants identified 100 % of the colours correctly, one participant had one wrong answer (90 % correct), and one participant named two colours wrongly stating that two others were hard (80 % correct). This might, however, be related to the fact that only three different hues were played. The participants' reactions showed that they were surprised when comparing the colours with and without CVD filter.

In regard to their chosen order there were no clear patterns identifiable. While two participants (P1, P3) with an IT background preferred to go in alphabetical order (A – J), the other six participants (P2, P4 – P8) tried to compare similarly looking colours with one another and hence did not ask for them in alphabetical order. Looking at different combinations chosen in the latter group of participants (P2, P4 – P8), the fields D and C, J and E, G and F, as well as H and J (see Figure 21) were chosen most frequently to be compared with one another (see Table 11). From these four combinations, only fields H and J showed the same hue (green), while the other three combinations were different hues.

	A	B	C	D	E	F	G	H	I	J
A	–	3	1	0	0	2	1	1	1	0
B		–	3	1	1	1	0	0	1	0
C			–	4	0	0	0	2	0	0
D				–	2	0	0	1	2	0
E					–	2	0	0	0	4
F						–	4	1	1	1
G							–	5	0	0
H								–	2	0
I									–	3
J										–

Data combined as order is not relevant.

Table 11 – Initial Pilot Study: Frequency of Combinations Chosen in Phase 3 (Participants who asked for colours in alphabetical order were excluded in this table)

5.6.3.3 Semi-Structured Post-Test Interviews and Observations

This chapter presents the results of both the semi-structured post-test interviews and observations made throughout the study. It is structured by the questions listed in Table 8.

***Question (a)** – Was anything particularly difficult? If so, what?*

It was observed that the majority of participants were able to remember the positions of the hues well throughout the study, and the vibration patterns were found to "work well and seem logical" (P4). Considering the limited time frame of half an hour, two participants stated it was too difficult to memorize the names of the hues. For P1 "it [was] easy to feel the motor but naming the hues [was] difficult as there [were] too many to remember within such a short time", and for P4 "it [was] easier to point to a colour than say it out loud because [he had] the visual mapping in [her] head". However, it needs to be considered that the participants used the wristband for maximum 30 minutes and memorizing twelve items is a rather high number for such a limited period.

Half of the participants reported to have issues distinguishing pulses from two motors – for three of them M1 and M2 were difficult (P4, P5, P7), while P2 found M1 and M3 hard to differentiate. Furthermore, two participants stated one motor felt stronger over the others two (P4: M1, P5: M3). It seems like especially M1 which is placed on the dorsal side of the wrist caused issues. If this is due to anatomic reasons remained unclear.

> *"Differentiating positions between red [M1] and blue [M3] was difficult." – P2*
>
> *"Red [M1] feels different. It always feels stronger than the other motors. It stands out a lot when used in combination with another motor. Green [M2] feels the weakest. Yellow is difficult." – P4*
>
> *"M3 is very strong, and distinguishing M1 and M2 is difficult." – P5*
>
> *"Positions between M1 and M2 are rather difficult. Especially Green-Yellow is confusing." – P7*

The tightness of the wristband seemed to be crucial to easily detect the pulses played. P3 stated that "the most difficult one was red [M1]", but after tightening the wristband it improved drastically. According to P4 "the wristband should be tighter to feel the vibrations better, but then it feels too tight".

Additionally, there seemed to be a correlation between the wrist circumference, in particular small wrist sizes, and the difficulty to encode the vibration patterns. All participants with wrist sizes up to 15.5 cm reported difficulties (P2, P5 – P7), and two of them (P2, P6) had a significantly lower accuracy when naming hues than all other participants. One of them "tried to repeat the haptic feeling by touching the wristband with the other hand shortly after the pulse" (P5). P7 felt like she was "losing the orientation", while the other three reported in a similar way that they "first tried to focus on the order of the vibrations, and then on their length" (P2), but having "to focus a lot on the position" (P5) made them "then sometimes [forget] the length of the pulse" (P6).

***Question (b)** – Which of the vibration patterns were easy and which were harder?*

Matching the results of the achieved accuracy, P1 ranked "the difficulties from easy to difficult: first single vibrations, then those in the middle (short-short), and then the rest". These results also matched the statements from P5, who found "two pulses [were] a lot more difficult than just one pulse", and P6, according to whom "combinations of long and short vibrations were hard; when it was only one vibration it was clear".

P2 stated "the mapping and the patterns make sense". While finding it logical, P5 pointed out that "one has to get used to it", and P7 thinks "you would need to train a bit". Only P6 found that for interpolated points "it would make a lot more sense if the dominant pulse would always come first", whereas right now a second pulse always followed in clockwise direction, and therefore some interpolated points started with a long, and some with a short vibration. The other participants stated that either a clockwise logic was most natural to them, or that they perceive both as equally logical.

***Question (c) and (d)** – Is the information about colour presented through the wristband sufficient? Should it be extended, and if so, in what way? Seeing the difference between the colours, do you think it would be useful to receive further information, such as the saturation?*

Participants had differing opinions on these questions and stated that "it is difficult to judge without a colour-blindness" (P6) and as they do not "know the problems of colour-blind people" (P2). Half of the participants found it useful to extend the information about colour (P2, P3, P5, P8), while the other half did not agree (P1, P4, P6, P7).

According to P7 "twelve hues are enough – it might get too complex if the number of hues is increased". Similarly, P6 stated that "the saturation is not so important, and the hues might be enough", and P4 did "not think more information than the twelve hues is needed – twelve is already quite much". One participant even suggested to decrease the number of encoded positions: "Twelve positions are too much. [He] would rather reduce the number of colours than increase it" (P1).

On the other hand, participants who thought extending the presented information would be useful highlighted that this would especially be relevant for users who got used to the device as they "could imagine that it gets too much in the beginning. More information could maybe be included later" (P2), but also that "it would require more training, but it could be useful after a while" (P3). P5 pointed out that her "learning curve was a lot steeper than expected, so [she] could clearly imagine it for young people, but it is questionable if it might be too difficult for elderly users". P8 emphasised that "it depends on the context. If something needs to match or if it is colour-relevant then more information would be relevant, for instance for clothes".

***Question (e)** – How could the wristband be improved?*

Potential improvements included changing the numbers of motors (P2), playing pulses simultaneously (P1, P3), and using sequential pulses instead of duration (P6).

> *"It could be a lot easier if only two instead of three motors are used." – P2*
>
> *"Maybe use two motors simultaneously." – P1*
>
> *"Maybe play vibrations simultaneously." – P3*
>
> *"Maybe use several pulses instead of length." – P6*

In regard to their arm posture, two participants pointed out that they were not holding their arm "in a natural position" (P4), and that they imagined recognizing would become "more difficult when the hand is positioned differently" (P2).

Further feedback from the pilot study included making the pulses less strong, but more focused (P7, P8). This should be considered for future prototypes.

> *"It would be better if the vibrations are a bit more concentrated." – P7*
>
> *"Make the vibrations subtler. At the moment, they were too strong." – P8*

Another participant (P7) found the patterns logical but proposed an idea representing each position on the wristband through the same duration, but to vary the durations distributed on the motors. She imagined interpolated points which are equally far away from two motors to be encoded with a pulse duration of 50 % for each of the motors (for instance yellow would mean 50 % M1 and 50 % M2), while interpolated points that are closer to one and further away from another motor would then be for example 20 % on one and 80 % on the other motor (for instance 20 % M1 and 80 % M2 for Yellow-Red), or similar. As the participant also found the other mapping logical, this does not rule out the current mapping of hues. Instead, taking this idea and transforming it to represent further information could be useful.

"How about defining a fixed length, which would be 100 %, and then splitting it up in the different pulses so that the total sum of pulse lengths always remains the same?" – P7

5.6.4 Limitations of Initial Pilot Study

Conducting the pilot study with more researchers might have led to more in-depth observations. With only one facilitator and several tasks to be done simultaneously, the cognitive workload was too high to continuously observe the participants throughout the whole study while moderating and operating as Wizard of Oz.

5.6.5 Discussion of Initial Pilot Study

In the following the questions defined in the study outline were answered.

***Usage** – How is the wristband used? Are there observable patterns in the usage?*

The wristband was adjustable in size, but the positioning of each of the motors was not. Due this fact, the distance between the two motors closest to the closing clip varied for each participant depending on their wrist size. Difficulties caused by this when decoding vibration patterns indicated that the size of the current prototype did not fit small wrists, which needs to be considered for future studies by either adjusting it to fit smaller wrists, or by recruiting participants with a wrist size from 15.5 cm upwards.

***Mapping** – Is the mapping between the colour wheel and the vibrations logical and understandable?*

Overall, participants quickly understood how the mapping between the colour wheel and the vibrations worked. Carcedo et al.'s [2], [3] research, as well as the results of this pilot study reported that the mapping and encoding used for the vibration patterns helped achieve a high accuracy and were perceived as logical. This led to the implication that there was no need to improve or change the decoding of hues.

Deducing the difficulty of different vibration patterns from both quantitative and qualitative data showed that one pulse per hue was the easiest, whereas two vibrations per pattern were more difficult. Participants reported that interpolated points with short and long pulses were more difficult than those with two short pulses. This indicated that decoding became more difficult for more complex vibration patterns. Hence, this implied that future designs with any form of vibration patterns should have a low degree of complexity.

***Information** – Is the information translated from the visual to the haptic sense sufficient to identify and represent different colours?*

Participants had differing opinions about whether the prototype should be extended with further information or not. This led to the implication that further investigations are required.

6 Project Execution

6.1 Design Alternatives

The design alternatives proposed in this chapter were developed based on the initial interviews (see Chapter 5.1) and the initial pilot study (see Chapter 5.6). This ensured that the proposed design complied with user needs and satisfied them rather than generating ideas varying strongly from their needs.

6.1.1 Design Ideas Based on User Feedback – Extending Information

As discussed in Chapter 5.1.3, interviewee I5 stated that receiving further information about colours than just the twelve hues he "would feel more secure, better, and more integrated". This is, in part, because it would enable him to participate in colour-related discussion, and would therefore serve as a medium enabling communication with others, which is one of the key characteristics of a wearable technology (see Chapter 3.3). Similarly, I1 pointed out that "it could be a user setting", as "it might be relevant for those who have a more severe CVD". Furthermore, I1 stated that a colour's saturation would be more relevant than its lightness. The results of the initial pilot study (see Chapter 5.6) showed that half of the participants found the idea of extending the prototype with further information on colours useful, whereas the other half did not agree, or imagined the solution to be too difficult or complex to use. This pointed towards the need of an investigation whether it was of actual benefit for people with CVD or not. Asking participants and interviewees how they could imagine more information on colours to be presented, they came up with several ideas as described hereinafter.

6.1.1.1 Sociocultural Meaning

As I5 described, comparing unknown colours to simple known objects, he suggested applying a similar technique to the wristband. Especially descriptive colour names, such as "fire red" and "wine red", would be of help for him. He could imagine such information to be presented in form of text on a small display mounted to the wristband. In his opinion using audible information would not be an option as he would prefer "to receive the information 'clandestinely'".

"What would be most interesting for me would be to have some kind of 'comparison component' to be able to imagine more what a colour means. For instance, with a descriptive colour name such as 'fire red', 'wine red', or 'bordeaux' I could compare the colour to other elements I know. That would make it easier and more concrete rather than saying 'it's a strong or weak red'. [...] If I want to dress up I would feel a lot better if knew if the colour of my shirt is 'wine red' or 'fire red'. [...] I could also imagine combining these two kinds of information and saying a strong red [pulse indicating red] always means 'fire red' or a dark red means 'wine red'. This could work similarly for other colours, like blue: sea blue, baby blue, sky blue. [...] The vibration would work well as a rough classification, but for more details I could imagine a small display with text that gives out the information of a descriptive colour, such as 'fire red'." – I5

This idea seemed very useful for people with CVD, however, it would imply a huge change in the interaction – instead of feeling pulses, one would have to look at a display and read it. Moreover, research showed that users are more prone to distraction from screens than from tactile feedback [84].

Aside from that, using comparison components could lead to cross-cultural differences in meanings or metaphors associated with colours. For instance, purple is perceived as inexpensive in the USA, but as expensive in Japan, China, and South Korea [85]. In parts of India, orange is considered a sacred colour, whereas in Zambian culture it is not even an own colour [85].

6.1.1.2 Increased Number of Motors

To represent more information, P5 suggested to increase the number of motors.

"Potentially move the motors closer to one another and use 6 or 8 motors instead to be able to show more information." – P5

As reported by [2] and [3] the accuracy achieved with three motors was the highest, reducing when increasing the number of motors. Therefore, the numbers of motors was not be increased when used in a similar scenario or design.

6.1.1.3 Sound

Similarly to research on sonification of colours [12]–[14], [16], P4 proposed to "maybe add sound". This does, however, contradict with the needs of colour-deficient people. For I4 one of the main characteristics of a supportive tool is using it without attracting attention, and I5 explained that sound should be avoided by all means.

"I think the main advantage of using a bracelet would be that you can use it secretly without anyone else noticing." – I4

"I used to feel ashamed or depressed when I was a kid and people found out I am colour-blind. Nowadays I accepted it, but I can imagine that there are still enough people who feel ashamed in adulthood just the way I felt ashamed as a child, or who do not want to accept the fact that they are colour-blind. That way it would be really bad if someone else could hear the wristband say a colour out loud. Connecting this to the aforementioned psycho-social aspect it would be better to receive the information 'clandestinely'. [Interviewer: So, audible information that is hearable for everyone around should really be avoided?] Yes definitely." – I5

While sonification could enhance the experience as a whole, the level of stigmatisation created through sound that is audible for people in the close environment might be high. Albeit small wireless Bluetooth headphones could be used ensuring only the user can hear the sound, they might still be visible to others, or interfere with other audible information from conversations or announcements when played simultaneously. This might, in turn, contradict with the second key attribute of wearables (see Chapter 3.3) highlighting users shall not be cut out from the outside world but be able to pay attention to other tasks [6, p. 453], [77].

6.1.1.4 Metric Scale

Making use of haptic feedback, I5 suggested applying a metric scale with different parameters of a colour to be represented in steps. The number of pulses would then represent a logical portion of the scale, such as ten pulses representing 100 % and one pulse 10 %. Presumably this design alternative would not increase the level of stigmatisation as it might be rather discrete. The layout of such a scale needed further investigation to determine an optimal extent which is neither too large or time-consuming nor too small or inaccurate.

"The strength or intensity could probably be represented via vibrations. Probably do not make use of stronger vibrations as other people might hear that, but maybe use a metric scale of ten and then indicate with number of buzzes how strong or intense a colour is. But generally, I could imagine it being helpful to know how strong or intense a colour is, for example when I want to buy a piece of clothing that is a similar colour to what I already own but would like it to have a different tone then that would be useful." – I5

6.1.1.5 Other Body Parts

P4 suggested to use larger body parts than the wrist as it is narrow. Larger areas could be useful for representing certain information through haptic feedback, but the device might become large and impractical for daily use. Furthermore, the sensitivities of different body parts would need to be investigated when exploring this design alternative.

"The wrist is a too narrow space. Think about using other body parts such as the shoulders." – P4

6.1.2 Narrowing Down of Design Alternatives

6.1.2.1 Representation of Hue and Saturation through HSL

The prototype presented by Carcedo et al. [2], [3] mapped the hues of an RGB wheel. To extend the information encoded through the device, a three-dimensional representation of RGB (see Chapter 3.1.4) was applied in the following prototyping and design phases. For this, HSL was to be preferred over HSV as its saturation is not affected by black or white (see Chapter 3.1.4). Based on the colour opponent process theory (see Chapter 3.2.2), it was argued that the luminance channel does not affect colour vision and can therefore be perceived by anyone without vision loss, including any form of CVD. This was further based on feedback from I1, an interviewed designer with CVD, who "would say saturation" is more relevant than lightness. Hence, the design alternatives presented in the next chapters focused on encoding the saturation of a colour in addition to the already given hue.

6.1.2.2 Basic Interaction Model with Two Settings

When introducing another parameter to the wristband it was of high importance to design a logical system that was easy to understand and to operate. Therefore, two different settings, as presented in Figure 23 and Figure 24, were created. As framed by I1 "it could be a user setting", the users were to be in control to freely switch between these two settings depending on their preferences and needs, as well as the task or activity performed, but also based on context and environment (see PACT framework in Chapter 3.4). Giving the user control over the device at any time also complied with the fourth attribute of wearables [6, p. 453], [77] (see Chapter 3.3).

Device Switched On – Setting 1: Only Hue

It should be possible for the user to receive information about only the hue. This was because information about the saturation might not be relevant for all people with CVD. While I5 stated "if [he] would have more information about the colour [he] would feel more secure, better, and more integrated", I4 and I1 reported that they only had problems distinguishing hues, but I1 thought "it might indeed be relevant […] for those who have a more severe CVD". Moreover, in certain situations a distinction between hues like 'red' and 'green' might be sufficient for the users and more detailed information about a colour might not be needed. Considering the users' learning curves and the fact that they need to learn the encoding of the vibration patterns, as well as the operation of the device, it might also be easier for some users to only use the *Hue Mode* in the beginning, and to activate the *Saturation Mode* after having adapted to the device. Substantiating this with feedback from the initial pilot study, P2 stated he "could imagine that it gets too much – at least at the beginning. More information could maybe be included later", and P3 imagined "it would require more training, but it could be useful after a while".

During *Setting 1*, the information presented to the user was only the hue. Once a colour was scanned and the haptic feedback was played, the device should automatically switch back to *Scanning Mode,* allowing the user to identify further colours (see Figure 23). Ideally, there should be an idle or notification between two encoded patterns making clear when one pattern ended and the other began (see *Transitions* in Figure 23 and Figure 24). The results of the initial pilot study concurred with those of Carcedo et al. [2], [3] in that there was no need to change the encodings of vibration patterns. Hence, the vibration patterns representing hues remained the same. The optimal design of aspects such as preferred duration of an idle, however, required further investigation. To stop scanning colours, the user could switch off the device.

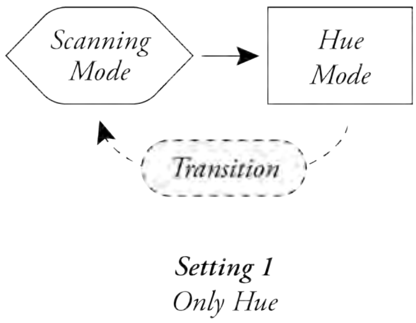


Figure 23 – Setting 1: Only "Hue Mode" Operating

Device Switched On – Setting 2: Hue and Saturation

The user should have the option to receive more information than just the hue. By activating the *Saturation Mode* in addition to the *Hue Mode* information about the saturation was presented. While for colour-deficient people the hue appeared to be the most critical parameter in colour identification, the saturation was only going to be displayed in addition to the hue, but not on its own – it could be seen as enhancing basic information (hue) with extended information (saturation). When scanning a colour, the user first received information about the hue, and subsequently about the saturation (see Figure 24). Following this, the device automatically went back to *Scanning Mode* enabling the user to identify more colours. To guide the user and to avoid confusion, the transition from *Hue* to *Saturation Mode* as well as to *Scanning Mode* needed to be clear and distinct from all other feedback. When the user wanted to stop receiving feedback on colours, the device could be switched off, or the functionality could be brought back to *Setting 1*.

