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Evaluation of Qualitative Colour Palettes for Tactile Maps

Jakub Wabiński [1,*] and Emilia Śmiechowska-Petrovskij [2]

1 Institute of Geospatial Engineering and Geodesy, Faculty of Civil Engineering and Geodesy, Military University of Technology, 00-908 Warsaw, Poland
2 Department of Special Education, Faculty of Education, Cardinal Stefan Wyszynski University in Warsaw, 01-938 Warsaw, Poland; e.smiechowska@uksw.edu.pl
* Correspondence: jakub.wabinski@wat.edu.pl

Abstract: Much attention is currently being paid to developing universally designed solutions. Tactile maps, designed for people with visual impairments (PVI), require both graphic and tactile content. While many more- or less-official guidelines regarding tactile symbols exist, the subject literature lacks clear guidance on creating legible, highly contrasting graphic symbols for visual perception by those with residual vision. This study specifically addresses the application of colour, a key graphic variable that Is most often used to differentiate area symbols. We wanted to verify whether it is possible to choose a universal qualitative colour palette for tactile maps. We have proposed four different palettes, each with eight colours, that were later evaluated in a controlled study by 16 PVI with varying sociodemographic characteristics, using the VIEW model. The model is widely applied in the area of marketing research and considers the following aspects: Visibility, Informational, Emotional Appeal, and Workability. Our results indicate a lack of unanimity in choosing the best qualitative palette. The results of three palettes are comparable, with a subtle preference for the palette optimized for colour differences using the Python algorithm. Notably, the palette commonly used in official tactile maps in Poland received the lowest scores in every analysed dimension.

Keywords: colour scheme; colour palette; colour contrast; tactile map; barrier-free cartography; visual impairment; colour vision deficiency

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1. Introduction

Maps serve as means of sharing geographic and thematic data, conveying ideas and relationships [1]. Colour, a primary attribute in map depiction, enhances comprehension [2]. However, the use of colour in cartography, as highlighted by Krygier and Wood [3], poses challenges, with improper application potentially diverting attention from the map's data and objectives.

The problem is that colour perception is a complicated and subjective process influenced by internal factors, e.g., age (pupil diameter shrinks with age, which diminishes the amount of light entering retina [4]) or sex (about 8% of men population are affected by some type of red–green blindness [5]); as well as external factors, e.g., lightning conditions and materials used.

Designing maps, which involves selecting colour palettes, is challenging and must consider the target medium [6,7]. But designing colours on tactile maps that are meant to be used by people with visual impairments (PVI) poses an even more serious challenge. Although tactile maps are usually associated with tactile content being perceived haptically by legally blind users, they should consist of both tactile content for haptic perception and graphic content for visual perception, whether residual or normal; in order to fulfil basic requirements of universal design. Thus, maps should be accessible to people with blindness, colour blindness, low-vision, and normal vision. This is especially important if we consider that out of 253 million PVI in the world, only 36 million are considered legally blind, while the remaining 217 million use their residual vision [8]. In the United States, approximately 3.3 million individuals, constituting 40% of the PVI population, are aged 65 years and above [9].

PVI form a highly diverse group in terms of visual functioning. This diversity arises from the inherent nature of the diseases they face and their associated consequences as well as from the efficacy of vision rehabilitation processes. Two individuals with vision impairments, even when sharing identical medical characteristics, may utilize their visual abilities in distinct ways. The most prevalent functional consequences encompass diminished visual acuity, visual field defects (including central, peripheral, scattered, and partial impairments), light perception disorders, colour vision anomalies, depth perception challenges, pain, and fatigue. It is crucial to emphasize that while many eye diseases lead to colour vision disorders, low vision itself does not equate to colour blindness. For instance, an individual with a limited peripheral field of vision but only slightly reduced visual acuity may not require font enlargement or increased contrast and still be able to perceive colours. In this case, visual deficits can be compensated through subtle head movements. Conversely, a person with significantly reduced visual acuity, yet without peripheral field loss, will necessitate font enlargement, high colour contrast, and, potentially, optical aids to enhance their visual experience [10].

Little attention is given to the visual content of tactile maps in the literature, with general statements about colour applications prevailing over specific research on colour palettes for tactile maps. Effective colour palettes for tactile maps should incorporate saturated and contrasting colours, differing not only in hue but also in value [5,11]. The contrast between colours should be clear, prioritizing distinction over aesthetic appeal [12], and, if possible, tactile colour codes should be applied on [13]. But most importantly, colours must be distinguishable by the widest spectrum of individuals, including people with colour vision deficiency (CVD) and complete colour blindness as well as those with low vision, who have troubles with the perception of certain aspects of colours and their combinations [14]. Other than that, particular colours should recall the features being mapped, e.g., blue is almost always used to map hydrographic features. Although for congenitally blind individuals, colours are abstractions, people with adventitious blindness have visual memories of images from the past, allowing them to correctly interpret colours [13]. Besides, as stated by Kim et al. [15], PVI share similar intuitions about colours to sighted people thanks to regular exposure to discussions about colours. Thus, a legible and contrasting colour palette is insufficient. It also requires well-thought-out colour assignments to their meanings.

Apart from perception issues, consideration must be given to potential applications of the designed colour palettes, with data on maps categorized as qualitative or quantitative. Particular variables are better for visualizing qualitative characteristics of features, e.g., hue and shape on graphic content and texture on tactile content, whereas others are better to present the intensity of a phenomenon, e.g., size and value on graphic content and height on tactile content.

Considering the above, designing a universal colour palette for tactile maps that is legible, is visually appealing to every individual with visual impairments, and unambiguously assigns colours to their meanings, is impossible. Thus, not only developing colour palettes but developing tactile maps in general is a matter of a trade-off between inclusivity, understood as fulfilling the diverse requirements and preferences of PVI, and visual appeal, keeping in mind that legibility is the most important feature of tactile maps [16]. On one hand, colours must consider the needs of the minorities, e.g., those with colour impairments, ensuring they can access and interpret the map's information effectively, while at the same time cater to those who appreciate aesthetically pleasing and easy-to-read maps.

Guidelines recommend using more than one variable to distinguish features on tactile maps [17]. The Use of Colour success criterion in the Web Content Accessibility Guidelines emphasizes the importance of not relying solely on colour to convey information [18]. PVI often rely on both graphic and tactile content when working with tactile maps, emphasizing the need to utilize the full potential of both sets of variables.

This research is part of a broader project aiming to develop technology for creating tactile maps of historic parks in various styles. While not intended for navigation, these maps convey the characteristics of parks designed in specific styles. To date, we have published our research on content selection for maps of parks in specific styles: renaissance, baroque, English, romantic, and Japanese [19] and on the methodology of testing tactile cartographic symbols in isolation and in context [20]. In this study, the focus is on the graphic content, specifically the colours used to differentiate area features.

We have posed the following research questions:

- RQ1: Which colour palette attracts the most attention?
- RQ2: What is the impact of the palette used on the legibility and understanding of maps?
- RQ3: Which colour palette is rated as the best by testers?

The research questions pertain to the four dimensions of colour palette evaluation outlined in the Section 2. While this research focuses solely on colour palettes, symbols on target maps will be distinguished using both colours and tactile textures, as previously established [20].

2. Materials and Methods

2.1. VIEW Model

Our methodology is based on the VIEW model, widely applied in the marketing domain [21] and originally applied to evaluate packaging [22], that assesses 4 dimensions of the graphic products:

- Visibility—being easily seen, attracting the most attention;
- Informational—transferring necessary information;
- Emotional Appeal—triggering emotions, judgements;
- Workability—functionality, reliability.

In the context of tactile maps and colour palettes, Visibility measures how easily a tactile map can be spotted and defines its visual attractiveness (RQ1). While laboratory instruments can be applied, using a small group of trained observers is sufficient to evaluate relative differences between palettes [22].

Two dimensions, Informational and Workability, are considered together for tactile maps. Tactile maps consist of a legend transmitting necessary information, and their purpose is to obtain information about spatial relations between presented objects. Therefore, symbols on tactile maps, including colours of area symbols, must be easily distinguishable and identifiable in a legend while resembling real-world features (RQ2).

For Emotional Appeal, a direct approach was taken by asking study participants to identify the best overall colour palette at the end of the study session (RQ3). Testers were aware of the context in which the maps would be used.

2.2. Case Study

2.2.1. Colour Palettes

For this study, we developed four colour palettes, each comprising six unique colours for denoting area symbols, with black for text, point, and line symbols and white for offsets between symbols and the general background colour. Recommended guidelines suggest 4–6 different textures for area symbols [23,24] and a maximum of 10–15 unique symbols in general on a single tactile map sheet [25]. To the best of our knowledge, there are no such guidelines for colours, but it is uncommon to use more than 8 colours on a single tactile map.

The developed colour palettes were based on the concept of contrast as defined in WCAG 2.1 [18]:

$$Contrast\ ratio = \frac{L1 + 0.05}{L2 + 0.05} \tag{1}$$

where:

*L*1, *L*2—relative luminance of the lighter and darker colours, respectively.

Our calculations are based on sRGB colour space to calculate the relative luminance of particular colours [26], normalized to 0 for pure black and 1 for pure white:

$$Relative\ luminance = 0.2126 \times R + 0.7152 \times G + 0.0722 \times B \tag{2}$$

where:

$$if\ RsRGB\ \leq 0.4045\ then\ R = \frac{RsRGB}{12.92} else\ R = \left(\frac{RsRGB + 0.055}{1.055}\right)^{2.4} \tag{3}$$

$$if\ GsRGB\ \leq 0.4045\ then\ G = \frac{GsRGB}{12.92} else\ G = \left(\frac{GsRGB + 0.055}{1.055}\right)^{2.4} \tag{4}$$

$$f\ RsRGB\ \leq 0.4045\ then\ R = \frac{RsRGB}{12.92} else\ R = \left(\frac{RsRGB + 0.055}{1.055}\right)^{2.4} \tag{5}$$

where: *RsRGB*, *GsRGB*, and *BsRGB* are the 8-bit values of particular colour channels divided by 255.

In adherence to the Web Content Accessibility Guidelines (WCAG), success criterion 1.4.11 for non-text contrast requires a 3:1 contrast ratio against the background for AA-level conformance. Achieving this contrast is straightforward for a single pair of colours but becomes impractical for palettes with more than five colours [18].

Considering this, only contrast might have been insufficient when designing colour palettes for tactile maps. Thus, we have also measured the change in visual perception of two given colours using the Delta E 2000. It is the newest and most accurate version of the former delta E concept, first introduced in 1976 by the International Commission on Illumination [27]. The calculations are based on LAB coordinates from the CIELAB colour space [28] which is considered a perceptually real colour space, where the Euclidean distance between two colours in this colour space reflect their difference when perceived by sight [29]. Values of delta E over 50 mean that the 2 colours considered are further apart than they are close to each other in the colour space. According to Mokrzycki and Tatol [30], for values of delta E higher than 5, the observer perceives two colours as completely different, but it is sufficient for delta E to be at least 2 for an unexperienced observer to notice the difference in colours (to the best of our knowledge, there was no research on the minimum differences in delta E for PVI to notice colour changes). The formulas are complex and will not be cited in this paper. All the calculations were carried out in spreadsheet software (Microsoft Excel version 2402).

