Color and Colorimetry
Multidisciplinary Contributions

Vol. XIX A

Edited by Filippo Cherubini and Andrea Siniscalco

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Introduction

The GdC - Associazione Italiana Colore organizes the Color Conference every year, and it reached its nineteenth edition in 2024.
The two-day international event featured three keynote speakers: Phil Green (University of Science and Technology, Gjøvik, NO), Vien Cheung (University of Leeds, UK) and Robin Kingsburgh (York University Toronto, CA).
During the conference, the "Color Award / Premio Colore 2024" was also conferred, which went to the extraordinary painter Valerio Adami.
A special thanks go to the Color Award Commission, in the person of Cristian Bonanomi, Lia Luzzatto, and Lisa Vergelli (author of the winner's presentation text), for their valuable contribution.
Heartfelt thanks to Filippo Cherubini (IFAC-CNR) for his valuable help in managing the conference and to all the session chairs who moderated the speeches: Luca Cogo (Università degli studi di Milano Bicocca), Marcello Picollo (IFAC-CNR), Francesca Fragliasso (Università degli studi di Napoli Federico II), Ingrid Calvo Ivanovic (Universidad de Chile), Alice Plutino (University of Amsterdam), Verena M. Schindler (AIC Study Group on Environmental Colour Design), Alessandro Rizzi (Università degli studi di Milano Statale), Lisa Vergelli (Sapienza Università di Roma), Beatrice Sarti (Università degli studi di Milano Statale).
Thanks also to all the people who contributed to the conference's digital moderation and ensured its success: Paola Bertoletti, Alessandro Bortolotti, Gianluca Guarini, Ivanka Dicheva, Plutino Alice, and Vergelli Lisa.
Final thanks to Konica Minolta, which generously sponsored the conference.

Enjoy the reading.

Andrea Siniscalco
December 2024

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A perceptual assessment of the chromatic scale of uncertainty in hypothetical virtual architectural 3D reconstruction

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Abstract

Chromatic multilevel scales and matrices are popular tools used by scholars to visually communicate uncertainty and other aspects in many scientific contexts, including that of hypothetical virtual 3D reconstruction of lost or never-built architecture. False-colour visualisations play a pivotal role in improving the transparency of the complex inference-based process that is inevitable when dealing with lacking data sets, nevertheless, there are still no standards of reference in this field. This paper investigates this topic and tries to formulate good practices for creating easily readable and effective multi-level chromatic scales that will be applied to shaded 3D models. Furthermore, a newly designed chromatic 7-level scale of colours that empirically proved to perform better than the previous scales will be proposed. The results of this study are supported by an on-field survey administered to 50 users.

Keywords: 3D virtual reconstruction, unbuilt heritage, uncertainty assessment, chromatic scale.

Introduction and background

In the field of hypothetical virtual 3D reconstruction of lost or never-built architectures, quantifying, visualising, and communicating the uncertainty together with documenting the reconstructive process are aspects of well-known importance. The scientific community over the years tried to give an answer to these needs by developing various reconstruction and assessment methodologies, however, in this contest, there are no shared standards of reference yet. The CoVHer Erasmus+ project (CoVHer website, 2022), among other objectives, tries to answer this lack of common ground by developing a series of good practices and a new and standardised methodology for the scientific, hypothetical reconstruction of lost or never-built architecture. The spread use of such a methodology in which the uncertainty assessment is a pivotal part would improve transparency, comparability, and reusability of reconstructive 3D architectural models. Being able to achieve these objectives would comply with the FAIR principles (Wilkinson et al., 2016), the Seville principles (ICOMOS, 2017), and the London charter (Denard, 2012), all of which are foundational reference documents in the field.

The uncertainty assessment object of this study was iteratively developed over the years (Apollonio, 2016; Apollonio et al., 2021, 2024). It is based on a seven-level scale of increasing uncertainty which can be reduced to five and three levels at need (Fig. 1). To each level, a colour, a numerical value, a percentage of uncertainty, and a textual definition are assigned. All these elements were designed to make the scale as user-independent as possible. The uncertainty of the 3D model is assessed element by element and a false-colour view is produced. Publishing these false-colour variants of the model together with the 3D textured or untextured reconstructive versions of the same model would help reduce the risk of generating historical falsehoods and misinterpretations for scholars and laypersons.

