Heritage Science

RESEARCH

Quantitative analysis methods for evaluating colour on architectural heritage: survey of colour restoration and perception of the Wen Yuan Ge in the Forbidden City

Jie Shao[1], Luke Li[1*], Yutong Jiang[1], Xin Liu[1] and Hong Yang[2]

Abstract

Three methods can be used to evaluate the colour used on architectural heritage: manual evaluation, instrumental measurement, and process restoration. Optical instruments that can obtain relatively accurate chromaticity data are ideal. As architectural heritage sites age, their colour fluctuates. Researchers must screen colour data and analyse the features based on experience with colour perception. This study combines quantitative colour analysis and a scaled perception survey to analyse the Wen Yuan Ge in the Forbidden City and provide a new reference for researching and designing colour in architectural heritage.

Keywords Wen Yuan Ge, Architectural heritage, Colour restoration, Colour perception

Introduction: theoretical foundations and subjects

Wen Yuan Ge, the single green building in the Forbidden City, holds special importance for architecture and colour restoration research. In 2021, it was studied for the first time using modern devices and techniques.

Three dimensions in colour study

Researchers have studied colour from physical, perceptual, and cultural dimensions. Colorimetric data are collected by measuring coloured surfaces with optical instruments.

The CIE standard colorimetric system, on which the International Commission on Illumination reached a consensus in the twentieth century, takes visible spectral reflectance data as a benchmark to establish the colour spaces of CIE-RGB, CIE-XYZ, and CIE-Lab.

The CIE-Lab colour space and its polar coordinates (CIE-LCH) more accurately capture human-perceived colour nuances and quantify subtle differences, aiding in identifying diverse colour schemes ([1], p. 202).

Colour affects people's psychological activities through visual senses. Under the influence of various interrelated factors, such as physiology, culture, and psychology, color perception is difficult to precisely capture with a single model ([2], p. 20) Colours can interact with words, arouse certain emotions and generate meanings that are correlated with colour perception and cultural background ([3], p. 105). Some cultural symbols originate from regional colour features shaped by the natural and cultural vernaculars.[1]([4], p. 5) Exploring differences in colour perception to refine colour evaluation can optimize colour design.

*Correspondence:
Luke Li
liluke@tsinghua.edu.cn
[1] Department of Architecture, Tsinghua University, Beijing 100084, China
[2] Palace Museum, Beijing, China

[1] <Colours of the World>: Due to factors diverse as geography, geological or aquatic environment, or light, which may not be independent of the sociocultural behaviours of the inhabitants, these colours determine and contribute to the affirmation of national, regional, or local identity. This data deserves analysis.

Primary issues in architectural heritage colour studies

Current research on colour in architectural heritage emphasizes physical, perceptual, and cultural dimensions. Each dimension falls into a specific sphere: physical chromaticity measurements, colour evaluation, and cultural meaning. These dimensions each influence the others and are complementary in theory.

Colorimetric measurements for architectural heritage are more intricate than measurements for modern architectural colour, encompassing colour design, colour chronology recording, and practical conservation concerns. Colour data reliability can be affected by instrumental issues, environmental changes, architectural surface complexity, finish texture ([5], p. 44), and colour surveyors' physical conditions. Moreover, data reliability is essential for accurate colour restoration.

Evaluating the colour of architectural heritage mainly entails an analysis of the correlation between colour and architectural space. Colour components, hue, and brightness interact fundamentally with architectural surface, volume, and space to influence appearance ([6], p. 1).

Research on the meaning of colours in architectural heritage aims to explore their usage and cultural symbolism as rooted in the building's history [7]. Colour survey results to identify pigments and materials, which are essential for evaluating the best solutions for protection and restoration, influence research into architectural colours. This research also scientifically supports investigative actions aimed at identifying different construction and execution techniques and reconstructing possible finishes in terms of colour and texture [8]. Colour meanings also exist in finishes other than pigments, which are applied mainly for aesthetic reasons [9].

Wen Yuan Ge's history and extant colour

The Yongle Emperor moved to Beijing in 1421 and rebuilt the imperial palace, which included Wen Yuan Ge, whose name and function as a library were created at that time. The initial Wen Yuan Ge in Ming-dynasty Beijing had a yellow tile roof ([10], p. 26). The initial building was destroyed approximately twenty years later by an internal fire.[2] It was rebuilt approximately thirty years after the damage. In the 1770s, during the Qing dynasty, Wen Yuan Ge was rebuilt and expanded to its current size and use as the imperial library.

The Qianlong emperor mandated the establishment of seven royal libraries to house the Complete Library of the Four Treasuries. Among these, only Wen Yuan Ge, completed in 1776, is located within the Forbidden City. Wen Yuan Ge, distinguished by its superior scale, form, and structure, represents the highest architectural standards among the seven libraries. It was the earliest to house the encyclopaedic book collection and served as the annual venue for the Classics Colloquium ([11], p. 161) symbolizing the construction of the ancient Chinese empire's discourse and national culture. Wang Pu Zi cited Wen Yuan Ge's construction expense register and verified the use of a green façade and colour in painting details in the Qing dynasty[3] ([12], p. 414). Since the establishment of the building in 1776, the colour has remained unchanged.

Fig. 1 Photograph of the Wen Yuan Ge (taken by the author in December 2021)

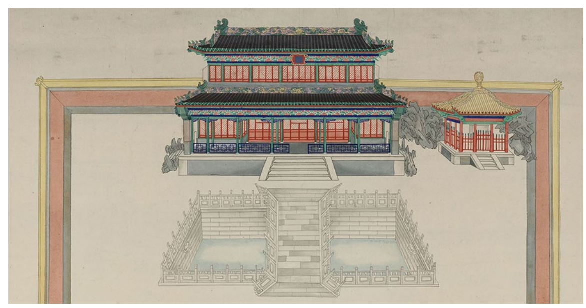

Fig. 2 Depiction of the site of the Wen Yuan Ge in the Yangshi Lei Archives (source: National Library of China)

In contrast to the present physical structure (Fig. 1), the colour recorded in the Yangshi Lei Archives has a distinct green tone (Fig. 2), which is notably bright and vivid, leaning more towards cyan green than the contemporary bamboo green. The archive's recorded colour palette is also rich, incorporating dark blue for railings and finials and pink, blue, yellow, and green for the ridge, providing a more contrast in the composition than in the current palette on the building.

[2] 1436–1449 in the reign of Emperor Yingzong of the Ming dynasty.

[3] Originally cited by Wang in Chinese [12], translated by Liu in his doctoral thesis in Appendix five [10].

In contemporary scholarship, the examination of the Wen Yuan Ge has centred on its distinctive green hue. In 1906, during the comprehensive analysis of the Forbidden City's architectural colour, Japanese scholars, including Tadatsugu Ito, categorized the dark green roof colour of the Wen Yuan Ge as a distinct type, setting it apart from the yellow-glazed roofs of other royal palaces ([13], p. 76) In 1935, Liu Dunzhen and Liang Sicheng conducted a comprehensive examination of the Wen Yuan Ge, providing a detailed description of its overall green appearance and the colouration of its various components, introducing the term "humble" style ([14], p. 112). Subsequently, scholars predominantly used "elements of water" and "fire prevention" to describe the finishes on the Wen Yuan Ge ([11], p. 203)

Objective reproduction and subjective expression of colour

Current methods for acquiring information about colour on architectural heritage can be broadly categorized into two groups: those reliant on large amounts of data to calculate simulated colours and those that are not. Utilizing tools such as the NCS colour reader alongside real painted samples enables the definition of hue, chroma, and lightness without colour data calculation and analysis. This approach has proven to be instrumental in guiding colour decisions for restoration purposes ([15, 16]). Alternatively, researchers can employ the 3D-reality-based colour managed modelling method, enabling simultaneous processing of both colour and shape data [17]. It is important to note that the NCS system lacks representation for primarily low-lightness colours [18], and the 3D model may be inadequate for capturing precise data [19].

The colour collection method used in this study was developed by Luke Li's team at Tsinghua University [20]. The research methodology comprises four key steps: an on-site colour survey, macro photography, dimension collection, and CIELab colour data collection. Colorimetric data are primarily gathered using portable microscopes or macro cameras for capturing microimages and colour catchers (Ral Nano) for identifying CIELab colour data [21]. On-site colour research involves dimension surveys, photography with a ColorChecker [22], and colour measurements. Subsequently, the researchers analysed and screened the collected data. Users can tailor different colour schemes based on specific applications.[4]

Building upon the abovementioned colour data collection methods, this study integrates colour perception research into personalized colour schemes based on personal preferences. These preferences reflect the maker's comprehension of design and are influenced by the maker's colour training and cultural background. Different mapping processes yield distinct colour effects, contributing to the exploration of colour perception rules (Fig. 3).

Wen Yuan Ge colour data analysis and visualization—colour simulation expression based on quantitative analysis

Colour measurement and analysis: visualization of colour data

Following manual screening of the measured colour data (Fig. 4), researchers derived the extremes of chroma (Figs. 5 and 6), simulating the restored colour data after removing impurities and dust (see Fig. 7).

In examining dynastic architectural colour, instrumental identification, which retrieves colour point by point and is less influenced by lighting and observer conditions than typical visual observation, yields relatively accurate and objective results. However, instrumental identification falls short of precisely reflecting colour perception during a specific historical time and cannot faithfully represent historical colour until precise sample detection and component section analysis are employed, which helps identify colour chronicles in layers.

Individual preferences for colour: visualization of individual observations

Aligning the measured colours with the drafter's observation, experience and personal preferences enables architectural heritage preservation practitioners to engage in reasoned hypotheses when exploring colour design.

In the colour scheme using extreme chroma values, the lead-white colour diverges from the typical white colour. To address this issue, the researchers increased the saturation and introduced more tint to achieve a neutral colour (Fig. 8). Following adjustments, the overall brightness contrast became relatively pronounced. The integration imparted a calm and peaceful ambiance, aligning closely with the identity of the "Royal Library".

The personalized colour scheme selects colours based on white balance-corrected images of the architecture (Fig. 9). This version relies primarily on personal preference without colorimetric data. Despite the absence of quantitative data, the observed results intuitively seem to align closely with the object's current state. The researcher's inclination towards less saturated colours in colour selection influences the colour results in Scheme C. In the initial phases of colour research, the colour-corrected

[4] It's crucial to emphasize that the schematic representation of colour measurement results in this context does not result in historical restoration colour. Instead, it represents the outcome of restoring a status quo colour, which stands for one or more restoration options, excluding the impact of factors such as dust and erosion on the colour surface.