In this study, we evaluated 4 colour palettes of 8 colours each that are meant to be used with qualitative data (Figure 1):

1. *Existing map*—from the existing maps of the European Union in the Tactile Atlas of Poland [31]. We have extracted only the 6 colours used for area symbols.
2. *Python optimizer*—we prepared an algorithm that generated the values of relative luminance (0–1) of each colour to maximize the minimum contrast between the closest (most similar) pairs of colours. Then, the particular RGB values were manually selected to match the hues forming subtractive (CMY) and additive (RGB) colours.
3. *Colour blindness*—colours extracted from the 15-colour palette designed by Martin Krzywinski [32] that considers the 3 most common types of colour blindness: deuteranopia, protanopia, and tritanopia. The goal was to maximize the contrast and differentiate hues as much as possible.
4. *Hand-picked*—a very subjective authors' selection of distinct colours from the visible spectrum to achieve the highest luminance differences, while maintaining the maximum saturation of colours.

EXISTING MAP								
Colour code	Visualization	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance
black		0	0	0	0.00	0.00	0.00	0.00
pink		224	5	133	0.75	0.00	0.23	0.18
violet		177	76	183	0.44	0.07	0.47	0.18
green		127	198	0	0.21	0.56	0.00	0.45
orange		254	186	97	0.99	0.49	0.12	0.57
yellow		253	236	137	0.98	0.84	0.25	0.83
blue		196	228	245	0.55	0.78	0.91	0.74
white		255	255	255	1.00	1.00	1.00	1.00

PYTHON OPTIMIZER								
Colour code	Visualization	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance
black		0	0	0	0.00	0.00	0.00	0.00
blue		0	0	165	0.00	0.00	0.38	0.03
red		154	0	15	0.32	0.00	0.00	0.07
green		10	119	15	0.00	0.18	0.00	0.13
magenta		232	0	234	0.81	0.00	0.82	0.23
cyan		0	185	185	0.00	0.49	0.49	0.38
yellow		241	203	0	0.88	0.60	0.00	0.61
white		255	255	255	1.00	1.00	1.00	1.00

COLOUR BLINDNESS								
Colour code	Visualization	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance
black		0	0	0	0.00	0.00	0.00	0.00
violet		73	0	146	0.07	0.00	0.29	0.03
brown		146	73	0	0.29	0.07	0.00	0.11
marine		0	146	146	0.00	0.29	0.29	0.23
blue		109	182	255	0.15	0.47	1.00	0.44
green		36	255	36	0.02	1.00	0.02	0.72
yellow		255	255	109	1.00	1.00	0.15	0.94
white		255	255	255	1.00	1.00	1.00	1.00

HAND-PICKED								
Colour code	Visualization	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance
black		0	0	0	0.00	0.00	0.00	0.00
blue		0	0	255	0.00	0.00	1.00	0.07
red		255	0	0	1.00	0.00	0.00	0.21
pink		255	130	255	1.00	0.22	1.00	0.44
cyan		100	220	255	0.13	0.72	1.00	0.61
green		100	255	0	0.13	1.00	0.00	0.74
yellow		255	255	0	1.00	1.00	0.00	0.93
white		255	255	255	1.00	1.00	1.00	1.00

Figure 1. The parameters of 4 colour palettes used in human subject testing. Confer Equations (1)–(5) for column meanings.

Originally, each palette had three variants with 6 to 8 distinct colours, but human subject testing was limited to four colour palettes, specifically, the variants with 8 colours, to avoid elongating study sessions and ensuring reliable results. Detailed colour parameters for each palette variant can be found in Appendix A.

2.2.2. Tactile Maps Stimuli

For this study, we modified two tactile maps initially prepared for our project, depicting the Baroque garden in Wilanów (level II) and the English garden in Krasiczyn (level II). These maps convey characteristics of their respective garden styles based on qualitative data, portraying features like symmetrical, man-made elements in the Baroque gardens (Figure 2). To align with our goal of testing colour palettes comprising six unique colours plus black and white, we enhanced the maps to include six types of area symbols. The original 3D models were flattened to 2D drawings, removing tactile elements such as black elements forming tactile textures (extruded over the map surface) and retaining only the colour patches (Figure 2).

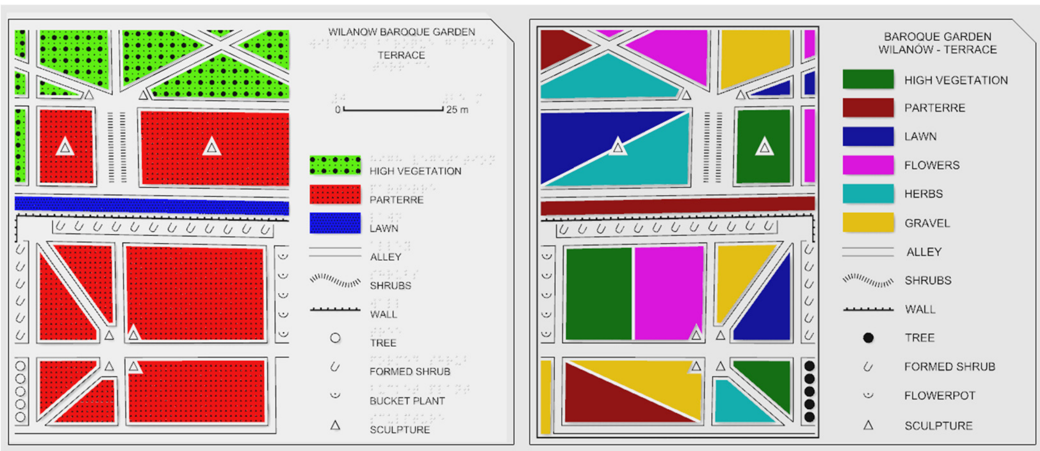

Figure 2. Original tactile map enhancement—adaptation of Baroque park level II map with additional mirroring applied. On the left is the original map, on the right is the modified version evaluated in this study.

Four map variants, each representing one of the four colour palettes, were prepared for each garden. To mitigate potential memorization during testing, half of the maps were modified by mirroring their content. In total, eight graphic variants of tactile maps were created for this study (Figure 3), with numbers 1–4 denoting types of colour palettes, and letters A and B referring to the mapped locations: English garden in Krasiczyn and Baroque garden in Wilanów, respectively.

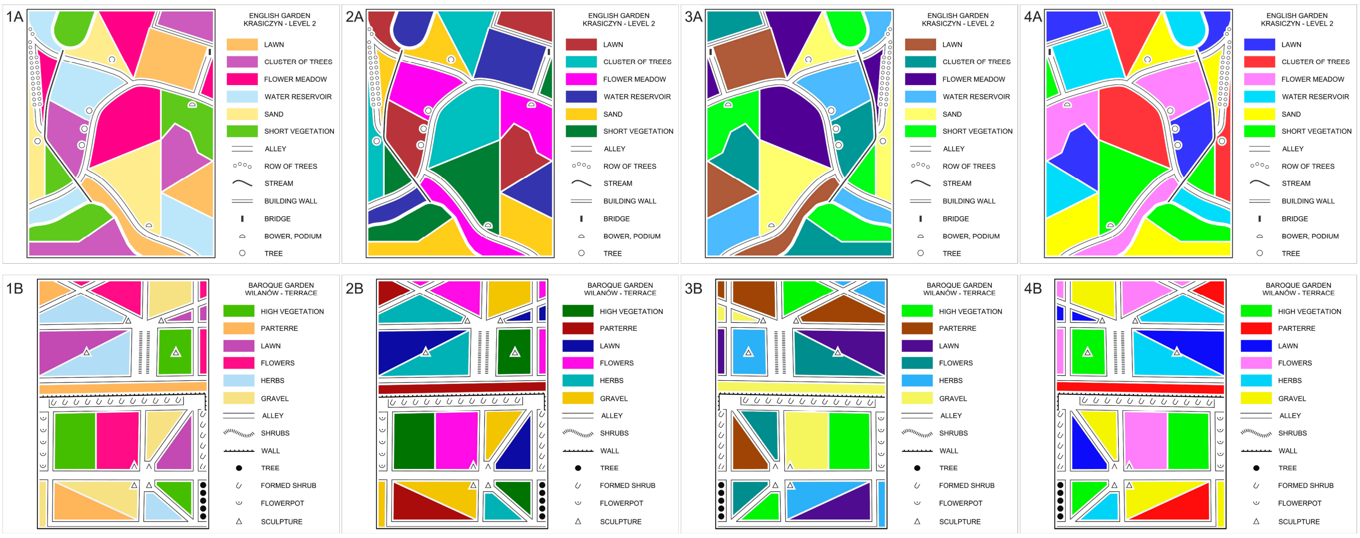

Figure 3. All the maps used during study sessions with their corresponding codes. The corresponding simulations considering deuteranopia, protanopia, and tritanopia can be found in Appendix B.

2.2.3. Study Session

We created a recruitment form, distributed through the Polish Blind Association via websites, social media, and mailing lists, resulting in 56 PVI interested in participating in our study, of which 16 PVI were selected. The selection ensured diversity in low vision causes, functional consequences, age, and tactile map reading experience.

Upon obtaining written consent, the testing phase began. The full session scenario along with task numbering is described in Appendix C. In the preliminary stage, study participants were asked a question: “In front of you are 4 graphic tactile maps—please indicate which one would you like to start with if you could choose and why?” We have noted the choices and reasonings that would indicate the most appealing map variant (Visibility). Each participant chose the most attractive map variant twice from a set of 4. In the first iteration, the 4 map variants shown were those that were used in the remaining part of the study session. The second iteration involved map variants unused for evaluation of the remaining dimensions, e.g., study participant C1 was presented with map variants 1A, 2B, 3A, and 4B in the first iteration and 1B, 2A, 3B, and 4A in the second iteration.

Each map variant from the first iteration was further assessed for the remaining VIEW model dimensions. They were presented to study participants in a controlled random order to eliminate potential confounding variables. The following procedure was repeated for each of the 4 map variants.

First, we asked the following question: “When you look at a map, which area would you like to explore and why? What is it?” (tasks X.1). Participants were supposed to point to areas that drew their attention (Visibility) but were also supposed to decode the meanings of the area symbols (Informational, Workability). If a participant was unable to decode the symbol, a researcher informed them of its meaning. We were noting the positions of the areas indicated and reasoning behind their decisions, as well as potential decoding errors.

Secondly, participants were asked to point and name each of the remaining area symbols that you see on the map variant (Informational, Workability—tasks X.2). We were noting any omissions, erroneous indications (collectively referred as errors), and protracted responses—situations in which a study participant referred to a legend more than once or had to repeat their scanning of the map.

Next, we asked participants to indicate which colours on the maps are very similar to each other and which differ the most (Informational, Workability—tasks X.3). We were noting pairs or groups of such colours.

Since the maps tested also included point and line symbols, we wanted to verify how the colour palettes tested influenced the legibility of the remaining symbol types on tactile maps. For this reason, participants were asked to indicate 2 point (tasks X.4) and 2 line symbols (tasks X.5) and explain their meanings (Informational, Workability). The symbols were chosen randomly; a researcher could also ask participant to indicate 2 instances of the same symbol.

In human subject testing, obtaining unstructured feedback is crucial. This is why we asked for loose remarks about each map variant tested (task X.6).

The procedure was then repeated for the remaining 3 map variants. At the very end of the study session, a researcher asked which of the 4 tested map variants was the best (Emotional Appeal). Some participants confidently chose a single variant, while others hesitated between multiple variants. In cases of hesitation, participants were asked to choose a maximum of two variants and rank them. A scoring system was then applied, assigning 3 points to the best variants and 1 point to those rated second best.