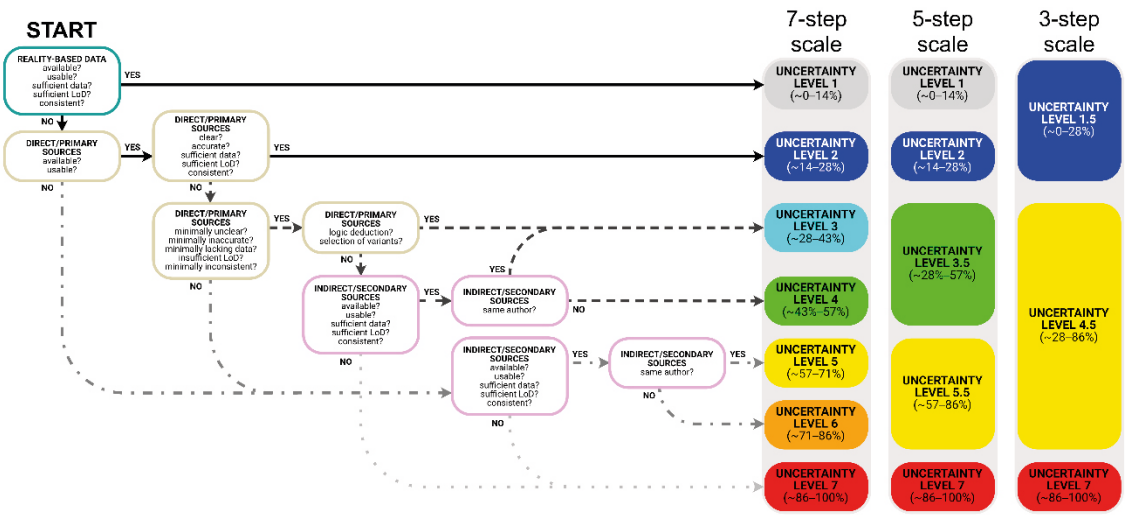

Fig. 1 - Uncertainty yes/no flow chart, elaboration of an image first published in (Apollonio et al., 2024).

It is important to design and use scales that are effective when applied to shaded 3D models while keeping in mind that particular lighting conditions can mislead the correct interpretation of colours (Lafer-Sousa et al. 2015; Rabin et al 2016 ; Adelson, 1995). The reference scale of this study, right from the earliest iterations, used a rainbow colour progression. Even if, in this context, this scale had empirically demonstrated to be capable of achieving consistent recognisability of colours, in some other contexts, similar rainbow-based colour progressions were evaluated as less effective in comparison to other colour schemes (Light and Bartlein, 2004). This raised the question of whether a different colour progression might perform better in our context.

This research, starting from the study of colour scales used in choropleth maps (Brewer et al. 1997) and colour gradients for data visualisation (Reda et al. 2018), and with on-field user's testing, tries to verify experimentally which colour scheme, among the ones tested, is more effective for false-colour visualisation of shaded 3D rendered architectural models, and aims to define good practices and guidelines concerning how the Lightness, Chroma, and Hue parameters (LCH) - as defined for the OKLCH encoding (Sitnik, 2024) - can contribute to achieve more effective results in this context. In the presented experiment various scales are put to the test, 50 users were prompted to look at a series of images of a shaded 3D model coloured with various 7-level colour scales and were requested to match the colours of the various elements of the model to the corresponding colours on a reference sorted legend.