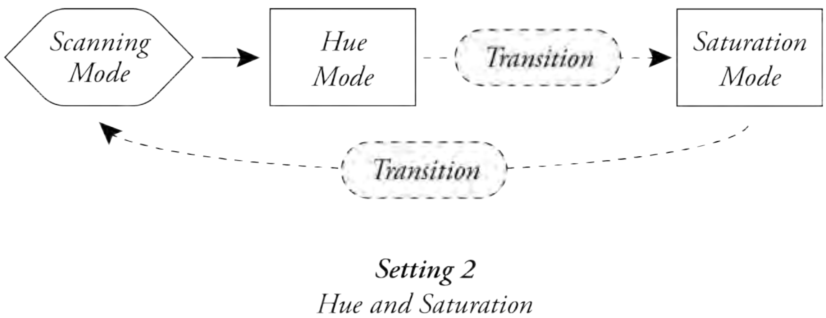


Figure 24 – Setting 2: "Hue Mode" and "Saturation Mode" Activated

As it was generally crucial to base the design on feedback from users to design for their needs, different ideas for the design of the *Saturation Mode* were discussed in in Chapter 6.1.1. However, most of them had disadvantages, such as increasing stigmatisation, being unhandy, or requiring the user to look on a display to receive the output from the device. Further, the design of the *Saturation Mode* should be somewhat consistent, yet distinct, with that of the *Hue Mode* as both were to be integrated in *Setting 2*. The precise design was evaluated in the second pilot study (see Chapter 6.2). Similarly to *Setting 1,* further parameters needed to be investigated, such as the transition from *Hue* to *Saturation Mode*, as well as the transition from *Saturation* back to *Scanning Mode* (see *Transitions* in Figure 24).

Device Switched Off

Ensuring haptic feedback only to be presented when wanted or required by the user it was vital for the wristband to be switched on and off. As emphasised by two interviewees the user should be able "to receive information 'clandestinely'" (I5) and to "use it secretly without anyone else noticing" (I4). An always-on device with permanent pulses could create stigmatisation as the sound of the motors vibrating on the skin might be audible, especially in quite environments. Further, users should be in control of when they received information. As reported by interviewees with CVD (see Chapter 5.1.3), they were not in need of a supportive device during most of their daily life, but they might want to receive feedback in certain contexts and during specific activities, such as purchasing or selecting colourful clothes.

Switching Between Settings Through User Input

As visualised in Figure 25, the user needed to be able to switch from one setting to the other at any point in order to be in full control of the device and the feedback given. While switching from one setting to another always required an action performed by the user, the implementation of such switch could be done in several ways. Tangible elements, such as sliders, switches, mode dials, selection wheels, or similar might be easy to use because the user could relate back to other known elements which, hence, facilitate the concept of affordance because the link between perception and required action is clear. Direct manipulation on tactile displays as explored by Gupta et al. [40] or gesture-based input as used in *OrCam* [31] could be design alternatives. While this was to be investigated in future studies, it was not considered for the scope of this thesis due to time limitations.

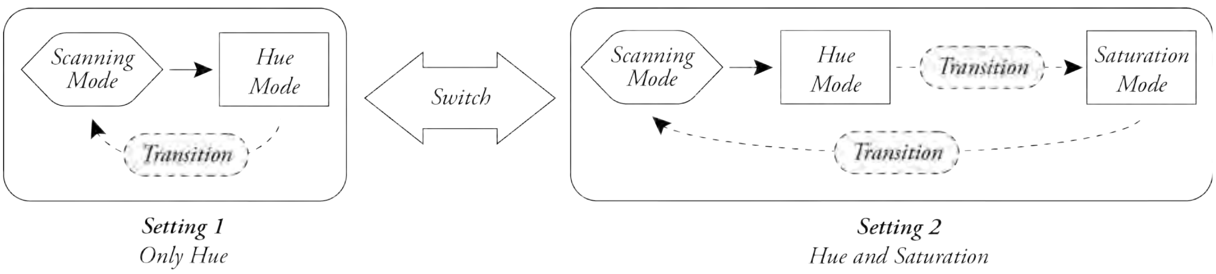


Figure 25 – Switching Between Setting 1 (Only Hue) and Setting 2 (Hue and Saturation)

6.1.2.3 Design Alternatives for Saturation Mode

The three following design alternatives were selected for the *Saturation Mode*, and later evaluated with users in the second pilot study (see Chapter 6.2).

Circular Formation

This design was based on a circular formation utilizing the three motors in a clock-wise manner being consistent to the direction applied in the *Hue Mode*. While participants of the initial pilot study (see Chapter 5.6) found interpolated points particularly difficult, this design alternative did not use any interpolation. Instead, the aim was to keep it simple and for it to require a potentially low cognitive workload. The design could be interpreted as a "progress circle" that filled up from 0 % to 100 % in clock-wise direction. If the saturation was low, M1 vibrated; for a medium saturation M1 and M2 played a pulse each in sequential order; for a high saturation the sensation went from M1, to M2, and then to M3 (see Figure 26). Each vibration lasted for 20 ms; between two consecutive pulses there was a delay of 20 ms. This design was labelled as *Condition A* in the second pilot study (see Chapter 6.2).

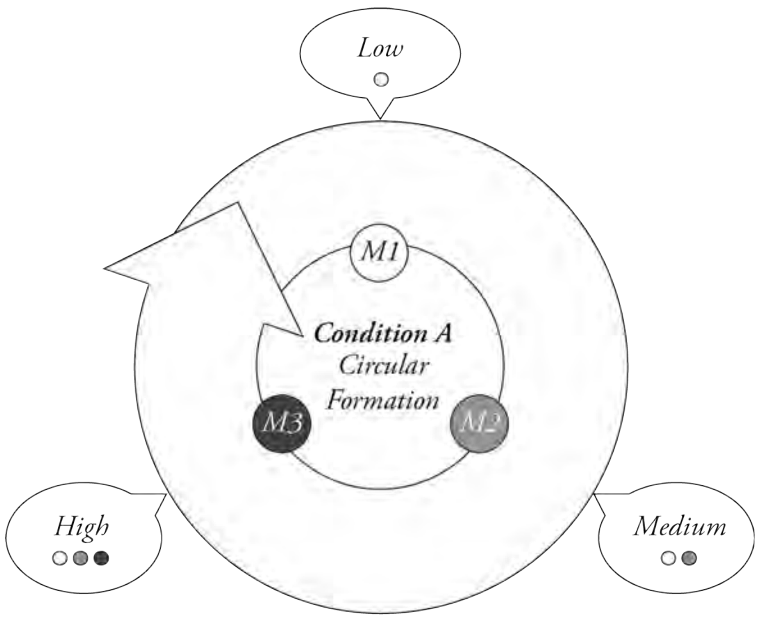


Figure 26 – First Design Alternative for Saturation Mode: Circular Formation with Sequential Pulses for Low (M1), Medium (M1, M2), and High (M1, M2, M3) Saturation; Condition A in Second Pilot Study (see Chapter 6.2)

Interpolated Metric Scale

This design built upon the encoded patterns used in the *Hue Mode* combined with a metric scale. As a consequence, the number of repetitions of a pattern used in the *Hue Mode* implied the level of saturation, which, for the context of this study, were defined on a scale of three (low, medium, high) as shown in Figure 27). The pulse patterns of the *Saturation* Mode therefore depended on the hue presented in the *Hue Mode.* While this design was potentially rather complex, it showed a high consistency in regard to the *Hue Mode* and was considered a coherent extension. As pauses between consecutive pulses used for interpolated points lasted 20 ms, an idle period of 40 ms was used between each repetition ensuring it was distinctive from the idle between pulses of one hue vibration pattern. During evaluation this design was named *Condition B* in the second pilot study (see Chapter 6.2).

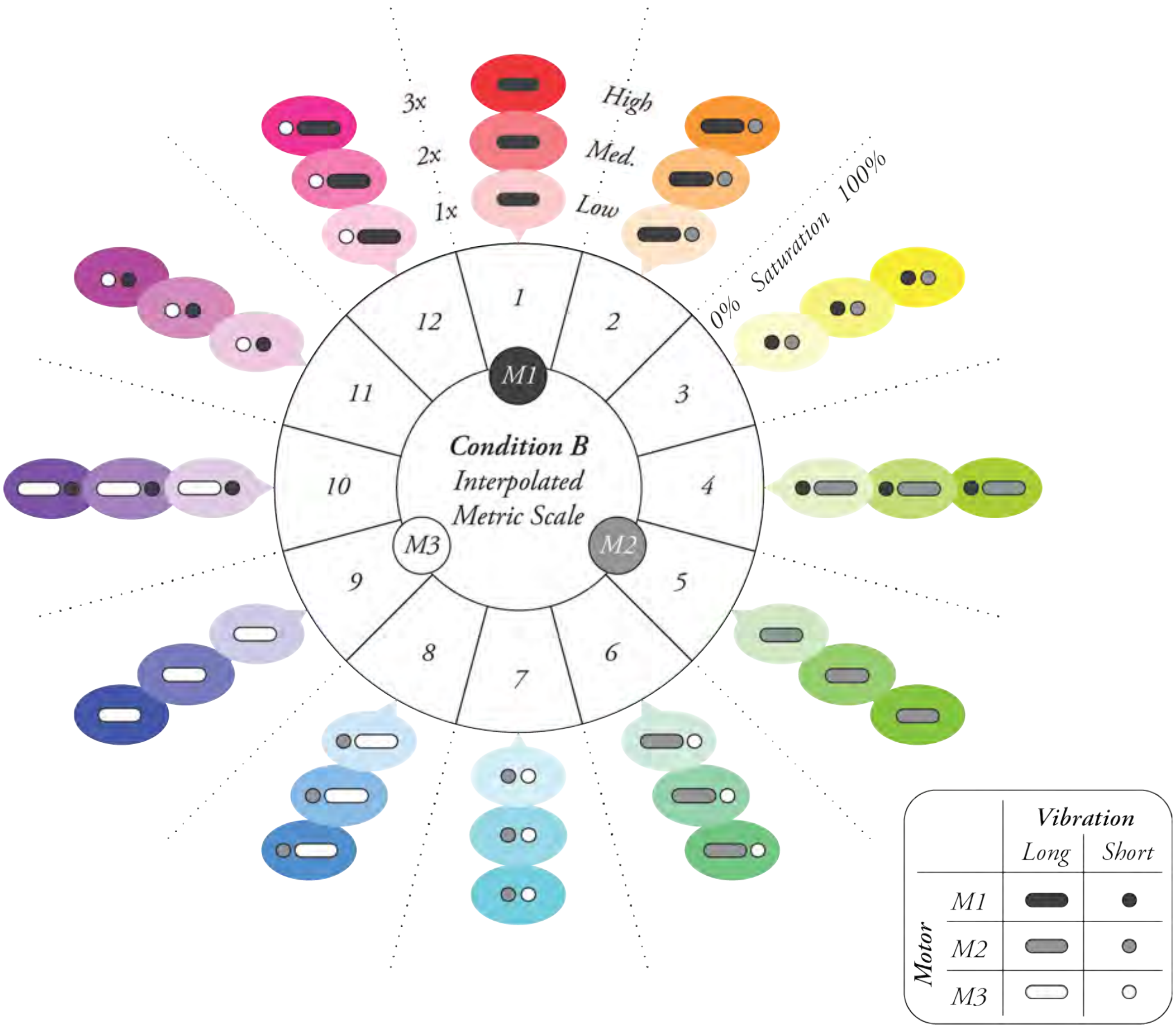


Figure 27 – Second Design Alternative for Saturation Mode: Interpolated Metric Scale with Sequential Pulses Depending on Interpolated Hue with Low (One Repetition), Medium (Two Repetitions), and High (Three Repetitions) Saturation; Condition B in Second Pilot Study (see Chapter 6.2)

Metric Scale (All Motors)

This design alternative also represented a metric scale but did not build upon interpolations from the *Hue Mode*. Instead, all three motors vibrated simultaneously – once for low, twice for medium, and thrice for high saturation (see Figure 28). Pulses lasted for 10 ms; between repeated pulses there was a short delay of 20 ms. For the scope of the second pilot study (see Chapter 6.2) this design was referred to as *Condition C.*

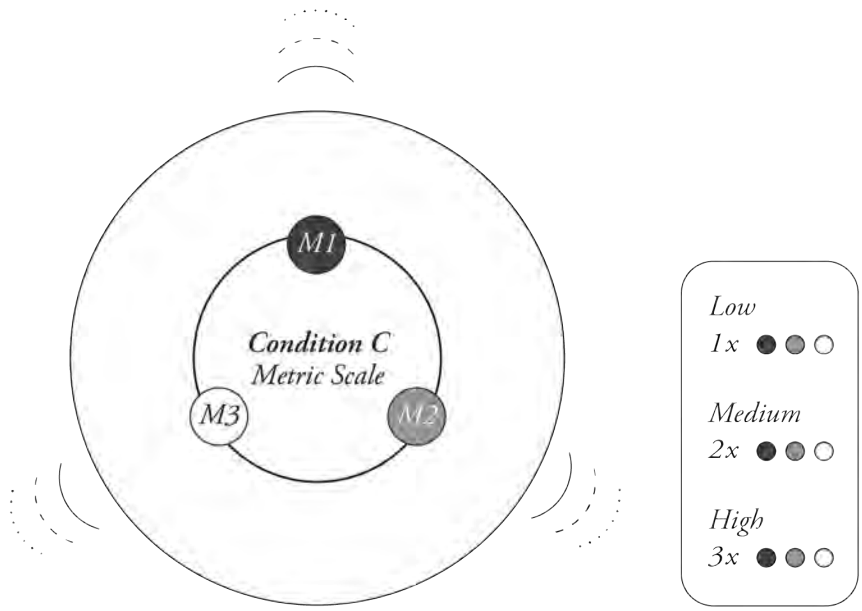


Figure 28 – Third Design Alternative for Saturation Mode: Metric Scale with Simultaneous Pulses of All Motors (M1, M2, M3) for Low (One Repetition), Medium (Two Repetitions), and High (Three Repetitions) Saturation; Condition C in Second Pilot Study (see Chapter 6.2)

6.1.3 Discussion of Narrowed Down Design Alternatives

The need for clear and consistent transitions from one mode to the other, in particular from *Hue Mode* to *Scanning Mode* (Setting 1), as well as from *Hue Mode* to *Saturation Mode* (Setting 2) and from *Saturation Mode* to *Scanning Mode* (Setting 2), was outlined. Their precise design, however, required further investigation. Additionally, the choice and design of the switch allowing the user to select one of the settings was not tested or investigated further for the scope of this project due to time limitations.

6.2 Second Pilot Study – Encoding of Saturation Mode

6.2.1 Objectives of Second Pilot Study

The goal of this study was to compare three design alternatives for the *Saturation Mode* and to help decide which of them was to be favoured for the final design. To this end, a simple system was needed that was neither too complex nor required a high cognitive load. While a vast number of different designs could be tested, this study investigated three selected designs that were created on the basis of user feedback. For the scope of this pilot study, the three design alternatives are referred to as *Condition A* (Circular Formation, see Figure 26), *Condition B* (Interpolated Metric Scale, see Figure 27), and *Condition C* (Metric Scale, see Figure 28).

6.2.2 Study Design of Second Pilot Study

6.2.2.1 Apparatus

The study was conducted by one facilitator and one participant at a time with a study setup as presented in Figure 20. The prototype as presented in Chapter 5.5 was used, however, all jumpers were taken off achieving more subtle vibrations as found necessary in the initial pilot study (see Chapter 5.6). All vibrations were played through a Wizard of Oz technique making use of the *Arduino Desktop IDE* and the code snippets presented in Appendix J.

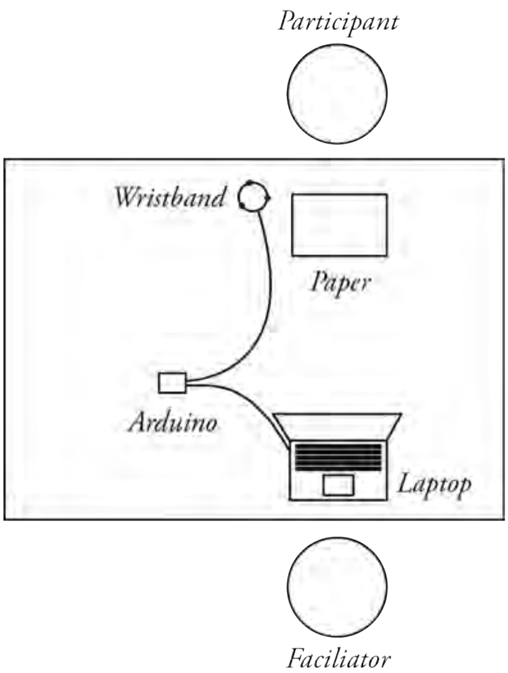


Figure 29 – Second Pilot Study: Setup

6.2.2.2 Procedure

Like in the previous pilot study (see Chapter 5.6), participants were introduced to the vibration patterns used to represent hues, and trained in a brief test block. To this end, all twelve patterns were played, and their position was named in clockwise order (from 1 to 12, as shown on the left in Figure 30) while a simplified version of the colour wheel (left side of Figure 30) was visible for the participants. Participants were asked if the explanation was clear and if they had any questions. While conducting the test, they were shown a simplified version of the prototype (right side of Figure 30) to be able to relate to the different motors during the test, and to refer to when explaining the different design before each condition.

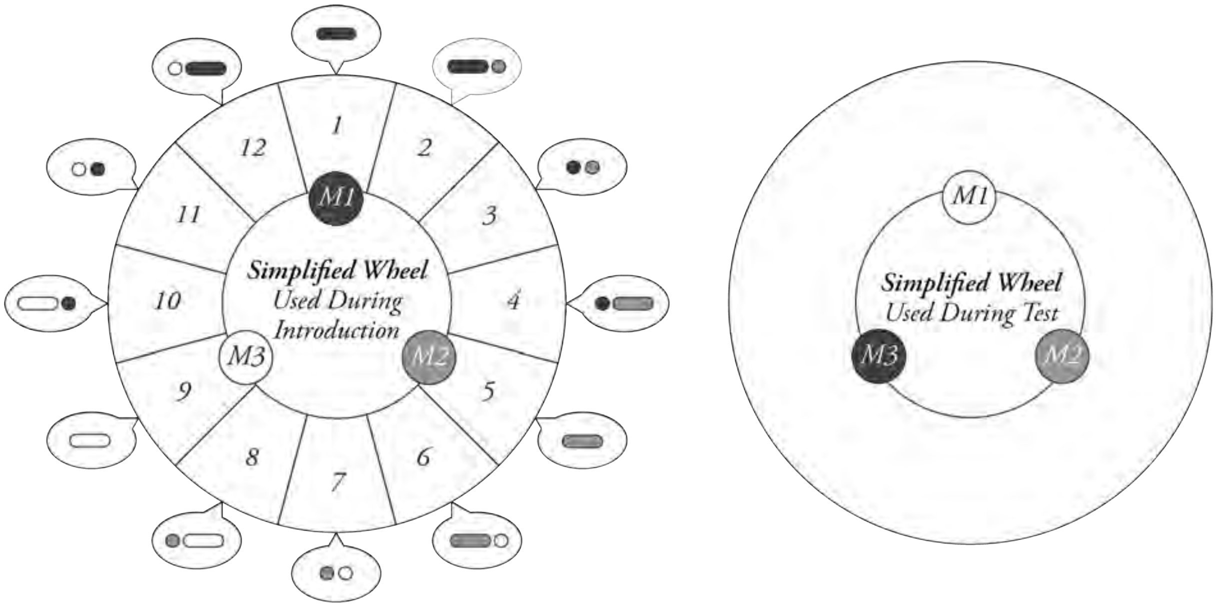


Figure 30 – Second Pilot Study: Graphics Shown to Participants

6.2.2.3 Data Collection

Before starting the actual test, participants were asked to sign a consent form and to fill out a pre-study questionnaire gathering demographic data (see Appendix I). Their wrists were measured to make sure they were larger than 15.5 cm. During the conditions their answers were noted by the facilitator to later ascertain the accuracy achieved for each of the three designs. After finishing each condition, participants were asked to fill out the standardized NASA TLX questionnaire [82] in its short from ("RTLX") to measure their perceived subjective workload. Additionally, a short semi-structured post-test interview followed investigating participants' preferred choice of condition and their reasons for it.

6.2.2.4 Participants

As identified in the initial pilot study (see Chapter 5.6), the prototype was too large for small wrists. Therefore, it was a requirement for participants of this study to have a minimum wrist circumference of 15.5 cm. Six participants (S1 – S6) without CVD were recruited within the university community, of whom five were males (see Table 12). Each test took approximately ten to fifteen minutes.