3. Results

3.1. Colour Calculations

Following the described methodology, we developed colour palettes. Figure 4 presents the results of contrast ratio and Delta E 2000 calculations for the four palettes applied on the stimuli meant to be tested during study sessions with PVI.

EXISTING MAP

Contrast ratio	black	pink	violet	green	orange	yellow	blue	white
black								
pink	4.53							
violet	4.59	1.01						
green	9.98	2.20	2.18					
orange	12.41	2.74	2.71	1.24				
yellow	17.54	3.87	3.82	1.76	1.41			
blue	15.76	3.48	3.44	1.58	1.27	1.11		
white	21.00	4.64	4.58	2.10	1.69	1.20	1.33	

Delta E 2000	black	pink	violet	green	orange	yellow	blue	white
black								
pink	41.08							
violet	39.71	15.54						
green	83.95	83.95	83.40					
orange	75.12	52.99	57.12	34.52				
yellow	93.37	67.51	69.69	21.73	17.58			
blue	84.44	51.21	38.27	42.01	37.96	35.93		
white	100.00	42.71	41.39	34.54	29.13	24.91	13.34	

PYTHON OPTIMIZER

Contrast ratio	black	blue	red	green	magenta	cyan	yellow	white
black								
blue	1.54							
red	2.38	1.54						
green	3.66	2.37	1.54					
magenta	5.62	3.64	2.36	1.54				
cyan	8.64	5.60	3.63	2.36	1.54			
yellow	13.28	8.61	5.58	3.63	2.36	1.54		
white	21.00	13.61	8.82	5.74	3.74	2.43	1.58	

Delta E 2000	black	blue	red	green	magenta	cyan	yellow	white
black								
blue	26.07							
red	35.12	45.13						
green	40.29	61.39	63.36					
magenta	46.04	38.07	42.63	89.73				
cyan	59.82	60.77	68.06	36.42	49.61			
yellow	80.43	97.42	60.69	44.71	77.72	44.61		
white	100.00	79.78	61.91	50.85	37.87	31.30	31.88	

COLOUR BLINDNESS

Contrast ratio	black	violet	brown	marine	blue	green	yellow	white
black								
violet	1.70							
brown	3.18	1.87						
marine	5.53	3.25	1.74					
blue	9.79	5.76	3.08	1.77				
green	15.40	9.07	4.85	2.79	1.57			
yellow	19.78	11.64	6.23	3.58	2.02	1.28		
white	21.00	12.36	6.61	3.80	2.15	1.36	1.06	

Delta E 2000	black	violet	brown	marine	blue	green	yellow	white
black								
violet	28.42							
brown	38.38	50.09						
marine	45.81	43.60	47.40					
blue	62.60	51.46	56.34	25.75				
green	88.22	80.93	66.21	42.26	60.54			
yellow	101.65	93.11	53.73	48.65	62.71	23.20		
white	100.00	62.47	53.49	39.39	28.70	33.15	28.16	

HAND-PICKED

Contrast ratio	black	blue	red	pink	cyan	green	yellow	white
black								
blue	2.44							
red	5.25	2.15						
pink	9.89	4.05	1.88					
cyan	13.22	5.41	2.52	1.34				
green	15.85	6.48	3.02	1.60	1.20			
yellow	19.56	8.00	3.72	1.98	1.48	1.23		
white	21.00	8.59	4.00	2.12	1.59	1.33	1.07	

Delta E 2000	black	blue	red	pink	cyan	green	yellow	white
black								
blue	32.95							
red	51.88	55.92						
pink	62.67	48.26	43.44					
cyan	76.21	57.49	73.29	47.78				
green	89.64	88.02	81.34	93.29	48.98			
yellow	102.58	102.29	61.65	79.65	51.91	21.51		
white	100.00	64.66	46.31	25.70	24.12	32.90	31.35	

Figure 4. Contrast ratio and Delta E 2000 calculations between particular colours (cf. Appendix A). Values of contrast ratio over 3:1 and Delta E 2000 of over 50 are marked in green. The remaining values are in red.

3.2. Map Evaluation

The eight variants of map stimuli were created using vector graphic software (Rhino 7), exported to PDF format in 600 DPI resolution, and printed on a Canon Pixma Pro-1 printer without colour corrections to faithfully reproduce the designed colours.

The testing phase occurred at the Polish Association of the Blind's headquarters in Warsaw over two days in September 2023, involving 16 paid PVI participants in sessions lasting approximately 60 min each. Participants were assigned codes (C1, C2, etc.) for anonymity. The same number of women and men took part in the study. The average age was 38 years (range: 20–53 years). Twelve people had higher education, and four had secondary education. The respondents' experience with tactile maps varied: eight people described it as low, seven as medium, and one as high. Most participants had experienced visual impairment from birth (12 people). Testers were individuals experiencing various visual system disorders and, consequently, diverse functional consequences. Six people pointed to a single condition as the cause of low vision, while ten people identified more. The participants most commonly experienced cataracts (seven), glaucoma (five), high myopia (five), retinopathy of prematurity (three), macular degeneration (three), optic nerve atrophy (three), microphthalmia (two), aphakia (two), and retina pigment degeneration (two). Single individuals mentioned corneal cone, achromatopsia, corneal leukoma, and nystagmus. Injuries affect different structures of the visual system, but the most common functional consequence is a significant reduction in visual acuity (thirteen people), leading to colour vision disturbance and decreased sensitivity to contrast as well as peripheral visual field losses and, consequently, night blindness, along with difficulty in adapting to changing lighting conditions (seven people). These effects are observed in both the central part of the retina (responsible for sharp vision and colour perception) and light perception (five people reported experiencing light sensitivity and susceptibility to glare). Visual disorders also cause significant eye strain. In practice, most participants require enlarged fonts for reading (without optical and electronic aids, six people read font size 16; four people, 18; and two people, 20 or larger), and two individuals indicated that they do not read visually without magnification assistance. The studied group exhibited a high degree of diversity in terms of visual capabilities.

Before testing, participants were asked about their preferences for lighting, position adjustments, or the need for handheld or desktop video magnifiers. During testing, we noted if participants used optical or non-optical aids in reading the maps. Most had no trouble with understanding the maps' content without additional aids. Some participants needed to enlarge the maps' content using either magnifiers (two participants), a different set of glasses (two participants), or a smartphone (one participant—Figure 5). Five of the study participants requested a lighting change.

Figure 5. One of the study participants during testing.

3.3. Visibility

Visibility of particular colour maps was evaluated, inter alia, by asking study participants to indicate the map variant that they would like to start working with when presented with four different variants in two iterations. Each variant was presented at least once to every participant in either first or second iteration of this test (cf. Section 2.2.3.). The *Python optimizer* palette drew the most attention, chosen by more than half of the testers in both iterations when presented in the set of four maps (Figure 6).

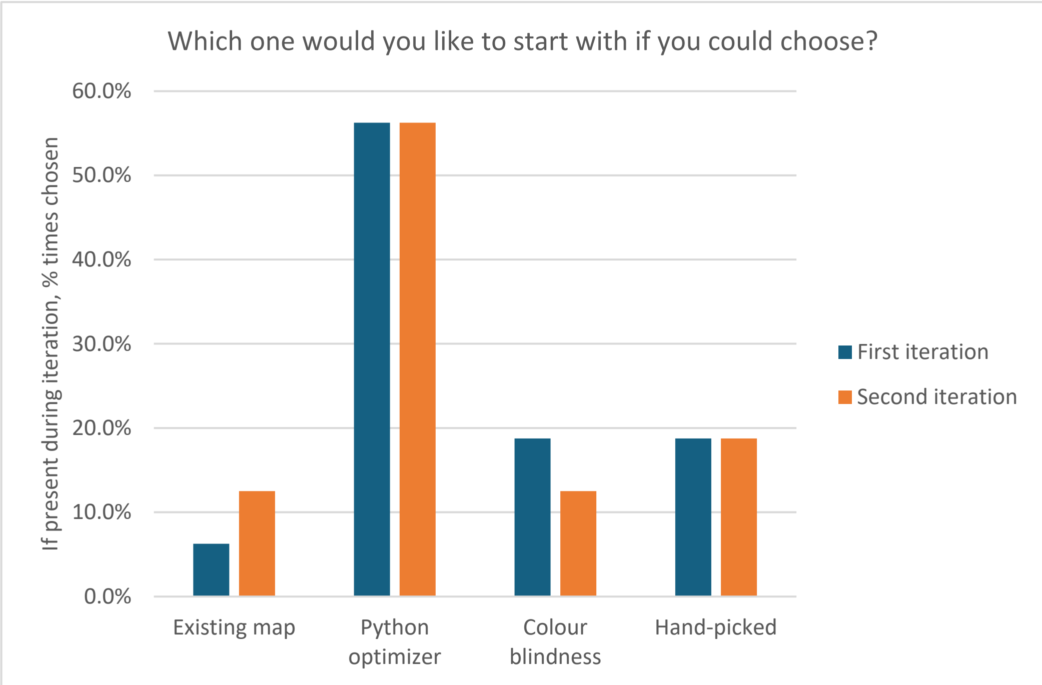

Figure 6. Evaluation of the colour palettes that drew the most attention (Visibility).

The analysis of participants' indications of areas from which they would like to begin working with a map (tasks X.1) reveals that the popularity of particular areas is determined not only by its colour but also by its position and shape. On the maps of the English garden in Krasiczyn, where mostly irregular areas appeared (map variants 1A–4A in Figure 3), the vast majority of study participants consistently pointed to the central parts of the map, covering two or three neighbouring areas. For the *Existing map* palette, this translates into five indications each of pink and yellow (cf. Figure 1 for colour names). For other palettes, the distribution was as follows: the *Python optimizer*—magenta (four indications), green (two), cyan (one); the *Colour blindness* palette—violet (six), yellow (two), marine (one); and the *Hand-picked* palette—blue (three), red (two), green (one).

However, for the maps of the Baroque garden in Wilanów, characterized by geometric shapes of area symbols and a distinct horizontal axis formed by the wall symbol (map variants 1B–4B in Figure 3), study participants most frequently pointed the large area divided into two rectangles below this axis and a similar area divided into two triangles above the axis. Here, the most popular indications were, for the *Existing map* palette: green (three) and pink (three); for the *Python optimizer* palette, magenta (five), green (two), and cyan (two); for the *Colour blindness* palette, yellow (six), green (three), violet (one), and marine (one); and for the *Hand-picked* palette, green (three), pink (three), blue (two), and cyan (two).

Indications on the maps of both gardens were the most consistent in the case of the *Python optimizer* palette. For other palettes, although usually the same colours were selected, the frequency of these indications varied significantly.

These results may be explained by the fact that both reduced visual acuity and deficits in peripheral vision (primary functional consequences experienced by the study participants) result in fixating the gaze on the central areas of the observed object. Therefore, when it is necessary to use the entire palette, less distinct colours should be applied for larger central areas.

3.4. Informational/Workability

Legibility and simplicity are crucial in tactile map design [16]. Errors and instances of protracted responses during tasks X.2, X.4, and X.5 were considered as indicators of the Informational and Workability parameters of the VIEW model (refer to Appendix C for full details on the testing procedure), where participants were asked to indicate on maps particular symbol types or decode the symbols on a map using the corresponding legend. Figures 7 and 8 present the numbers of errors committed and instances of protracted responses, considering the type of symbol geometry affected, for each palette.