Investigating various colour progressions for user's testing

Numerous colour progressions were studied and considered for the users' testing. Scales from A to F in Table 1, are designed to have uniform perceptive steps while varying only one LCH parameter at a time, all these scales were designed by using the OKLCH Colour picker available online (Sitnik, 2024) limiting the colour gamut to sRGB in order to make them compatible with most displays, and thanks to this tool it was possible to maximise the colour ranges between adjacent steps at given LCH parameter of choice. In particular, on scales A and B, the Lightnesses were set to maximise the Chroma range at the chosen Hues. The same principle was followed for the scales C and D where the Hues were set to maximise the Lightnesses ranges at the chosen Chromas. In scale E, Lightness and Chroma were chosen to maximise Hue intervals, and in scale F the hue range was reduced artificially to make a traffic-light-like scale at constant lightness and chroma. Other traffic-light-like scales which varied all LCH parameters were considered (G, H) because using progressions from red to green

might have helped to intuitively interpret the uncertainty levels in this context since laypersons nowadays, in traffic-light-like colour progressions, tend to interpret the red colour as a message for alert/error and green as its opposite, however, these kinds of scales are very poorly perceived by persons with red-green colour vision deficiencies (CVD), so, sadly, they were excluded from the user's testing. Scales from I to L come from well-known colour gradients used in data analysis (Rudis et al., 2024) which in some contexts are considered better alternatives to rainbow gradients because they are more colour-blind friendly. Scales from M to Q are rainbow-like scales, where M and N are well-known (Mikhailov, 2019), O is the rainbow scale with max saturation used in (Apollonio, 2016), P is the variation presented in (Apollonio et al. 2021; 2024), and Q is a new colour scale derived by these first two references, where LCH parameters are varied to make it more colour-blind friendly. From this preliminary investigation, only the most relevant scales were tested in the survey (indicated with * in Table 1). A, C, D, and E scales were expected to perform poorly but they were included in the testing as control scales to investigate how the individual variation of the LCH parameters impacted the perception of colours in a shaded 3D model.

Table 2: investigated 7-level colour scales (* indicates the ones tested in the crowdsourced survey).

	Scales Name	Colour progression in HEX format						
A	Uniform Chroma steps*	#5AF32A	#74EF57	#89EA74	#9BE48B	#ABDEA0	#BAD8B3	#C7D1C5
B	Uniform Chroma steps 2	#F82DF9	#EB52EB	#DE69DC	#CF7ACD	#C585C0	#C088BE	#9E9E9E
C	Uniform B&W*	#060606	#222222	#414141	#636363	#878787	#AEAEAE	#D6D6D6
D	Uniform Lightness steps*	#3D0245	#572060	#733B7C	#905699	#AE72B7	#CD8FD6	#ECADF6
E	Uniform Hue steps*	#EC8DAB	#EB9666	#C0AF4D	#73C385	#2AC4CC	#70B3F7	#BA9CEF
F	Uniform Hue steps 2	#F57FA7	#FB8275	#F28E42	#D9A00E	#B1B228	#7AC05E	#1FC893
G	Traffic light	#7A0403	#FF0000	#FF8200	#FFFF00	#99FF53	#36D000	#00740E
H	Extended Traffic light	#6E0253	#CA0D2E	#FE8506	#FFF019	#63FA0E	#2AAC54	#197F8A
I	Virdis*	#440154	#443983	#31688E	#21918C	#35B779	#90D743	#FDE725
J	Inferno	#000004	#320A5E	#781C6D	#BC3754	#ED6925	#FBB61A	#FCFFA4
K	Magma	#000004	#2C115F	#721F81	#B73779	#F1605D	#FEB078	#FCFDBF
L	Plasma*	#0D0887	#5C01A6	#9C179E	#CC4778	#ED7953	#FDB42F	#F0F921
M	Turbo	#7A0403	#EA4E0D	#F8BE39	#A3FD3C	#19E4B8	#4682F8	#30123B
N	Jet	#7A0403	#FF0000	#FF8200	#FFFF00	#7EFF81	#007FFF	#000080
O	Rainbow (max sat) (2016)*	#FF0000	#FF7F00	#FFFF00	#00FF00	#00FFFF	#0000FF	#FF00FF
P	Rainbowhite (2021)	#FF0000	#FF7F00	#FFFF00	#00FF00	#00FFFF	#0000FF	#FFFFFF
Q	RainbowhiteLCH (2024)*	#800C1B	#CD8503	#FFFF00	#95DB78	#43AAB3	#0C3DFE	#E6E6E6