Participant	Gender	Age	Colour Vision	Professional Background	Handedness	Wrist Circumference
S1	Male	20	No CVD	Student (IT)	Right	17.3 cm
S2	Male	23	No CVD	Student (IT)	Left	17.3 cm
S3	Male	24	No CVD	Student (IT)	Right	18.3 cm
S4	Male	21	No CVD	Student (IT)	Right	17.3 cm
S5	Female	20	No CVD	Student (IT)	Right	16.0 cm
S6	Male	20	No CVD	Student (IT)	Right	18.0 cm
Total	**Female: 1** **Male: 5**	–	**CVD: 0** **No CVD: 6**	**Technical: 6**	**Left: 1** **Right: 5**	–
Mean	–	**21.3**	–	–	–	**Female: 16.0 cm** **Male: 17.5 cm** **All: 17.4 cm**

Table 12 – Second Pilot Study: Demographic Data of Participants (S1 – S6)

6.2.2.5 Conditions

The three different designs of the *Saturation Mode* presented in Chapter 6.1.2 were tested in this pilot study. *Condition A* was the *Circular Formation* (see Figure 26), *Condition B* was the *Interpolated Metric Scale* (see Figure 27), and *Condition C* was the *Metric Scale* (see Figure 28).

They were laid out on the basis of a three-level scale representing low (0 % – 33 %), medium (34 % – 66 %), and high (67 % – 100 %) saturation. This was due to the fact that *Condition A* was utilizing the maximum number of motors available, which was three, and because all three conditions were supposed to be consistent biasing participants as little as possible.

As for Condition B different positions were related to different hues, the following three were picked by example. They were, however, the same for each of the participants:

– *Low Saturation* (One Repetition): Field 6 (Green-Cyan)
– *Medium Saturation* (Two Repetitions): Field 7 (Cyan)
– *High Saturation* (Three Repetitions): Field 5 (Green)

The study was a within-subjects design [86, p. 75] meaning that each participant conducted all of the conditions. To counterbalance order effects, the participants tested the conditions in varying orders (see Table 13). For each of the conditions, the same sets of saturations were encoded and played achieving a consistency and allowing to compare the results. To ensure participants could not remember the order of saturation levels from previous conditions, orders varied between the conditions for each of the participants as follows (see Table 13).

Participant	First Condition	Second Condition	Third Condition
S1	A {L; M; H}	B {M; H; L}	C {H; M; L}
S2	A {M; L; H}	C {L; H; M}	B {H; M; L}
S3	B {H; L; M}	A {L; H; M}	C {M; L; H}
S4	B {L; H; M}	C {M; H; L}	A {H; L; M}
S5	C {L; M; H}	A {H; M; L}	B {M; L; H}
S6	C {H; L; M}	B {L; M; H}	A {M; H; L}

Table 13 – Second Pilot Study: Counter-Balanced Conditions A, B, and C With Shuffled Order of Low (L), Medium (M), and High (H) Saturation

6.2.3 Results of Second Pilot Study

6.2.3.1 Accuracy

Overall, *Condition A* and *C* were accurately decoded in 100 % (Standard Deviation (SD) = 0) of all trials, while for *Condition B* participants only stated the correct answer in 38.9 % (SD = 0.33) of all trials (see Table 14).

	Participants						
Condition	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**Mean**
Condition A	100 %	100 %	100 %	100 %	100 %	100 %	100 %
Condition B	0 %	33.3 %	100 %	33.3 %	33.3 %	33.3 %	38.9 %
Condition C	100 %	100 %	100 %	100 %	100 %	100 %	100 %

Table 14 – Second Pilot Study: Means of Accuracy for Condition A, B, and C by Participant (S1 – S6)

6.2.3.2 Workload

Evaluating the NASA TLX tests to ascertain the workload of the three conditions (see Figure 31) showed that, on average, *Condition A* was rated least *frustrating* ($\bar{x}$ = 17.5; SD = 23.6), while *Condition B* achieved the lowest *Temporal Demand* ($\bar{x}$ = 23.3; SD = 23.0). In all remaining four categories *Condition C* was rated the lowest with $\bar{x}$ = 15.8 (SD = 12.0) for *Mental Demand*, $\bar{x}$ = 8.3 (SD = 4.1) for *Physical Demand*, $\bar{x}$ = 10.0 (SD = 8.37) for *Performance*, and $\bar{x}$ = 13.3 (SD = 9.8) for *Effort*. Particularly demanding was *Condition B* in terms of *Mental Workload* ($\bar{x}$ = 50.8; SD = 14.6), *Performance* ($\bar{x}$ = 35.0; SD = 27.4), as well as *Effort* ($\bar{x}$ = 38.3; SD = 29.8).

Overall, *Condition C* resulted the lowest workload with $\bar{x}$ = 15.1 (SD = 14.47) on a scale of 100, followed by *Condition A* with $\bar{x}$ = 18.9 (SD = 17.81), whilst *Condition B* was rated highest with $\bar{x}$ = 31.1 (SD = 24.41).

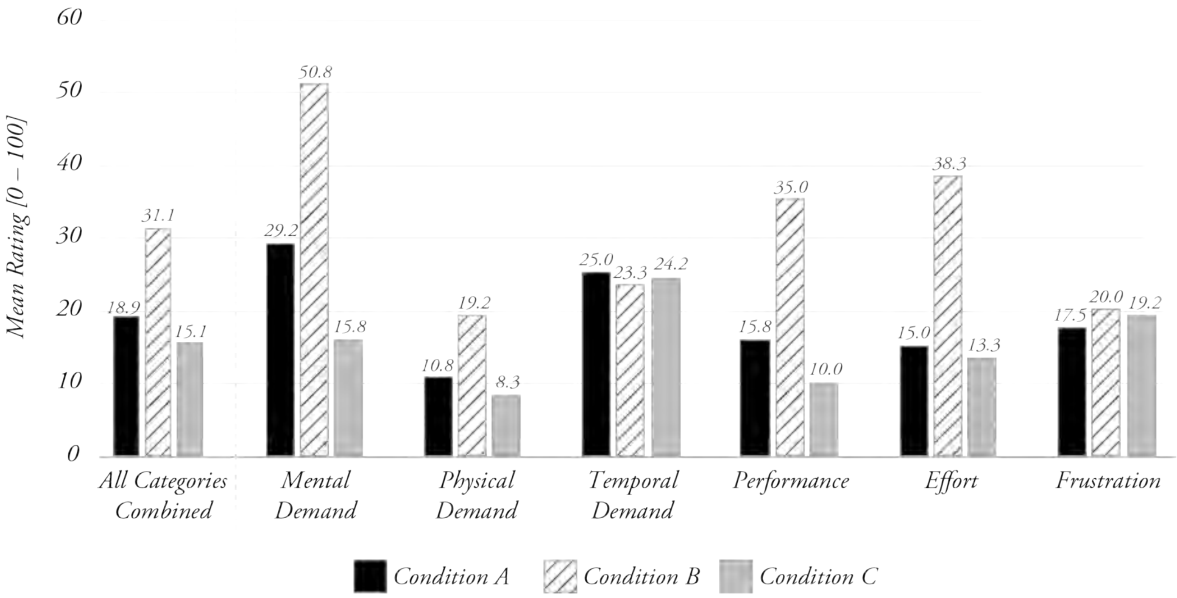


Figure 31 – Second Pilot Study: Mean Workload (NASA TLX) for Condition A, B, and C

To see if there was a statistical difference, the overall workload of the three conditions was tested with a one-way ANOVA. As Mauchly's test showed a violation of sphericity (0.18, $p < 0.05$), Greenhouse-Geisser-corrected (GGe = 0.55) values were reported. A significant effect of the conditions on the overall workload was found ($p < 0.05$, ges = 0.41). However, Bonferroni-corrected post-hoc paired t-tests did not find a significant difference between the different conditions. Investigating the different items of the NASA TLX, a one-way ANOVA with Greenhouse-Geisser correction showed a significant difference for *Mental Demand* ($p = 0.030$). Post-hoc paired t-tests with Bonferroni correction showed that *Condition B* and *C* differed significantly for *Mental Demand* ($p = 0.014$) which means the probability of *C* being less mentally demanding than *B* lies at 98.6 %.

6.2.3.3 Preferred Condition

Each participant had a clear favourite condition with *Condition A* and *C* each being preferred by half of the participants, while nobody liked *Condition B* most. Participants stated the following about the conditions (see Table 15).

Condition	Quotes
Condition A	*"It felt easiest to remember, and to explain. I enjoyed the first one." – S2* *"This was most intuitive and easy to distinguish; even if you miss the first pulse you can still find out which level it was because you always go to the next motor." – S4*
Condition B	*"This was slow." – S2* *"It was difficult to decode patterns. I was always waiting for the next vibration." – S3* *"This was quite hard and slow. It was quite difficult to determine which pattern it is." – S4* *"The hardest was B." – S6*
Condition C	*"This was the easiest. It was very easy and most natural. I would get used to the other two, but it would be a matter of time." – S1* *"The clearest was with all motors simultaneously because I didn't have to be focused on the direction." – S5* *"This was a quick one." – S4*

Table 15 – Second Pilot Study: Preferred Condition

6.2.4 Limitations of Second Pilot Study

While all design alternatives (see Chapter 6.1) were based on user feedback, the scope of the thesis project limited the number of alternatives to be evaluated with users, and therefore only three possible designs of the *Saturation Mode* were tested. With six participants the population size was rather small. Besides that, the test subjects were not very diverse; all participants had a similar technical background, and only one female participated, which was strongly related to the limitation of including only people with a wrist circumference larger than 15.5 cm.

6.2.5 Discussion of Second Pilot Study

In terms of accuracy and preferred condition, both *A* and *C* scored the same results, clearly outranking *Condition B*. The only significant difference was reported between *Condition B* and *C* for *Mental Demand,* meaning that the chance of *C* being less mentally demanding than *B* is larger than 95 %, whereas it is highly unlikely that for any of the other items to be statistically different. This implies that *Condition C* was presumably too complex in comparison to the other two conditions. Considering that the *Hue Mode*, with twelve different vibration patterns, was already rather complex, the *Saturation Mode* was aimed to be as little mentally demanding as possible. Even though there were no significant differences between the conditions overall, it was decided to use *Condition C,* the interpolated metric scale, as favourite design for the *Saturation Mode* to be tested in the final user study, as it resulted in the lowest workload, and, in particular, was the least mentally demanding of all conditions. Moreover, the scope of the final user study would have been unreasonably large and complex if several designs options had been included for the *Saturation Mode*. The fact that the results did not point towards significant differences might also have been connected to the small population size of six participants.

6.3 Prototyping

6.3.1 Physical Prototype

The physical prototype remained the same as presented in Chapter 5.5, apart from the fact that all jumpers were taken off achieving more subtle vibrations as found necessary in the initial pilot study.

Additionally, a colour sensor (Adafruit Flora TCS34725) was placed on the dorsal side of the wristband and connected to the shield (see Figure 32) with the instructed support of a technical student from TUL. This allowed it to scan colours, and thus for the user to receive the respective haptic sensations without the need of Wizard of Oz techniques. Its positioning was, however, chosen for rather practical reasons – the plastic clip on the volar side prevented easy mounting. Whether the positioning was useful demanded further testing. The circuit diagram including the colour sensor is presented in Appendix K.

When the sensor was active, a LED illuminated the object in front of the sensor. After testing it was found that the sensor worked most accurately when placed with a distance of about 2 cm to 3 cm from the item. Whenever it was placed too close, the reflection of the LED was to strong and the scanned colour was recognized as white with RGB {256, 256, 256} and HSL {0, 0, 1}.

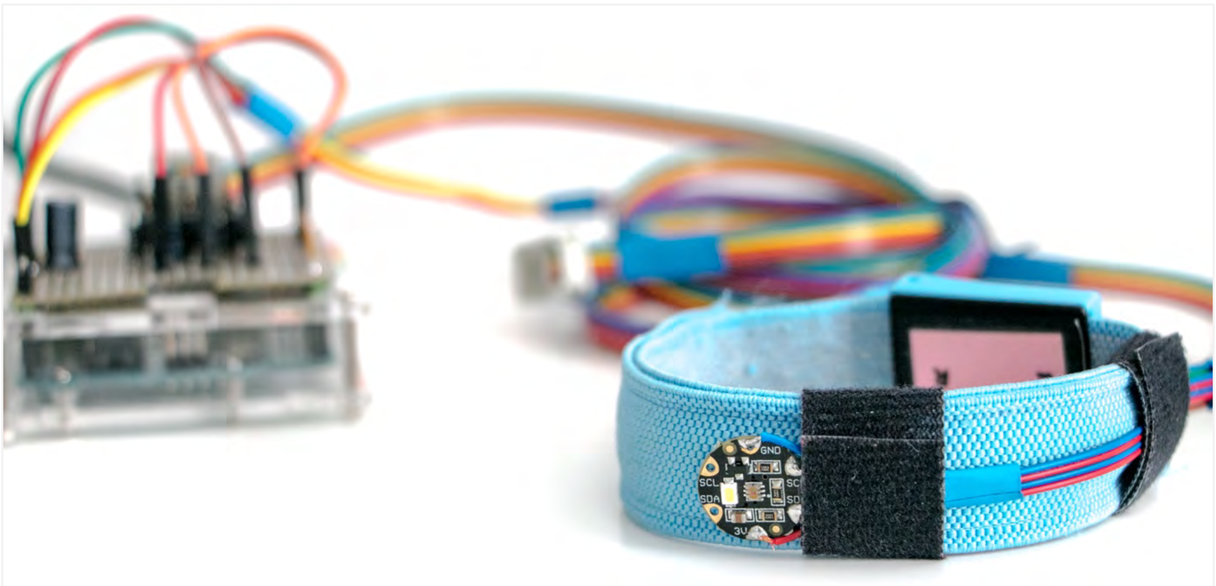


Figure 32 – Physical Prototype with Colour Sensor (Adafruit Flora TCS34725)

6.3.2 Arduino Code

As the colour sensor served as a replacement of Wizard of Oz techniques, it was required to automate vibration patterns based on the sensor measurements. Data output from the colour sensor was given in RGB and had therefore be converted to HSL (see Chapter 3.1.4) to receive the required values of hue and saturation. To convert RGB to HSL parts of the library *RGB Converter* were used [87]. While lightness values were not considered, the twelve hues and three levels of saturation were defined for the ranges given in Table 16. Using if-statements, each of these ranges was to be played depending on the sensor measurement. Pulses for the *Hue Mode* remained the same as before, and pulses for the *Saturation Mode* lasted 100 ms each with a delay of 200 ms between repetitions. An idle of 1500 ms was used as transition between *Hue* and *Saturation Mode.* The transition from *Saturation* to *Scanning Mode* lasted for 5000 ms making sure it was distinctively longer than all other pauses. The values scanned in RGB as well as those converted to HSL were printed in the *Arduino Desktop IDE's* serial monitor allowing to see what the sensor detected.

Hue	**Saturation**
`H>=345 && H<=360 || H>=0 && H<15 // Red`	`S>=0 && S<=0.33 // Low Saturation`
`H>=15 && H<45 // Red-Yellow`	`S>0.33 && S<=0.66 // Medium Saturation`
`H>=45 && H<75 // Yellow`	`S>0.66 // High Saturation`
`H>=75 && H<105 // Yellow-Green`	
`H>=105 && H<135 // Green`	
`H>=135 && H<165 // Green-Cyan`	
`H>=165 && H<195 // Cyan`	
`H>=195 && H<225 // Cyan-Blue`	
`H>=225 && H<255 // Blue`	
`H>=255 && H<285 // Blue-Magenta`	
`H>=285 && H<315 // Magenta`	
`H>=315 && H<345 // Magenta-Red`	

Table 16 – Arduino Code: Ranges Defined for Hue (H) and Saturation (S)

6.4 Final User Study

6.4.1 Test Objectives of Final User Study

The final user study was conducted to test the proposed design with users who have a CVD, and to investigate whether it fit their needs. The primary aim was to investigate workload and usability of two conditions, and to compare them. Hence, the focus did not lie on merely examining how accurately or well a user performed, but rather compare two designs with one another in terms of usability and workload, and investigate if the newly proposed design was useful for potential users of the wristband. The study was conducted with individuals who have a CVD, and helped answer the following:

- Which is the preferred condition (*Condition A:* Only Hue, vs. *Condition B:* Hue and Saturation)?
- In which context might the wristband and the two conditions be used?
- Which aspects are positive and / or negative about receiving additional information to the hue, in this case the saturation?
- Is there a measurable difference between the two conditions in terms of usability and workload?

6.4.2 Study Design of Final User Study

6.4.2.1 Apparatus

The study was conducted in quiet room and was a controlled laboratory environment with a setup as presented in Figure 33. Seated opposite of the participant the observer and moderator had pen and paper at hand for note-taking, a smartphone for audio recordings during the post-test interview, as well as ten items of clothing. The moderator was provided with a written script to be partially read out (Appendix O). The observer operated the prototype as well as the *Arduino IDE* and noted down answers given by the participant and values measured by the colour sensor in an *Excel* sheet. The laptop served as power supply for the *Arduino* and enabled uploading different codes for the various study parts. For the whole study the same prototype was used – it only differed in the Arduino code used for the different conditions. Jumpers were taken off from the prototype ensuring the pulses were not too strong. Connected to the Arduino, the wristband with its colour sensor was placed on the participant's dominant wrist. Informed consent form with pre-test questionnaire (Appendix N), and a colour wheel that were printed for each participant (Appendix P). A measuring tape was present to ascertain the participants' wrist circumference.

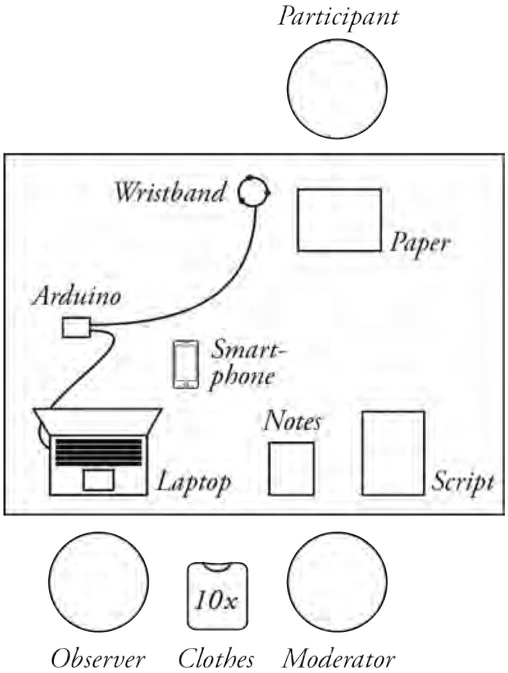


Figure 33 – Final User Study: Setup

In each test, a participant, a moderator, and an observer were involved. While the default language of the study was English, three participants preferred to conduct the study in Polish (see Table 18). Participants were asked to think-aloud while conducting the test, and to fill out the questionnaires. The observer operated the laptop with the Arduino interface, took notes from participants' think-aloud, and recorded audio during the semi-structured interview. While the observer was the same person for all studies, the moderator varied. Therefore, each moderator was briefed before conducting a study. He or she was responsible for leading the study, introducing participants, asking them to fill out the informed consent form and pre-test questionnaire (see Appendix N) as well the two post-task questionnaires (SUS: see Appendix R, NASA TLX: [82]), explaining the study procedure and tasks, and conducting the post-test interview. A written script was at hand in Polish and English (see Appendix O) and read-out to the participant ensuring each participant received the same information [86, p. 158], [88, pp. 287 – 296]. Further, the moderator aimed to make participants feel comfortable and answer questions they had at any point during the study. It was important to always be neutral towards participants and not to judge them, and not to bias participants in their answers. To ensure questions in the post-test interview were asked in a way that they did not lead to a specific answer or influence participants in coming up with own ideas, back-up questions were prepared allowing to re-phrase a question without giving a particular example when a participant struggled with the original question (see Appendix O). For studies held in Polish, the moderator was also responsible for noting participants' comments or translating them to the observer, as the observer was a non-Polish speaker.

6.4.2.2 Procedure

Each study included four parts: an introduction, two conditions, and a post-test interview (see Table 17). Before each of the two conditions, participants were introduced to the respective condition and a training block helped them get used to the vibration patterns. After training and before the conditions were tested, it was made sure they had no questions.