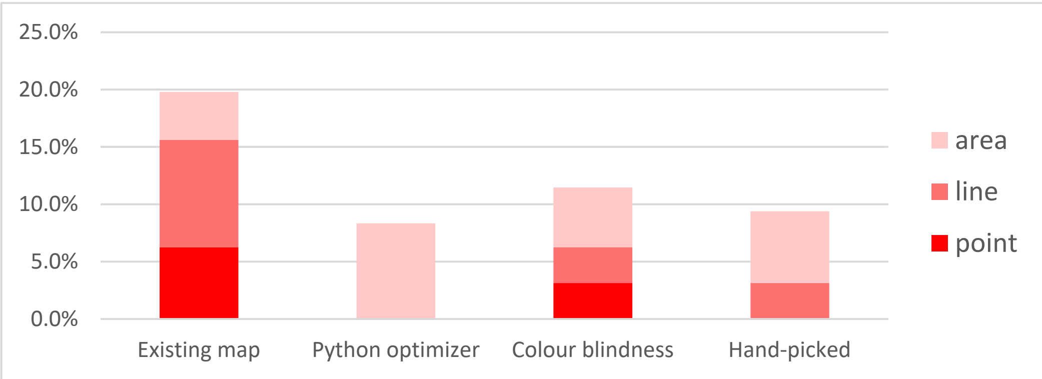

Figure 7. Errors committed (omissions and erroneous indications) by symbol geometry.

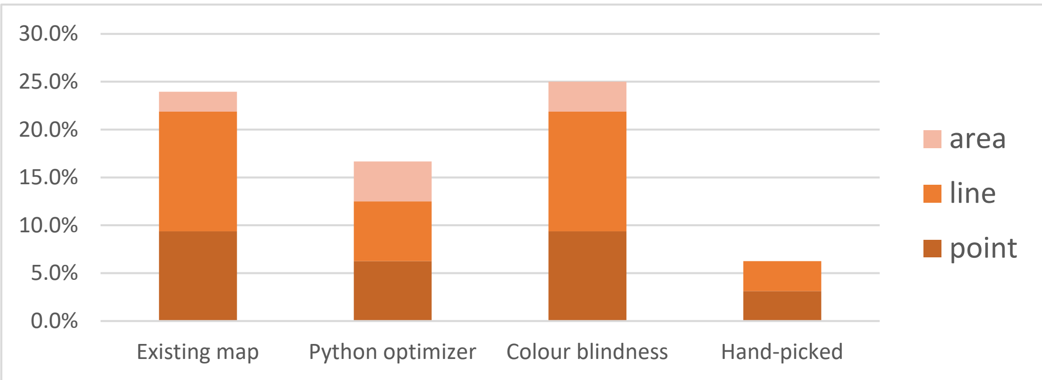

Figure 8. Protracted responses by symbol geometry.

The total number of errors per palette during sessions varied from 7 to 9, with participants indicating two point, two line, and six area symbols on each map. Three of the palettes are characterized by an approximate error rate of 10%, with the *Existing map* palette standing out negatively with an error rate of 20%. However, although we have tested colour palettes in context and counted errors committed for each type of symbol geometry, in this research, we focus mainly on area symbols that use the colours designed. Having this in mind, the *Colour blindness* palette is characterized by the lowest number of errors related to area symbols, i.e., 5.2%.

During our past study sessions with PVI [33], study participants often expressed their need to be able to comprehend tactile maps content immediately after seeing or touching them. For this reason, we have noted the instances of protracted analyses during the study session. The *Hand-picked* palette fulfils this requirement with only 6.3% of tasks requiring protracted analyses and none of them related with area symbols. For the *Python optimizer* palette, the total number of such situations sums to 16.7% with one-fourth related to area symbols. The results of the remaining two palettes are comparable.

Study participants were also asked (task X.3 in Appendix C) to name colours and/or their meanings from legends that seemed most similar to each other (similar colours matrices in Figure 9—the higher the score, the worse) and the most different from each other (contrasting colours matrices in Figure 9—the higher the score, the better). We have counted these indications with weights assigned, with 1 meaning a strong statement of a study participant and 0.5 for doubtful statements, e.g., a response from participant C10, "If I had to choose something, then I would say that flowers and herbs look similar", was assigned 0.5 weight.

SIMILAR COLOURS MATRICES

Existing map	pink	violet	green	orange	yellow	blue
pink		10.0				
violet			1.0	1.0	1.5	
green						1.0
orange					4.0	1.0
yellow						2.5
blue						

Python optimizer	blue	red	green	magenta	cyan	yellow
blue			2.0	1.5	1.5	
red				1.0	0.5	
green				2.0	7.5	
magenta					0.5	
cyan						
yellow						

Colour blindness	violet	brown	marine	blue	green	yellow
violet		1.0				
brown			3.0			
marine				3.0	3.5	
blue					1.0	
green						1.0
yellow						

Hand-picked	blue	red	pink	cyan	green	yellow
blue		1.0	3.0	1.0	1.0	
red			6.0			
pink					1.0	
cyan					2.0	
green						
yellow						

CONTRASTING COLOURS MATRICES

Existing map	pink	violet	green	orange	yellow	blue
pink		1.0	4.0		5.0	3.0
violet				1.0	1.0	1.0
green					1.0	
orange						
yellow						
blue						

Python optimizer	blue	red	green	magenta	cyan	yellow
blue						5.0
red						3.5
green				4.0		2.0
magenta						5.0
cyan						1.0
yellow						

Colour blindness	violet	brown	marine	blue	green	yellow
violet				1.0		6.0
brown			2.0	1.0	1.0	1.0
marine						1.0
blue						
green						3.0
yellow						

Hand-picked	blue	red	pink	cyan	green	yellow
blue			1.0			3.0
red					2.0	1.0
pink				1.0	3.0	1.0
cyan						
green						
yellow						

Figure 9. Similar and contrasting colours matrices. Numbers present the weighted number of times, when study participants indicated given pairs of colours as similar (similarity score) and/or contrasting (contrast score).

These values help with identifying colours that should not appear together on the same map. A similarity score of at least 4 (25% or more of the study participants indicated colour pairs as similar, marked in red on the left side of Figure 9) characterizes the following pairs of colours: pink and violet (10) and orange and yellow (4) from the *Existing map* palette; green and cyan (7.5) from the *Python optimizer* palette; and red and pink (6.0) from the *Hand-picked* palette. Additionally, light yellow highlights potential troublesome pairs with similarity scores between two and four (left side of Figure 9). Contrast scores can be used to select the most contrasting colours from the proposed eight-colour palettes if only a limited number is needed for a given tactile map. The summed values of similarity and contrast scores for each palette are presented in Table 1.

Table 1. Summed similarity and contrast scores.

Palette	*Similarity Score*	*Contrast Score*
Existing map	22.0	17
Python optimizer	16.5	20.5
Colour blindness	12.5	16
Hand-picked	15.0	12

Clearly, the *Existing map* palette is characterized by the highest similarity score, with two colour pairs contributing significantly. Other palettes show comparable results, with the *Colour blindness* palette having the lowest score and no pairs with a score of four or more. The *Python optimizer* palette achieved the highest contrast score, although this parameter is less critical for the study.

3.5. Emotional Appeal

At the end of each session, participants ranked the map variants for Emotional Appeal. Most of the participants were unable to unanimously indicate a single map palette and ranked them by indicating the best and the second-best map (10 participants). Scoring was applied, assigning three points for the best palette and one point for the second best (Figure 10).

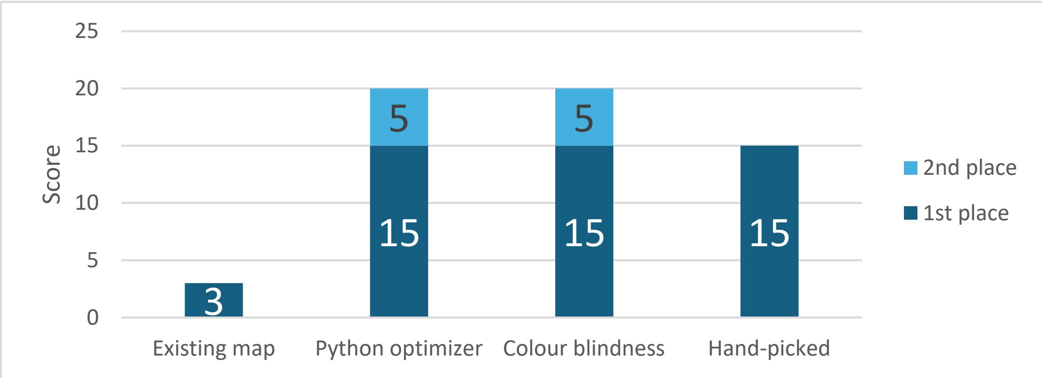

Figure 10. Emotional Appeal score.

The *Python optimizer*, *Colour blindness*, and *Hand-picked* palettes were chosen as the best an equal number of times (five each), with two of them obtaining an additional five points for being selected as the second best. The *Existing map* palette stood out negatively, being selected only once.

Participants were asked to pick a map to start the session and indicate the best map at the end. Figure 11 shows how participants' choices changed over the study sessions. Regarding Visibility, responses were counted only in the first iteration, and for Emotional Appeal, only responses ranking palettes as "the best" were considered.

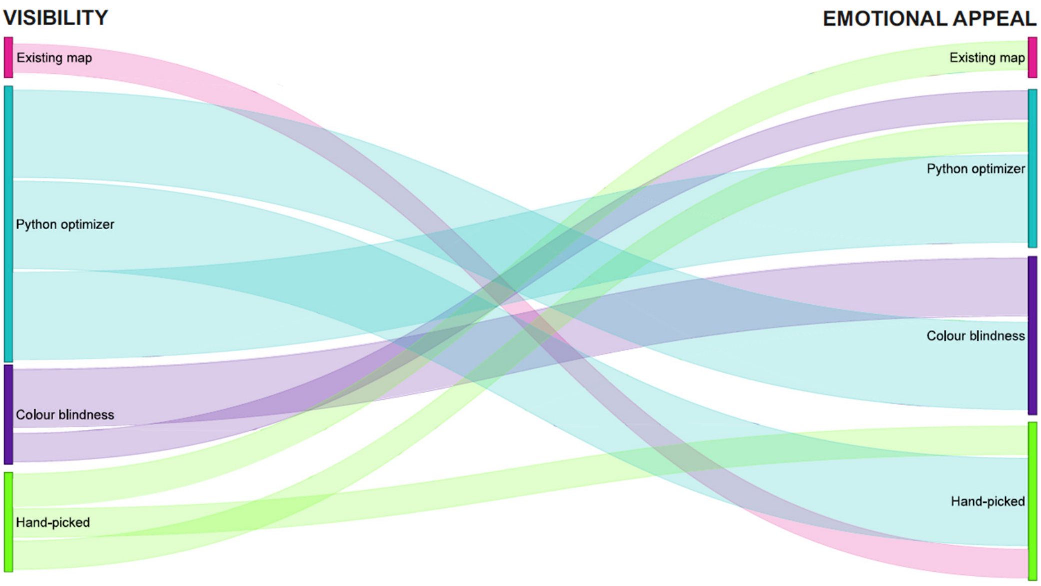

Figure 11. Transitions of participants' opinions within Visibility and Emotional Appeal domains.