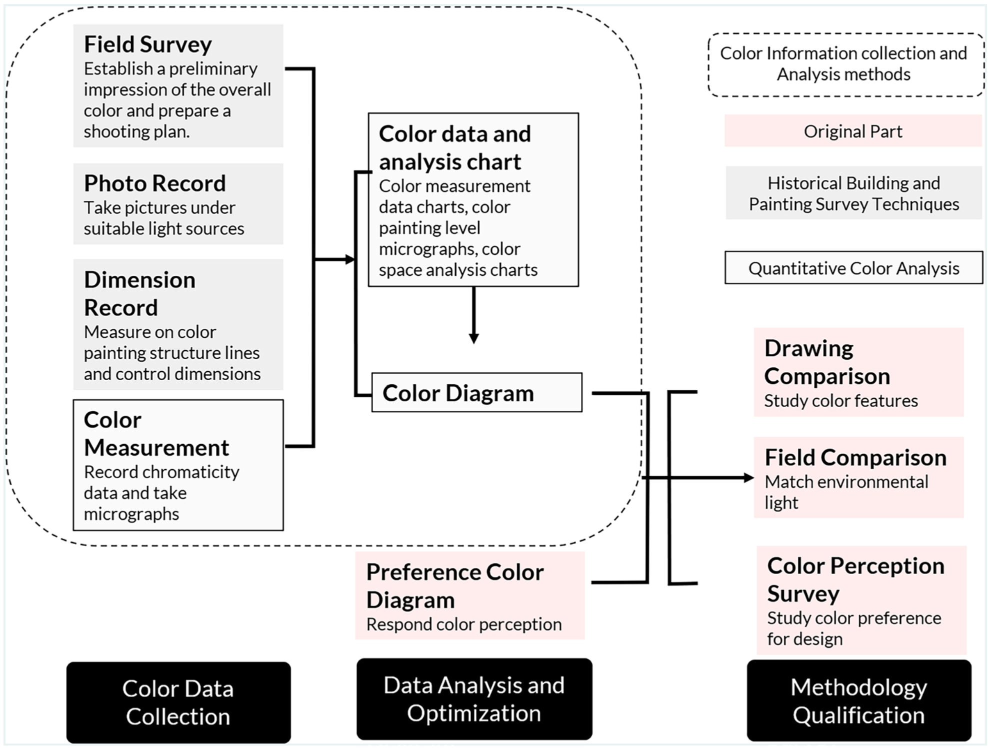

Fig. 3 Colour research flow chart

photo version in Scheme C was an illustrative representation of colour relationships and a preliminary foundation for colour design (see Fig. 10).

On-site colour scheme calibration

The effects of colour vary in different environments, with influencing factors, such as colour materials and observer conditions. Following colour measurement and analysis, the optimal approach is to restore the original process and pigments and place the paints on-site for further calibration in actual light. However, due to cost constraints, site-space limitations and other factors, this study opts for on-site calibration using colour cards (Fig. 11) with minimal printing differences in colour.

The colorimetric data sources utilized in the colour cards in this study include colour measurements and colour data extracted from photos. In the creation of these colour cards, researchers specifically selected the four primary colours of the paintings—red, green, blue, and white—as reference objects for comparison.

Researchers categorized the available colour data into hue intervals, using the average value as the typical colour. Subsequently, derived colours were generated based on uniform changes in luminance and chroma within a specific hue range and were prepared for subsequent calibration. The 8 cm colour blocks following variation in hue and brightness were organized in a matrix using Photoshop on A4 paper for each hue. The matrix paper was then printed from a laser printer with the least printing differences. Finally, the matrix colour was placed on-site for colour selection to match the current structure's colour (see Fig. 12).

The researchers identified that the field observation instruments, including direct visual assessment or cameras, along with factors such as observation distance, time and environmental lighting, can influence the results. This influence is correlated with the hue and area of colour. Hence, in addition to selecting the colour that closely matches the physical object, the researchers also recorded immediate comments to describe any observed colour disparities for further analysis after calibration.

Based on the calibration results, researchers developed two different versions of these schemes (see Figs. 13, 14).

Colour's physical presentation

The colour scheme derived from colorimetric measurements is typically presented in electronic drawings or prints, which may convey a different impression from the one suggested by the actual pigments after application. Pigment analysis methods have matured [23] to identify historical painting materials with insights from historical archives. Artisans employed the "original materials

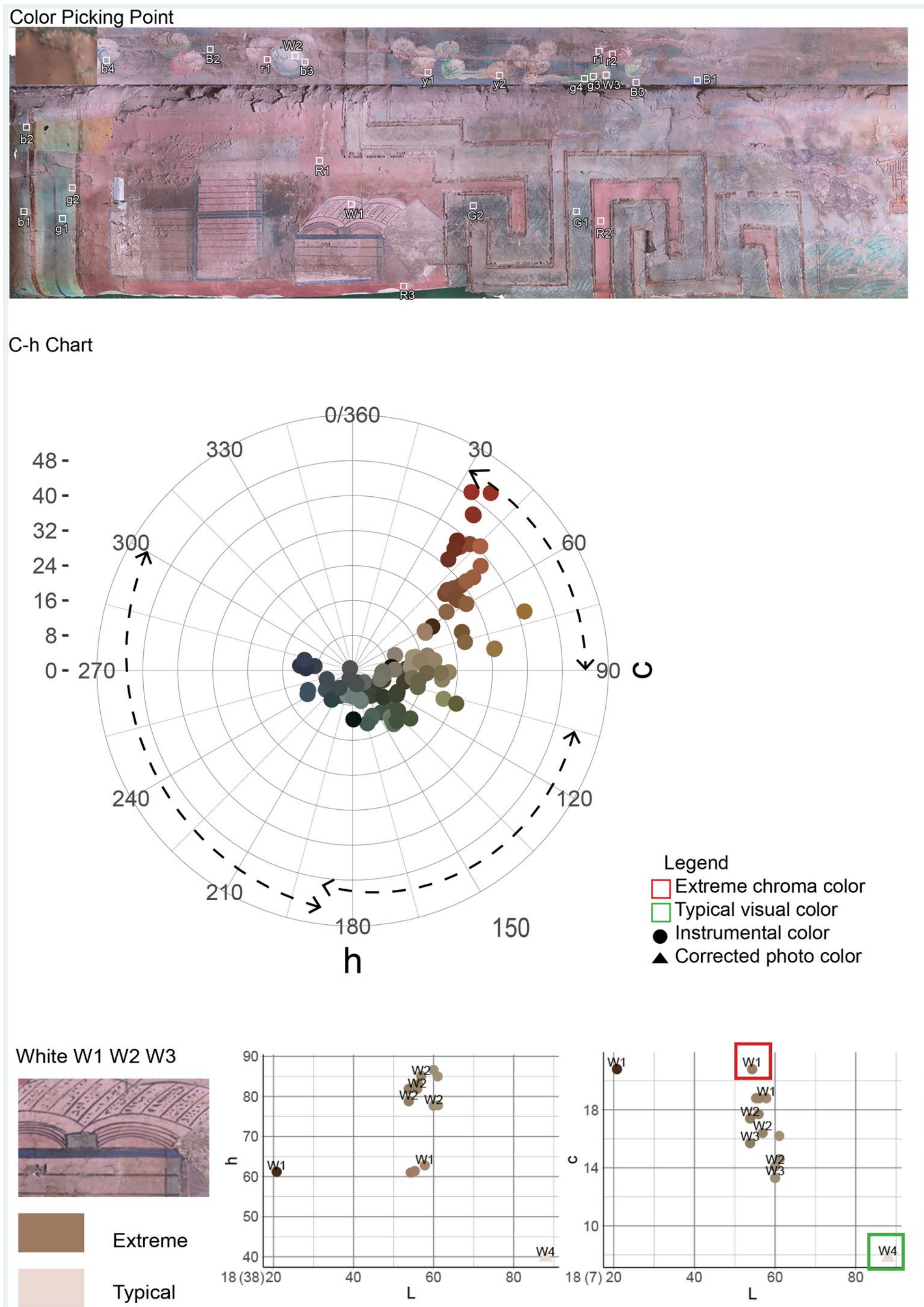

Fig. 4 Colour measurement data screening process

and the original process" to produce a painting sample sized to match the original based on the pigment analysis results [5] [24]. The colours of this sample, which were scientifically matched to the historical colour of the finished painting, differ significantly from those of the three previously mentioned colour versions (Fig. 15).

Observation instruments play a crucial role in perception. Electronic drawings derived from measured

[5] Yihua Zheng is also from Luke Li's study group in Tsinghua University, using the same pigment analysis method in her study, see reference.

Color Name	Point		L	a	b	c	h	Color
White	W1,W2,W3	Extreme Chroma color	54	10	18	21	61	
		Typical visual color	93	-1	4	4	105	
Red	R1 R2 R3	Extreme Chroma color	39	29	27	39	43	
		Typical visual color	55	15	16	22	47	
Cyan	B1,B2,B3	Extreme Chroma color	24	1	-12	12	275	
		Typical visual color	33	-3	-19	19	261	
Green	G1,G2,G3	Extreme Chroma color	34	-9	10	13	134	
		Typical visual color	43	-4	-1	4	194	
cyan	b1	Extreme Chroma color	49	-7	2	7	165	
		Typical visual color	42	4	-11	12	290	
cyan	b2	Extreme Chroma color	35	-4	-6	8	234	
		Typical visual color	28	5	-19	20	285	
red III	r1	Extreme Chroma color	36	41	32	51	38	
		Typical visual color	58	13	9	16	35	
red IV	r2	Extreme Chroma color	28	30	24	38	39	
		Typical visual color	45	24	11	26	25	
cyan IV	b3	Extreme Chroma color	27	-7	-5	8	216	
		Typical visual color	37	3	-18	18	279	
cyan V	b4	Extreme Chroma color	43	-1	17	17	92	
		Typical visual color	71	4	1	4	14	
green II	g1	Extreme Chroma color	37	-12	3	13	164	
		Typical visual color	47	-9	0	9	180	
green III	g2	Extreme Chroma color	45	-12	9	15	143	
		Typical visual color	51	-7	8	11	131	
green IV	g3	Extreme Chroma color	57	-7	21	22	107	
		Typical visual color	48	-1	20	20	92	
green V	g4	Extreme Chroma color	33	-12	10	15	139	
		Typical visual color	35	-11	13	17	130	
yellow III	y1	Extreme Chroma color	49	28	29	41	46	
		Typical visual color	48	35	17	39	26	