Phase	Activities
(1) Introduction	Consent Form – Pre-Test Questionnaire
(2) First Condition	Training Block – Test Block (Scanning of Clothing) – NASA-TLX – SUS
(3) Second Condition	Training Block – Test Block (Scanning of Clothing) – NASA-TLX – SUS
(4) Post-Test	Semi-Structured Interview

Table 17 – Final User Study: Procedure

For each participant ten pieces of colourful clothing (see Figure 34) were presented during the two conditions which participants were supposed to scan (see Figure 35) in order to find out the colour's hue *(Condition A),* or the colour's hue and saturation *(Condition B).* Their order, however, varied between *Condition A* and *Condition B* ensuring participants could not remember the order. After finishing each condition, participants were asked to fill out two standardised questionnaires, namely a NASA TLX and a SUS. Additionally, a semi-structured post-test interview followed at the very end.

Figure 34 – Final User Study: Ten Coloured Pieces of Clothing

Figure 35 – Final User Study: Scanning of Clothes

6.4.2.3 Data Collection

Before starting the actual test, participants were asked to sign a consent form and to fill out a pre-study questionnaire gathering demographic data and to investigate their form of CVD (see Appendix N). Data gathered during the study included both performance and preference data [86, pp. 165 – 166]. In terms of performance, the accuracy of participants' answers when decoding a vibration pattern was measured. In particular, it was noted if their answer was correct or incorrect. To measure participants' subjective feelings and opinions two standardised questionnaires were used after each condition, namely a NASA TLX in its short form [82] ("RTLX") to measure the perceived workload, and a SUS [80, p. 198], [81] to measure the perceived usability of the wristband. While there was no Polish translation available of the NASA TLX, a Polish translation of the SUS had been evaluated [89]. Therefore, the SUS was available for participants in both English and Polish (see Appendix R), whereas the NASA TLX was at hand in English as a non-standardized or non-evaluated translation might have led to incorrect results. In the very end of the study, a semi-structured post-test interview (Appendix O) followed aiming to help answer the objectives of this study (see Chapter 5.6.1). The interviews were audio recorded, transcribed, and, when necessary, translated to English, before analysing them.

6.4.2.4 Participants

The target group of participants consisted of people with CVD. To recruit them, the first step was the creation of posters (see Appendix L), which were placed on TUL's campi. Secondly, it was promoted through several social media channels (see Appendix M). These measures were taken in English and Polish to reduce language barriers, and participants were given the possibility to conduct the study in English or Polish. As an incentive, it was possible for students of TUL to receive a participation certificate (see Appendix O). The tool *Calendly* allowed for simple scheduling, re-scheduling, and contacting of participants. The tests, lasting between 30 minutes and 60 minutes, were conducted within a time-span of nine days.

Even though it was a requirement for participants to have some form of CVD, it was decided not to take any CVD test prior the study to identify the participants' colour vision. While Ishihara plates generally help identify red-green-weaknesses, they do not work for other forms of CVD. Moreover, they need to be presented on a calibrated screen, or printed with a calibrated colour printer to ensure correct results. Instead, participants were asked for their form of CVD, and were trusted in the correctness of their answer.

	Participant	Gender	Age	Form of CVD	Professional Background	Handedness	Wrist Circumference	Study Language
Group A	U1	Male	37	Unknown	Insurance Agent	Right	15.9 cm	Polish
	U3	Male	21	Unknown	Student	Right	18.1 cm	Polish
	U5	Male	22	Deuteranopia	Student (Automatics and Robotics)	Right	17.0 cm	English
	U7	Male	29	Unknown	Engineer	Right	18.8 cm	Polish
Group B	U2	Male	26	Protan	Student (Business and Technology)	Right	17.2 cm	English
	U4	Male	23	Deuteranomaly	Student (Computer Science)	Right	16.5 cm	English
	U6	Male	21	Deuteranopia	Student (IT)	Right	17.6 cm	English
	U8	Male	19	Unknown	Student (Technical)	Left	16.9 cm	English
	Total	**Female: 0** **Male: 8**	–	**Protan: 1** **Deutan: 3** **Unknown: 4**	**Technical: 1** **Non-Technical: 7**	**Left: 1** **Right: 7**	–	**English: 5** **Polish: 3**
	Mean	–	24.75	–	–	–	**17.5 cm**	–

Table 18 – Final User Study: Demographic Data of Participants (U1 – U8); Group A started with Condition A, while Group B started with Condition B

Altogether, eight males with a wrist circumference larger than the required 15.5 cm participated in the study and were equally distributed to *Group A* and *B* to counterbalance the order of the study's conditions (see Table 18). While all of them stated to have a CVD, only four knew the precise form. The majority of participants were students of technical programmes aged between 19 and 26 years, while two participants were working in insurance and engineering being 29 years and 37 years old. The average age of all participants was 24.75 years. In total, three studies were conducted in Polish, while five were held in English with a native Polish-speaker being present in case translations were required.

6.4.2.5 Conditions

In this study two conditions, the two settings outlined in Chapter 6.1.2.2, were compared. *Condition A* considered the representation of only the hue of a colour [2], [3], and *Condition B* included both the hue and saturation.

The study was a within-subjects design [86, p. 75], meaning that each participant performed all tasks. To counterbalance order effects, the participants were divided in two groups. *Group A* started with *Condition A,* while *Group B* began with *Condition B*. Which group a participant belonged to alternated (see Table 18) to ensure the study was counterbalanced even if someone cancelled last-minute.

6.4.3 Results of Final User Study

6.4.3.1 Accuracy

The correctness of vibration patterns decoded in the test blocks of each condition depended on the colour sensor's measurements. Hence, the measured values were noted and compared with the participants' answers. In total, each condition included ten items of clothes examined (see Figure 34). For *Condition B* only answers with both the correct hue and the correct saturation were considered accurate.

Overall participants were able to decode the patterns in $\bar{x}$ = 80 % (SD = 0.24) of all trials with *Condition B* being slightly more accurate ($\bar{x}_{\text{Condition B}}$ = 83.8 %; SD = 0.16) than *Condition A* ($\bar{x}_{\text{Condition A}}$ = 76.3 %; SD = 0.31) (see Table 19). While participants in *Group B* achieved the same accuracy for both conditions ($\bar{x}_{\text{Condition A and B}}$ = 92.5 %; SD = 0.10), *Group A* on average improved over time ($\bar{x}_{\text{Condition A}}$ = 60 %, SD = 0.37; $\bar{x}_{\text{Condition B}}$ = 75 %, SD = 0.17). Notwithstanding this, a two-tailed paired t-test showed that the difference between the means of the *Condition A* and *B* was not significant (p = 0.50), but a two-tailed unpaired t-test showed that the difference between the *Group A* and *B* was significant (p = 0.04). This means, that having to decode more information did not lead to a lower accuracy.

		Mean Accuracy		
	Participant	**Condition A**	**Condition B**	**Both Conditions**
Group A	**U1**	60 %	80 %	70 %
	U3	10 %	80 %	45 %
	U5	100 %	90 %	95 %
	U7	70 %	50 %	60 %
Group B	**U2**	80 %	100 %	90 %
	U4	100 %	80 %	90 %
	U6	100 %	90 %	95 %
	U8	90 %	100 %	95 %
Means Overall	**Group A**	**60 %**	**75 %**	**67.5 %**
	Group B	**92.5 %**	**92.5 %**	**92.5 %**
	Both Groups	**76.3 %**	**83.8 %**	**80 %**

Table 19 – Final User Study: Accuracy of Decoded Vibration Patterns

While five out of eight participants reached a mean accuracy 90 % or more, three participants (U1, U3, U7), all of whom were in *Group A*, had a mean accuracy of 45 % to 70 % (see Table 19). Reconciling this with the wrist circumferences, U3's wrist was 15.9 cm which might be correlated to problems in decoding vibration patterns due to the size of the prototype fitting larger wrists better. U1 and U7, however, had wrist sizes larger than 18 cm, and the prototype size might therefore not be connected to the achieved accuracy. Given the quantitative data it remained unclear why their accuracy was lower than the others'.

6.4.3.2 Workload

Evaluating the NASA TLX showed that overall *Condition B* was rated to be more demanding ($\bar{x}$ = 25.1; SD = 21.3) compared to *Condition A* ($\bar{x}$ = 22.3; SD = 20.3) as shown in Figure 36. A paired two-tailed t-test showed, however, that the means are not significantly different (p = 0.60).

While *Condition A* was rated lower than *Condition B* in all categories of the NASA TLX except of *Performance* (see Figure 36), a paired two-tailed t-test showed that none of these differences were significant ($p_{\text{Mental Demand}}$ = 0.61; $p_{\text{Physical Demand}}$ = 0.50; $p_{\text{Temporal Demand}}$ = 0.83; $p_{\text{Performance}}$ = 0.34; p_{Effort} = 0.50; $p_{\text{Frustration}}$ = 0.50). This means, that adding additional information did not imply more cognitive load on the user.

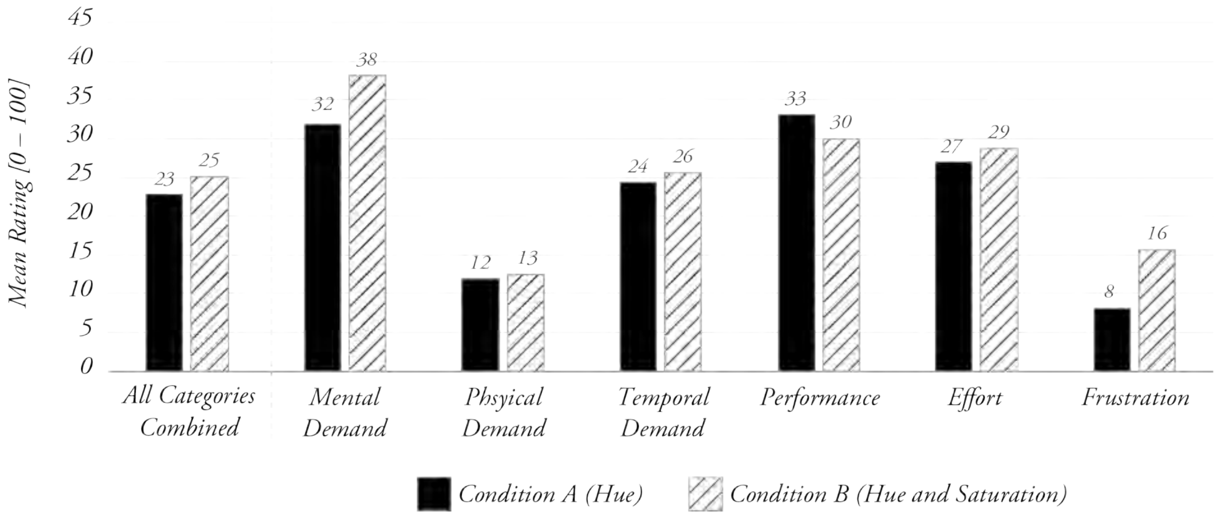


Figure 36 – Final User Study: Results of NASA TLX

6.4.3.3 Usability

To determine the overall SUS, a template [90] was used ensuring the correct weights of positively and negatively weighted questions [80, pp. 198 – 199]. The calculated overall score reached from 0 to 100 with steps of 2.5 [80, p. 199]. Only the overall SUS were analysed as "scores for individual items are not meaningful on their own" [81, p. 194].

Comparing the overall means, *Condition A* was rated to have a SUS of $\bar{x}_{\text{Condition A}} = 73$ (SD = 10.3) and *Condition B* reached $\bar{x}_{\text{Condition B}} = 76$ (SD = 9.2) as shown in Figure 37. However, a paired two-tailed t-test showed the difference is not significant (p = 0.55). The means of the perceived usability increased over time for both groups. *Group A* who started with *Condition A* on average judged the usability to be higher for *Condition B* ($\bar{x}_{\text{Condition A}} = 68$, SD = 11.4; $\bar{x}_{\text{Condition B}} = 78$, SD = 8.3), whereas *Group B* who started with *Condition B* rated the opposite ($\bar{x}_{\text{Condition B}} = 74$, SD = 10.9; $\bar{x}_{\text{Condition A}} = 79$; SD = 6.6). Hence, the condition conducted last was rated as more useable than the first. While this might correlate to training and adaptation effects, an unpaired two-tailed t-test showed the difference between *Group A* and *Group B* was not significant (p = 0.49).

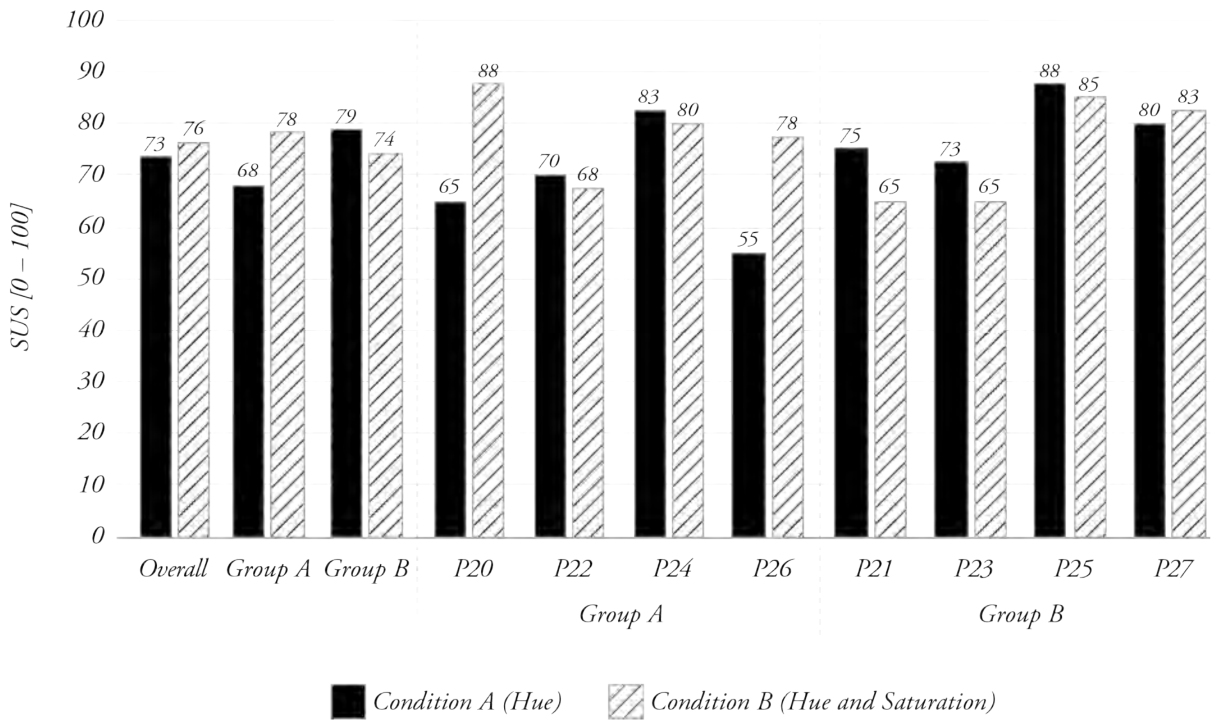


Figure 37 – Final User Study: Results of SUS

6.4.3.4 Semi-Structured Post-Test Interviews

The recorded qualitative interviews were transcribed, and those conducted in Polish translated to English. After merging them in a table, the answers to the ten questions (see Appendix O) were analysed in terms of reappearing patterns and frequency of appearance. The first and second questions helped answer which of the two condition participants preferred, questions three to six focused on the potential context of use, and questions seven to ten investigated the qualities and usefulness of the *Saturation Mode*.

Preferred Condition

Overall, six participants preferred *Condition A* (U1, U2, U4 – U6, U8), while two liked *Condition B* more (U3, U7). Those who liked *Condition A* more stated different reasons, such as it being faster than *B* (U2, U4, U8), being able to see saturation (U4 – U6, U8), not needing saturation as an information (U2, U5, U6), or it being "easier to do something wrong if there are more signals" (U5). The two who preferred *Condition B* perceived it as "more accurate" (U7), and "more logical […] to use […] [as] generally [they] see the colours, so for [them] the saturation is important (U3)".

Three participants stated they could imagine using both conditions and switching between them in different situations (U6 – U8). U6 would generally prefer *Condition A* but would switch to *Condition B* to when "playing with graphic design". Likewise, U8 could imagine switching to *Condition B* when buying a car "and there are different kinds of red cars, and [he] would like to have the most intense red one".

Context of Use

Those who did not experience many problems during their daily life did not see the need for a supportive tool. U6 stated he "was colour-blind for a very long time and didn't even know it […, and as] it is not […] a difficulty in a normal life at the day [… he does] not think [he] would use this very often". Others found the wristband would "not make such a big difference in [their] life" (U3) or change their life "not in a huge amount or huge way [… as] it would be mostly a convenience thing" (U4), but even if it did not change their life "significantly, […] in some situations it would help a lot" (U8). U6 pointed out "the need for the bracelet to be put very close to the object – because [he does] not very often have a problem where [he has] an object and […] absolutely need[s] to know what colour it is when […] holding it". While not finding the wristband useful for himself, U1 stated that "maybe sometimes women would look […] better [at him] if [he] could determine the colour. For [him], as man, the information which hue it is, is not necessary".

The participants imagined different application areas and situations where they might use it. As U4 thought "both can be used in sort of similar things", participants generally found it difficult to think of different use cases for *Condition A* and *Condition B* but described situations that might apply for the wristband in general without distinguishing between the two conditions.

U5 found it "useful during work or study" and U1 could imagine using it if he would "work in a job, where discrimination of colours is needed". Such professions included examples like "some kind of graphic designer or a painter I would use it every day" (U8).

Others would find it helpful in everyday situations such as "shopping, for example choosing fruits and vegetables, because normally, I am not sure if they are fresh" (U1). Likewise, U2 had problems when buying bananas for ripe and unripe being "like totally the same for [him]".

Using it for selecting and purchasing clothes was the most mentioned theme, with five out of eight of participants pointing it out. This might, perhaps, be due to the fact that participants tested the device with clothes. While U2 and U4 stated to use it for "buying clothes", U7 and U8 focused on "clothes selection" (U7) and "choosing the right style of wearing stuff" (D27). U3 and U8 also pointed out they could imagine using it for or together with their partner for "buying the dress with my girlfriend" (U3) or when his "wife is telling [him to] 'go and buy me a green dress' [… he] would measure all of them and say, 'this is the best green'" (D27).

Other contexts of use mentioned by only one participant each were the following:

> *"I believe it would be helpful for colour matching reasons." – U7*

> *"When reading diagrams or schemes it sometimes is a problem. […]. It's the matter of how large the object is – if the object is really small, it's harder to tell." – U5*

> *"When I was a child I would often ask my friends 'Hey what colour is this crayon?'. If I had this [wristband] back then, I would have definitely used it. I would point it at my crayons and coloured pencils." – U4*

> *"I would for sure use it for fun sometimes. Just to check and to be sure if I see some colours correctly. So, I would first make a guess and then I would check it." – U6*

> *"Maybe choosing the right colour for the room [wall paint] in the shop. First measure it at home, and then chose the same one at the shop. That would be great, because you can't really tell is it white or, you know, grey-white, or something like that. So, that would be helpful a lot." – U8*

Saturation Mode

As aforementioned, most participants did not see many differences in potential application areas between *Condition A* and *Condition B.* Four participants could, however, see use of the saturation in the following:

> *"Maybe when I am in a second-hand clothes store and I want to know how many times it has been laundered." – U2*

> *"Maybe if I did more artistic work, indeed, with paint or something." – U4*

> *"When it comes to graphic design the recognition of colours and saturation is quite important. So, I would probably use it in that case." – U6*

> *"That option would be useful, in my opinion. If I would buy a car and there are different kinds of red cars, and I would like to have the most intense red one, I would use it then." – C8*

Some participants found that "the levels of saturation are necessary" (U3), "interesting" (U4), or "okay" (U1), while others stated to "not see direct benefits when it comes to [their] daily life apart from graphic design" (U8), or that they "cannot think of any use for the saturation" (U6). The latter was mainly related to the fact that they said they stated to perceive saturation visually (U4 – U6, U8) and, therefore, found it was additional information that might have been unnecessary (U2, U6). For U3, in comparison, it was the other way around as "generally, [he sees] the colours, so for [him] the saturation is important".

