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The Chromatic Evolution of Public Spaces in a Global-Local City: A Computational Analysis of Macau's Urban Identity

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Abstract*—Urban color plays a crucial role in shaping a city's identity and influencing residents' experiences. In the context of globalization and tourism, how historical cities like Macau preserve their distinctive color characteristics has become an important research question. While previous studies have mainly concentrated on building facades, there remains a lack of quantitative research on the overall color evolution of urban public spaces and the forces driving these changes. To address this gap, this study adopts a combination of cultural analytics and computer vision methods to conduct a long-term, large-scale analysis of color dynamics in Macau's public spaces. A multi-dimensional analytical framework integrating spatial and temporal perspectives is proposed to systematically quantify the evolutionary patterns of urban color. Using Google Street View (GSV) images as the primary data source, thousands of images covering Macau's major public areas—including historic squares, modern waterfronts, and residential streets—were collected. Through semantic segmentation, key elements such as sky, vegetation, buildings, and ground were extracted, and k-means clustering was applied to identify the dominant colors of each element. These were then quantitatively analyzed across four dimensions: color complexity, harmony, saturation, and brightness. The results reveal a marked evolution in the color characteristics of Macau's public spaces over the past two decades. Historic squares have gradually converged toward a unified "heritagized" palette dominated by yellows and pinks, whereas modern waterfronts exhibit increasing diversity and commercialization. Although overall color saturation has risen, color harmony shows divergent trends among different areas. These patterns reflect the interplay between heritage conservation policies, tourism development, and urban modernization. By uncovering the dynamic processes and multiple drivers of urban color change, this study provides a new quantitative perspective for urban color planning and heritage conservation, emphasizing that color should be regarded as a dynamic socio-cultural ecosystem rather than a static aesthetic attribute—an approach that can help better balance local identity with global influences.

Keywords—Urban Color, Public Space, Macau, Computer Vision, Cultural Analytics

1. Introduction

The color of a city is a powerful, albeit often subconscious, element that shapes its identity, influences the perceptions of its inhabitants, and defines the experience of its visitors [1]. As a critical dimension of the urban built environment, color transcends mere aesthetics; it is a language that communicates cultural values, historical narratives, and social dynamics [2]. In cities like Macau, a unique crucible of Eastern and Western cultures for over four centuries, the urban color palette serves as a living archive of its complex history. The city's inclusion as a UNESCO World Heritage site in 2005 further underscored the global significance of its unique architectural and urban landscapes, where color plays a pivotal role.[3] However, the dual pressures of rapid tourism-driven development and the imperative of heritage conservation have created a complex field of forces acting upon Macau's visual identity. This raises a critical question: How do these forces collectively shape the chromatic landscape of Macau's public spaces, and what are the temporal and spatial patterns of this evolution?

Previous research on urban color has largely followed two main streams. The first, rooted in the tradition of Lenclos's "Geography of Color," has focused on qualitative and ethnographic methods to document and interpret the characteristic colors of a place, emphasizing their connection to local materials, climate, and culture [4]. The second stream has concentrated on the psychological and perceptual effects of color in urban settings [5]. While invaluable, these studies are often limited to specific sites or building facades and tend to provide a static snapshot rather than a dynamic, longitudinal analysis. More recently, the advent of computational methods, particularly the analysis of large-scale visual data from sources like Google Street View (GSV), has opened new frontiers for urban studies [6]. This "cultural analytics" approach allows for the quantitative analysis of urban environments at an unprecedented scale and granularity. Yet, its application to the dynamic evolution of urban color, especially within the context of public spaces in heritage cities, remains underexplored.