Fig. 5 Colour measurement data

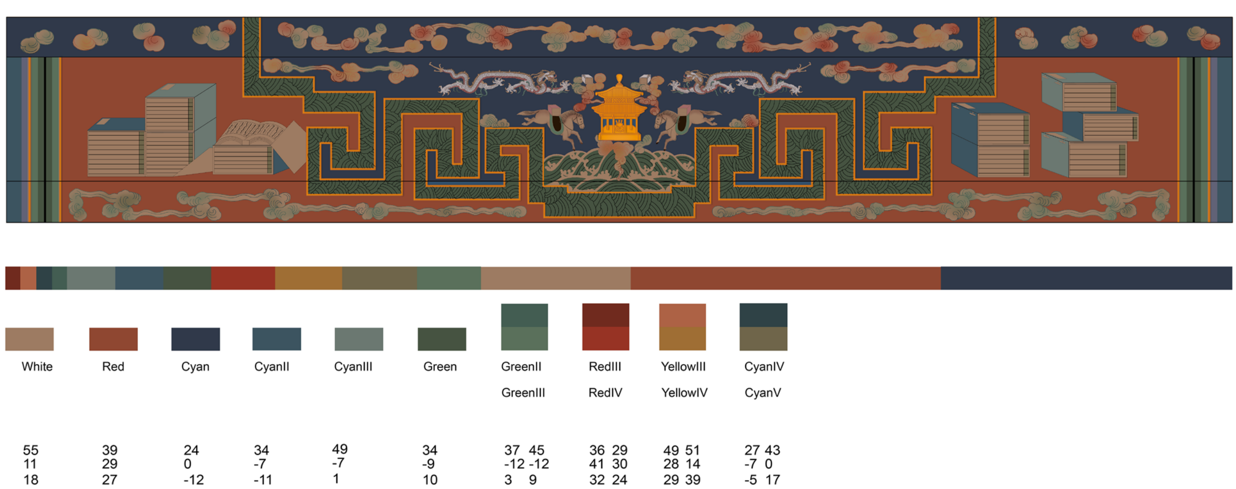

Fig. 6 Colour painting of the fifth unit of the Wen Yuan Ge: Extreme chroma values—Scheme D (Source: author)

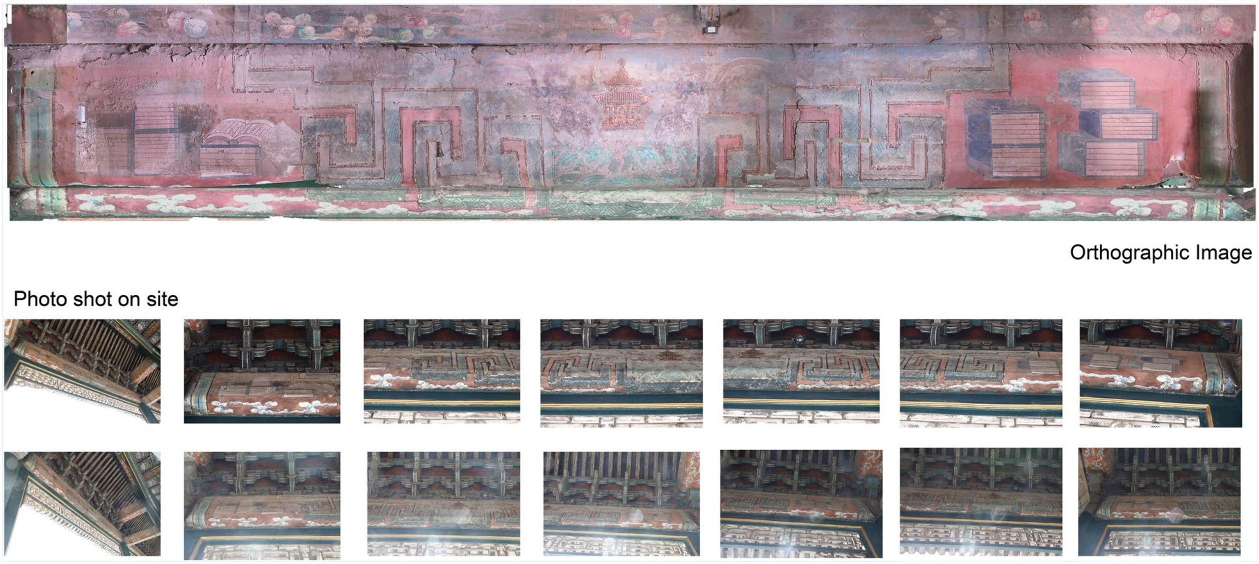

Fig. 7 Orthophotographs and photographs taken on site (Source: author)

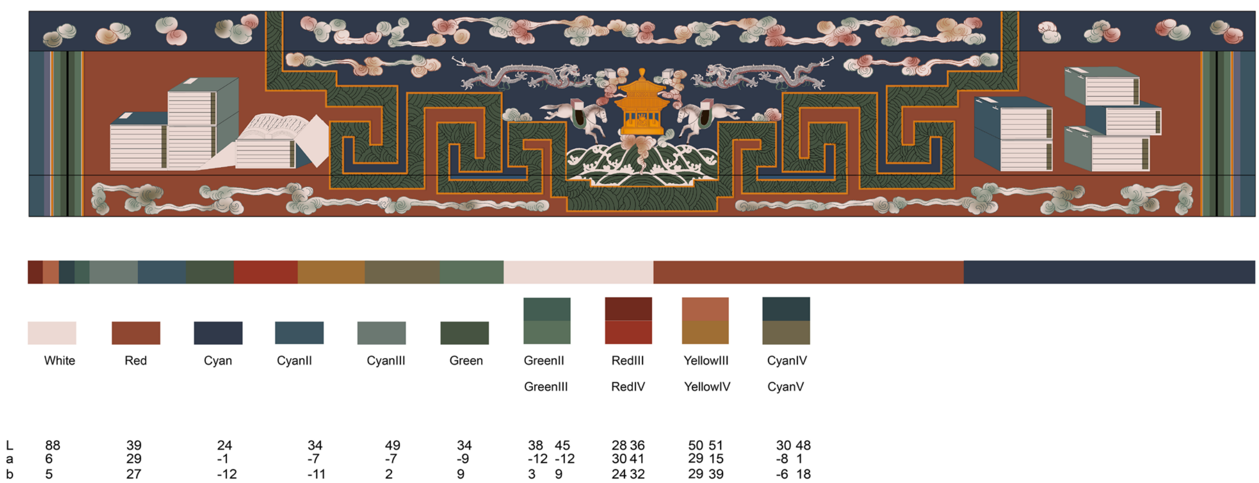

Fig. 8 Colour painting of the fifth unit of the Wen Yuan Ge: The combined version – Scheme E (Source: author)

data are divorced from field environment observations and actual material, leading to variations in colour perception. Although the researchers followed scientific and rigorous steps in colour measurement, sampling, and analysis before the artisan's reproduction, there was a gap between the physical characteristics of pigment expression and the conversion of colour data. Moreover, in the drawing process, artisans inevitably introduced personal preferences influenced by drawing experience and personal aesthetics, potentially accentuating colour contrasts, which certainly affected their painting. The colour perception survey and study involved a preliminary analysis of the factors leading to these variations in perception.

For example, the chromaticity values of the same building using actual pigments vary significantly between 1982 (Fig. 17) and 2022 (Fig. 16), despite being painted with the same presumed colour palette, notably produced in rooms of different sizes and proportions. Different artisans have their own painting styles and approaches to colour (Figs. 17 and 18).

Summary: comparison of colorimetric data of different schemes

Brightness: F > C > AB > DE.

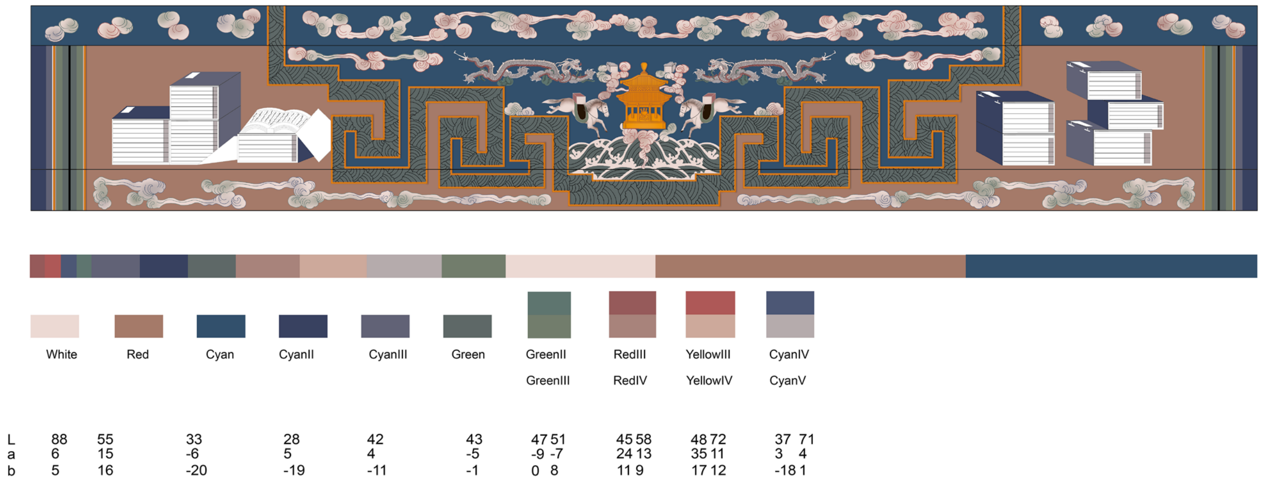

Fig. 9 Colour painting of the fifth unit of the Wen Yuan Ge: Colour-corrected photo version—Scheme C (Source: author)

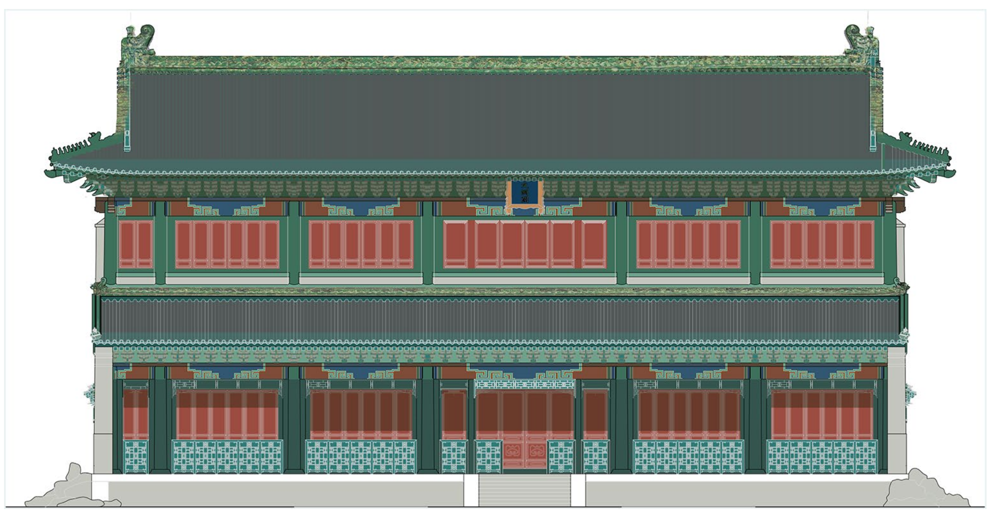

Fig. 10 Depiction of the colour diagram of the Wen Yuan Ge (Source: Author)

Colour: F > AB > DE > C.