Asking what they disliked about the *Saturation Mode*, opinions were split. Three participants found "everything was great" (U3), or had no problems" (U1, U7), while three others were not satisfied with the pace (U2, U4, U5, U8) and were therefore wondering "why [he had] to wait for the signal intensity [referring to saturation] if [he does] not need it" (U8). In particular, those who stated to be able to see saturation "thought it takes more time to say something not necessary" (U2) and that "it is easier to do something wrong if there are more signals" (U5). U8 highlighted that he had to stay concentrated and "sometimes when [he] was too focused on thinking about the colours and the motors, [he] did not recognize the lowest saturation. That would be a little problem, but maybe you just have to be a little more patient, more focused on it". Some said they were "sometimes confused" (U6) but, generally, imagined getting "used to it" (U1, U6) over time.

On the other hand, participants also liked plenty of aspects about the *Saturation Mode*, such as it being a "very easy" (U3) and "efficient way of passing the information" (U2), as well as being "important" (U3), and "more logical" than the *Hue Mode*. Similarly, U2 and U4 liked that it was "faster" (U2) and "quick – when the hue was concerned it took a bit longer to process" (U4). In particular, using a scale of three to represent low, medium, and high levels of saturation was positively judged as being "enough" (U1), "appropriate" (U7), "easy [… and a] very good number" (U4). While four participants would not increase the size of the scale (U1, U4, U6, U7) as "it is simple, and […] it is good to keep it simple" (U6), U8 could imagine to "extend it to maybe five or something".

Moreover, three participants suggested to change the design of the *Saturation Mode* and proposed the same idea (U5, U6, U8). They would prefer to "have more information in the same signal" (U5) meaning they would like to "intensify signals" (U8) so that the saturation would be presented simultaneously to the hue by varying the intensity of pulses. Hence, the twelve vibration patterns from the *Hue Mode* would "vibrate a bit stronger or less strong" (U6) depending on the level of saturation as "that would be easier because now [he has] to count the signals" (U8).

6.4.3.5 Observations and Think-Aloud

Considering the short time participants were using the wristband and learned the different vibration patterns, some participants had to focus strongly. U1 stated he had to concentrate a lot in the beginning, and U4 had problems focusing on decoding whilst the moderator was talking. Similarly, U2 found it "for now demanding, but with practice it would get easier", and U8 had to "focus on the whole cycle". Even though durations were not stopped, it was observed that U1 and U7 were overall slower than other participants, and U5 was strikingly quick.

Other interesting insights gathered from think-aloud were the following:

> *"It's easier to feel the colour than to recognize it with my eyes." – U8*

> *"I finished music school, and I projected two notes based on what I felt. Often have visual effects when listening to music." – U2*

They also stated that they "felt the top motor [M1] a bit stronger" (U7), and that motors should be placed with a bigger distance (U1). Referring to the *Saturation Mode,* U6 similarly found "it feels like only motor one [M1] is vibrating when all vibrate", and U2 stated "when one motor vibrates everything else vibrates". U1 also pointed out to "to hear more than" he feels due to the sound created through pulses.

Three participants were wondering how the colours white (U2) or brown (U5) would be represented as those were not visible on the colour wheel (see Appendix P). U5 further pointed out that "it could show more colours on more motors. It's not much, and usually that is not the scale [he has] problems with[, but] larger scales when there are more colours and they are not the most common ones, but more complicated".

The positioning of the colour sensor made half of the participants turn their arm (U1 – U3, U5) so the dorsal side pointed downwards when the object they wanted to scan was laying on the table (see right side in Figure 38). This, however, was difficult or confusing as the mental model learned during the training block was while having the dorsal side point upwards (see left side in Figure 38). U2 stated "the positioning [he] learned the colours, [he has] to flip around" and U5 said it is "difficult as [he was] training in the other direction". When rotating their arm so that their wrist was postured in the same direction as during the training and clothes to be scanned held above the sensor, as opposed to below it, this problem was solved (see left side in Figure 38). It needs, however, to be considered that participants were in a seated position and did not test the wristband in a standing position. U2 asked for several additional trials to compare different arm postures and found that decoding vibration patterns was "a lot more difficult when the hand touched the table than when it [was] in the air".

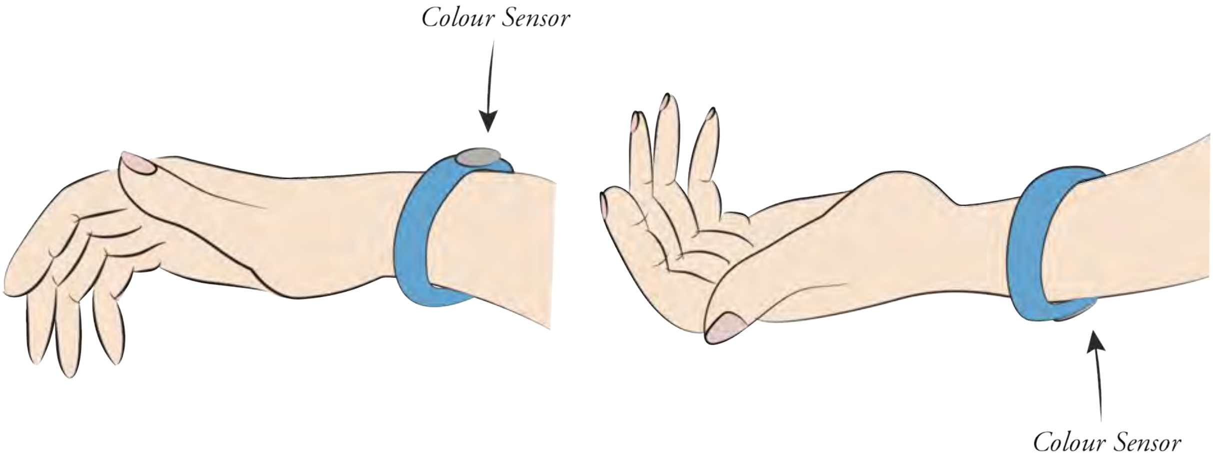


Figure 38 – Final User Study: Different Arm Postures

6.4.4 Limitations of Final User Study

Of the eight participants with CVD that were recruited, the fact that they were only males with an academic and mostly technical background can be seen as a limitation. Yet, considering the prevalence of CVD (see Chapter 3.2.3) the number of participants was seen as sufficient for the scope of this project and the imbalance of represented genders was not beyond expectation.

As the study was conducted in Poland, all participants were native Polish-speakers and some felt more comfortable conducting the test in their mother tongue. This required for a Polish-speaker to be present during all tests, for all document to be bilingual, and led to a variety of limitations which needed to be considered when interpreting the results of the study. The only document that was not available in Polish was the NASA TLX as there was no standardized translation available. As some parts had to be translated on the spot from the English NASA TLX certain details might have been interpreted or translated differently. Furthermore, it might have been problematic that transcripts and translations of the post-test interviews were conducted by a variety of people. In particular, those done by people who were not present during the study might be considered less reliable due to the inevitability of the translations being influenced by the translators' interpretation. Also, none of the translations had a second person to go over them. During the analysis of qualitative data, it was found that not all moderators formulated questions the way they were prepared. While all questions were supposed to be open-ended, with the aim of avoiding terse yes- or no-answers, this was disregarded by some moderators and led to brief answers. This hampered the original goal of gaining deeper insights about the thoughts and opinions of the participants.

The study aimed to resemble a shopping-like environment by using clothes as realistic items in a controlled laboratory environment. Despite this, participants were in a seated position which might not have resembled the posture when shopping in a store. On the other hand, the controlled environment allowed to test each participant in the same way and to easily compare those results with one another without having to consider a variety of external factors.

Another limitation of the study might be that training sessions for *Group A* and *B* varied slightly (see Appendix O) as *Condition B* included the *Hue* and *Saturation Mode.* This is due to the fact that *Condition B* required more explanation when it came first *(Group B),* but less when it came second because participants were already trained for the *Hue Mode (Group A).* Similarly, *Condition A* required more training when it came first *(Group A),* and less when it came second because the *Hue Mode* was trained beforehand *(Group B).*

6.4.5 Discussion of Final User Study

The questions formulated as objectives of this study were answered as follows.

Which was the preferred condition?

Analysing the qualitative data showed that overall, six participants preferred *Condition A*, while two liked *Condition B* more. For those who could see hues saturation was important, as opposed to those able to see saturation but needing support with hues. Only two participants could imagine switching between the conditions depending on the context. This indicated that different users have different needs, most likely depending on the impact their CVD has on their colour vision, and that only the kind of data posing difficulties to them is of high relevance. Therefore, both hue and saturation are important when designing for people with CVD, but ideally a supportive tool shall be adaptable or configurable to the individual needs and preferences of the user.

In which context might the wristband and the two conditions be used?

For most participants the wristband would not make a huge difference in their life, but might be useful in certain situations, such as work-related tasks for professions like graphic designers or painters, grocery shopping and knowing when fruits are ripe, or selecting and purchasing clothes. This implies that supportive tools might only be used for certain occasions or in specific contexts. As a consequence, the user should be given control over the device, such as switching between different settings or options, as needs might vary for different contexts.

Which aspects are positive / negative about receiving additional information to the hue, in this case the saturation?

Half of the participants did not find any situations where the information about the saturation would be helpful for them, while four others named examples such as graphic design, arts, second-hand clothes, and purchasing a car. Overall, the *Saturation Mode* was perceived as simple and logical. The scale of three representing low, medium, and high saturation seemed satisfying, but three participants suggested a different design where pulses representing the hue would be intensified to simultaneously give information about the saturation. This implies that a scale of three is suitable for the *Saturation Mode*, but that it should be further explored whether the proposed idea of combining the information of hue and saturation might be better.

Is there a measurable difference between the two conditions in terms of usability and workload?
Quantitative data showed that among the eight participants the overall achieved accuracy lied at 80 % with no significant difference between *Condition A* and *B*. In terms of workload, there was neither a significant difference between the two conditions, nor among the six categories of the NASA TLX, meaning that *Condition A* and *B* required a similar workload. Likewise, the perceived usability rated in the SUS for the two conditions was not significantly different. This indicates that *Condition A* and *B* are overall similar in terms of accuracy, usability, and workload. Adding saturation to the prototype as extra information to the hue neither made the device more demanding nor less usable.

6.5 Discussion of Final Design

Based on the results of the final user study, the final design contributed the following, but was also limited in certain aspects as described hereinafter.

6.5.1 Contributions of Final Design

Answering the research question *"How and to which extent can haptic feedback be utilised to communicate information about colour variations presented to people with CVD while achieving a high accuracy?"*, it can be said that by applying two parameters of the HSL colour system, namely hue and saturation, the final design extended the information about colours presented to the user through haptic feedback. In one condition, the user received information about the hue of on object as presented by Carcedo et al. [2], [3], and in another condition they were informed about both hue and saturation. The design of the *Saturation Mode* was a simple metric scale representing low, medium, and high saturation through repetitive pulses on all motors simultaneously, and was found to be simple and logical. While some users with CVD stated they can see saturation, others can see hues. Hence, the usefulness of those two conditions depended on their colour perception. It is suggested to give the user the option to switch between conditions, but to have both options available.

This was implemented with a functional prototype which included a colour sensor and, based on real-time data, eliminated the need for Wizard of Oz techniques. The two conditions were evaluated in a controlled test environment with colourful clothes representing realistic artefacts that can be challenging for people with CVD.

6.5.2 Limitations of Final Design

First and foremost, it needs to be considered that the proposed and evaluated design was one of many potential options. Due to time constraints it was not possible to test more alternatives.

Using vibrotactile sensations to communicate information was overall perceived as positive and interesting. Pulses should, however, be subtle as strong vibrations are hard to locate and can also be audible. When designing a wristband with haptic feedback it needed to be considered that different wrist circumferences impact the distance between motors, and therefore different sizes of the wristband should be available when testing with different users. Similarly, the tightness of the wristband was important for accurate decoding.

As participants pointed out, the wristband did not represent colours such as white, black, grey, or brown in a simple manner. While grey would be a hue with low saturation, the *Saturation Mode* could indicate this, but certain knowledge about colour would be required. As the third parameter of HSL, lightness, was not included as a parameter, it was not clear for participants how black or white were represented.

The prototype currently worked for objects held in front of the colour sensor, but participants pointed out that in their daily lives they experience difficulties with items that are either small or far away. Another limitation of the prototype was that a LED is permanently shining with a rather bright light illuminating objects to be scanned. Generally, external factors such as ambient light might have influenced the accuracy of the measurements. Further, while testing, the prototype was always either on or off, and did not include the possibility to switch between settings. For the time being idles were used as transitions between the different modes; it was, however, not investigated whether there might be other, more preferable, design alternatives. Initially it was planned to decrease the prototype in size and to make it wireless; due to time constraints and prolonged delivery times both steps were, however, not accomplished. The positioning of the colour sensor was decided for practical reasons, but not investigated further. Moreover, the issue concerning varying wrist sizes, but non-adjustable placement of the motors was not solved.

7 Conclusion

7.1 Summary of Contributions

Building upon previous research [1]–[3], a supportive tool for people with CVD was further developed to help in colour identification and comparison tasks. The potential of using haptic feedback in a wristband to translate colours into tactile sensations was explored, and the following contributions were achieved.

Understanding

To gain an initial understanding of CVD as well as of the needs and problems of people with CVD, five colour-vision deficient people were interviewed. It was investigated how the prototype could help them in the identified needs and problems. The current state of research on supportive tools for CVD was reviewed, and an initial pilot study helped understand how the *HaptiColor* prototype was used and how it could be improved.

Prototyping

Applying parameters of the HSL colour space, the prototype was enhanced to detect an object's saturation in addition to the already existing functionality of representing the hue. This was achieved through user-centred, iterative design. The physical Arduino-based prototype in form of a wristband was made more stable and reliable. Additionally, it was equipped with a colour sensor eliminating the need for Wizard of Oz techniques when operating it.

Design Alternatives and User Testing

After several iterations of designing, and testing with users, different design alternatives were generated. The final design was evaluated with eight colour-vision deficient individuals in a controlled laboratory setting utilizing coloured items of clothing as realistic artefacts which can pose challenges for people with CVD.

7.2 Conclusions from Results

Initial interviews with five people found that their CVD affected their daily lives. In particular, selecting and purchasing colourful clothing was a reappearing theme. For most interviewees, receiving information about the hue of confusing colours would be sufficient, but for one person, who perceived his CVD as rather strong, more information was relevant. One person also mentioned it to be useful for those with stronger a CVD.

Results from the initial pilot study conducted with eight participants showed that overall participants found the mapping of vibration patterns decoding hues logical and understandable. However, encoding interpolated points with more complex patterns was more difficult as opposed to less complex patterns. Users' wrist size in relation to the size of the wristband needed to be considered for future studies. Opinions about whether the information about colour presented to them, namely the hue, was sufficient, were split, which led to the conclusion that future investigation was needed.

Based on user feedback from the initiation phase design, alternatives were generated. A basic interaction model with two device settings was outlined expanding the prototype to present not only a colour's hue but also its saturation making use of the HSL colour space.

To investigate and narrow down the precise design representing saturation, a second pilot study was conducted with six participants. Three design alternatives with vibrotactile information about the saturation were tested, of which a metric scale was found to require the lowest workload.

After equipping the prototype with a colour sensor and making it function automatically, the prototype with its two settings was evaluated in a final user study with eight colour-vision deficient individuals. Overall, the two modes resulted in a similar workload and usability. The majority of participants had a clear opinion about which kind of information about a colour is useful for them. Due to the fact that some stated they can see saturations but need support with hues, and others who see hues but no saturation, the proposed *Saturation Mode* was found useful by some users, while others preferred the already existing *Hue Mode*. In conclusion, it is suggested to give the user the option to switch between settings and to have both options available.

7.3 Future Work

To enable testing in the field, the prototype should be made wireless. This could be achieved with Bluetooth and a battery as power supply, while maintaining a reduced size allowing the user to move without limitations. Furthermore, different colour sensors could be tested aiming to avoid having to illuminate the object in question when scanning a colour, but also the optimal positioning of the colour sensor should be examined as for now it was placed on the dorsal side of the wrist only for practical reasons.

Investigating the use and interactions from an embodied interaction perspective could bring interesting insights. In particular, gesture-based interactions could be explored from a somaesthetical view and potentially be considered for switching between different settings. Next steps should also include exploring design alternatives for switching between settings, as well as transitions within each setting as for now transitions simply idled. In addition, it could be tested whether users prefer the current design of the *Saturation Mode* compared to the idea proposed of having pulses representing the hue be intensified to simultaneously give information about the saturation.

As many participants stated they can imagine getting used to vibration patterns, decoding, and the wristband as a whole over time, learning should be investigated in a future study. Potentially, cultural differences could also be looked into. Other future work may include examining the usage in other application areas, such as work- or art-related contexts, but also how to use the device for objects which are further away from the user.

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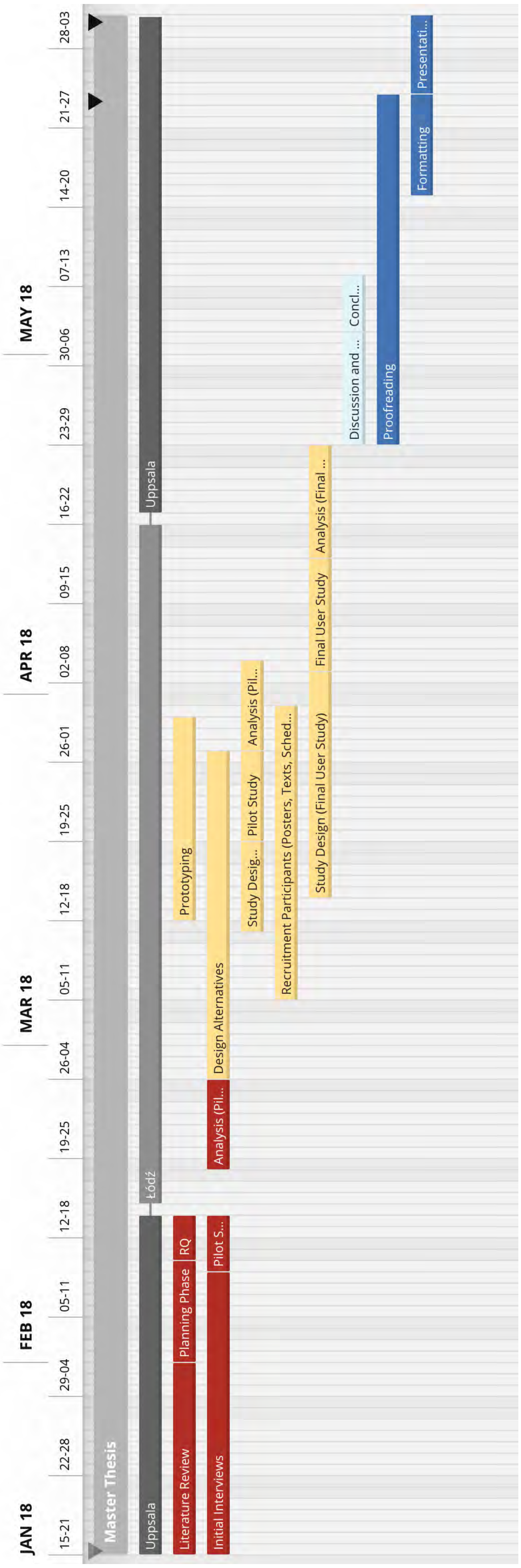
Appendix