At the beginning of the session, the *Python optimizer* palette dominated, with nine participants pointing to it as the most attention-grabbing. Later, preferences shifted more evenly, with three palettes chosen as the best by five participants each. The *Existing map* palette remained unpopular throughout the whole session.

3.6. Final Score

Analysing particular colour palettes for specific dimensions of the VIEW model can be useful, but we decided to determine a final weighted score that would consider each dimension tested in our methodology. We applied the min–max normalization for every score cited in the previous sections to reduce them to a common range of values. The weights assigned to every component of the final score are listed in Table 2.

Table 2. Weights assigned to components of the final score.

Dimension	*Component*	*Weight*	*Total Weight*
Visibility	First iteration	0.75	1
	Second iteration	0.25	
Informational/Workability	Errors—point	−0.25	3
	Errors—line	−0.25	
	Errors—area	−0.5	
	Protracted analyses—point	−0.125	
	Protracted analyses—line	−0.125	
	Protracted analyses—area	−0.25	
	Similarity score	−1	
	Contrast score	0.5	
Emotional Appeal	n/a	1	1

When it comes to Visibility, we decided to differentiate participants' decisions from the first and second iterations (Figure 6) by assigning a higher weight to their preferences in the first iteration, when they had to choose from the map variants later used for the remaining part of testing procedure.

Since legibility is the most important factor in tactile maps' design, we assigned the highest weights to the Informational and Workability dimensions. Within these dimensions, error rates (Figure 7) are more important than protracted analyses (Figure 8), and within each of these parameters, higher weights were assigned to errors and protracted analyses related to area symbols than to point and line symbols. The same applies to greater importance of a similarity score than a contrast score (Table 1).

Finally, the Emotional Appeal is described by only one value: the Emotional Appeal score (Figure 10). We did not consider the transitions of participants' opinions when calculating the final score. The weighted scores are presented in Table 3.

Table 3. Normalized weighted scores of each palette in each dimension along with the final score.

Palette	*Visibility*	*Informational/ Workability*	*Emotional Appeal*	*Final Score*
Existing map	0.00	0.00	0.00	0.00
Python optimizer	1.00	0.77	1.00	1.00
Colour blindness	0.19	1.00	1.00	0.80
Hand-picked	0.22	0.94	0.80	0.72

Our results clearly show that the *Existing map* palette scored the worst in each of the analysed dimensions, whereas the *Python optimizer* palette obtained the best results in Visibility and Emotional Appeal, which translated into the highest final score. However, considering the fact that the pragmatic aspects of tactile maps use are best described by the Informational and Workability dimensions, one might argue that the *Colour blindness* palette should better be applied on tactile maps presenting qualitative phenomena.

3.7. Qualitative Feedback

During study sessions, participants were encouraged to share their feelings and comments, being asked questions like, "Do you have any remarks about the map?" We also documented spontaneous comments made during the session, providing valuable feedback to understand the needs of PVI and make necessary adjustments to future maps and solutions.

However, the needs and preferences of people with visual disfunctions are very diverse, and therefore, individual comments should not be treated as universal opinions of the entire group of respondents. Some comments contradicted each other, such as participants C3 and C8 finding the yellow colour in the *Colour blindness* palette too bright and contrasting, causing vision tiredness, while testers C6 and C13 suggested that the colour was too pale and should be more contrasting. Despite these comments, colour palettes on tactile maps should use yellow as a high-contrast colour, not affected by most types of CVD, especially for highlighting prominent data on the map [34].

Nevertheless, we noted noteworthy recurring comments (from at least three participants) and our responses to them:

- COMMENT: It would be easier to distinguish area symbols if colours were enhanced with tactile patterns.
- RESPONSE: The final maps of historic parks will include both graphic content and tactile patterns, enhanced with audio descriptions. However, during colour palette testing, only the graphic content was used.
- COMMENT: In general, darker colours were preferred. Brighter colours should be replaced, e.g., yellow in the *Existing map* palette.
- RESPONSE: The palettes evaluated not only were optimized in terms of contrast and colour distances (Delta E 2000) but also considered people with complete colour blindness. Variability in brightness ensures legibility in grayscale, and participants could alter lighting conditions during the session.
- COMMENT: Labels were legible but could be improved. The black print font should be bold with increased spacing between characters.
- RESPONSE: We used a standard uppercase 16 pt Arial font for black print labels and will modify the font used on future maps.
- COMMENT: The construction lines of point symbols and line symbols are too thin.
- RESPONSE: Graphic variants of symbols used during tests were based on tactile counterparts evaluated previously [20]. We will modify their graphic variants on future maps.
- COMMENT: The colours applied did not recall characteristics of the real-world features they depicted.
- RESPONSE: The study focused on colour contrasts in different combinations, using mock-up maps. In the second iteration of tests (cf. Section 4), actual historic parks were evaluated to maintain associations between colours and mapped objects.

4. Discussion

Currently, colour palettes on tactile maps lack a systematic selection process. Most people with visual impairments (PVI) perceive tactile maps through both vision and touch, but the current design focuses on haptic symbols and rules.

In this research, we applied the VIEW model to learn which of the proposed qualitative colour palettes: draw the most attention (RQ1), are the most efficient (RQ2), and are, subjectively, rated as the best by study participants (RQ3). When it comes to the Visibility aspect (RQ1), the palette that drew the most attention was undoubtedly the *Python optimizer* palette with more than a half of participants expressing their willingness to begin the study with this palette in both the first and second iterations. During the study session, many of the participants highlighted the fact that this palette consists of highly saturated (unlike the *Existing map* palette), but at the same time, aesthetically pleasant colours (unlike the *Hand-picked* palette), which might explain such a high score.

To evaluate the Informative aspect and Workability of the evaluated palettes (RQ2), we have measured the number of errors committed and instances of protracted analyses when working with particular map variants and also calculated the similarity and contrast scores. The lowest number of errors was committed when participants worked with the *Python optimizer* palette, but all of the errors were related to area symbols. A slightly higher error rate was true for the *Hand-picked* palette, but again, most of them were associated with area symbols. In contrast, the lowest error rate for area symbols was true for the *Existing map* palette, but at the same time, the total error rate was much higher than that for other palettes. In this case, the *Colour blindness* palette can be considered as the best compromise. When considering protracted analyses, the lowest ratio was for the *Hand-picked* palette, which might be related to the extreme saturation of colours applied at the expense of faster eyestrain when using this palette.

Of the two scores calculated, the similarity score is more important. The *Colour blindness* palette obtained the lowest similarity score, whereas the highest contrast score was achieved by the *Python optimizer* palette. Taking all the above into account and based on the calculations from Section 3.6, we conclude that the *Colour blindness* palette is the most efficient one in conveying the spatial information to PVI.

For Emotional Appeal (RQ3), an unambiguous scoring system was applied. The *Python optimizer* and *Colour blindness* palettes received equally high ratings. Some participants who were initially drawn to the *Python optimizer* palette changed their preference to the *Colour blindness* palette after solving tasks, and vice versa, resulting in equal ratings for both palettes.

In summary, the *Colour blindness* and *Python optimizer* palettes are not only the most efficient and legible palettes but also proved to be equally preferred in terms of Emotional Appeal.

Although not directly related with our research questions, we also calculated a weighted final score for each of the palettes, with *Python optimizer* receiving the highest score and *Colour blindness* receiving the second highest. Notably, the palette currently used on tactile maps in Poland (*Existing map* palette) performed poorly in our evaluation, underscoring the importance of involving the target groups in design assessments.

Nevertheless, we have decided to apply the *Colour blindness* palette on our final maps of historic parks. This decision results from the previously highlighted importance of legibility, which is reflected by the results in the Informational and Workability dimensions, in which the *Colour blindness* palette obtained the highest score. We selected a diverse group of PVI for our study, some with experience in tactile maps and others without, affected by different conditions and with varying functional consequences. However, only one study participant reported achromatopsia. Thus, the fact that this palette is adapted for use by people with CVD was not appreciated by most study participants. However, as we want to make our final maps as universal as possible, we must also consider this aspect.

During every human subject testing conducted by our research team, we encouraged the study participants to express their comments regarding the study with a strong emphasis on the improvements we could make to the solutions proposed. To our surprise, many of the study participants expressed their gratitude that research is finally being carried out with visually impaired people, who usually use both touch and vision. This confirmed our assumptions that little attention is being paid to the graphic content of tactile maps.

We received valuable suggestions for improving the graphic symbols on our final maps of historic parks. We have thus decided to create a separate set of graphic symbols (from the existing tactile symbols set) with adjustments suggested by the study participants. On our final maps, the graphic underlay will slightly differ from the extruded tactile overlay. For example, based on the suggestions from study participants, the minimum width/radius of the constructing elements of graphic symbols were increased from 0.6 to 0.8 mm. Some of the troublesome point and line symbols were also modified, e.g., by filling the small areas where only outlines formed a symbol (Figure 12). We have also decided to modify the font by applying the one with bigger spacing.

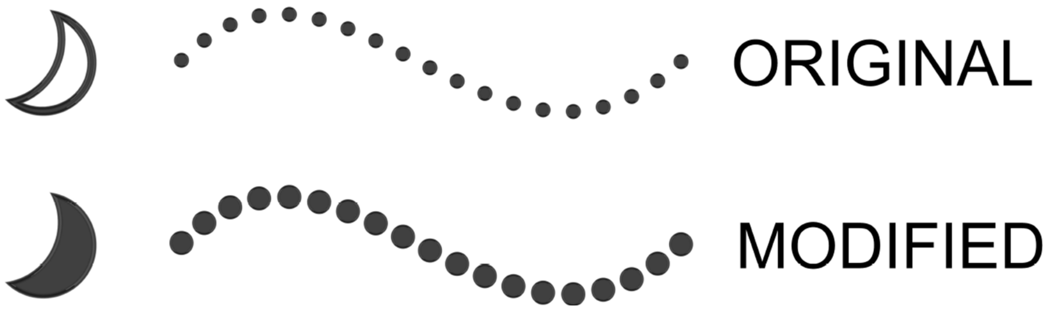

Figure 12. Original tested symbols and their modifications after considering participants' feedback.

After implementing these modifications, we conducted another study session with 15 PVI (out of which 13 were the same as in the first session) to ask, inter alia, whether the newly developed set of graphic symbols is legible. Describing the results of this study session is not within the scope of this research, but we would like to highlight that the tactile maps of actual historic parks with modified graphic symbols and the *Colour blindness* palette applied were rated as legible, informative, and pleasant to use.

Despite conducting exhaustive sessions with sociodemographically diverse study groups, their small size (15–16 PVI) might be considered as a limitation of this study. The nature of our study requires in-person meetings, being troublesome while trying to maintain geographic diversity of the study participants. Nevertheless, by evaluating only four palettes, we were able to thoroughly verify them in different dimensions of visual perception: attractiveness, functionality, and legibility. If we were testing more palettes, we would have to focus on a single dimension of visual perception. The sessions lasted 60 min and already caused tiredness in some participants. Although there are numerous possibilities to create different qualitative colour palettes for tactile maps, we believe that evaluating only four was sufficient.

Future studies could explore quantitative and divergent palettes or focus on the minimum values of delta E needed for individuals with residual vision to notice colour changes, as suggested by Mokrzycki and Tatol [30].