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This study aims to fill this gap by providing a large-scale, quantitative analysis of the chromatic evolution of public spaces in Macau over the last two decades. We move beyond the singular focus on architecture to consider the holistic color environment of public spaces, including buildings, ground surfaces, and street furniture. By leveraging a longitudinal dataset of GSV imagery and employing a combination of computer vision and statistical analysis, we seek to answer the following questions: (1) How have the color characteristics (complexity, harmony, saturation, and brightness) of different types of public spaces in Macau evolved over time? (2) What are the significant spatial variations in these color characteristics between historic, commercial, and residential areas? (3) What do these chromatic shifts reveal about the underlying processes of "heritagization," commercialization, and modernization in Macau? By addressing these questions, this paper contributes a new computational paradigm to the study of urban color, offering a data-driven approach to understanding and managing the visual identity of historic cities in an era of globalization.

2. Related Work

2.1. Urban Color, Heritage, and Place Identity

The study of urban color is deeply rooted in the understanding that color is a fundamental component of place identity. Jean-Philippe Lenclos's pioneering work on the "Geography of Color" established a foundational methodology for systematically studying the colors of a specific region, linking them to local factors such as geology, climate, light, and traditional materials [4]. This perspective treats color not as a superficial decoration but as an intrinsic expression of a region's terroir. Subsequent research has built upon this foundation, exploring how the chromatic palette of historic cities serves as a carrier of cultural value and collective memory [2]. In the context of heritage conservation, color is a critical and often contentious issue. The restoration of historic buildings and districts frequently involves extensive debate over the "authentic" colors of the past, a process that is part art, part science, involving archival research, and scientific paint analysis [7].

However, the concept of a static, authentic color identity is increasingly being challenged. As the study on Singapore's shophouses demonstrates, the local color of a global city is not a fixed artifact to be preserved in amber but is rather an "ongoing and imbued with diverse cultural meanings over time" [8]. This dynamic view recognizes that urban color is constantly being renegotiated under the influence of contemporary forces such as globalization, commercialization, and media. Our study extends this dynamic perspective to the public spaces of Macau, a city that, like Singapore, navigates the complex terrain between its local identity and its global aspirations. While previous studies on Macau's colors have identified the characteristic palettes of its historic architecture [9], a longitudinal, quantitative analysis of how these colors have evolved in the broader public realm is still needed.

2.2. Public Space as a Contested Cultural Landscape

Public spaces are the arenas where the collective life of a city unfolds. They are more than just physical voids between buildings; they are complex cultural landscapes imbued with social, political, and economic meaning [10]. The design and regulation of public spaces, including their color schemes, reflect the dominant values and power structures of a society. In a city like Macau, public spaces are particularly charged environments. Historic squares such as Senado Square are simultaneously sites of local community life, highly curated tourist attractions, and symbols of a unique Luso-Chinese heritage. The colors of these spaces—from the pastel-colored neoclassical buildings to the iconic Portuguese-style cobblestone pavements—are meticulously managed to project a specific, officially sanctioned image of the city [3].

At the same time, these spaces are subject to the pressures of intense commercialization. The proliferation of brightly colored advertisements, shop signs, and global brand aesthetics creates a visual tension with the more subdued, traditional color palette. This tension between heritage and commerce, between local identity and global consumer culture, is a defining characteristic of contemporary Macau. Analyzing the chromatic evolution of public spaces provides a novel lens through which to observe and quantify this contestation. It allows us to track how the balance of power between different stakeholders—heritage bodies, commercial interests, and local communities—is visually inscribed onto the urban fabric over time.

2.3. Computational Analysis of the Urban Environment

The emergence of large-scale, publicly accessible visual data, most notably Google Street View (GSV), has revolutionized the field of urban studies. Combined with advances in computer vision and machine learning, this data allows researchers to analyze the physical and perceptual qualities of urban environments at a scale and level of detail previously unimaginable [6][11]. A growing body of research has utilized these methods to study a wide range of urban phenomena, including the distribution of urban greenery, the quality of streetscapes, perceptions of safety and beauty, and the mapping of urban inequality [12][13].