Appendix A – Overview of Various Supportive Applications

App	Functions and Features	Target Group	Availability	Developer
Be My Eyes	Platform connecting visually impaired and sighted volunteers via live video calls when assistance is requested. Registered users as of January 2018: > 839.000 volunteers, > 56.000 blind people,	Community of sighted volunteers and people with vision loss.	Android, iOS	bemyeyes.com
Chromatic Glass	Three modes to distinguish, find, and simulate colours. Extensive information about colour in question (chromaticity diagram, colour names, colour values in different colour systems, e.g. RGB, Munsell, various CIE standards). Extensive functionality, but interface seems not intuitive. Unlike other apps it does not add filters to simplify distinguishing different colours, instead confusing colour is recognized and highlighted through blinking area.	People with CVD; People without CVD	iOS, Web-based	asada.tukusi.ne.jp/chromaticglass/e
Color Binoculars	Filters supporting people with CVD in colour identification. By changing colours different colour combinations become more easily distinguishable (red-green, green-red, or blue-yellow).	People with CVD	iOS	microsoft.com/en-us/garage/profiles/color-binoculars
Color Inspector	Colour identification. Colour namings presented as text: broad "colour family" and a more detailed description of colour in question. Possibility to zoom, adjust sample size, and to record video and to go back to specific points. VoiceOver compatibility.	People with CVD; People with other visual impairments	iOS	colorinspector.com
Eye Music	Mainly for people with vision loss. Sonification of visual images, i.e. converting visual information into soundscape. Focus on training and learning process. Project by *Amir Amedi lab* (Hebrew University of Jerusalem) still in beta version.	People with vision loss	Android, iOS	amedilab.com
Eye of Providence	Identification of colours and text in captured images. Information presented audibly or as text.	People with CVD	iOS	geteyeofprovidence.com

App	Functions and Features	Target Group	Availability	Developer
NowYou-See	Filters supporting people with CVD in colour identification by changing colours (all six protan, deutan, and tritan forms). Colour picker identifies up to 150 colours by name. Additional filters simulating CVD for people without normal colour vision.	People with CVD	Android, iOS	areyoucolor-blind.com
Red Stripes	For red-green deficiencies. Different striped patterns can be selected to replace red and / or green parts of colours.	People with CVD	iOS, macOS	michelf.ca/soft-ware/red-stripe
SeeingAI	Extensive functionality: Text-to-speech (including handwritings*); Identification and scanning of barcodes; Recognition of people (including their facial expressions, other characteristics, as well as estimated age); Description of surrounding environment*; identification of currencies on bills*; description of perceived colours*, sonification of brightness. * Still in beta mode	People with vision loss	iOS	microsoft.com/en-us/seeing-ai
Sim Daltonism	Filters simulating different forms of CVD. Good for testing if a design is “colour-blind-friendly”.	People without CVD	iOS, macOS	michelf.ca/pro-jects/sim-daltonism
TapTapSee	Mainly for people with vision loss. By double-taping the screen a photo is taken, that is then analysed. Identified information is presented audibly via VoiceOver.	People with vision loss	Android, iOS	taptapseeapp.com

Appendix B – Screenshot of Web-Based Gantt Chart



Appendix C – Initial Interviews: Guiding Questionnaire for I1 – I3

- Is it a sensitive topic for you to talk about your CVD?
- Which kind of CVD do you have?
- When and how did you find out that you are colour-blind for the first time?
- In which situations do you actually notice that you have a colour-blindness?
- Are there situations where you are happy to be colour-blind, or when you benefit from it?
- When and what kind of problems have you experienced so far?
- Imagine you would have a tool that would support you with colour identification, where or when would you use it?
- What qualities should it not have (e.g. appearance, look and feel, price, etc.)?
- Have you heard about the Enchroma glasses? What would make you try or not try them?
- [Explain what *HaptiColor* is.] The *HaptiColor* wristband has haptic feedback only at the moment (small pulses with different vibration patterns). Which combination with other senses could you imagine?

Appendix D – Initial Interviews: Guiding Questionnaire for I4 – I5

- Explain how contact to them started. Introduce myself and project topic.
- Could you introduce yourself and tell what you are currently working/studying?
- What form of colour-blindness do you have?
- Did you ever try to understand how a colour-blindness arises?
- Do you have a system for colours in terms of remembering / seeing /recognizing them?
- How do people in your entourage name colours?
- Which problems do you have with colours, e.g. in daily life?
- How do you handle buying clothes?
- How would you imagine buying clothes when you are on your own and nobody is around to help?
- How do you know which colours harmonise well with one another?
- Could you imagine using a supportive tool for colours?
- [Explain *HaptiColor*.] In what way could it be relevant or useful for you if *HaptiColor* would be extended with more information than just the current twelve hues [e.g. HSL]?
- Which expectations would you have for such a wristband, e.g. qualities, functionalities, look and feel?

Appendix E – Initial Interviews: Informed Consent Form

Informed Consent Form (Interview)

The following provides you with information about the research project carried out by Alexandra Kandler from Uppsala University to help you decide if you want to participate.

The purpose of the research project is to investigate the potential of a wristband as supportive tool for people with colour vision deficiency. Using vibration motors, colours are translated into haptic feedback.

Your participation is solicited, yet strictly voluntary. You may refuse to answer any question. If you agree to participate, please be aware that you are free to withdraw at any point without any negative consequences for you – no questions will be asked, and your information will be discarded.

The results of this project may be published online, or in print form. All information will be kept confidential, and your name will not be associated with any data or findings.

Your participation in this study will require approximately 15 to 30 minutes. It will involve an interview during which an audio recording will be made, and / or notes will be taken.

If you have any further questions concerning this study, please feel free to ask questions at any point, or to send them via email:
Alexandra.Kandler.0899@student.uu.se

Please indicate with your signature below that you understand your rights and agree to participate in the study.

____

First Name (please print)

____

Last Name (please print)

____

Date

____

Signature

Do you wish to receive a copy of the final research paper via E-Mail? ☐ No ☐ Yes

____

Email (if yes, please print)

Facultative Information

Gender: ☐ Male ☐ Female ☐ Other

____

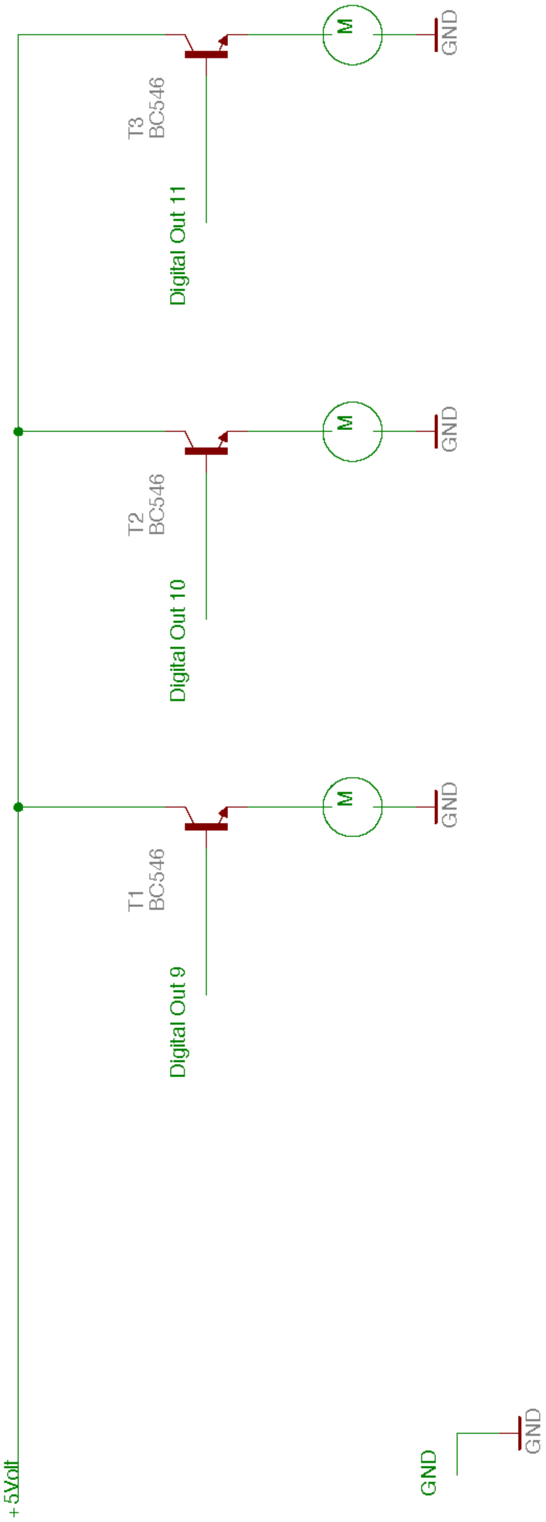
Age

Do you have a colour vision deficiency? ☐ No ☐ Yes

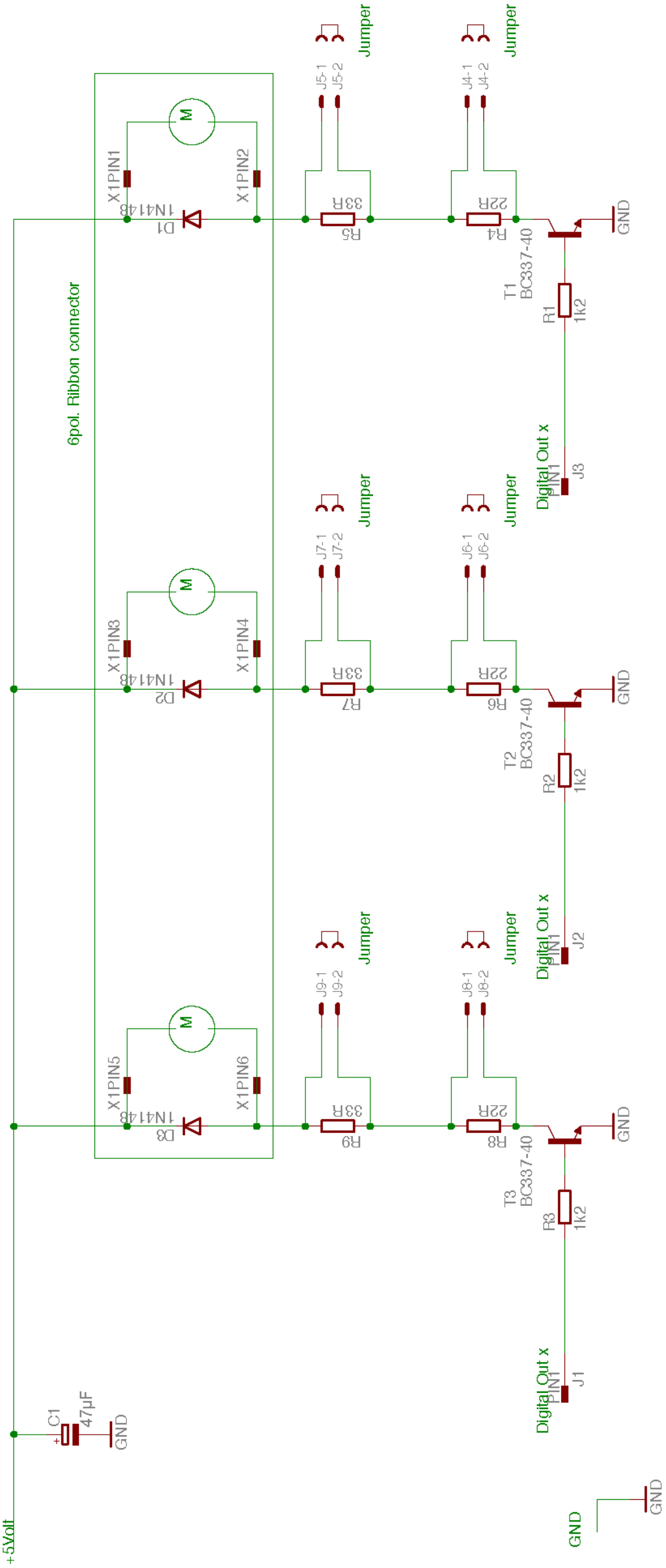
____

If yes, which form? (please print)

Appendix F – Circuit Diagram: Based on Carcedo et al.’s [2] Prototype



Appendix G – Circuit Diagram: Initial Adjustments



Adjustments:

– *Capacitor C1* is placed on 5 Volt to prevent a voltage drop when switching on the motors.

– *Base resistors R1, R2, and R3* 1200 Ohm limiting the transistor's base current.

– *Transistors T1, T2, and T3* are now placed in the negative line of the motor.

– *Resistors R4/R5, R6/R7, and R8/R9* with a resistance of 22 Ohm / 33 Ohm to decrease the motor current. This is necessary as most vibrating motors are made for 3 Volt; at 5 Volt, they might overspeed, and thus might get damaged.

– Jumpers J4, J5, J6, J7, J8, and J9 allowing to bridge the resistor.

– *Flyback diodes D1, D2, and D3* (model 1N4148) preventing peaks of inductive voltage when switching off.

– *Vibrating Motors M* are now connected towards +5 Volt.

– Transistor type changed from BC546 to BC337-40 for higher maximal current (800 mA).

– *X1 6pin ribbon connector* added for cable connection to the Velcro wristband.

Appendix H – Initial Pilot Study: Informed Consent Form

Informed Consent Form (Pilot Study)

The following provides you with information about the research project carried out by Alexandra Kandler from Uppsala University to help you decide if you want to participate.

The purpose of the research project is to investigate the potential of a wristband as supportive tool for people with colour vision deficiency. Using vibration motors, colours are translated into haptic feedback.

Your participation is solicited, yet strictly voluntary. You may refuse to answer any question. If you agree to participate, please be aware that you are free to withdraw at any point without any negative consequences for you – no questions will be asked, and your information will be discarded.
The results of this project may be published online, or in print form. All information will be kept confidential, and your name will not be associated with any data or findings.

Your participation in this study will require approximately 15 to 30 minutes, and you will be asked to use the prototype. It will involve a test during which audio recording may be made, and / or notes will be taken.

If you have any further questions concerning this study, please feel free to ask questions at any point, or to send them via email:
Alexandra.Kandler.0899@student.uu.se

Please indicate with your signature below that you understand your rights and agree to participate in the study.

____
First Name (please print)

____
Last Name (please print)

____
Date

____
Signature

Do you wish to receive a copy of the final research paper via E-Mail? ☐ No ☐ Yes

____
Email (if yes, please print)

Facultative Information

Gender: ☐ Male ☐ Female ☐ Other

____

Age

Do you have a colour vision deficiency? ☐ No ☐ Yes

____

If yes, which form? (please print)

Appendix I – Second Pilot Study: Informed Consent Form

Informed Consent Form (Pilot Study)

The following provides you with information about the research project carried out by Alexandra Kandler from *Uppsala University* (Sweden) in collaboration *with Łódź University of Technology* to help you decide if you want to participate.

The purpose of the research project is to investigate the potential of a wristband as supportive tool for people with colour vision deficiency. Using vibration motors, colours are translated into haptic feedback.

Your participation is solicited, yet strictly voluntary. You may refuse to answer any question. If you agree to participate, please be aware that you are free to withdraw at any point without any negative consequences for you – no questions will be asked, and your information will be discarded.

The results of this project may be published online, or in print form. All information will be kept confidential, and your name will not be associated with any data or findings.

Your participation in this study will require approximately 15 – 30 minutes, and you will be asked to use the prototype. It will involve a test during which audio recording may be made, and / or notes will be taken.

If you have any further questions concerning this study, please feel free to ask questions at any point, or to send them via email:
Alexandra.Kandler.0899@student.uu.se

Please indicate with your signature below that you understand your rights and agree to participate in the study.

____

First Name (please print)

____

Last Name (please print)

____

Date

____

Signature

Do you wish to receive a copy of the final research paper via E-Mail? ☐ No ☐ Yes

____

Email (if yes, please print)

Facultative Information

1) Gender ☐ Male ☐ Female ☐ Other / Prefer not to answer

2) Age ______________________ ☐ Prefer not to answer

Please state your age

3) Do you have a colour vision deficiency (“colour-blindness”)?

☐ Yes ____

If yes, which form (or confusion colours)?

☐ No ☐ Prefer not to answer / Do not know

4) Professional Background or Occupation

____

Please state your background or profession

☐ Prefer not to answer

5) Handedness

☐ Right ☐ Mix of right- and left-handed

☐ Left ☐ Prefer not to answer / Do not know

6) Wrist Size ___________________________ ☐ Prefer not to answer

Will be measured for you

Appendix J – Second Pilot Study: Code Snippets of Arduino Code

For Condition A the following code was used:

```
case '1': // low saturation, M1
digitalWrite(vib1Pin, HIGH);
delay(200);
digitalWrite(vib1Pin, LOW);
delay(200);
break;

case '2': // medium sat., M1 + M2
digitalWrite(vib1Pin, HIGH);
delay(200);
digitalWrite(vib1Pin, LOW);
delay(200);
digitalWrite(vib2Pin, HIGH);
delay(200);
digitalWrite(vib2Pin, LOW);
break;
```

```
case '3': // high sat., M1 + M2 + M3
digitalWrite(vib1Pin, HIGH);
delay(200);
digitalWrite(vib1Pin, LOW);
delay(200);
digitalWrite(vib2Pin, HIGH);
delay(200);
digitalWrite(vib2Pin, LOW);
delay(200);
digitalWrite(vib3Pin, HIGH);
delay(200);
digitalWrite(vib3Pin, LOW);
break;
```

For Condition B the following code was used:

```
// green-cyan, low saturation, 1x
case '4':
digitalWrite(vib2Pin, HIGH);
delay(200);
digitalWrite(vib2Pin, LOW);
delay(200);
digitalWrite(vib3Pin, HIGH);
delay(200);
digitalWrite(vib3Pin, LOW);
break;

// green, high saturation, 3x
case '6':
for (int i=0; i<3; i++){
digitalWrite(vib2Pin, HIGH);
delay(200);
digitalWrite(vib2Pin, LOW);
delay(400);
}
break;
```

```
// cyan, medium saturation, 2x
case '5':
for (int i=0; i < 2; i++){
digitalWrite(vib2Pin, HIGH);
delay(200);
digitalWrite(vib2Pin, LOW);
delay(200);
digitalWrite(vib3Pin, HIGH);
delay(200);
digitalWrite(vib3Pin, LOW);
delay(400);
}
break;
```