5. Conclusions

In conclusion, the intricate challenge of designing a tactile map that embodies qualities such as informativeness, durability, versatility, and, most crucially, legibility remains a daunting task. The existing body of research on the tactile and visual perception, redaction, and generalization of tactile maps contributes significantly to addressing these challenges. Interestingly, the lack of past research on colour applications for tactile maps stands out, despite the current emphasis on the haptic perception of tactile map content. In light of the aging of societies globally, it is imperative to redirect attention towards researching appropriate colour applications not only in tactile maps but also in graphic products more broadly.

Moreover, the ongoing surge in low-cost production technologies, coupled with the increasing ease of their utilization, presents numerous opportunities. Many of these technologies facilitate rapid prototyping, enabling the verification of new design solutions at a fast pace. The growing acknowledgment of people with special needs and the development of more universal solutions contribute to increased social awareness.

However, the problem is that many of such solutions are still being developed only in laboratories without thorough validation within the target user groups. We believe that the above highlights the importance of interdisciplinary research, involving scientists, practitioners, and finally, target user groups with different backgrounds. This collaborative approach is essential to developing applicable solutions that authentically meet the real needs of users, fostering a more inclusive and accessible environment for everyone.

Author Contributions: Conceptualization, Jakub Wabiński and Emilia Śmiechowska-Petrovskij; data curation, Jakub Wabiński; investigation, Jakub Wabiński and Emilia Śmiechowska-Petrovskij; methodology, Jakub Wabiński and Emilia Śmiechowska-Petrovskij; visualization, Jakub Wabiński; writing—original draft, Jakub Wabiński and Emilia Śmiechowska-Petrovskij; writing—review and editing, Emilia Śmiechowska-Petrovskij. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Anonymized research data will be shared upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Numerical parameters of colours in each of the palette developed.

Existing Map—**8 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
pink		224	5	133	0.75	0.00	0.23	0.18	49	76	−8
violet		177	76	183	0.44	0.07	0.47	0.18	49	51	−39
green		127	198	0	0.21	0.56	0.00	0.45	73	−42	70
orange		254	186	97	0.99	0.49	0.12	0.57	80	18	53
yellow		253	236	137	0.98	0.84	0.25	0.83	93	−5	49
blue		196	228	245	0.55	0.78	0.91	0.74	89	−9	−13
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1
Existing map—**7 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
violet		162	81	144	0.36	0.08	0.28	0.16	46	39	−20
green		116	180	60	0.17	0.46	0.05	0.37	67	−37	51
orange		247	170	95	0.93	0.40	0.11	0.49	76	23	49
blue		184	222	241	0.48	0.73	0.88	0.69	86	−11	−15
yellow		255	244	130	1.00	0.90	0.22	0.88	95	−8	54
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1
Existing map—**6 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
orange		236	108	45	0.84	0.15	0.03	0.29	61	47	56
green		116	180	60	0.17	0.46	0.05	0.37	67	−37	51
blue		184	222	241	0.48	0.73	0.88	0.69	86	−11	−15
yellow		255	244	130	1.00	0.90	0.22	0.88	95	−8	54
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

Table A1. *Cont.*

***Python Optimizer*—8 colours**

Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
blue		0	0	165	0.00	0.00	0.38	0.03	16	48	−82
red		154	0	15	0.32	0.00	0.00	0.07	32	54	40
green		10	119	15	0.00	0.18	0.00	0.13	43	−45	42
pink		232	0	234	0.81	0.00	0.82	0.23	55	86	−58
cyan		0	185	185	0.00	0.49	0.49	0.38	68	−41	−13
yellow		241	203	0	0.88	0.60	0.00	0.61	83	2	82
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Python Optimizer*—7 colours**

Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
blue		0	0	180	0.00	0.00	0.46	0.03	19	51	−87
red		172	0	10	0.41	0.00	0.00	0.09	36	59	47
green		0	137	0	0.00	0.25	0.00	0.18	49	−51	50
pink		254	72	255	0.99	0.06	1.00	0.33	64	81	−55
yellow		243	194	40	0.90	0.54	0.02	0.58	81	7	74
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Python Optimizer*—6 colours**

Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
blue		5	0	200	0.00	0.00	0.58	0.04	22	56	−94
red		197	0	14	0.56	0.00	0.00	0.12	42	65	51
green		30	162	0	0.01	0.36	0.00	0.26	58	−55	57
yellow		245	180	20	0.91	0.46	0.01	0.52	78	15	76
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Colour Blindness*—8 colours**

Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
violet		73	0	146	0.07	0.00	0.29	0.03	29	49	−63
brown		146	73	0	0.29	0.07	0.00	0.11	40	28	49
marine		0	146	146	0.00	0.29	0.29	0.23	54	−34	−11
blue		109	182	255	0.15	0.47	1.00	0.44	71	−9	−45
green		36	255	36	0.02	1.00	0.02	0.72	88	−78	76
yellow		255	255	109	1.00	1.00	0.15	0.94	98	−14	67
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Colour Blindness*—7 colours**

Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
marine		0	73	73	0.00	0.07	0.07	0.05	27	−22	−7
blue		0	109	219	0.00	0.15	0.71	0.16	46	7	−65
orange		219	109	0	0.71	0.15	0.00	0.26	58	40	65
pink		255	182	219	1.00	0.47	0.71	0.60	82	30	−9
yellow		255	255	109	1.00	1.00	0.15	0.94	98	−14	67
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

Table A1. *Cont.*

***Colour Blindness*—6 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
marine		0	73	73	0.00	0.07	0.07	0.05	27	−22	−7
blue		0	109	219	0.00	0.15	0.71	0.16	46	7	−65
pink		182	109	255	0.47	0.15	1.00	0.28	59	49	−63
green		36	255	36	0.02	1.00	0.02	0.72	88	−78	76
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Hand-Picked*—8 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
blue		0	0	255	0.00	0.00	1.00	0.07	29	67	−113
red		255	0	0	1.00	0.00	0.00	0.21	54	80	69
pink		255	130	255	1.00	0.22	1.00	0.44	72	59	−43
cyan		100	220	255	0.13	0.72	1.00	0.61	82	−28	−29
green		100	255	0	0.13	1.00	0.00	0.74	89	−69	81
yellow		255	255	0	1.00	1.00	0.00	0.93	98	−17	92
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Hand-Picked*—7 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
blue		0	0	255	0.00	0.00	1.00	0.07	29	67	−113
red		255	0	0	1.00	0.00	0.00	0.21	54	80	69
cyan		100	220	255	0.13	0.72	1.00	0.61	82	−28	−29
green		100	255	0	0.13	1.00	0.00	0.74	89	−69	81
yellow		255	255	0	1.00	1.00	0.00	0.93	98	−17	92
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

***Hand-Picked*—6 colours**											
Colour code	Colour	RsRGB	GsRGB	BsRGB	R	G	B	Relative luminance	L	a	b
black		0	0	0	0.00	0.00	0.00	0.00	0	−1	−1
red		255	0	0	1.00	0.00	0.00	0.21	54	80	69
blue		100	220	255	0.13	0.72	1.00	0.61	82	−28	−29
green		100	255	0	0.13	1.00	0.00	0.74	89	−69	81
yellow		255	255	50	1.00	1.00	0.03	0.93	98	−17	92
white		255	255	255	1.00	1.00	1.00	1.00	100	−1	−1

Table A2. Contrast ratio and Delta E 2000 calculations for colour pairs. In green, values of contrast ratio over 3:1 and Delta E 2000 of over 50 are marked. The remaining values are in red.

EXISTING MAP 8 COLOURS	**Contrast Ratio**	**black**	**pink**	**violet**	**green**	**orange**	**yellow**	**blue**	**white**	**Delta E 2000**	**black**	**pink**	**violet**	**green**	**orange**	**yellow**	**blue**	**white**
	black									black								
	pink	4.53								pink	41.08							
	violet	4.59	1.01							violet	39.71	15.54						
	green	9.98	2.20	2.18						green	83.95	83.95	83.40					
	orange	12.41	2.74	2.71	1.24					orange	75.12	52.99	57.12	34.52				
	yellow	17.54	3.87	3.82	1.76	1.41				yellow	93.37	67.51	69.69	21.73	17.58			
	blue	15.76	3.48	3.44	1.58	1.27	1.11			blue	84.44	51.21	38.27	42.01	37.96	35.93		
	white	21.00	4.64	4.58	2.10	1.69	1.20	1.33		white	100.00	42.71	41.39	34.54	29.13	24.91	13.34	

EXISTING MAP 7 COLOURS	**Contrast ratio**	black	violet	green	orange	blue	yellow	white	**Delta E 2000**	black	violet	green	orange	blue	yellow	white
	black								black							
	violet	4.12							violet	37.08						
	green	8.34	2.03						green	60.45	70.05					
	orange	10.87	2.64	1.30					orange	48.51	48.51	38.21				
	blue	14.76	3.59	1.77	1.36				blue	80.11	44.66	40.32	39.20			
	yellow	18.51	4.50	2.22	1.70	1.25			yellow	96.77	67.67	24.66	24.67	38.75		
	white	21.00	5.10	2.52	1.93	1.42	1.13		white	100.00	43.84	34.86	30.26	15.76	25.86	

EXISTING MAP 6 COLOURS	**Contrast ratio**	black	orange	green	blue	yellow	white	**Delta E 2000**	black	orange	green	blue	yellow	white
	black							black						
	orange	6.75						orange	55.75					
	green	8.34	1.24					green	60.45	51.95				
	blue	14.76	2.19	1.77				blue	49.45	49.45	40.32			
	yellow	18.51	2.74	2.22	1.25			yellow	96.77	41.36	24.66	38.75		
	white	21.00	3.11	2.52	1.42	1.13		white	100.00	39.70	34.86	15.76	25.86	

PYTHON OPTIMIZER 8 COLOURS	**Contrast ratio**	black	blue	red	green	pink	cyan	yellow	white	**Delta E 2000**	black	blue	red	green	pink	cyan	yellow	white
	black									black								
	blue	1.54								blue	26.07							
	red	2.38	1.54							red	35.12	45.13						
	green	3.66	2.37	1.54						green	40.29	61.39	63.36					
	pink	5.62	3.64	2.36	1.54					pink	46.04	38.07	42.63	89.73				
	cyan	8.64	5.60	3.63	2.36	1.54				cyan	59.82	60.77	68.06	36.42	49.61			
	yellow	13.28	8.61	5.58	3.63	2.36	1.54			yellow	80.43	97.42	60.69	44.71	77.72	44.61		
	white	21.00	13.61	8.82	5.74	3.74	2.43	1.58		white	100.00	79.78	61.91	50.85	37.87	31.30	31.88	

Table A2. *Cont.*

	Contrast ratio	black	blue	red	green	pink	yellow	white
PYTHON OPTIMIZER 7 COLOURS	black							
	blue	1.66						
	red	2.76	1.66					
	green	4.58	2.76	1.66				
	pink	7.59	4.57	2.75	1.66			
	yellow	12.56	7.57	4.55	2.74	1.66		
	white	21.00	12.66	7.61	4.59	2.77	1.67	

	Delta E 2000	black	blue	red	green	pink	yellow	white
PYTHON OPTIMIZER 7 COLOURS	black							
	blue	27.37						
	red	38.08	47.52					
	green	45.39	65.37	67.26				
	pink	54.47	45.20	47.56	92.50			
	yellow	77.43	91.92	53.34	41.29	70.38		
	white	100.00	75.87	58.53	46.86	31.48	31.44	