Designing a new more colour-blind-friendly and effective colour progression

The scale RainbowhiteLCH, shown in Table 1 at letter Q, was derived from the Rainbow scale (O) used in (Apollonio, 2016). In 2021 (Apollonio et al., 2021) the scale was slightly changed to address some issues already evident from preliminary on-field tests (P). In particular, the magenta colour was substituted with white/grey because it was the only level referring to real-world physical evidence (e.g., ruins) while the other levels of the scale referred to inferences from graphical or documental sources so it made sense to differentiate it from the other levels. Furthermore, by removing magenta, the progression from red/orange to green/blue passing through yellow allowed it to get closer to the semaphoric trichromacy and improve the intuitive matching between colours and relative uncertainty. The updated scale also aimed to preserve backwards compatibility with previous works that used the 2016 scale. Lastly, the colours of the new scale were not rigidly imposed with specific RGB values by design, the colours were chosen to be easily nameable (red, orange, yellow, green, cyan, blue, and white), this choice was aimed at fostering the adoption of the scale allowing users to shift them slightly based on various contexts and needs without loosing comparability between different projects. Starting from this scale, the RainbowhiteLCH scale shifts slightly the LCH parameters aiming to improve readability for CVD users, not reducing or even improving the readability for normal colour vision (NCV), while preserving their Hue recognizability for backward compatibility. In particular, the Lightness of the colours at the boundaries of the scale was reduced in order to simplify their discerning for users who struggle to recognise specific hues, this last variation helped

in particular to differentiate more the red and green which in the new version of the scale are much farther apart in terms of Lightness. A yellow or blue component was added to all the Hues in the red and green proximities relatively, in order to help users with CVD in the red-green spectra to discern those colours better. This LCH manipulation inevitably reduced the perceptual distance (CIEDE2000) between some adjacent colours as shown in Fig. 2 however the progression of colours is now more uniform, and the colours are more differentiated in terms of lightness, without losing the nameability based on their hue. Last but not least the new scale is less punchy and more perceptively harmonious which is considered a nice-to-have feature in some non-academic contexts such as in the field of dissemination (e.g. museums, docufilms) and could contribute to adopting it more often.

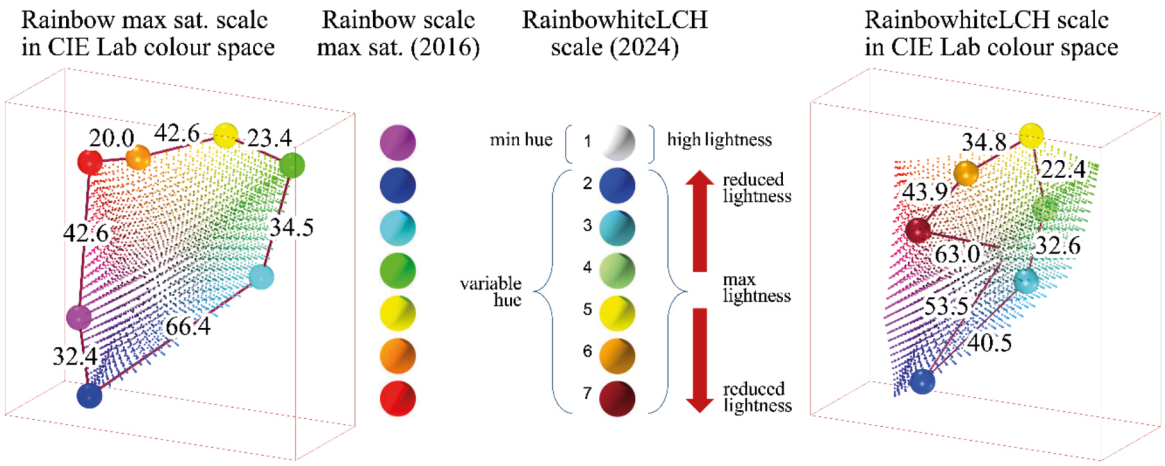

Fig. 2 – (Left) Comparison between the scale used in (Apollonio, 2016) and the new RainbowhiteLCH scale. (Right) RainbowhiteLCH scale visualised in CIE Lab colour space, the numbers between the spheres are the CIEDE2000 (calculated with: http://www.brucelindbloom.com/index.html?ColorDifferenceCalc.html).