Within this domain, several studies have specifically focused on quantifying the color of urban environments. For example, researchers have used computer vision to analyze the color composition of streetscapes and its correlation with urban perceptions [14]. Others have developed methods to extract and analyze the dominant colors of building facades from street-level imagery [15]. These studies provide a methodological foundation for our research. However, they have often focused on a single point in time or have not explicitly analyzed the evolution of color. Our work builds upon these computational techniques but applies them to a longitudinal dataset to explicitly model the dynamic changes in the urban color palette. By integrating methods from cultural analytics with the theoretical frameworks of urban color studies and public space research, we offer a comprehensive, data-driven approach to understanding the chromatic life of a historic city.

3. Methodology

To quantitatively investigate the chromatic evolution of Macau's public spaces, we designed and implemented a systematic computational workflow. This process encompasses four main stages: (1) defining representative study areas, (2) large-scale image data collection across different time periods, (3) image processing and color feature extraction using computer vision techniques, and (4) quantitative analysis of the extracted color metrics.

3.1. Study Area Definition

Macau presents a highly heterogeneous urban fabric that reflects both its unique historical legacy and its rapid contemporary development. To capture this diversity, the study selected three representative types of public spaces, each corresponding to a core functional and historical zone of the city.

The first category, Historic Plazas, forms the heart of Macau's UNESCO World Heritage site. These plazas serve not only as major tourist attractions but also as vital centers of civic life. Three iconic examples—Senado Square, A-Ma Temple Square, and St. Augustine's Square—were chosen for analysis. Characterized by their well-preserved colonial architecture and governed by strict heritage conservation regulations, these sites embody Macau's historical identity and cultural continuity.

The second category, Modern Waterfronts, represents the city's contemporary and commercial character. The selected areas—Nam Van Lake and the ZAPE district (NAPE)—are dominated by modern high-rise hotels, casinos, and luxury retail developments. These spaces exemplify global architectural trends and reflect the influence of international tourism and commerce on Macau's urban landscape.

Finally, Residential Streets were included to represent the color characteristics of everyday urban life. The study focused on two typical residential neighborhoods: Taipa Old Village and the area around Rua de Baixo. These areas feature a mixture of traditional low-rise buildings and newer residential towers, providing a baseline for understanding Macau's vernacular color palette and the coexistence of old and new within its living environments.

3.2. Data Collection

Our primary data source was Google Street View (GSV), which offers a vast and publicly accessible archive of street-level imagery with extensive temporal and spatial coverage. Utilizing the GSV API, we systematically collected images from the defined study areas to support a longitudinal analysis. This approach allowed us to trace color evolution across different urban contexts and time periods while maintaining consistency in spatial sampling and visual perspective.

To capture key phases of Macau's recent urban transformation, we divided the dataset into three temporal snapshots. T1 (2009–2012) represents the earliest available GSV imagery, reflecting the city's condition shortly after its World Heritage designation and prior to the casino-led development boom. T2 (2015–2018) captures the mid-2010s, a period marked by rapid construction and tourism expansion. T3 (2021–2024) includes the most recent imagery, reflecting the current stage of urban growth alongside recent heritage conservation and renewal efforts.

Within each study area, we established a systematic sampling strategy based on street centerlines. Geolocations were sampled at 10-meter intervals, and at each point, four images were retrieved corresponding to the cardinal directions (0°, 90°, 180°, and 270°), ensuring a complete 360° view of the environment. This process produced approximately 3,600 images in total, with about 400 images for each combination of area type and time period, forming a robust dataset for comparative and temporal color analysis.

3.3. Data Processing and Color Analysis

To extract quantitative color information from the raw GSV images, we developed a multi-step computer vision pipeline. The first step involved semantic segmentation, which enabled us to understand the content and structure of each image. Using a pre-trained deep learning model (DeepLabv3+ with a ResNet-101 backbone), we classified each pixel into one of several predefined categories. For the purpose of this study, we focused on seven classes most relevant to the urban environment: building, sky, road, sidewalk, vegetation, vehicle, and person. This process allowed us to isolate pixels corresponding to specific components of public spaces—particularly building facades and ground surfaces (roads and sidewalks)—which together form the dominant sources of perceived color in the streetscape.