Colorimetric comparison: F > AB > DE > C.

Brightness comparison: F > AB > C > DE. (See Figs.19, 20).

Each colour scheme was based on the four predominant colours of red, green, blue, and white but varied within their hue ranges. Scheme F, extracted from the artisan's reproduction, exhibits the highest brightness and colour contrast, evoking the most vivid and bright sensation. On the other hand, based on photographic observation, Scheme C has the lowest colour value and colour contrast but shows pronounced brightness contrast, resulting in more noticeable variations between light and dark. The extreme chroma values in Scheme D have the lowest brightness contrast. Schemes A and B, verified on-site, along with the adjusted scheme E, introduce additional brightness contrasts to the values represented in D. The adjustments, rooted in colour measurement and influenced by colour perception, seek to enhance the contrast between light and dark variations.

The six colour schemes are drawn on different bases and express different degrees of historical information. The current colour in light on scene, as observed by the human eye, does not match well with the measured colour data.

Personal colour experience is a crucial factor in screening and adjusting colour schemes based on chromaticity measurements or an artist's aesthetics. Tailoring

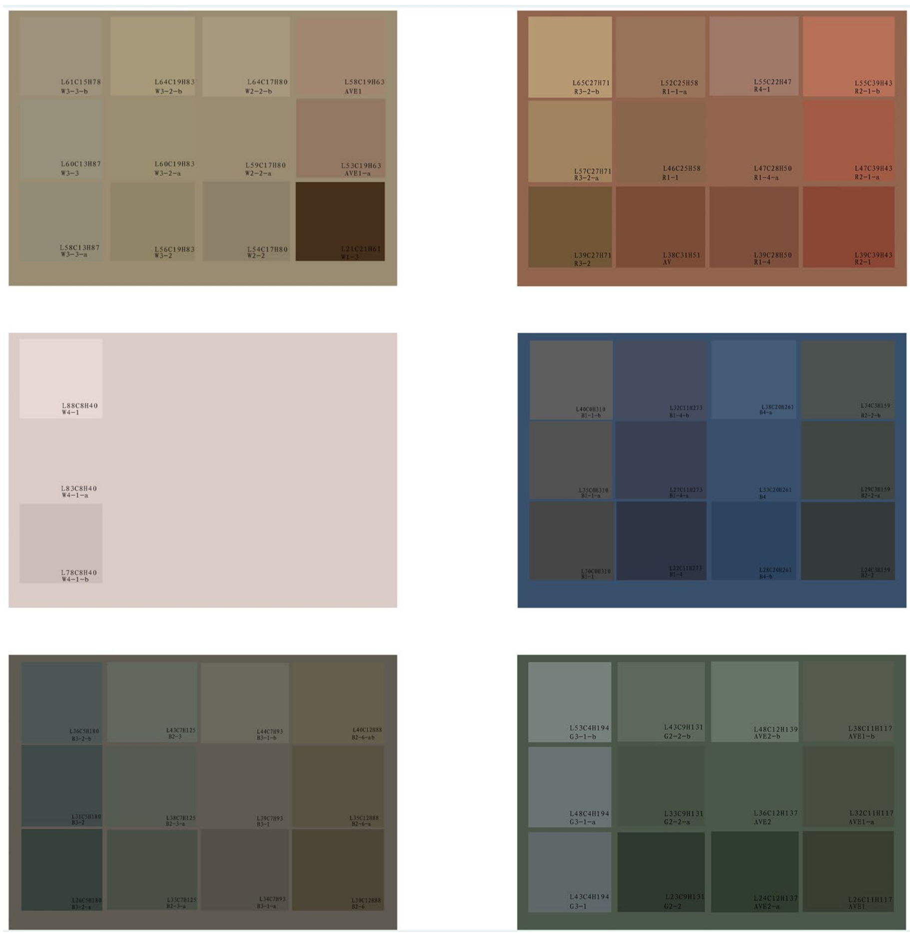

Fig. 11 Colour card scales for calibration (Source: author)

colour restoration efforts to the preferences of diverse groups can lead to effective plans and promising designs (Figs. 21, 22).

Wen Yuan Ge colour perception survey—quantitative analysis of colour perception

The effect of colour presentation on the viewer (Figs. 18–19) is related to many factors, including objective physical factors such as light and materials, as well as the viewer's physiological conditions (e.g., whether they are colour blind or myopic) and psychological state (e.g., whether they give much attention to colour). Excluding Schemes G and H, with their distinct ratios and placements in the Wen Yuan Ge, this discussion focuses on Schemes A to F. These schemes are organized from closest to the present to the most historically original in the order of AB < C < DE < F. According to the previous chromaticity analysis, the colorimetric contrast order was F > AB > DE > C, and the luminance contrast order was F > AB > C > DE (See Figs. 19, 20).

The Wen Yuan Ge colour perception questionnaire comprises twenty-eight questions in four parts (See Additional file 1). The introductory survey gathers basic information such as age, gender, current occupation, education, and colour experience to discern colour preferences using a Likert scale for a scientific model [26]. The primary section assesses preferences and distinguishes colours specifically for the Wen Yuan Ge's façade and colour paintings, complementing the colour data research to explain the causes of various colour schemes.[6].

According to the results, the order of preference for all the populations was C > AB > DE > F (See Fig. 23). People all favoured C, which had the least colour value contrast and was made according to the colour of the photo.

Regarding restoration colour selection, D and E were assumed to theoretically represent the ideal colour after cleaning and restoration; instead, people favoured

[6] The full questionnaire content can be found in the Additional file 1.

Date	04/27/2022
Weather	Light rain 18,North wind force 1-2
Observation	Eye
Distance	15m-30m
Time	3mins for each card
People	nearsighted and wear glasses, have experience in color studies

Minolta Colorimeter Color Measurement	L	a	b	c	h	Color
Calibrated Color: CW-2-AVE	85	1	5	5	76	
PrintI-Extreme:EW-1-AVE	70	6	9	11	56	
PrintI-Photo:PW-1-AVE	107	4	-8	9	297	
PrintI-Combination: MW-1-AVE	107	4	-8	9	297	
PrintII-Extreme: EW-2-AVE	77	2	14	14	82	
PrintII-Photo: PW-2-AVE	106	1	12	12	85	
PrintII-Combination: MW-2-AVE	106	1	12	12	85	

Nano Colorimeter Color Measurement	L	a	b	c	h	Color
Calibrated Color: CW-2-AVE	70	2	15	15	82	
PrintI-Extreme: EW-1-AVE	56	7	18	19	69	
PrintI-Photo: PW-1-AVE	89	2	7	7	74	
PrintI-Combination: MW-1-AVE	88	2	5	5	68	
PrintII-Extreme: EW-2-AVE	63	6	17	18	71	
PrintII-Photo: PW-2-AVE	76	6	15	16	68	
PrintII-Combination: MW-2-AVE	90	3	12	12	76	

Fig. 12 Colour card calibration of white (Source: author)

C > AB > DE > F (See Fig. 24). This preference for schemes with higher brightness and contrast aligns consistently with the findings in aesthetic preference rankings. Across various colour studies, similar patterns emerged in evaluating different colour schemes, indicating a universal preference for brighter colours. This alignment shows

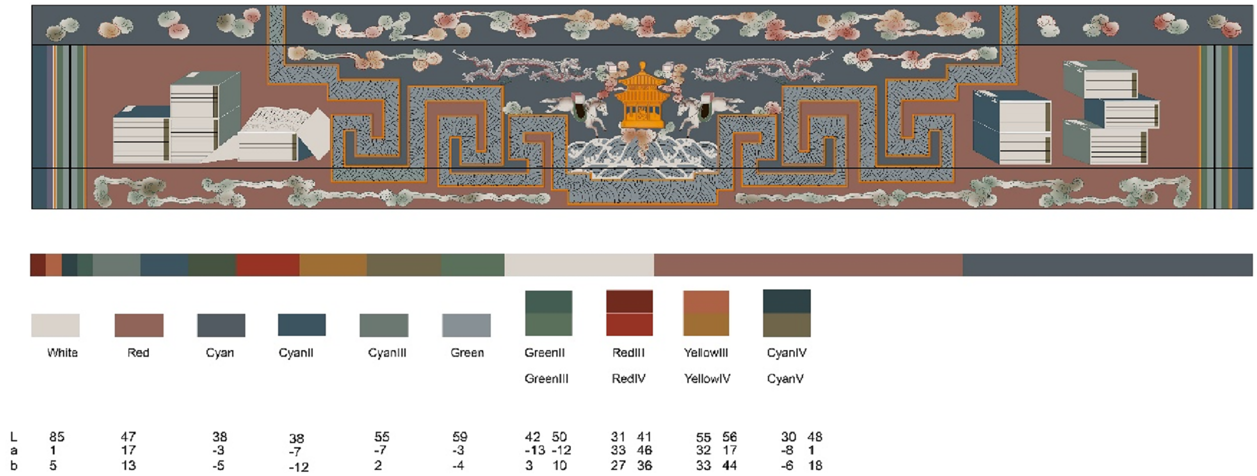

Fig. 13 Colour painting of the fifth unit of the Wen Yuan Ge: Calibrated on-site version -Scheme B (low brightness) (Source: author)