	Contrast ratio	black	blue	red	green	yellow	white
PYTHON OPTIMIZER 6 COLOURS	black						
	blue	1.84					
	red	3.38	1.84				
	green	6.22	3.38	1.84			
	yellow	11.42	6.21	3.38	1.84		
	white	21.00	11.41	6.21	3.37	1.84	

	Delta E 2000	black	blue	red	green	yellow	white
PYTHON OPTIMIZER 6 COLOURS	black						
	blue	28.90					
	red	42.06	49.43				
	green	53.12	70.66	71.52			
	yellow	73.84	86.80	44.98	40.16		
	white	100.00	72.24	53.60	41.46	32.69	

	Contrast ratio	black	violet	brown	marine	blue	green	yellow	white
COLOUR BLINDNESS 8 COLOURS	black								
	violet	1.70							
	brown	3.18	1.87						
	marine	5.53	3.25	1.74					
	blue	9.79	5.76	3.08	1.77				
	green	15.40	9.07	4.85	2.79	1.57			
	yellow	19.78	11.64	6.23	3.58	2.02	1.28		
	white	21.00	12.36	6.61	3.80	2.15	1.36	1.06	

	Delta E 2000	black	violet	brown	marine	blue	green	yellow	white
COLOUR BLINDNESS 8 COLOURS	black								
	violet	28.42							
	brown	38.38	50.09						
	marine	45.81	43.60	47.40					
	blue	62.60	51.46	56.34	25.75				
	green	88.22	80.93	66.21	42.26	60.54			
	yellow	101.65	93.11	53.73	48.65	62.71	23.20		
	white	100.00	62.47	53.49	39.39	28.70	33.15	28.16	

	Contrast ratio	black	marine	blue	orange	pink	yellow	white
COLOUR BLINDNESS 7 COLOURS	black							
	marine	2.05						
	blue	4.21	2.05					
	orange	6.20	3.03	1.47				
	pink	12.97	6.33	3.08	2.09			
	yellow	19.78	9.65	4.70	3.19	1.53		
	white	21.00	10.25	4.99	3.39	1.62	1.06	

	Delta E 2000	black	marine	blue	orange	pink	yellow	white
COLOUR BLINDNESS 7 COLOURS	black							
	marine	24.83						
	blue	40.81	31.11					
	orange	53.30	52.40	54.12				
	pink	75.52	66.09	47.34	40.79			
	yellow	101.65	69.17	79.18	43.35	54.61		
	white	100.00	63.72	47.04	41.69	21.84	28.16	

Table A2. *Cont.*

	Contrast ratio	black	marine	blue	pink	green	white	**Delta E 2000**	black	marine	blue	pink	green	white
COLOUR BLINDNESS 6 COLOURS	black							black						
	marine	2.05						marine	24.83					
	blue	4.21	2.05					blue	40.81	31.11				
	pink	6.62	3.23	1.57				pink	50.06	43.06	29.25			
	green	15.40	7.52	3.66	2.33			green	88.22	64.32	72.90	64.83		
	white	21.00	10.25	4.99	3.17	1.36		white	100.00	63.72	47.04	35.51	33.15	

	Contrast ratio	black	blue	red	pink	cyan	green	yellow	white	**Delta E 2000**	black	blue	red	pink	cyan	green	yellow	white
HAND-PICKED 8 COLOURS	black									black								
	blue	2.44								blue	32.95							
	red	5.25	2.15							red	51.88	55.92						
	pink	9.89	4.05	1.88						pink	62.67	48.26	43.44					
	cyan	13.22	5.41	2.52	1.34					cyan	76.21	57.49	73.29	47.78				
	green	15.85	6.48	3.02	1.60	1.20				green	89.64	88.02	81.34	93.29	48.98			
	yellow	19.56	8.00	3.72	1.98	1.48	1.23			yellow	102.58	102.29	61.65	79.65	51.91	21.51		
	white	21.00	8.59	4.00	2.12	1.59	1.33	1.07		white	100.00	64.66	46.31	25.70	24.12	32.90	31.35	

	Contrast ratio	black	blue	red	cyan	green	yellow	white	**Delta E 2000**	black	blue	red	cyan	green	yellow	white
HAND-PICKED 7 COLOURS	black								black							
	blue	2.44							blue	32.95						
	red	5.25	2.15						red	51.88	55.92					
	cyan	13.22	5.41	2.52					cyan	76.21	57.49	73.29				
	green	15.85	6.48	3.02	1.20				green	89.64	88.02	81.34	48.98			
	yellow	19.56	8.00	3.72	1.48	1.23			yellow	102.58	102.29	61.65	51.91	21.51		
	white	21.00	8.59	4.00	1.59	1.33	1.07		white	100.00	64.66	46.31	24.12	32.90	31.35	

	Contrast ratio	black	red	blue	green	yellow	white	**Delta E 2000**	black	red	blue	green	yellow	white
HAND-PICKED 6 COLOURS	black							black						
	red	5.25						red	51.88					
	blue	13.22	2.52					blue	76.21	73.29				
	green	15.85	3.02	1.20				green	89.64	81.34	48.98			
	yellow	19.60	3.73	1.48	1.24			yellow	102.58	61.65	51.91	21.51		
	white	21.00	4.00	1.59	1.33	1.07		white	100.00	46.31	24.12	32.90	31.35	

Appendix B

Maps Used during Study Sessions: Simulations of Different Types of Colour Vision Deficiency. Numbers 1-4 denote types of colour palettes, and letters A and B refer to the mapped locations (cf. Section 2.2.2.).

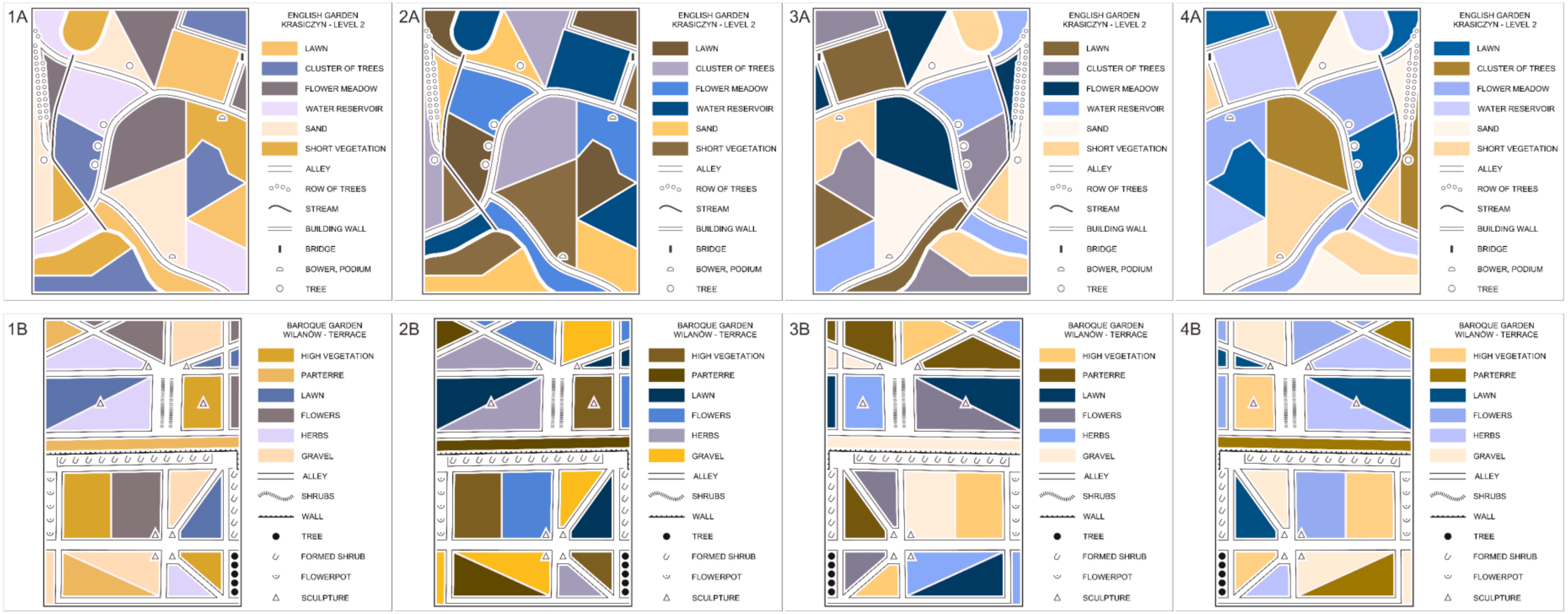

Figure A1. Deuteranopia.

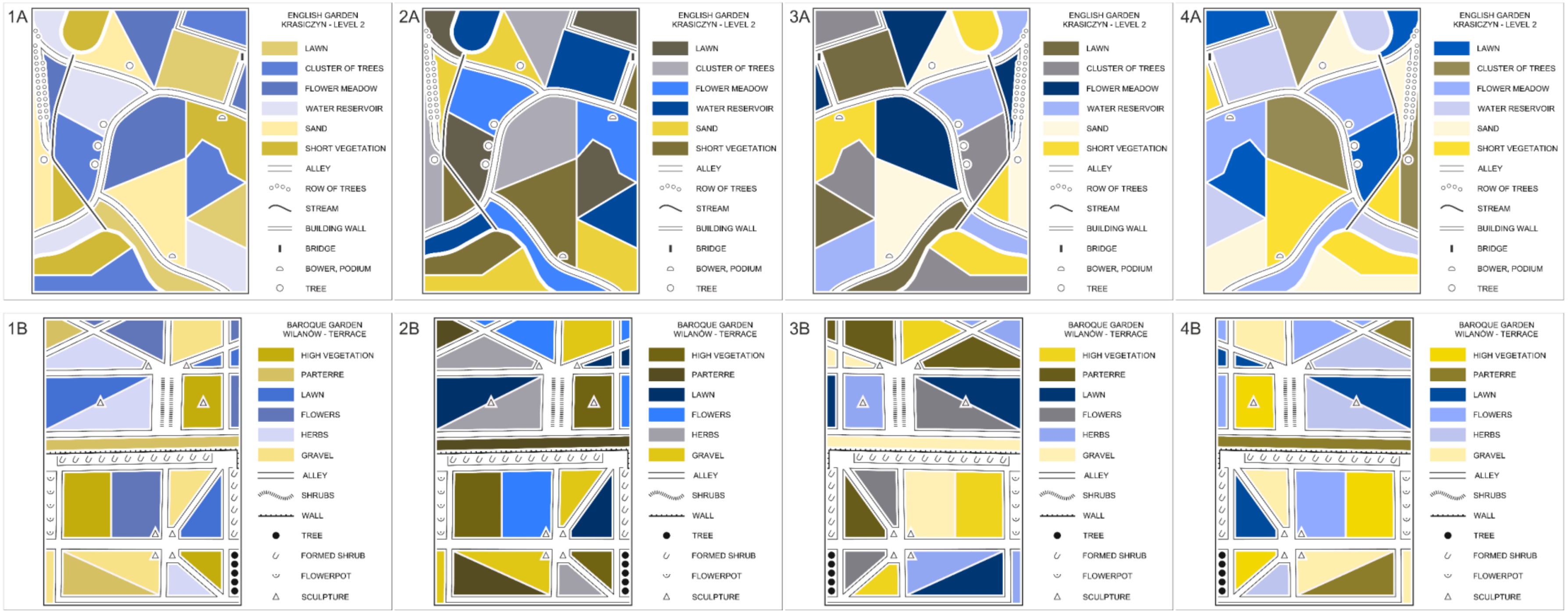

Figure A2. Protanopia.