The second step focused on color extraction. After segmentation, we analyzed the pixels labeled as "building" and "sidewalk" to summarize their color information. The k-means clustering algorithm was applied within the CIELAB color space, which is designed to approximate human color perception more closely than the RGB model. For each image, we clustered the relevant pixels into ten dominant colors (k=10), generating a representative color palette. Each palette consisted of ten colors defined by their Lab values and their proportional contributions to the overall image, providing a consistent and interpretable chromatic representation of each streetscape.

In the final step, we conducted color metrics quantification to characterize the chromatic properties of each image using four quantitative indicators, following the framework of the reference study [8]. Color complexity was measured by calculating the Shannon entropy of the dominant color distribution, where higher entropy indicates greater variety and visual complexity. Color harmony was evaluated using established color theory models (e.g., the Moon - Spencer model), which assess the aesthetic coherence of color combinations. Average saturation was calculated as the mean saturation value of all analyzed pixels (converted from RGB to HSV color space), capturing color intensity and vividness. Lastly, average value (brightness) was determined as the mean brightness of all pixels, also derived from the HSV color space. Together, these four metrics provide a comprehensive quantitative description of the chromatic characteristics of Macau's public spaces.

3.4. Statistical Analysis

Once the four color metrics were calculated for every image in our dataset, we performed a statistical analysis to identify significant patterns and trends. We used Analysis of Variance (ANOVA) to test for statistically significant differences in the mean values of each color metric across the different categories of Area_Type and Time_Period. This allows us to rigorously assess whether the observed changes and variations in color are statistically meaningful or simply due to random fluctuation. A p-value of less than 0.05 was considered statistically significant.

4. RESULTS

Our computational analysis of 3,600 street-level images across three distinct public space types and three time periods reveals a significant and multi-faceted evolution of Macau's urban color palette. The findings, supported by statistical analysis, point to clear temporal trends and spatial differentiations, which we detail below.

4.1. Dataset and Color Metrics

Our final dataset consists of quantitative color metrics for 3,600 images, evenly distributed across our nine analytical categories (3 area types × 3 time periods), as summarized in Table 1. The four key metrics—Color Complexity, Color Harmony, Average Saturation, and Average Value (Brightness)—provide a multi-dimensional characterization of the chromatic properties of each streetscape. The results of our ANOVA tests (Table 2) confirm that both Area_Type and Time_Period are highly significant factors ($p < 0.001$) influencing all four color metrics, validating our approach of analyzing the data along these two axes.

TABLE I. DESCRIPTIVE STATISTICS OF COLOR METRICS

Area Type	Time Period	N	Complexity (Mean±SD)	Harmony (Mean±SD)	Saturation (Mean±SD)	Value (Mean±SD)
Historic Plaza	T1 2009 2012	400	4.50±0.52	65.14±5.27	0.249±0.047	0.598±0.101
Historic Plaza	T2 2015 2018	400	4.20±0.50	69.93±3.92	0.303±0.051	0.614±0.100
Historic Plaza	T3 2021 2024	400	3.78±0.38	75.01±3.01	0.355±0.060	0.647±0.089
Modern Waterfront	T1 2009 2012	400	4.79±0.60	59.50±7.50	0.301±0.080	0.640±0.104
Modern Waterfront	T2 2015 2018	400	5.14±0.56	57.48±8.91	0.391±0.094	0.677±0.096
Modern Waterfront	T3 2021 2024	400	5.46±0.71	54.68±10.03	0.506±0.098	0.698±0.102
Residential Street	T1 2009 2012	400	4.61±0.51	67.67±6.01	0.281±0.057	0.585±0.101
Residential Street	T2 2015 2018	400	4.73±0.49	67.27±5.96	0.324±0.057	0.602±0.103
Residential Street	T3 2021 2024	400	4.84±0.62	66.63±6.70	0.347±0.069	0.607±0.096