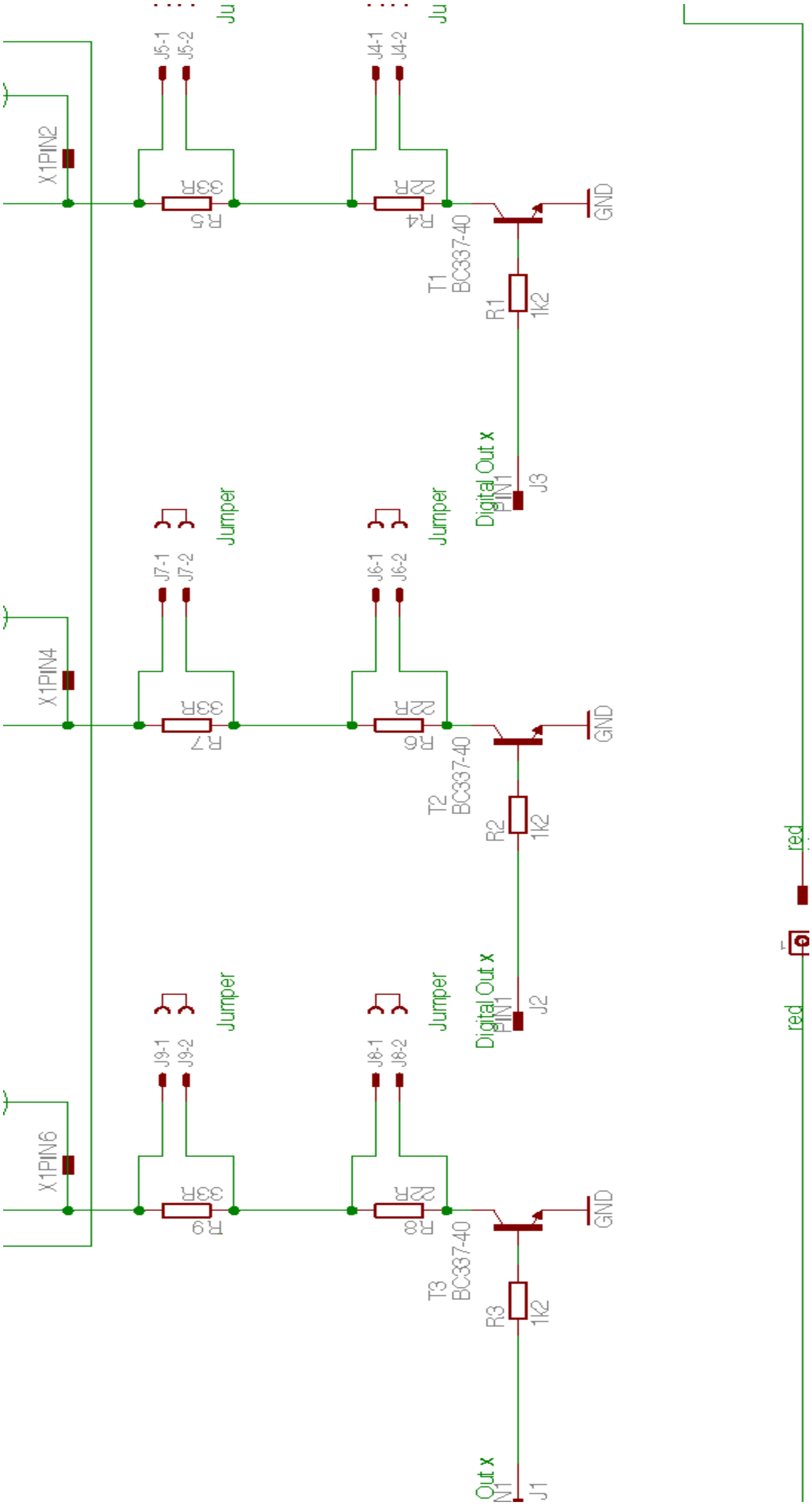
For Condition C the following code was used:

```
// low saturation, all motors 1x
case '7':
for (int i=0; i < 1; i++){
digitalWrite(vib1Pin, HIGH);
digitalWrite(vib2Pin, HIGH);
digitalWrite(vib3Pin, HIGH);
delay(100);
digitalWrite(vib1Pin, LOW);
digitalWrite(vib2Pin, LOW);
digitalWrite(vib3Pin, LOW);
delay(200);
}
break;

// medium saturation, all motors 2x
case '8':
for (int i=0; i < 2; i++){
digitalWrite(vib1Pin, HIGH);
digitalWrite(vib2Pin, HIGH);
digitalWrite(vib3Pin, HIGH);
delay(100);
digitalWrite(vib1Pin, LOW);
digitalWrite(vib2Pin, LOW);
digitalWrite(vib3Pin, LOW);
delay(200);
}
break;

// high saturation, all motors 3x
case '9':
for (int i=0; i < 3; i++){
digitalWrite(vib1Pin, HIGH);
digitalWrite(vib2Pin, HIGH);
digitalWrite(vib3Pin, HIGH);
delay(100);
digitalWrite(vib1Pin, LOW);
digitalWrite(vib2Pin, LOW);
digitalWrite(vib3Pin, LOW);
delay(200);
}
break;
```

Appendix K – Circuit Diagram: Prototype with Colour Sensor



Appendix L – Final User Study: Posters for Recruitment of Participants (English and Polish)

Politechnika Łódzka
Lodz University of Technology
UbiCOMP
STUDENCKIE KOŁO NAUKOWE
UPPSALA UNIVERSITET
CZY WIESZ, ŻE 10% MĘŻCZYZN
DOTYKA ZABURZENIE
ROZPOZNAWANIA BARW?
10%
JEŚLI CIEBIE TEŻ TO DOTYCZY
I CHCESZ "POCZUĆ" KOLORY,
SKONTAKTUJ SIĘ Z NAMI.
WEŹ UDZIAŁ W BADANIU
NAUKOWYM NA PŁ
W MARCU 2018
KONTAKT
HAPTICOLOR.STUDY@GMAIL.COM
HAPTICOLOR.STUDY@GMAIL.COM
HAPTICOLOR.STUDY@GMAIL.COM
HAPTICOLOR.STUDY@GMAIL.COM
HAPTICOLOR.STUDY@GMAIL.COM
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HAPTICOLOR.STUDY@GMAIL.COM
HAPTICOLOR.STUDY@GMAIL.COM

Appendix M – Final User Study: Social Media Posts for Recruitment of Participants (English and Polish)

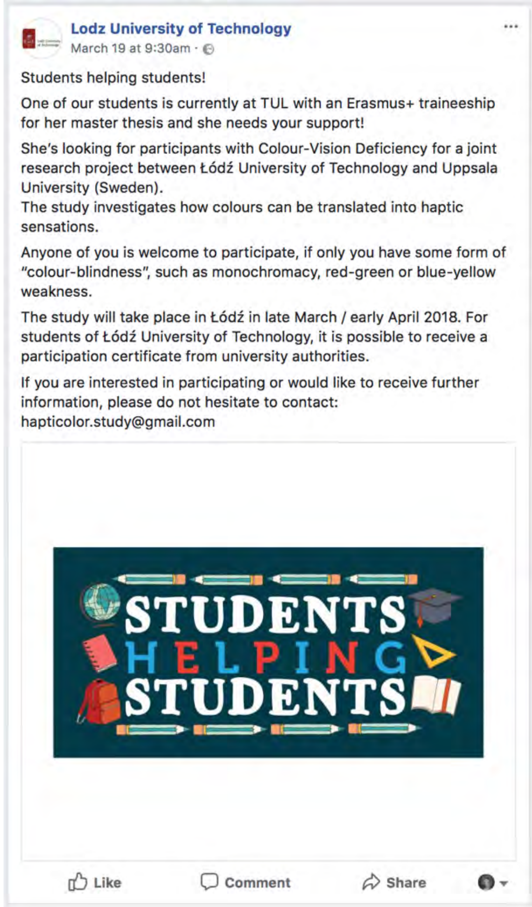
Facebook Group: Erasmus 2017/2018 - Lodz University of Technology 12 March 2018, 14:35

Facebook Group: Intercultural communication 2017/2018 Łódź 12 March 2018, 18:05

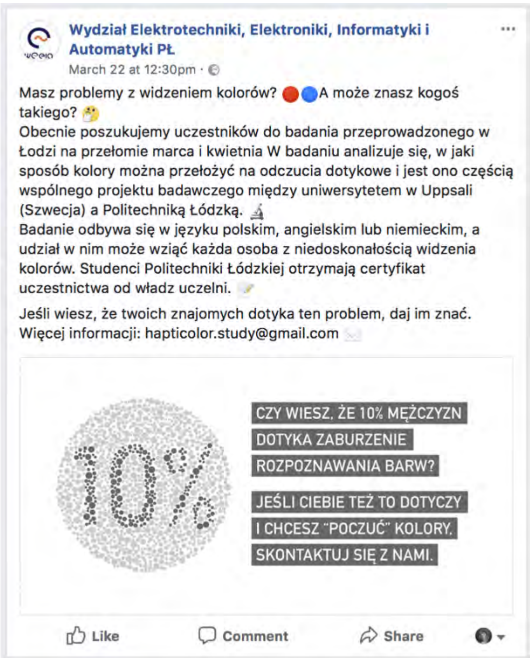
Facebook Group: Foreigners in Lodz 13 March 2018, 18:07

Facebook Group: Erasmus Lodz 2017/2018 13 March 2018, 20:17

Twitter: Andrzej Romanowski
12 March 2018, 15:42



Facebook Page: Lodz University of Technology
19 March 2018, 09:30



Facebook Page: WEEIA (Faculty of Electrical, Electronic, Computer and Control Engineering)
22 March 2018, 12:30

Appendix N – Final User Study: Informed Consent Form (English and Polish)

Informed Consent Form (User Study)

The following provides you with information about the research project carried out by Alexandra Kandler from *Uppsala University* (Sweden) in collaboration with *Łódź University of Technology* to help you decide if you want to participate.

The purpose of the research project is to investigate the potential of a wristband as supportive tool for people with colour vision deficiency. Using vibration motors, colours are translated into haptic feedback.

Your participation is solicited, yet strictly voluntary. You may refuse to answer any question. If you agree to participate, please be aware that you are free to withdraw at any point without any negative consequences for you – no questions will be asked, and your information will be discarded.

The results of this project may be published online, or in print form. All information will be kept confidential, and your name will not be associated with any data or findings.

Your participation in this study will require approximately 30 to 60 minutes, and you will be asked to use the prototype. It will involve a test during which audio recording may be made, and notes will be taken.

If you have any further questions concerning this study, please feel free to ask questions at any point, or to send them via email:
Alexandra.Kandler.0899@student.uu.se

Please indicate with your signature below that you understand your rights and agree to participate in the study.

____

First Name (please print)

____

Last Name (please print)

____

Date

____

Signature

Do you wish to receive a copy of the final research paper via E-Mail? ☐ No ☐ Yes

____

If yes, please print your email address

Facultative Information

7) Gender ☐ Male ☐ Female ☐ Other / Prefer not to answer

8) Age ____________________ ☐ Prefer not to answer

Please state your age

9) Do you have a colour vision deficiency ("colour-blindness")?

☐ Yes ____

If yes, which form (or confusion colours)?

☐ No ☐ Prefer not to answer / Do not know

10) Professional Background or Occupation

____

Please state your background or profession

☐ Prefer not to answer

11) Handedness

☐ Right ☐ Mix of right- and left-handed

☐ Left ☐ Prefer not to answer / Do not know

12) Wrist Size ____________________ ☐ Prefer not to answer

Will be measured for you

Zgoda na udział w badaniu

Niniejszy dokument zawiera informacje o badaniu prowadzonym przez Alexandrę Kandler, *Uppsala University* (Szwecja) we współpracy z Politechniką Łódzką i jest poświadczeniem dobrowolnego udziału w badaniu.

Celem projektu jest przebadanie użycia bransolety wyposażonej w wibratory, w celu wspierania osób dotkniętych zaburzeniem percepcji kolorów. Postrzeganie koloru jest przetwarzane na wrażenie czuciowe.

Udział w badaniu jest dobrowolny. Przysługuje Ci prawo przerwania badania w dowolnym momencie lub odmowy odpowiedzi na dowolne pytanie. W przypadku wcześniejszego zakończenia badania, zebrane wyniki nie będą przetwarzane.

Wyniki badania będą publikowane na różne sposoby. Żadne z informacji nie będą mogły zostac powiązane z Tobą – udział w badaniu jest anonimowy z punkty widzenia dalszego przetwarzania wyników.

Badanie potrwa około 30 – 60 minut. Podczas badania nagrywany będzie dźwięk, ekperymentator może również notować.

W razie jakichkolwiek wątpliwości, proszę pytać w dowolnym momencie lub przesłać zapytanie pod adres: *Alexandra.Kandler.0899@student.uu.se*

Proszę poświadczyć podpisem, że zrozumiał(a) Pan/Pani swoje prawa i zgłasza chęć udziału w badaniu.

____

Imię

____

Nazwisko

____

Data

____

Podpis

Życzę sobie otrzymać kopię końcowej publikacji drogą mailową: ☐ Nie ☐ Tak

____

Adres e-mail

Dodatkowe Informacje

1) **Płeć** ☐ Mężczyzna ☐ Kobieta ☐ Inna/Odmowa odpowiedzi

2) Wiek ____________________________ ☐ Odmowa odpowiedzi

Proszę podać swój wiek

3) Czy dotyczą Pana/Panią zaburzenia postrzegania kolorów?

☐ Tak ____

Jeśli tak, to jakiego rodzaju?

☐ Nie ☐ Nie wiem / Odmowa odpowiedzi

4) Zawód

____

Proszę podac swój zawod

☐ Odmowa odpowiedzi

5) Ręka dominująca

☐ Prawa ☐ Jestem oburęczny

☐ Lewa ☐ Nie wiem / odmowa odpowiedzi

6) Obwód nadgarstka ____________________________

Zostanie Panu/Pani zmierzony

Appendix O – Final User Study: Script (English and Polish)

Script

During the study the yellow parts should be read out to ensure the same information is given to each participant. If this feels awkward, please tell the participant: "I will read the following to you to make sure that each participant receives the exact same information, and also so I don't forget anything important."

(1) Introduction (Both Groups)

- Welcome participant and introduce ourselves briefly (names, universities; project part of Alex' master thesis)
- Ask them to sign consent form and pre-study questionnaire
- Measure their wrist circumference
- Explain *briefly* context of this study: "With this wristband [show wristband] we are trying to translate colours from one sense to another, so that they can be *felt* instead of seen. That means, you can receive information about colours through different vibration patterns. And to do that, the wristband has three motors on its inside, and a colour sensor on the top."
- Explain difference between hue and saturation: "First, I want to explain two basic things that are going to be relevant for today. And that are the two terms *hue* and *saturation:*"
  - "Hue can be seen as a basic colour, such as yellow, red, green, blue, magenta, etc."
  - "Saturation shows you how intense a colour is. A low saturation means, the colour is dull and grey-ish. A high saturation means, the colour is very intense. This does, however, *not* mean the same as darkness or lightness. So, it does not say whether a colour is dark or bright, but only how similar or different it is from grey."
  - Make sure they don't have any questions about this
- "About the procedure today: First we're going to start with a training session, so you get used to the different vibrations. And then we are going to have two different settings that we would like to compare. After each setting we would like you to fill out two questionnaires, and in the end we have a few more questions for you. If anything is unclear or you need a break, please just let us know. You can also ask questions at any time. And what is most important: we're not testing you today, but the wristband!"
- Place wristband on their *dominant* arm, but don't plug in Arduino yet. Make sure it is tight enough, but not too tight. "If it doesn't feel comfortable at some point, we can always adjust it, or take it off and take a break."

(2) Group A

(2.1) Setting 1: Only Hue Mode (Only Group A)

- *Show colour wheel* and explain vibration patterns
  - "In this setting different vibration patterns will be played representing different hues, so different basic colours. The wristband represents a colour wheel that has twelve positions. We have twelve hues that are positioned around the wrist. There are three motors on the wristband – one on the top (M1), one on the right (M2), and one on the left (M3). Whenever you feel a single long vibration, it means it's the hue directly under the motor [point to fields on colour wheel]. As you see, there are also always three positions between the motors that do not have an own motor. So, to represent those, we make use of the *two* motors that are closest to the position. That means, you will feel two vibrations *after* one another. If the vibrations are equally long, then the point is also equally far away from the two motors – so it is in the very middle [point to fields on colour wheel]. If one of the two vibrations is longer than the other, it means the position is closer to the one that vibrated longer [point to fields on colour wheel]."
- Plug in Arduino
- Make sure correct Arduino code is uploaded: "Training-Setting1"
- Training block (without colour sensor)
  - Play all patterns once in clock-wise order and say which colour it is so participant can follow and feel each pattern once
  - Make sure participants understood the patterns; answer questions they have
  - Play ten test patterns in random order, so participants get used to decoding the patterns and positions
- "So, this was a training block. We would now switch on the colour sensor, that is here [point to sensor] on the wristband. Once the colour sensor is active, a bright LED will shine next to it. Please don't look in the light at any point because it could harm your eyes!" [Please remind them throughout the study not to look into the LED!]
- "To scan colours, it works best when you move the sensor very close to the fabric of the clothes. Sometime the sensor doesn't work accurately, so it's fine if you scan a colour several times to be sure you get the same result several times."
- Make sure correct Arduino code is uploaded: "Setting1"
- Ask participants to *think-aloud* during the next part and to name the hue "felt"
- Have several clothes available that participants can scan and "feel"

- Note down their answers (especially if correct or incorrect, but also other notes, i.e. what participants think-aloud)
- In the very end, ask them to fill out questionnaires (NASA TLX and SUS)

(2.2) Setting 2: Hue and Saturation Mode (Only Group A)

- "In the next setting you will receive additional information about the saturation. That means you will first feel the hue (like before), and after a short break you will feel either one, two, or three buzzes. Here, all motors will vibrate at the same time. If they vibrate once, it means the saturation is low; if they vibrate twice, it means the saturations is medium; and if they vibrate three times it means the saturations is high."
- Make sure they this is clear, and they don't have any answers
- Make sure correct Arduino code is uploaded: "Training-Setting2"
- Training block
  - Play all patterns once (without the saturation), and tell them which level of saturation it is (low, high, medium)
  - Make sure participants understood the patterns; answer questions they have
  - "Now we will first play the hue, and after a short break the saturation"
  - Play five test patterns in random order, so participants get used to decoding the patterns and positions
- "So, this was a training block. We would now switch on the colour sensor again. So please, don't look at it directly."
- Make sure correct Arduino code is uploaded: "Setting2"
- Ask participants to *think-aloud* during the next part and to name the hue "felt"
- Have several clothes available that participants can scan and "feel"
- Note down their answers (especially if correct or incorrect, but also other notes, i.e. what participants think-aloud)
- In the very end, ask them to fill out questionnaires (NASA TLX and SUS)

(3) Group B

(3.1) Setting 2: Only Hue Mode (Only Group B)

- *Show colour wheel* and explain vibration patterns
  - "In this setting different vibration patterns will be played representing different hues, so different basic colours. The wristband represents a colour wheel that has twelve positions.

We have twelve hues that are positioned around the wrist. There are three motors on the wristband – one on the top (M1), one on the right (M2), and one on the left (M3). Whenever you feel a single long vibration, it means it is the hue directly under the motor [point to fields on colour wheel]. As you see, there are also always three positions between the motors that do not have an own motor. So, to represent those, we make use of the *two* motors that are closest to the position. That means, you will feel to vibrations *after* one another. If the vibrations are equally long, then the point is also equally far away from the two motors – so it is in the very middle [point to fields on colour wheel]. If one of the two vibrations is longer than the other, it means the position is closer to the one that vibrated longer [point to fields on colour wheel]."

    - "After a short break you will receive additional information about the saturation. That means you will first feel the hue, and then – after a short break – you will feel either one, two, or three buzzes. Here, all motors will vibrate at the same time. If they vibrate once, it means the saturation is low; if they vibrate twice, it means the saturations is medium; and if they vibrate three times it means the saturations is high."
- Make sure correct Arduino code is uploaded: "Training-Setting2"
- Training block
    - Hue:
        - Play all patterns once in clock-wise order and say which colour it is so participant can follow and feel each pattern once
        - Make sure participants understood the patterns; answer questions they have
        - Play ten patterns in random order, so participants get used to decoding the patterns and positions
    - Saturation:
        - Play all patterns once (without the saturation), and tell them which level of saturation it is (low, high, medium)
        - Make sure participants understood the patterns; answer questions they have
        - "Now we will first play the hue, and after a short break the saturation"
        - Play five test patterns in random order, so participants get used to decoding the patterns and positions
- "So, this was a training block. We would now switch on the colour sensor, that is here [point to sensor] on the wristband. Once the colour sensor is active, a bright LED will shine next to it. Please

don't look in the light at any point because it could harm your eyes!" [Please remind them throughout the study not to look into the LED!]

- "To scan colours, it works best when you move the sensor very close to the fabric of the clothes. Sometime the sensor doesn't work accurately, so it's fine if you scan a colour several times to be sure you get the same result several times."
- Ask participants to *think-aloud* during the next part and to name the hue "felt"
- Have several clothes available that participants can scan and "feel"
- Note down their answers (especially if correct or incorrect, but also other notes, i.e. what participants think-aloud)
- In the very end, ask them to fill out questionnaires (NASA TLX and SUS)

(3.2) Setting 1: Hue Mode and Saturation Mode (Only Group B)

- "This setting works basically just like the one before, but you will only get information about the hue, not about the saturation. So, it's only going to be the twelve positions, and not the patterns saying low/medium/high saturation."
- Make sure correct Arduino code is uploaded: "Training-Setting1"
- Training block
    - Play five patterns in random order, so participants get used to decoding the patterns and positions
    - Make sure participants understood the patterns; answer questions they have
- Make sure correct Arduino code is uploaded: "Setting1"
- Ask participants to *think-aloud* during the next part and to name the hue "felt"
- Have several clothes available that participants can scan and "feel"
- Note down their answers (especially if correct or incorrect, but also other notes, i.e. what participants think-aloud)

In the very end, ask them to fill out questionnaires (NASA TLX and SUS)

(4) Semi-Structured Post-Test Interview (Both Groups)

Record audio, so it can be transcribed and translated later. Read questions out so they are the same for each participant but still try to keep it a rather open conversation. It's okay to reply to their answers but avoid judging the answer. If they struggle with the standard question, use the backup.