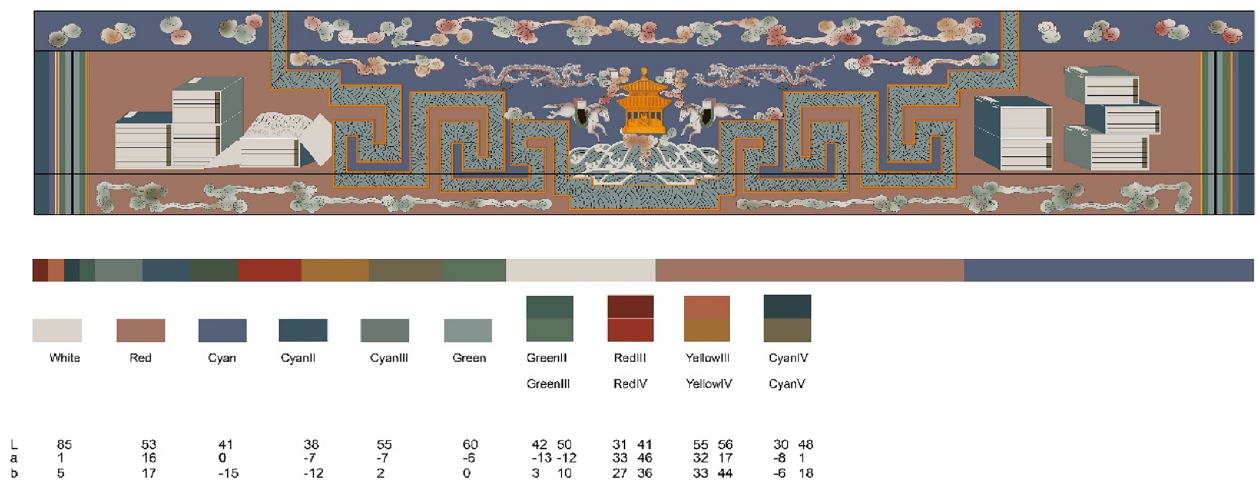

Fig. 14 Colour painting of the fifth unit of the Wen Yuan Ge: Calibrated on-site version – Scheme A (high brightness) (Source: author)

Fig. 15 Photograph of the artisan's restored sample (Source: author)

that colour preference is unavoidable during colour recognition and research, partly explaining the dramatic colour difference between colour schemes C and F. However, the museology students favoured ABC's restoration effect over practitioners, who preferred DEF. According to their comments, people in the field of museology paid more attention to the actual restoration project results

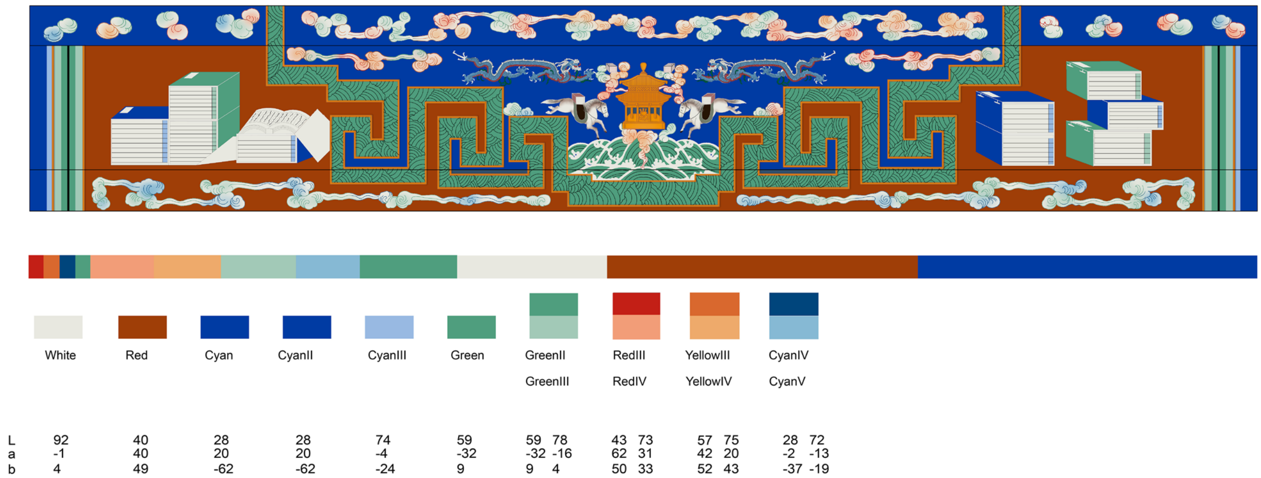

Fig. 16 Colour painting of the fifth unit of the Wen Yuan Ge: Extracted from the artisan's restored sample in 2022—Scheme F (source: author)

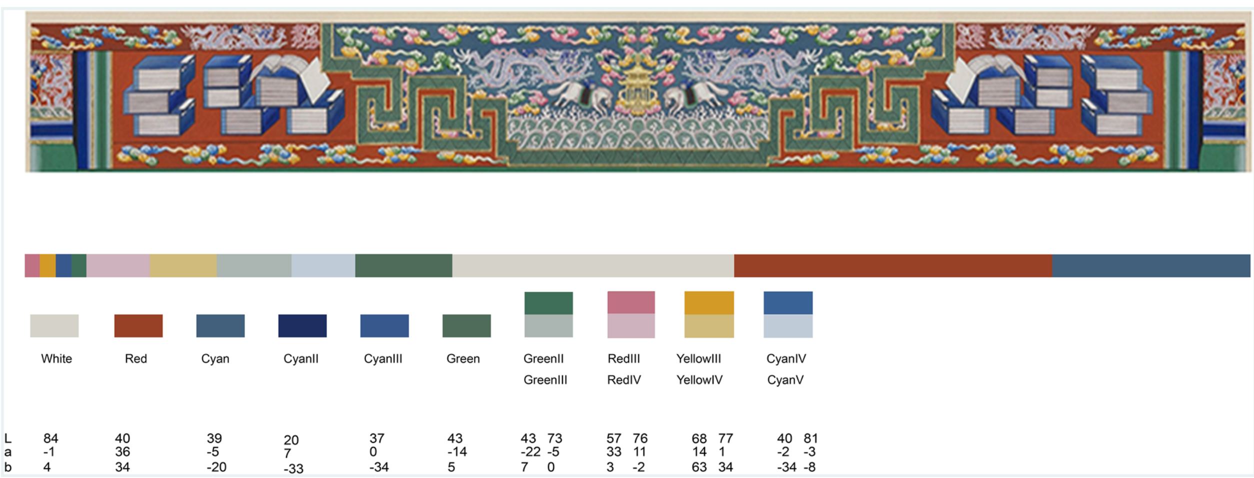

Fig. 17 Colour painting of the fourth unit of the Wen Yuan Ge: extracted from the artisan's restored sample in 1982 (source: The Palace Museum)

concerning real pigments, painting techniques and the actual architectural environment.

Colour preference also distinguishes modern and ancient people. Historically, one black and white photograph of the Wen Yuan Ge was colorized in red by people unfamiliar with the actual building colour at the time of the Republic of China (Fig. 25). The colour preference survey compared the perceptions of this red façade from "photographs" with those of the existing green façade, questioning respondents about their fit with the Wen Yuan Ge's cultural identity. The outcomes of this comparison are outlined below (see Fig. 26).

In assessing the two façade colours, the consensus was that the current green façade was more representative of the image of the royal library, with colour painting scholars particularly endorsing this choice. However, the red façade, which is different from the original colour, which indicated water and fire prevention, received notable recognition for its special cultural identity among those with some with colour study experience, particularly those studying architecture, art and design.

Colour perception encompasses objective colour discrimination, such as colour recognition, which is unaffected by personal preference, and subjective aspects, such as aesthetic review, restoration evaluation, and design assessment, which are influenced by individual tastes. The results of the colour perception survey can be summarized as follows.

Aesthetic preference: C > AB > DE > F.

Colour recognition (with the current photo): ABC > DE > F.

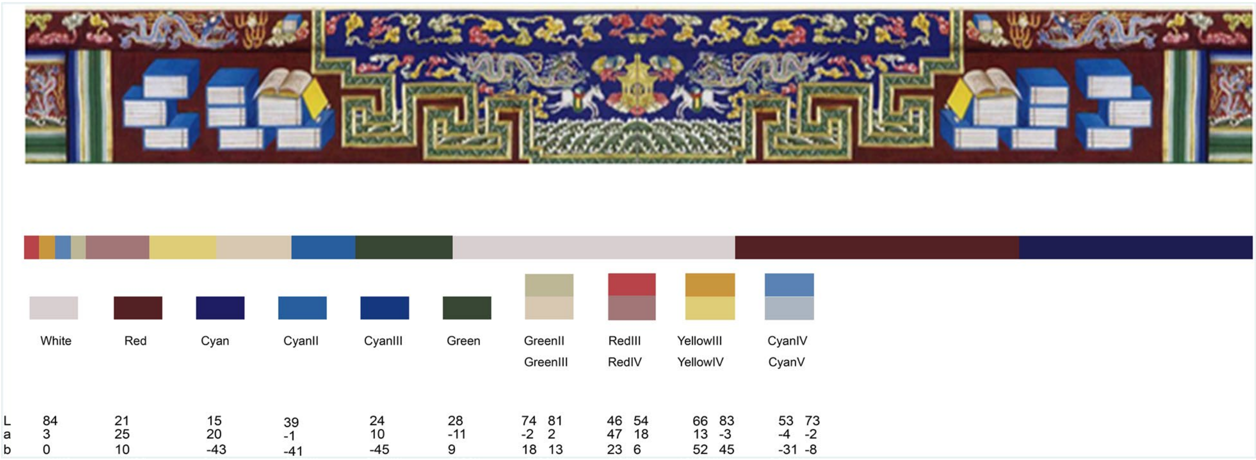

Fig. 18 Colour painting of the fourth unit of the Wen Yuan Ge: extracted from the artisan's restored sample in Colour Paintings of Ancient Chinese Architecture (Source: Colour Paintings of Ancient Chinese Architecture ([25], p.204))