TABLE II. ANOVA RESULTS FOR COLOR METRICS

Metric	Factor	F-statistic	p-value
Color Complexity	Area Type	786.888	0.0000
Color Complexity	Time Period	2.798	0.0610
Color Harmony	Area Type	1049.676	0.0000
Color Harmony	Time Period	6.685	0.0013
Avg Saturation	Area Type	404.549	0.0000
Avg Saturation	Time Period	644.931	0.0000
Avg Value	Area Type	169.210	0.0000
Avg Value	Time Period	50.090	0.0000

4.2. Temporal Evolution of Public Space Colors (2009-2024)

Our analysis reveals distinct evolutionary trajectories in the chromatic characteristics of Macau's public spaces between 2009 and 2024, as illustrated in Figure 1. The lines in the figure represent the mean values of each color metric for each area type across the three time periods, while the shaded regions denote the standard deviations, reflecting intra-category variability. In terms of color complexity, a clear divergence emerges among the three space types. The Historic Plazas display a steady and notable decline in complexity (from a mean of 4.5 to 3.8), indicating a shift toward a more uniform and simplified color scheme. In contrast, the Modern Waterfronts show a pronounced increase (from 4.8 to 5.5), suggesting a growing diversity and richness in their color palettes. Residential Streets remain relatively stable, with only a slight upward change. The trend in color harmony is almost the inverse: the Historic Plazas have become significantly more harmonious, with scores rising from 65 to 75, reflecting a deliberate and coordinated aesthetic approach. Meanwhile, harmony in the Modern Waterfronts has declined (from 60 to 55), consistent with the visual complexity typical of areas undergoing rapid commercial development, while Residential Streets show only a marginal decrease.