To improve the readability of false-colour representation of 3D models it is always better to reduce as much as possible contrast caused by strongly lit scenes, Fig. 3 shows how the readability of the scale improves by using diffuse lights which generate ambient-occlusion-like shadows. However, since this research aims to define good practices to create false-colour scales applicable in various scenarios, the subsequent analyses were all performed on strongly lit 3D models with high contrast between shaded and lit areas to consider the worst, but sometimes used, lighting conditions.

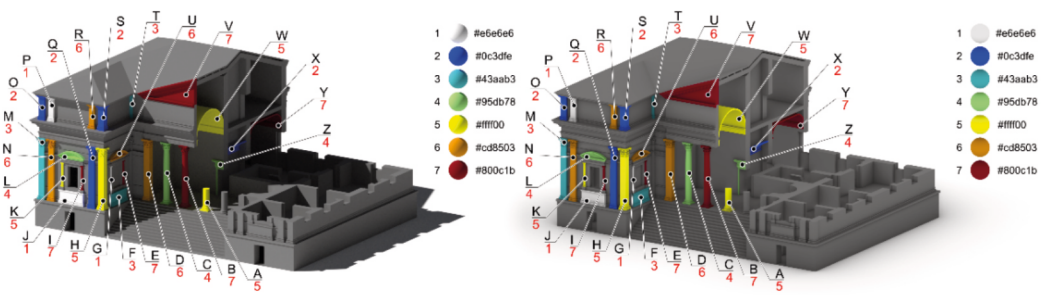

Fig. 3 – Same colour scale (RainbowhiteLCH) with different lighting setup. (Left) Direct light with high contrast, sharp shadows; (Right) diffuse light with uniform soft ambient-occlusion-like shadows.

All the scales presented in Table 1 were applied to a sample 3D shaded model and qualitatively assessed for CVD users by processing them in the Colour-Blindness simulator (Wickline, 2001). A comparison between the Colour-Blindness assessments of scales O and Q is presented in Fig. 4. In O the cyan and green levels and the red, orange and magenta levels are already difficult to discern even

for NCV users, while in Q they are easier to recognise thanks to the varied Lightness. In weak CVD simulations, Q manifests clear improvements, while for severe colour-blindness simulations, there is a minor improvement, but some colours are still ambiguous. Monochromacy simulation is completely unreadable for both O and Q.