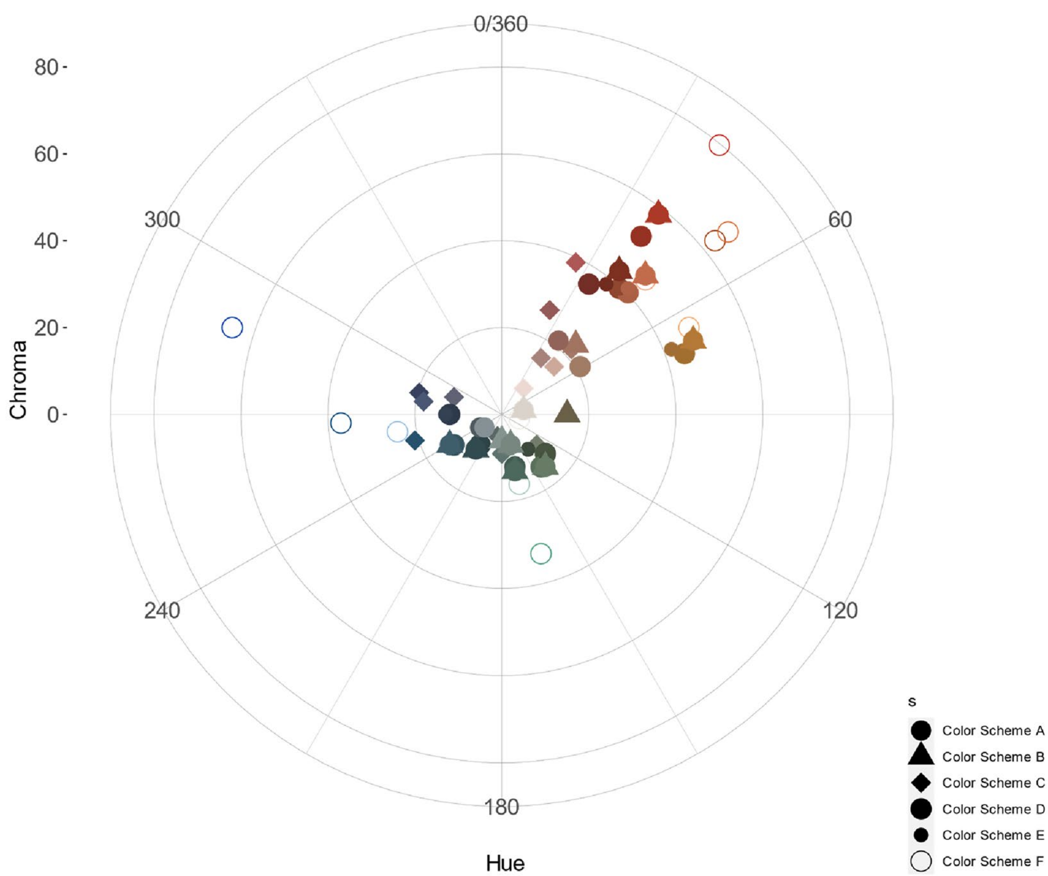

Fig. 19 Hue and colour distribution of schemes A–F (Source: author)

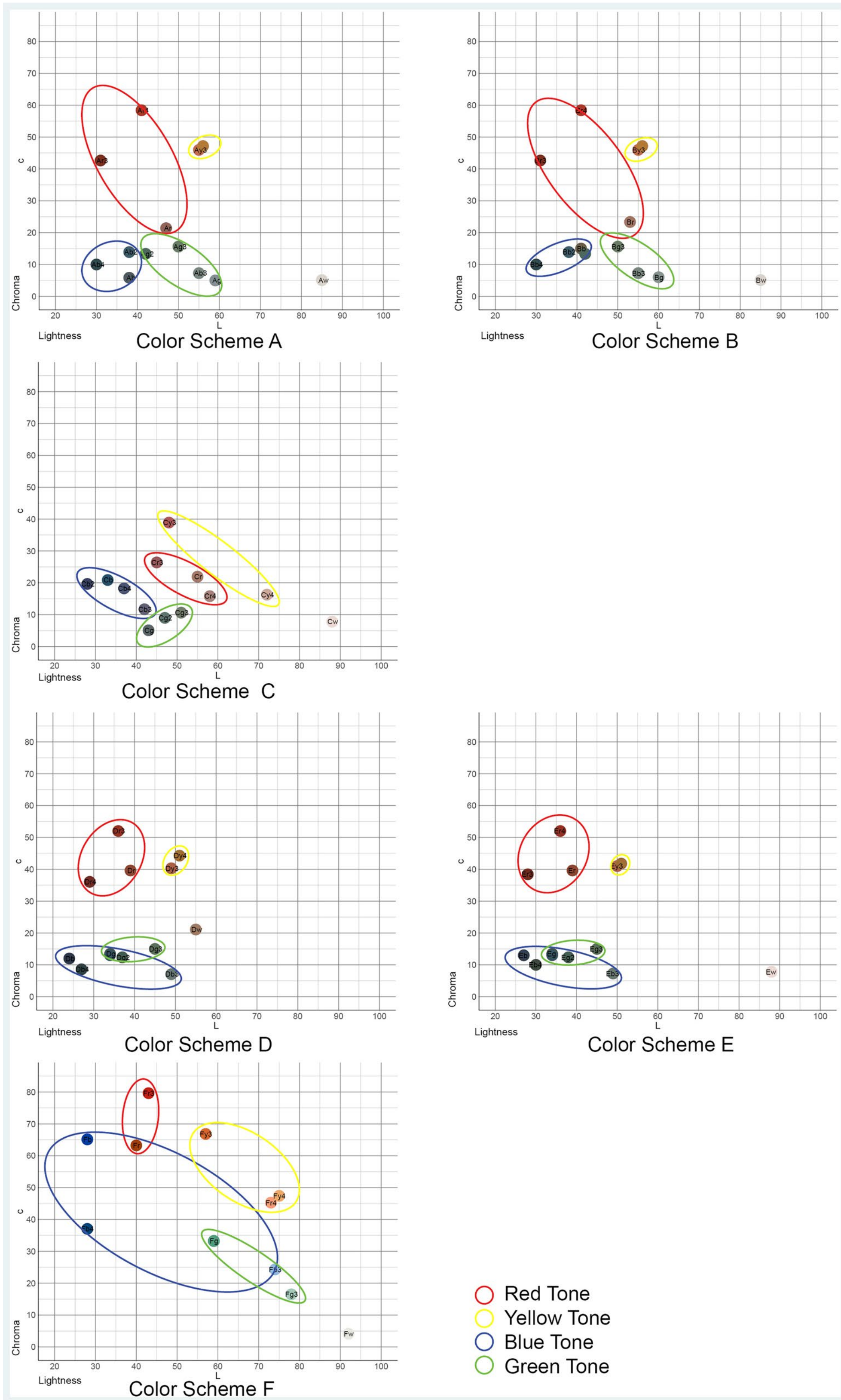

Fig. 20 Colour chroma and brightness distribution of schemes A–F (Source: author)

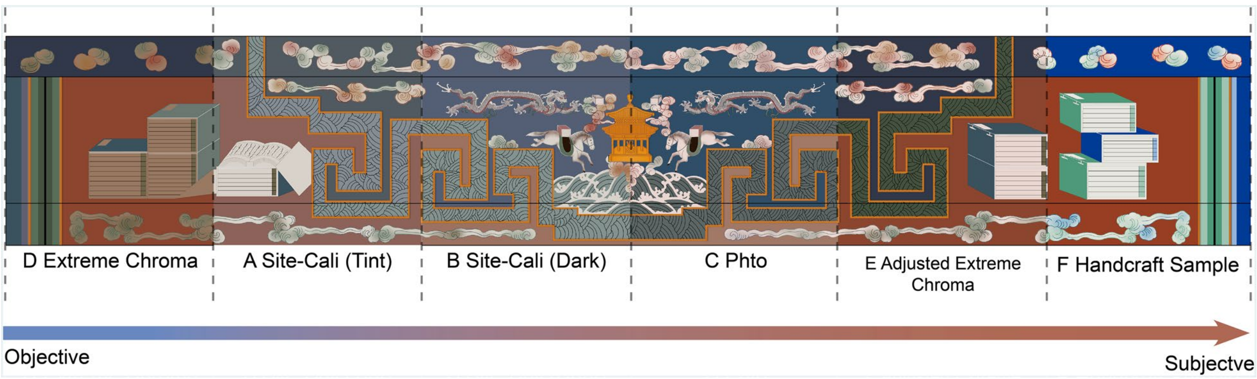

Fig. 21 Colour information comparison A—from objective (direct colour measurement) to subjective (adjustment based on colour perception) (source: author)

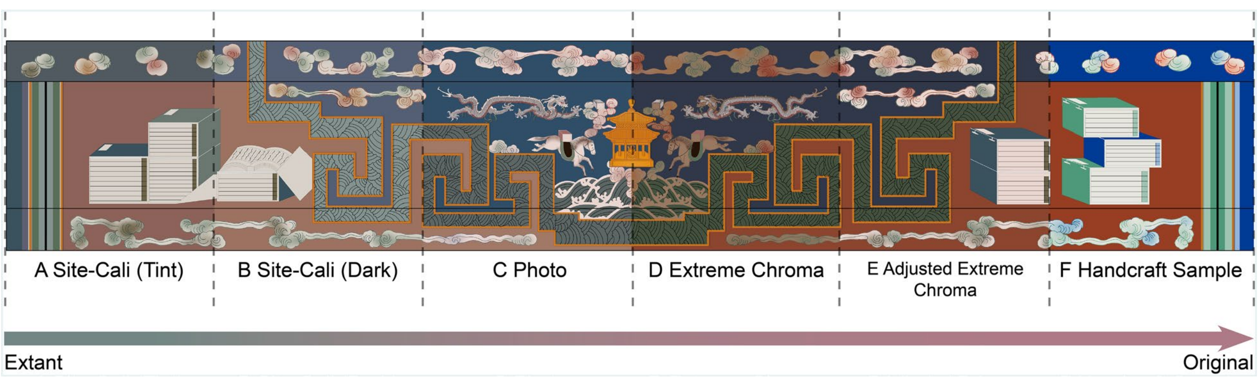

Fig. 22 Colour Information Comparison B—from Current to Original Conditions (Source: Author)

Colour restoration evaluation: C > AB > DE > F.