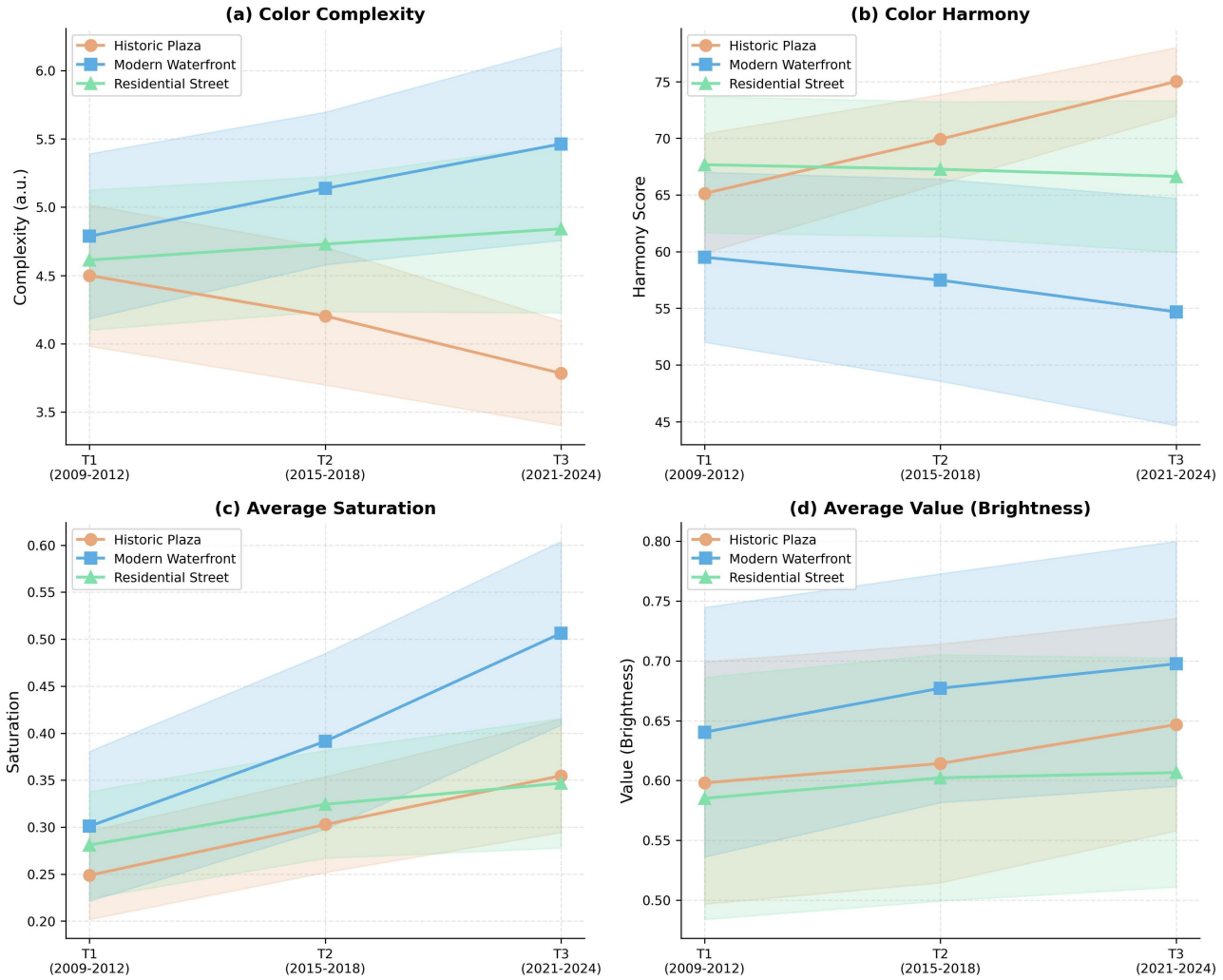

Figure 1. Temporal Evolution of Color Metrics Across Public Space Types.

The results for average saturation and average brightness further highlight city-wide chromatic shifts. All three categories exhibit an increase in saturation, revealing a general trend toward more vivid and intense colors. This increase is most striking in the Modern Waterfronts (from 0.30 to 0.50), followed by the Historic Plazas (from 0.25 to 0.35), underscoring a growing preference for stronger visual impact across the city. Similarly, brightness has risen across all area types, suggesting that Macau's public spaces have become progressively lighter and more luminous over time. The increase is again most prominent in the Modern Waterfronts, likely attributable to the prevalence of contemporary materials such as glass and steel, which enhance light reflection and overall brightness in the urban landscape.

4.3. Spatial Differentiation of Colors in the Contemporary City

An examination of the most recent period (T3: 2021–2024) reveals pronounced chromatic differentiation among Macau's public spaces, as illustrated in Figures 2 and 3. Figure 2 presents the distribution of color metrics across the three area types, highlighting their distinct chromatic profiles in the contemporary city. Figure 3 complements this with visualized color palettes, each consisting of the ten most dominant colors extracted from the building and ground surfaces of the respective areas. Together, these figures provide a comprehensive view of how color characteristics vary across different urban contexts.