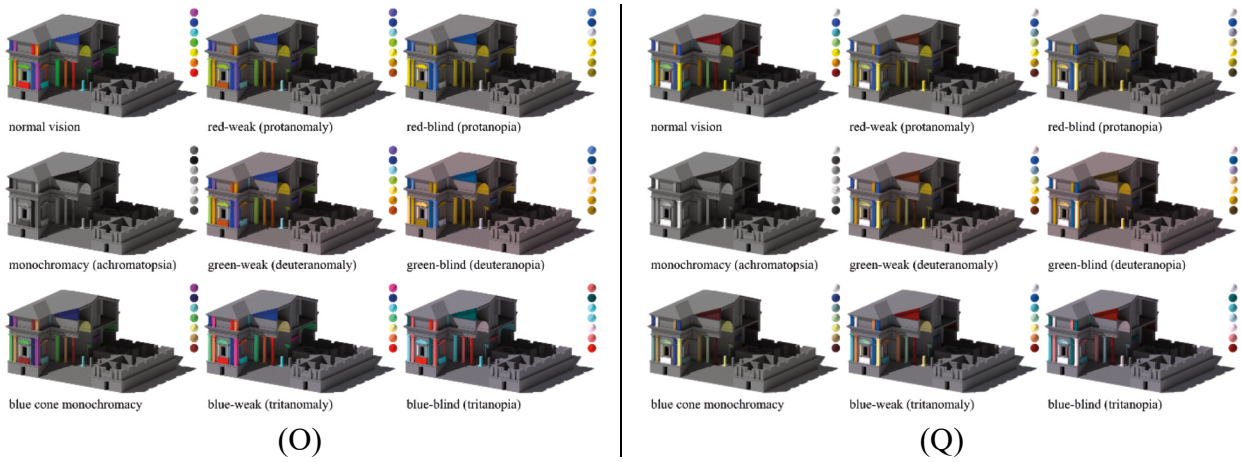

Fig. 4 – Colour-Blindness simulation (Wickline, 2001) of the Rainbow with maximum saturation scale (O) (Apollonio, 2016), and the RainbowhiteLCH scale (Q).

Survey

The survey was designed as follows. In the first two questions, a colour arrangement test (Colblindor, 2021a) and an Ishihara 38 plate test (Colblindor, 2021b) were submitted to all the participants to verify if they had some sort of CVD or if they were using a heavily uncalibrated display, in case of positive result the survey submitted by these candidates were excluded. We chose not to use a designated calibrated display to run the survey because the scales of uncertainty are usually visualised on any type of display, and testing them only on a perfectly calibrated display could have biased the result. Each colour progression selected for the testing (the entries marked with * symbol in Table 1) was applied to various elements on a 3D shaded exemplificative model and a series of rendered false-coloured images were produced (Fig. 5).

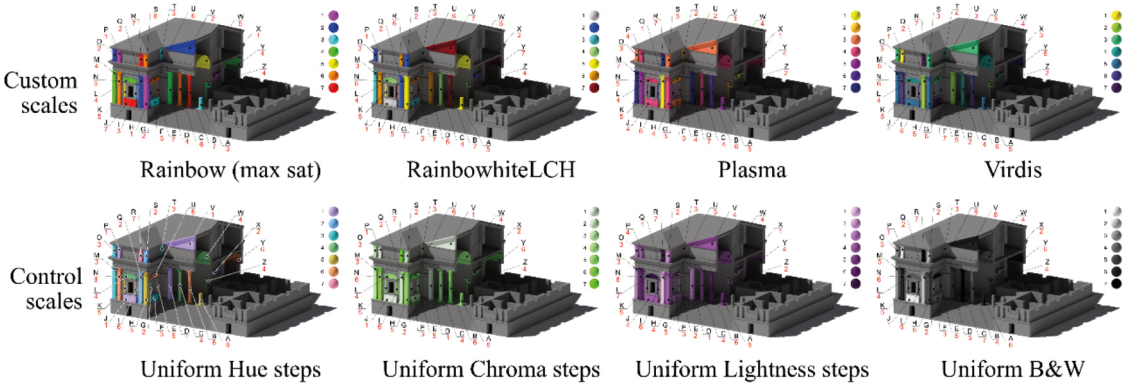

Fig. 5 – The 8 pictures of models submitted to the 50 participants of the survey. The red text indicates the correct answers which were not visible to the participants.

For each image, the participants were requested to match 10 randomly selected elements to the corresponding colour on the reference 7-colour legend, for each question the number of wrong and right answers were registered. After each question, the participants were asked to indicate how hard was the task on a scale from 1 to 10 where 1 was the hardest, and 10 was the easiest.

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Survey results

The results of the survey are reported in Table 2. As expected the control scales with perceptually uniform Chroma and Lightness intervals (A, C, D) performed poorly plausibly because these two parameters are more subject to shifting in a shaded scene depending on lighting conditions. The scale with perceptually uniform Hue steps (E), performed better because, when the light in the scene is white (which was a requirement of this experiment) the colours are less affected by hue shifting due to lighting conditions. However, despite being the scale with the maximum possible hue range in the sRGB gamut, the users still committed several errors, probably due to the fact that in order to have equal lightness and chroma for all steps, the chroma could not be maxed out relative to the selected hue for each step, which caused the colours to be less saturated and thus more susceptible to misinterpretation in a shaded scene. Surprisingly Viridis (I) and Plasma scales (L), despite being more saturated compared to the previous scale (E), in this context performed badly, probably because they cover a small Hue range and rely too much on lightness variation which was proven by the previous tests to be unreliable in shaded scenes. The two better-performing scales were the Rainbow with maximum saturation (O) with 62,50% of candidates who matched correctly 10 colours out of 10, and 27,50% of candidates who matched 9 colours out of 10, for a total of 90% of users who guessed correctly 9 or 10 colours out of 10; and the RainbowhiteLCH (Q) with 87,50% of candidates who matched correctly 10 colours out of 10, and 12.5% candidates who matched correctly 9 colours out of 10, for a total of 100% of users who guessed correctly 9 or 10 colours out of 10.