Colour restoration design evaluation: CDE > AB > F.

The colour perception questionnaire results indicate that in addition to individuals experienced in colour painting research, the public generally shows low acceptance of Scheme F, which is ideal for quantifying restored colour choices via scientific surveys and analysis.

Modern preferences for ancient building colours lean towards harmony in colours with lower contrast, as revealed by quantitative surveys. Colours with high saturation and contrast (as in Scheme F) are generally less accepted, even if this representation of historical colour choice is supported by scientific measurements. Aesthetic preferences unavoidably shape the evaluation of restoration design effectiveness. The unique preferences for Scheme F among those experienced in colour research and those in arts and culture-related fields suggest varied interpretations of colour restoration and its historical context.

For public education, presenting the restoration process and its colours can create a more comprehensive impression of the aspects of colour in architectural heritage, inviting visitors to engage in the colourising process and enhancing their understanding and appreciation of colour restoration.

Conclusions: reflections on innovative approaches to historical colour research and application

This research contrasts traditional manual colour restoration with a more scientific and precise colour survey method. It employs CIELab colorimetry to provide foundational data for further colour research and restoration.

Unlike similar colorimetry research, this study focuses on data analysis and application to create colour schemes while integrating colour psychology to understand colour preferences among the public and professionals of ancient colour preservation on architectural heritage [27]. The study also values individual aesthetic

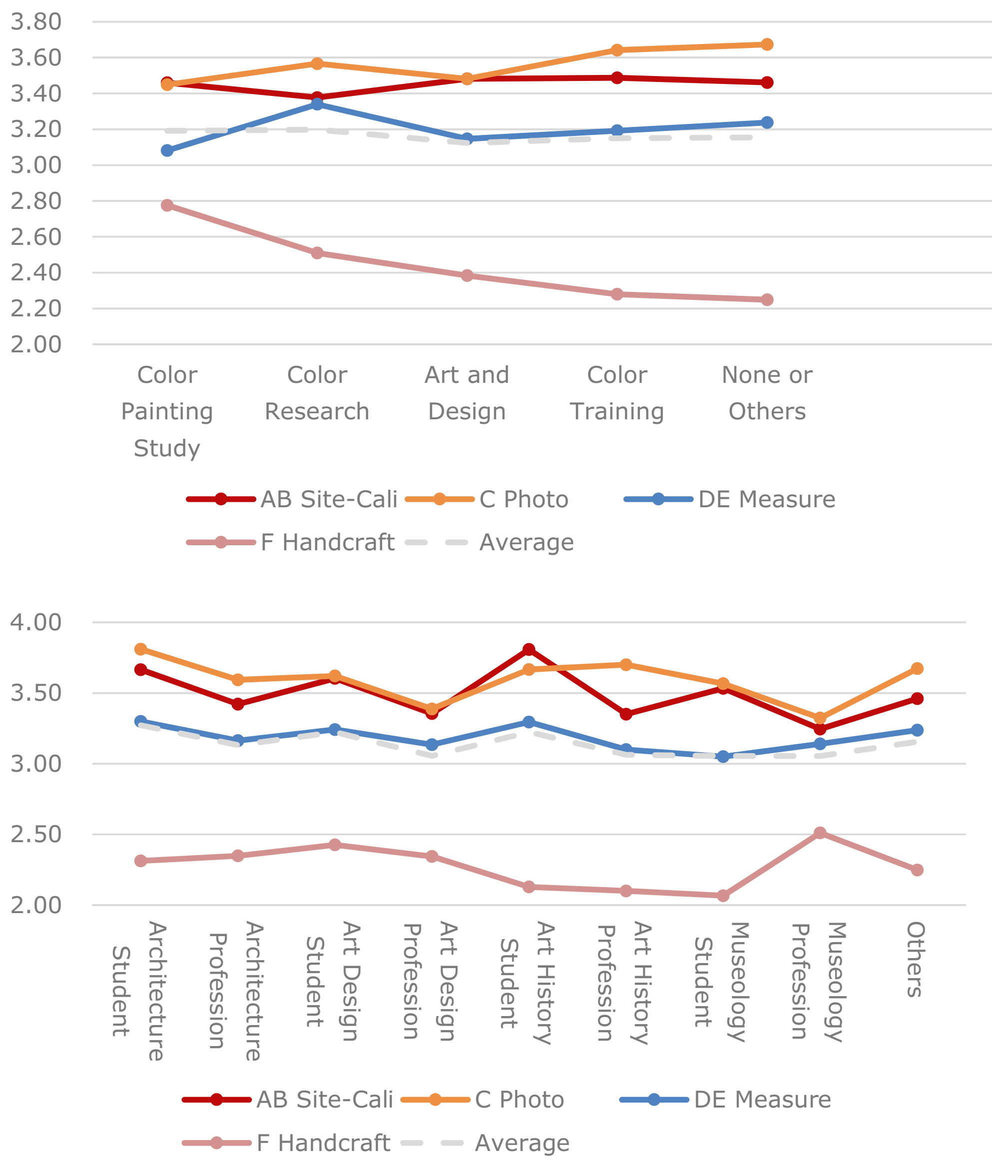

Fig. 23 Q: Please rate whether each of the above diagrams matches your aesthetic sense

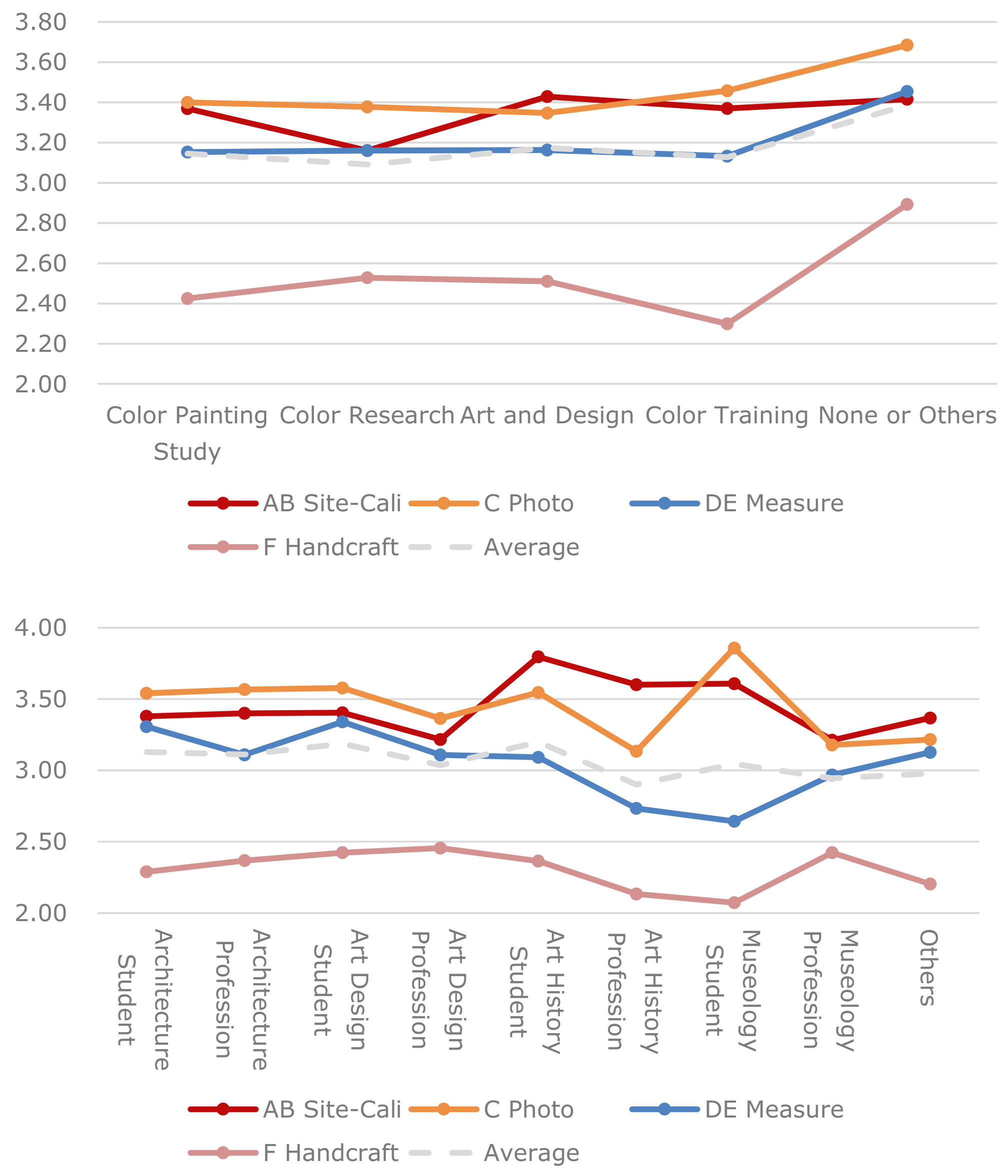

Fig. 24 Q: Please evaluate whether each of the above diagrams meets your expectations of the effect after restoration and dust removal for the conservation of this painting

Fig. 25 Colourisation of the photographs of the Wen Yuan Ge during the Republic of China. source: Taipei National Palace Museum

preferences and is closely aligned with historical facts, taking professional feedback into account.