		Standard Question	Backup
Preferred Setting	1.	Which of the two settings did you generally prefer? [Follow-up:] Why? What did you like or dislike?	Did you like the first or second part of the study more? One was only about hue (12 basic colours), and the other first about hue and then saturation (3 levels: low, medium, high). What did you like about them? What did you not like?
	2.	Imagine the following: You have used the wristband for a while, and all the vibration patterns become easier to decode, and you can decide which of the two settings you can use. Would you always use the same setting or switch between them depending on the situation? If only one, which?	Right now, the whole device is pretty new to you. Imagine a situation where you have used the wristband for a longer time. Would you use always one of the two settings, or would you switch between them in different context or for different activities? If only one, which?
Context of Use	3.	How would the wristband change your daily life?	Imagine you're using the wristband regularly. What might change in your life?
	4.	In which situations could you imagine using the wristband?	When and where would you use the wristband? For which activities would you use it? In which environment / context would you use it?
	5.	In which situations would you use the setting that only shows the hue, and in which the setting that presents information on saturation and hue?	When would you use the first setting, and when the second? When is only the hue relevant for you, and when also the saturation?
What is pos./neg. about saturation?	6.	When would it be helpful for you to know the saturation and not just the hue [basic colour]?	When would you like to not only know the basic colour (e.g. red vs. green), but also how intense a colour is?
	7.	How did it feel to know how intensely saturated a colour was?	How did you perceive the information about the saturation? How would you benefit from this information?
	8.	How did it feel to have three levels of saturation (low, medium, high)?	How did you perceive having the distinction between low, medium, and high saturation?
	9.	What did you like in particular about the saturation?	What was good about the saturation? How did you like to know whether a colour is highly or lowly saturated?
	10.	What did you dislike in particular about the saturation?	What was bad about the saturation? What did you not like about it?

(5) End – Both Groups

- Thank participant for participating
- Hand out participation certificate if wanted

Skrypt badania

Fragmenty zaznaczone na żółto wymagają tłumaczenia na polski. W celu upewnienia się, że każdy uczestnik otrzymuje dokładnie te same instrukcje, należy je odczytać. Pierwej należy wygłosić niniejszą formułę: „Będę odczytywał Pani/Panu kolejne instrukcje, aby zapewnić powtarzalność badania I nie pominąć niczego istotnego."

(1) Wprowadzenie (wspólne dla obu grup)

- Wprowadzenie do badania I przedstawienie się (Dane osobowe, cel badania)
- Prośba o podpisanie formularza udziału oraz kwestionariusza wstępnego.
- Pomiar obwodu nadgarstka.
- Objaśnić kontekst badania: "Z użyciem tej bransoletki, chcemy zmeinić postrzeganie kolorów, tak aby można było je poczuć, zamiast zobaczyć. Oznacza to, że informację o kolorze będziesz otrzymywać poprzez różne rodzaje wibracji. W tym celu, bransoletka ma zamontowane 3 wibratory, a także sensor koloru w jej górnej części."
- Wyjaśnić różnicę, pomiędzy odcieniem I nasyceniem: „Na początku, chcielibyśmy wyjaśnić dwa kluczowe czynniki, które będą dzisiaj analizowane. Są to mianowicie – odcień oraz nasycenie barwy:"
  - „Odcień może być postrzegany jako po prostu kolor, przykładowo żółty, czerwony, zielony, niebieski, fioletowy, itp."
  - „Nasycenie określa jak intesywna jest barwa. Niskie nasycenie oznacza, że barwa jest wyblakła lub szarawa. Wysokie nasycenie oznacza bardzo intensywną barwę. Nie jest to jednak to samo co jasność koloru. Nie określa to, jak jasny lub ciemny jest kolor, a w jak odległy jest od koloru szarego."
  - Upewnić się, że wszystko do tej pory jest jasne.
- „Jeśli chodzi o przebieg badania, rozpoczniemy od wprowadzenia I treningu, abyś mógł poznać różne sposoby wibracji bransolety. Następnie, poprosimy cię o przetestowanie układu w dwóch różnych ustawieniach, które chcemy porównać. Po każdym tescie, poprosimy cię o wypełnienie dwóch formularzy, na końcu, będziemy chcieli zadać Ci jeszcze kilka pytań. W razie wszelkich wątpliwości, śmiało zadawaj pytania w dowolnym momencie, jeśli będziesz potrzebować przerwy, powiedz nam to śmiało. Co najważniejsze, przedmiotem badania jest urządzenie, a nie Ty!"
- Umieść opaskę na ręce dominującej, niezasiloną. Upewnij się, że jest komfortowo osadzona. „W razie wszelkiej niedogodności, możesz poprawić opaskę w dowolnym momencie lub poprosić o przerwę."

(2) Grupa A

(2.1) Ustawienie 1: Pomiar Odcienia barwy (Grupa A)

- Okaż koło barw I wyjaśnij zasadę wibrowania urządzenia.
    - „W tym ustawieniu, różne wibracje będą reprezentować różne odcienie barw. Opaska reprezentuje 12 różnych odcieni, takich jak na kole. Każdy z 12 odcieni posiada odpowiadający zestaw wibracji opaski. Opaska posiada trzy wibratory – jeden na górze opaski (M1), jeden z prawej (M2), jeden z lewej (M3). Pojedyńcza, długa wibracja oznacza odczytanie koloru, umieszczonego bezpośrednio na wibratorze [zgodnie z reprezentacją na kole]. Pozycje będące pomiędzy wibratorami są kodowane poprzez połączenie wibracji z dwóch sąsiadujących wibratorów. Poczujesz dwie wbracje następujące po sobie. Jeśli ich czas trwania będzie sobie równy – barwa zanjduje się dokładnie pomiędzy wibratorami [zgodnie z reprezentacją na kole]. Jeśli jedna z nich trwa dłużej, oznacza że barwa jest bliższa temu wibratorowi [zgodnie z reprezentacją na kole].”
- Zasilić układ
- Sprawdzić poprawność wgranego kodu.
- Trening – bez użycia sensora
    - Odtworzyć wszystkie wibracje dla kolorów po sobie, zgodnie z ruchem wskazówek zegara.
    - Upewnić się, że wszystkie wibracje zostały zrozumiane. Odpowiedzieć na ewentualne pytania.
    - Odtworzyć 10 wibracji dla losowych barw, aby uczestnik mógł nauczyć się dekodowania wibracji do barw.
- „To było wstępne zadanie treningowe. Teraz uruchomimy sensor kolor. Gdy sensor jest włączony, dioda zapali się. Prosimy unikać spoglądania na diode, gdyż może ona łatwo oślepić.”
- „Aby zbadać kolor, proszę przysunąć sensor blisko badanego materiału. Zdarza się, że sensor jest niedokładny, więc śmiało można badać ten sam kolor kilkukrotnie.”
- Wgrać kod: “Setting1”
- Poprosić uczestnika, aby głośno komentował “poczute” kolory.
- Udostępnić ubrania do badania przez uczestnika.
- Notować odpowiedzi, ich poprawnosc oraz komentarze uczestnika
- Na koniec, poprosić o wypełnienie dwóch kwestionariuszy.

(2.2) Ustawienie 2: Pomiar odcienia I nasycenia barwy (Grupa A)

- „Od teraz, poza informacją o odcieniu, otrzymasz także informację o nasyceniu barwy. Najpierw, otrzymasz dokładnie taką samą informację jak ostatnio, a po krótkiej przerwie poczujesz 1, 2 lub 3 wibracje. Wszystkie wibratory będą działać jednocześnie. Pojedyńcza wibracja oznacza niskie nasycenie, podwójna średnie, a potrójna wysokie."
- Upewnić się, że wszystko jest zrozumiałe
- Wgrać kod: "Training-Setting2"
- Trening – bez użycia sensora
  - Odtworzyć wszystkie wibracje I kolejno I upewnić się, że są one zrozumiałe.
  - „Teraz odtworzymy pierwszy odcień, a następnie jego nasycenie."
  - Odtworzyć pięć barw o różnym nasyceniu I pozwolić je odkodować.
- „To było wstępne zadanie treningowe. Teraz ponownie włączymy sensor. Prosimy nie patrzeć wprost na diodę."
- Wgrać kod: "Setting2"
- Poprosić o głośne komentowanie badania I nazywanie odczutych kolorów
- Udostępić odzież do badania uczestnikowi.
- Notować odpowiedzi, ich poprawnośc oraz komentarze uczestnika
- Na koniec, poprosić o wypełnienie dwóch kwestionariuszy.

(3) Grupa B

(3.1) Ustawienie 2: Pomiar odcienia I nasycenia barwy (Grupa B)

- Okaż koło barw I wyjaśnij zasadę wibrowania urządzenia.
  - „W tym ustawieniu, różne wibracje będą reprezentować różne odcienie barw. Opaska reprezentuje 12 różnych odcieni, takich jak na kole. Każdy z 12 odcieni posiada odpowiadający zestaw wibracji opaski. Opaska posiada trzy wibratory – jeden na górze opaski (M1), jeden z prawej (M2), jeden z lewej (M3). Pojedyńcza, długa wibracja oznacza odczytanie koloru, umieszczonego bezpośrednio na wibratorze [zgodnie z reprezentacją na kole]. Pozycje będące pomiędzy wibratorami są kodowane poprzez połączenie wibracji z dwóch sąsiadujących wibratorów. Poczujesz dwie wbracje następujące po sobie. Jeśli ich czas trwania będzie sobie równy – barwa zanjduje się dokładnie pomiędzy wibratorami [zgodnie z reprezentacją na kole]. Jeśli jedna z nich trwa dłużej, oznacza że barwa jest bliższa temu wibratorowi [zgodnie z reprezentacją na kole]."

    - „Po krótkiejj przerwie otrzymasz informację o nasyceniu barwy. Najpierw, otrzymasz informację o odcieniu, a po krótkiej przerwie poczujesz 1, 2 lub 3 wibracje. Wszystkie wibratory będą działać jednocześnie. Pojedyńcza wibracja oznacza niskie nasycenie, podwójna średnie, a potrójna wysokie."
    - Wgrać kod: „Training-Setting2"
- Zadanie treningowe
    - Odcień
        - Odtworzyć wszystkie odcienie zgodnie z ruchem wskazówek zegara, objaśniając kolejne barwy
        - Upewnić się, że wszystko jest zrozumiałe
        - Odtworzyć 10 losowych barw, aby uczestnik mógł samodzielnie odkodować kolory.
    - Nasycenie:
        - Odtworzyć wszystkie barwy kolejno, bez nasycenia, a następnie określić ich nasycenie.
        - Upewnić się, że wszystko jest zrozumiałe.
        - „Odtworzymy teraz odcień, a następnie jego nasycenie"
        - Odtworzyć 5 losowych barw, pozwalając użytkownikowi odkodować barwy.
- „To było wstępne zadanie treningowe. Teraz uruchomimy sensor kolor. Gdy sensor jest włączony, dioda zapali się. Prosimy unikać spoglądania na diode, gdyż może ona łatwo oślepić."
- „Aby zbadać kolor, proszę przysunąć sensor blisko badanego materiału. Zdarza się, że sensor jest niedokładny, więc śmiało można badać ten sam kolor kilkukrotnie."
- Poprosić o głośne komentowanie badania I nazywanie odczutych kolorów
- Udostępić odzież do badania uczestnikowi.
- Notować odpowiedzi, ich poprawnośc oraz komentarze uczestnika
- Na koniec, poprosić o wypełnienie dwóch kwestionariuszy.

(3.2) Ustawienie 1: Pomiar Odcienia barwy (Grupa B)

- „To ustawienie jest identyczne jak poprzednie, nie będzie jednak podawana informacja o nasyceniu koloru. Poczujesz tylko wibracje określające odcień barwy."
- Wgrać kod: "Training-Setting1"
- Zadanie treningowe
    - Odtworzyć 5 losowych barw, pozwalając uczestnikom dekodować barwy.
    - Upewnić się, że wszystko jest zrozumiałe

- Wgrac kod: “Setting1”
- Poprosić o głośne komentowanie badania I nazywanie odczutych kolorów
- Udostępić odzież do badania uczestnikowi.
- Notować odpowiedzi, ich poprawnośc oraz komentarze uczestnika
- Na koniec, poprosić o wypełnienie dwóch kwestionariuszy.

(4) Wywiad końcowy (wspólne dla obu grup)

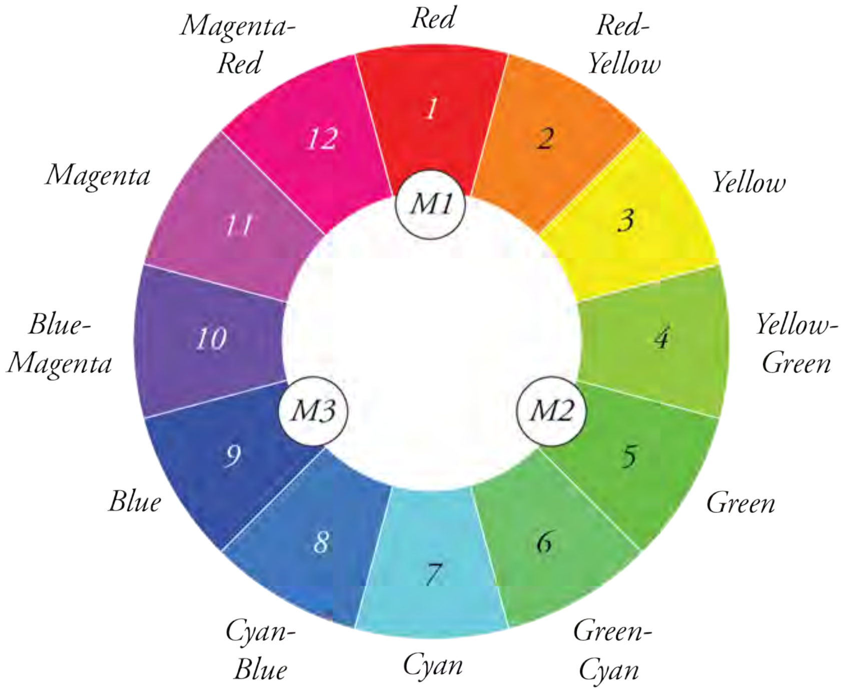
Nagrywać audio, aby można było przygotować transkrypt. Odczytywac pytania, starając się utzymać naturalną konwersację. W razie potrzeby posłużyć się pytaniami pomocniczymi.

		Pytania główne	Pytania pomocnicze
Preferowane ustawienie	1.	Które ustawienie urządzenia jest dla Ciebie bardziej dogodne? Co Ci się podobało, co ci przeszkadzało?	Która część badania podobała Ci się bardziej? Pierwsze – oparte tylko o odcień, czy drugie uwzględniające nasycenie?. Co Ci się podobało, co Ci przeszkadzało?
	2.	Zakładając, że używasz opaski już jakis czas, a wibracje stały się naturalne do dekodowania – które usatwienie być wybrał? Czy zawsze używałbyś tego samego usatwienia, czy jest to zależne od sytuacji? Jeśli jednego, to którego?	Wyobraź sobie, że jestes oswojony z urządzeniem. W jakich sytuacjach byś je stosował? Czy używałbys obu trybów? Kiedy uzywałbyś poszczególnych trybów ustawień?
Sytuacje użytkowe	3.	Czy I jak opaska mogłaby wpłyąć na Twojecodzienne życie?	Zakładając, że już dorze znasz urządzenie, co mogłoby ono zmienić w twoim zyciu?
	4.	W jakich sytuacjach mógłbyś użyć opaski?	Gdzie I kiedy używałbys opaski? W jakich sytuacjach mogłaby sie ona przydać?
	5.	Kiedy używałbyś ustawienia ograniczonego do odcienia, a kiedy rozszerzonego o nasycenie?	Gdzie I kiedy używałbys poszczególnych trybów ustawień? Co decydowałoby o użyciu tego a nie innego trybu?
Jak oceniasz pomiar nasycenia?	6.	Kiedy przydatna byłaby funkcja piaru nasycenia, a keidy wystarczy sama informacja o odcieniu?	Gdzie I kiedy uznałbyś informację o nasyceniu za przydatną?
	7.	Jakie masz odczucia odnośnie pomiaru nasycenia?	Jak postrzegasz informację o nasyceniu koloru? Czy uważasz ją za potrzebną?
	8.	Czy trzystopniowa skala nasycenia ma dla Ciebie sens?	Jak postrzegasz 3-stopniowe rozróżnienie nasyceń barw? Czy taka klasyfikacja ma sens?
	9.	Co konkretnie podobało Ci się w pomiarze nasycenia barw?	Co Ci się podobało? Czy pomiar nasycenia jest dla Ciebie wartościowy w jakikolwiek sposób?
	10.	Co Ci się nie podobało w pomiarze nasycenia barw?	Co Ci sie nie podobało? Jakie problem odnośnie pomiaru nasycenia zauważyłeś.

(5) Zakończenie (wspólne dla obu grup)

- Podziękowanie za udział w badaniu
- Wręczenie certyfikatu, jeśli o taki prosił.

Appendix P – Final User Study: Colour Wheel Visible for Participants



Appendix Q – Final User Study: Participation Certificate

Politechnika Łódzka
Lodz University of Technology

UPPSALA
UNIVERSITET

THIS IS TO CERTIFY THAT

PARTICIPATED IN

RESEARCH STUDY – TRANSLATING COLOURS INTO HAPTIC FEEDBACK

IN APRIL 2018

CONDUCTED BY

ALEXANDRA KANDLER

AS PART OF A JOINT RESEARCH BETWEEN

UPPSALA UNIVERSITY
AND
POLITECHNIKA ŁÓDZKA

DR ANDRZEJ ROMANOWSKI
POLITECHNIKA ŁÓDZKA

ALEXANDRA KANDLER
UPPSALA UNIVERSITY

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STUDENCKIE KOŁO NAUKOWE

Appendix R – Final User Study: SUS (English and Polish)

System Usability Scale (English)

	1 Strongly disagree	*2*	*3*	*4*	*5* Strongly agree
1. I think that I would like to use the system frequently.	○	○	○	○	○
2. I found the system unnecessarily complex.	○	○	○	○	○
3. I thought the system was easy to use.	○	○	○	○	○
4. I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
5. I found the various functions in the system were well integrated.	○	○	○	○	○
6. I thought there was too much inconsistency in this system.	○	○	○	○	○
7. I would imagine that most people would learn to use this system quickly.	○	○	○	○	○
8. I found the system very awkward to use.	○	○	○	○	○
9. I felt very confident using the system.	○	○	○	○	○
10. I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

This will be filled out for you: Participant: __________ Setting: __________

System Usability Scale (Polish), Based on Borkowska and Jach [89]

	Absolutnie się nie zgadzam 1	2	3	4	*W pełni się zgadzam* 5
1. Myślę, że często używałbym/używałabym tego system.	○	○	○	○	○
2. Odbieram ten system jako niepotrzebnie skomplikowany.	○	○	○	○	○
3. Myślę, że system jest łatwy w użyciu.	○	○	○	○	○
4. Myślę, że potrzebowałbym/potrzebowałabym wsparcia asystenta, aby używać tego systemu.	○	○	○	○	○
5. Uważam, że różne funkcje tego system są dobrze zintegrowane.	○	○	○	○	○
6. Myślę, że w tym systemie jest za dużo niespójności.	○	○	○	○	○
7. Wydaje mi się, że większość ludzi nauczyłaby się bardzo szybko używać tego systemu.	○	○	○	○	○
8. Odbieram ten system jako bardzo niewygodny w użyciu.	○	○	○	○	○
9. Czułem/czułam się bardzo pewnie używając tego systemu.	○	○	○	○	○
10. Musiałem/musiałam nauczyć się wielu rzeczy, zanim zacząłem/zaczęłam właściwie posługiwać się tym systemem.	○	○	○	○	○

Uzupelnia eksperymentator: Participant: __________ Setting: __________