Table 3: Survey results. The RainbowhiteLCH (Q) outperformed the others, with the Rainbow max sat (O) as a close second.

Correct answers (max 10/10)	Uniform chroma steps (A)	Uniform B&W (C)	Uniform Lightness steps (D)	Uniform hue steps (E)	Virdis (I)	Pasma (L)	Rainbow max sat (O)	Rainbo-white LCH (Q)
10/10	0	0	0	26	7	5	25	35
9/10	0	0	0	9	9	6	11	5
7–8/10	12	1	0	5	18	26	4	0
0–6/10	28	39	40	0	6	3	0	0
10/10 (%)	0,00%	0,00%	0,00%	65,00%	17,50%	12,50%	62,50%	**87,50%**
10/10 + 9/10 (%)	0,00%	0,00%	0,00%	87,50%	40,00%	27,50%	90,00%	**100,00%**

Among the 50 total candidates tested we excluded five who tested positive for CVD, one who clearly answered randomly, and the two worst and two best results for each scale to exclude eventual outliers. Despite the five tested users with CVD do not represent a relevant sample, we can say that the results gathered so far are in line with what was observed in the simulated images produced with the Colour-blindness simulator. Concerning the qualitative opinions of the candidates, they are synthesised in Table 3. The Rainbow scale with max saturation (O) was considered the easiest to use, with the RainbowhiteLCH (Q) placing second. This result is interesting because, in the empirical tests, their ranking was swapped. This is probably due to the fact that colours higher in Chroma stand out more in a shaded 3D scene, however, strongly disuniform perceptual interval might make the closest colours more susceptible to be mistaken for the adjacent ones, in fact, in scale O, the most mistaken pairs of colours were red/magenta, and green/cyan.

Table 4: Candidates' opinions on the ease of the task.

Opinion of the candidates (1=hard 10=easy)	Uniform chroma steps (A)	Uniform B&W (C)	Uniform Lightness steps (D)	Uniform hue steps (E)	Virdis (I)	Pasma (L)	Rainbow max sat (O)	Rainbo-white LCH (Q)
10/10	0	0	0	6	0	1	26	28
9/10	0	0	0	15	1	8	11	5
7–8/10	3	2	4	12	15	17	3	7
0–6/10	37	38	36	7	24	14	0	0
10/10 (%)	0,00%	0,00%	0,00%	15,00%	0,00%	2,50%	65,00%	**70,00%**
10/10 + 9/10 (%)	0,00%	0,00%	0,00%	52,50%	2,50%	22,50%	**92,50%**	82,50%

Conclusions

The novel RainbowhiteLCH scale is a more perceptually uniform variation of the Rainbow scale with max saturation used for the first time in (Apollonio, 2016) and updated in (Apollonio et al. 2021; 2024), it was designed to be more colour-blind friendly by shifting the colours in the proximity of the red and green hues toward the blue/yellow axis, and by varying the lightness and chroma of the most ambiguous colours of the previous scale to simplify their recognisability in shaded scenes (in particular the pairs magenta/red, and cyan/green). The survey was submitted to 50 candidates and empirically revealed that the novel scale improved the recognisability of colours in the exemplificative 3D shaded scene for NCV users. The colour-blind simulation revealed that also users with CVD might benefit from this updated scale. Nevertheless, despite the gathered preliminary data looking promising, a greater sample of users with CVD is required in order to draw robust conclusions for those subjects. The effectiveness of the scale for users with some of the most severe types of CVD is still unsatisfactory, in these cases, a completely different approach should be considered.

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