The chronology of colour paintings has special historical significance and value. Colour changes on architectural paintings are similar to the "patina" on artefacts, which has historical, cultural, and aesthetic significance [28], p. 101) Brandi emphasized three kinds of architectural heritage historicity, namely, the first duration when it was just created, a second intervening interval, and the third interval when people become aware of the object as a work of art ([29], p. 61). This study objectively restores the colours of the intermediate period through

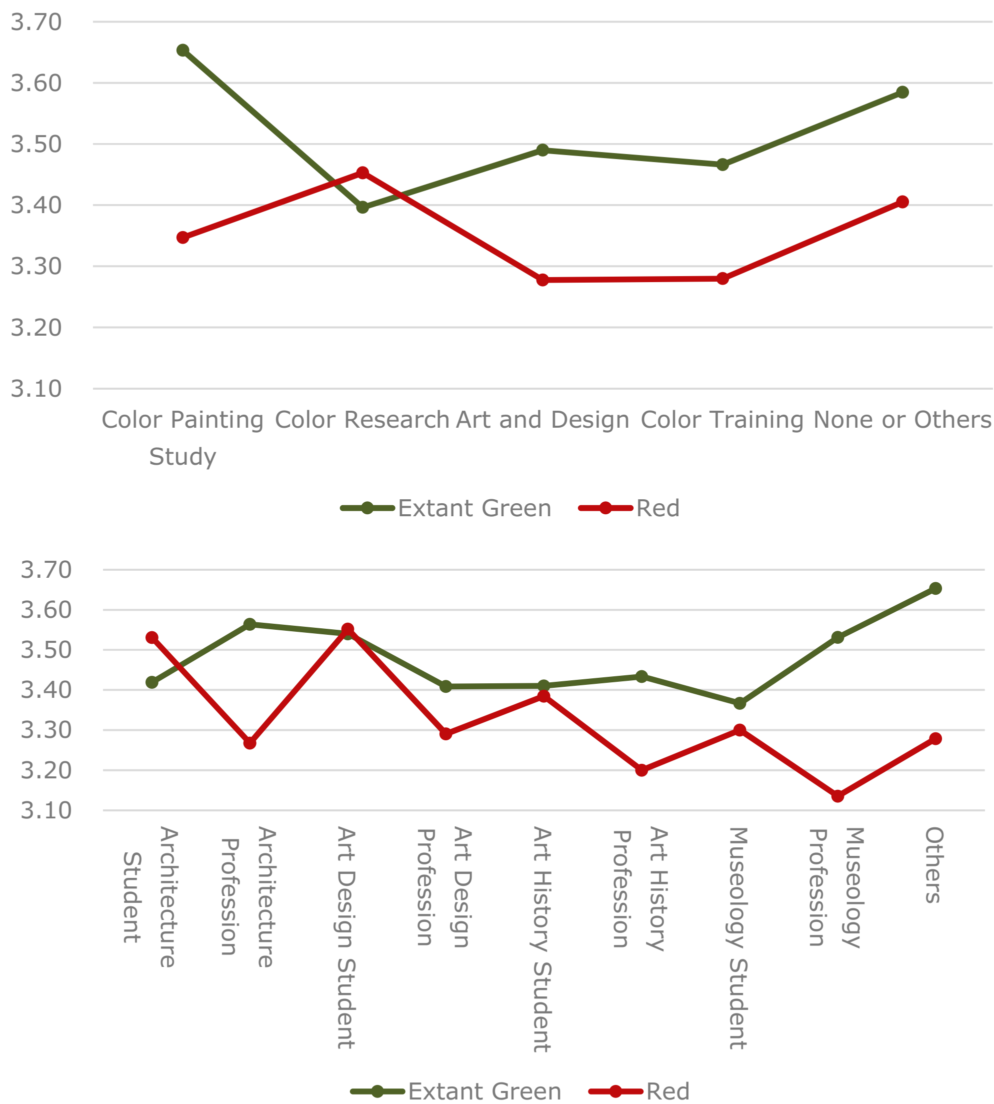

Fig. 26 Q: Do you think the above façade matches the image of the "royal library and the place where the scripture feasts were held" in your mind?

chromaticity research (i.e., colour measurement scheme D), produces the derived colours of the intermediate period through on-site calibrations and drawing adjustments (ABCE), and includes the restored colours in the small samples of the "original materials and the original process" as an alternative (Scheme F)

This study not only explored the multiple possibilities for colour restoration on architectural heritage through surveys but also investigated the symbolic meanings of colour paintings, the aesthetic appeal of ancient architecture, and the intricate diversity of colour studies. Furthermore, the extraction and derivation of colours with solid cultural symbolism can reproduce the unique function and national cultural symbolic function of the Wen Yuan Ge as the "Royal Library" for the public. This approach can serve as a reference for similar cultural architectural designs aiming to retrieve the symbolic meaning of colours [30] and refine colour restoration practices [31].

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01218-0.

Additional file 1: Appendix S1. Color Perception Questionnaire.

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Author contributions
JS wrote the paper. LL and JS designed the research. JS, YJ and XL performed the research. JS analysed the data. LL, XL, YJ and HY reviewed the entire text and provided comments and suggestions to improve it. HY provided access to the site and devices.

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Availability of data and materials
The datasets used and analysed in the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Shevell SK. The science of color. 2nd ed. Amsterdam: Elsevier; 2003.
2. Meerwein G, Rodeck B, Mahnke FH. Color—communication in architectural space. Berlin: De Gruyter eBooks; 2007. https://doi.org/10.1007/978-3-7643-8286-5.
3. Kobayashi S. Colorist: a practical handbook for personal and professional use. 1st ed. Tokyo: Kodansha International; 1998.
4. Lenclos JP, Lenclos D, Barré F, Bruhn GP. Colors of the world : the geography of color. New York: W W Norton & Co; 2004. p. 15.
5. Gaiani M, Apollonio FI, Ballabeni A. Cultural and architectural heritage conservation and restoration: which colour? Color Technol. 2021;137(1):44–55.
6. Sirnoff L. Dimensional color. Boston: Birkhäuser; 1989.
7. Gage J. Color and meaning: art, science, and symbolism. London: Thames & Hudson Ltd; 1999.
8. Scopinaro E, Ceccarelli S. Coloured cities: iconography and scientific evidence for colours reconstruction of built heritage in central Italy. In: Rossi M, Casciani D, editors. Color and colorimetry multidisciplinary contributions. Milano: Gruppo del Colore-Associazione Italiana Colore; 2023.
9. Droghini F, Giamello M, Guasparri G, Sabatini G, Scala A. The colour of the facades in Siena's historical centre: I. Glazings (calcium oxalate films s.s.) and other finishes on the stone materials of the Cathedral's main facade. Archaeol Anthropol Sci. 2009. https://doi.org/10.1007/s12520-009-0009-0.
10. Shan S. Wen Yuan Ge. Palace Museum Journal. (Chinese) 1979(02):26–31. https://doi.org/10.16319/j.cnki.0452-7402.1979.02.004
11. Liu C. The Ch'ing Dynasty Wen-Yuan-ku imperial library: architecture and the ordering of knowledge. Princeton: Princeton University; 1997.
12. Wang P. Supplementary notes on the architectural works of the Wen Yuan Ge of the Qing Dynasty—a compilation of historical materials on the architecture of the Forbidden city, vol. 3. Beijing: Editorial Board of Beijing Shi Yuan, Beijing Municipal Institute of Social Sciences; 1985.
13. Tsunegorō O, Tōkyō Teikoku Daigaku, Kōka Daigaku. Decoration of Palace Buildings of Peking (Japanese). Ogawa Kazumasa Shuppanbu; 1906.
14. Liang S, Liu D. A description of the actual measurement of Wen Yuan Ge in the Qing Dynasty (Chinese). In: Liang S, editor. The Complete Works of Liang Sicheng, volume 3, vol. 3. 1st ed. Beijing: China Construction Industry Press; 2004.
15. Hazin M, Pernão J. The NCS color notation as a guide to produce colors from traditional pigments in conservation. The case study of two painted ceilings from eighteenth-Century Churches in colonial Brasil. Milano: AIC 14th Congress; 2021.
16. Valge C, Ceccarelli S, Bertacchi S, et al. Colour measurement and documentation in historical buildings: the case study of the Kirna Manor House in Estonia. Cult Sci Colore Color Cult Sci. 2022;14(01):123–30.
17. Apollonio FI, Gaiani M, Baldissini S. Color definiton of open-air architectural heritage and archaeology artworks with the aim of conservation. Dig Appl Archaeol Cult Herit. 2017;7:10–31.
18. Pastilha RC, Linhares JMM, Rodrigues AIC, Nascimento SMC. Describing natural colors with Munsell and NCS color systems. Color Res Appl. 2019;44(3):411–8.
19. Gaiani M, Apollonio FI, Ballabeni A, Remondino F. Securing color fidelity in 3D architectural heritage scenarios. Sensors. 2017;17(11):24–37.
20. Li L. New exploration on the construction of chinese traditional color system—quantitative analysis of color and chromatographic generation practice based on literature (Chinese), objects and techniques. Beijing: Culture and Arts Publishing House; 2019. p. 15–38.
21. Jiang Y, Li L, Zheng Y. Finding the real color-quantitative color examination and restoration of Chinese historical architecture. SCIRES-IT Sci Res Inform Technol. 2022;12(1):121–32. https://doi.org/10.2423/i22394303v12n1p121.
22. Carnevali L, Lanfranchi F, Martelli L, Martelli M. Colourimetric calibration for photography, photogrammetry, and photomodelling within architectural survey. Int Arch Photogram Remote Sens Spatial Inf Sci. 2021;XLVI-4/W5-2021:151–8.
23. He J, Zhou W, Hu D, Liu S, Otero J, Rodriguez-Navarro C. A multi-analytical approach for the characterization of materials, manufacturing process and damage mechanisms of wall paintings in Samye Temple, Tibet. Dyes Pigments. 2022;207: 110704.
24. Zheng Y, Guo W, Li L, et al. Exotic blue pigments in the polychrome interior of Yongle Taoist temple: a case of international trade during the Yuan and Qing dynasties. Archaeometry. 2023. https://doi.org/10.1111/arcm.12916.
25. Sun D. Ancient Chinese architectural colored drawings (Chinese). Beijing: China Architecture Industry Press; 2005.
26. He F, He Y, Sun L. Gender differences in color perceptions and preferences of urban façades based on a virtual comparison. Build Environ. 2023;245: 110907.
27. Plutino A, Simone G. The limits of colorimetry in cultural heritage applications. Color Technol. 2021;137(1):56–63.
28. Brandi C, Basile G. Theory of restoration/Cesare Brandi. Roma: Istituto centrale per il restauro; 2005.
29. Barchino AT, Verdú JL, Lluch JS. Recovering chromatic space as a sign of identity in the historic city. In: Amoruso G, editor. Putting tradition into practice: heritage, place and design. Cham: Springer International Publishing; 2018.
30. Ferretti V, Comino E. An integrated framework to assess complex cultural and natural heritage systems with multi-attribute value theory. J Cult Herit. 2015;16(5):688–97.
31. de la Torre Fornés I, Serra Lluch J, Torres Barchino A. Analysis and proposal for the chromatic recovery of the façade of the church of our lady of the angels. In: Agustín-Hernández L, Muniesa AV, Fernández-Morales A, editors. Graphical heritage. Cham: Springer International Publishing; 2020.