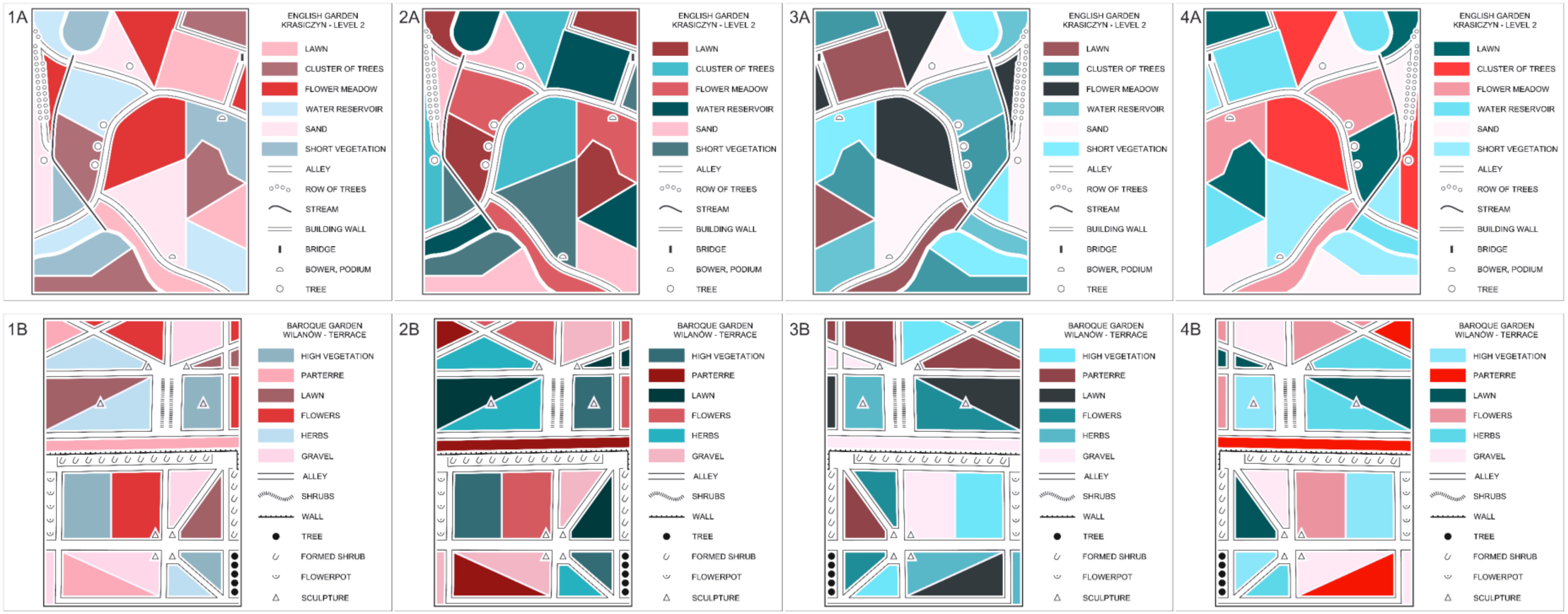

Figure A3. Tritanopia.

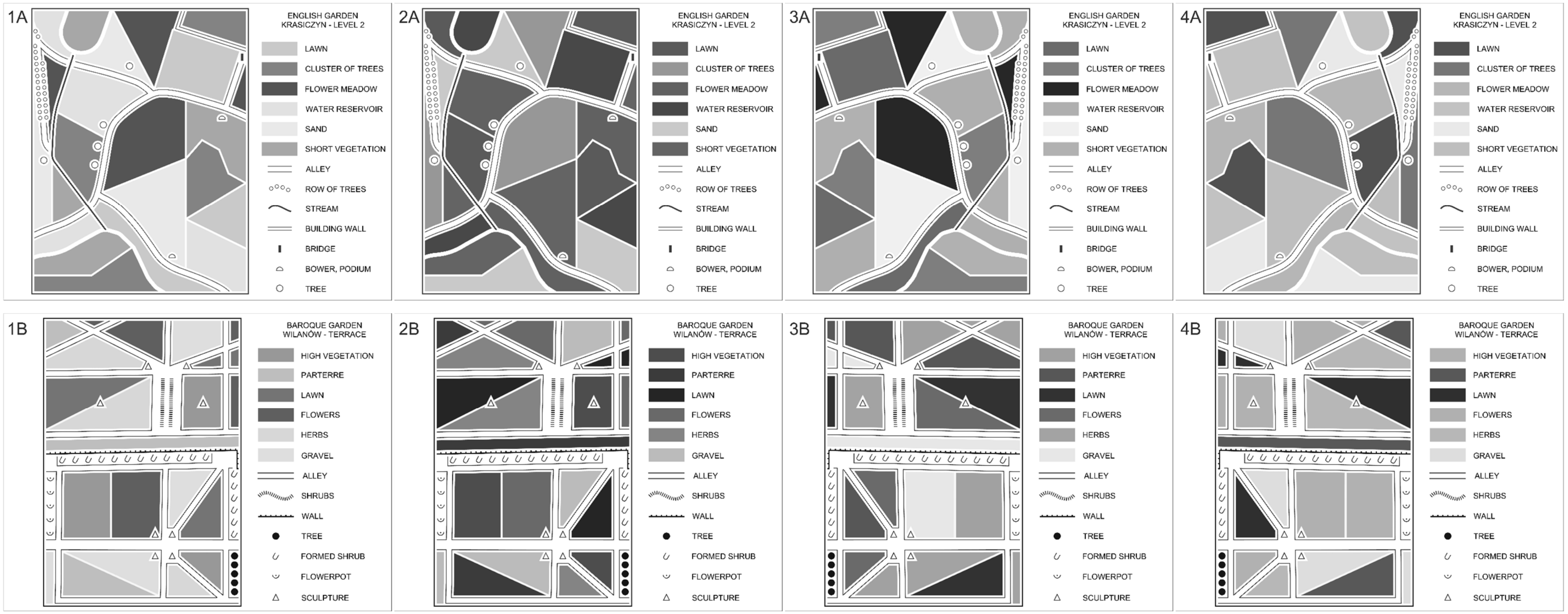

Figure A4. Achromatopsia.

Appendix C. Study Session Scenario

TESTING COLOUR PALETTES FOR GRAPHIC VARIANTS OF TACTILE MAPS

We provide an introduction to the study, obtain written consent to participate in the study, and determine a participant code for further use.

You have been invited to take part in this study to evaluate colour palettes to be applied on tactile maps of historic parks in different styles. This study is a part of a bigger project, whose aim is to develop a technology for creating tactile maps of historic parks. Your data will be anonymized by assigning a code to your personal data and study results.

We determine whether the viewing conditions in the room are appropriate for the study participant. If necessary, lighting conditions are adjusted. Participants are encouraged to use any of his/her optical or non-optical aids during the study. Some basic magnifiers with additional light source are provided by the researchers.

All the instances of aid usage throughout the study, requests to change the lighting conditions, inability to read the text, as well as the estimated observation distance are noted in the study form.

In case you have any questions or comments now or later during the study, please let us know. Can we continue?

First, four maps, which will be tested by the study participant, are shown. Each of them were prepared using a different colour palette. The goal is to determine the most visually attractive one.

In front of you are four graphic tactile maps. Please indicate which one you would like to start with if you could choose. Why? (VISIBILITY)

Second, the remaining four map variants are presented to the participant (those that will not be used during this particular session).

In front of you are another four graphic tactile maps. Please indicate which one you would like to start with if you could choose. Why?

Next, each of the four tested maps is presented to the study participant in a predefined order. The following steps are repeated for every map. The first map is presented (Visibility, Informational, and Workability aspects).

X.1 When you look at the map, which area would you like to explore? Why? What does it represent? (VISIBILITY, INFORMATIONAL, WORKABILITY)

Positions of the area indicated along with justification (and all the additional notes during the study) can be marked on the mock-up maps (Figure 1).

X.2 Please indicate and name each of the remaining area symbols that you see on the map. Each type should be indicated at least once with its meaning explained. (INFORMATIONAL, WORKABILITY)

All the errors, omissions, and instances of protracted responses are noted on a mock-up map. If necessary, help the tester in reading the symbol's explanation in the legend.

X.3 Which colours on the map are very similar to each other? Which colours are the most different from each other? (INFORMATIONAL, WORKABILITY)

All the indications of similar and different colours are marked on colour similarity and colour contrast matrices, respectively.

X.4 Please indicate (researcher names two point symbols), e.g., a tree and a sculpture. (INFORMATIONAL, WORKABILITY)

All the errors, omissions, and instances of protracted responses are noted on a mock-up map.

X.5 Please indicate (researcher names two line symbols), e.g., an alley and shrubs. (INFORMATIONAL, WORKABILITY)

All the errors, omissions, and instances of protracted responses are noted on a mock-up map.

X.6 Do you have any comments about the map?

All the comments are noted in the study form.

Next, the procedure from points X.1–X.6 is repeated for the three remaining maps being tested.

Which map do you think is the best? (EMOTIONAL APPEAL)

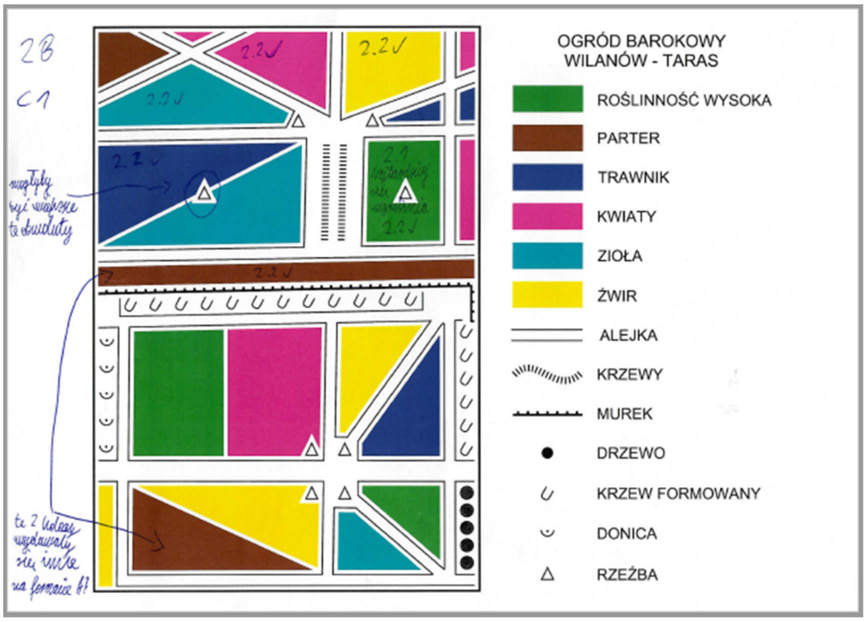

Figure A5. Sample mock-up map used by a researcher during a study session with notes taken for further analysis. The handwriting visible in the figure are the notes taken during the research session. They were then transcribed into a digital form.

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