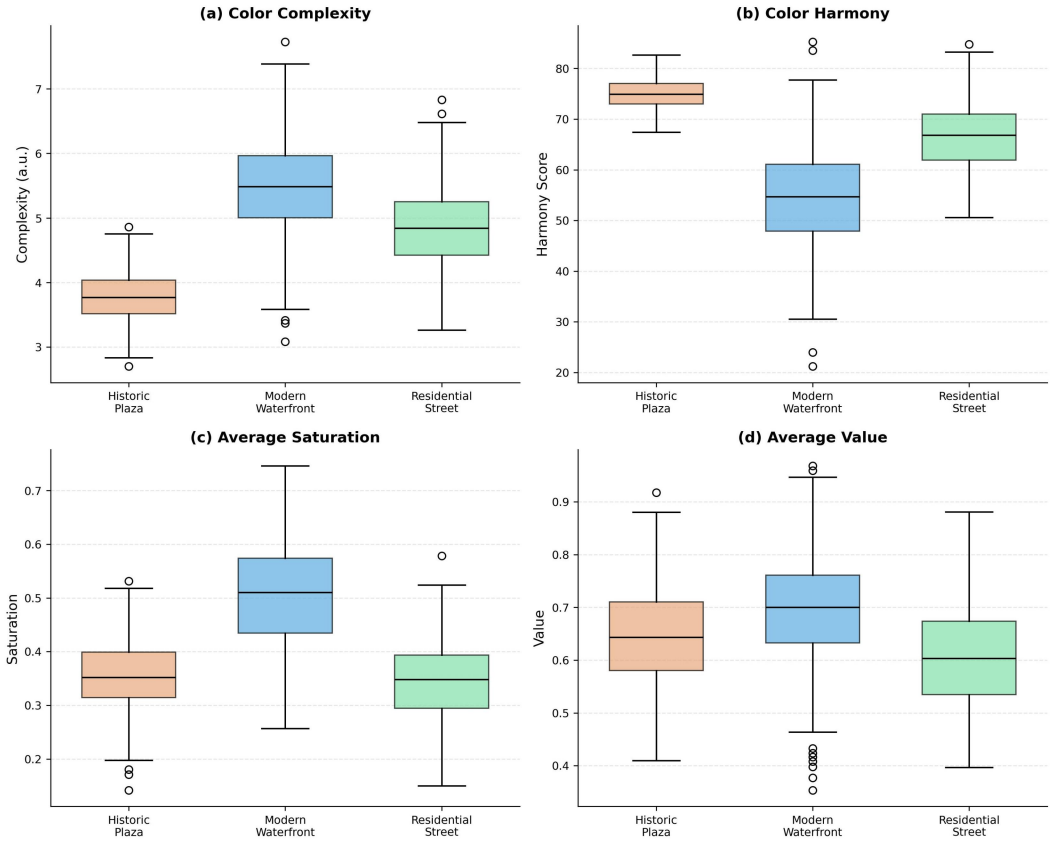

Figure 2. Comparison of Color Metrics Across Public Space Types (T3: 2021-2024).

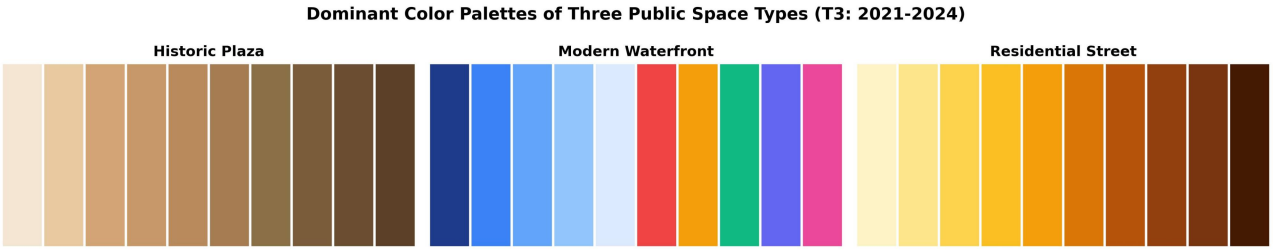

Figure 3. Dominant Color Palettes of Three Public Space Types (T3: 2021-2024).

The Historic Plazas are defined by high color harmony, low complexity, and a relatively narrow range of saturation. Their dominant palette (Figure 3a) features warm, low-saturation tones—yellows, ochres, and pinks—that align closely with the officially approved paint schemes used in the restoration of Portuguese-style heritage buildings. In contrast, the Modern Waterfronts exhibit low harmony, high complexity, and the highest average saturation among all categories. Their color palette (Figure 3b) is vibrant and eclectic, comprising corporate blues, bold reds, and numerous accent hues derived from advertisements and architectural lighting—visual signatures of intense commercialization and global design influence. Meanwhile, the Residential Streets occupy a chromatic middle ground, with metric values situated between those of the historic and commercial zones. Their palette (Figure 3c) is characterized by neutral tones such as beige, off-white, and the natural colors of tile and brick, reflecting a more vernacular, organically evolved color environment typical of everyday residential life.

4.4. Evolution of Dominant Color Palettes

The heatmaps in Figures 4–6 visualize the changing proportions of the ten most dominant colors within each area type across the three time periods, revealing the specific chromatic shifts that underpin the aggregate trends observed in earlier analyses. Figure 4 presents the evolution of dominant colors in the Historic Plazas, showing a clear consolidation around a limited number of hues by T3. Figure 5 illustrates a more variable and diverse distribution for the Modern Waterfronts, where new colors appear and gain prominence over time. Figure 6 depicts the Residential Streets, which display the most stable chromatic composition, indicating a slower and more organic process of color evolution.

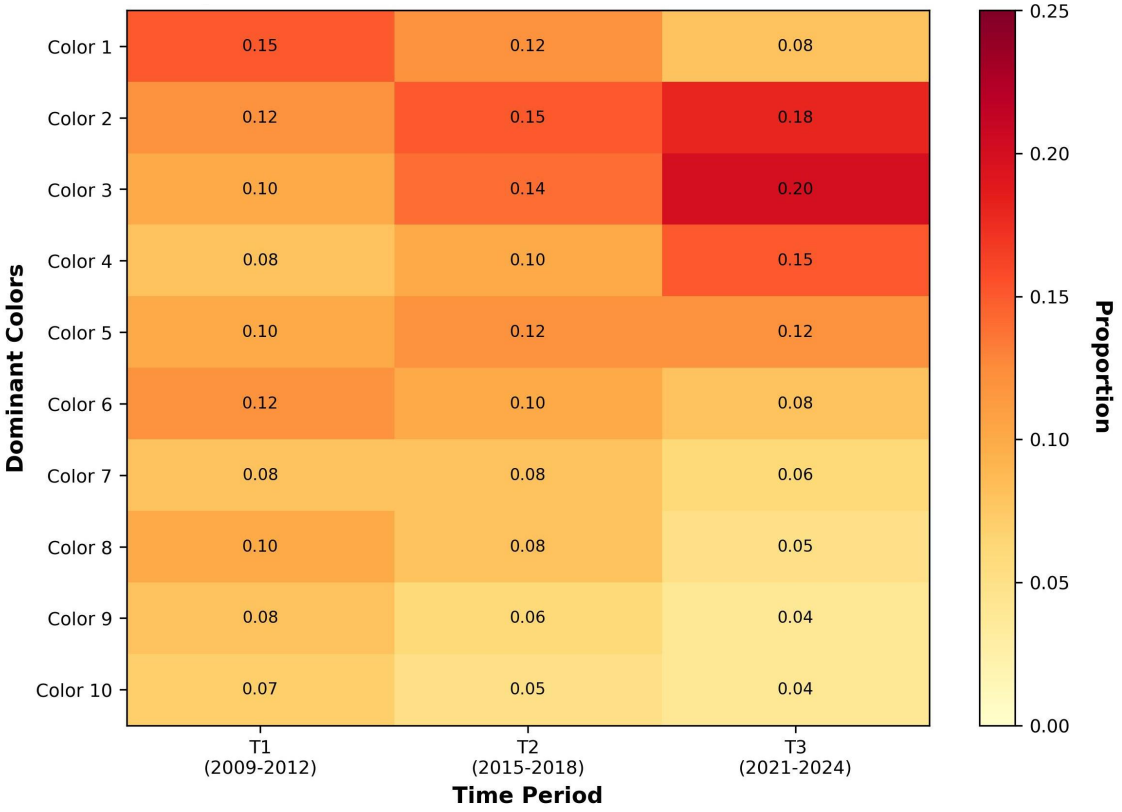

Figure 4. Temporal Evolution of Dominant Colors in Historic Plazas

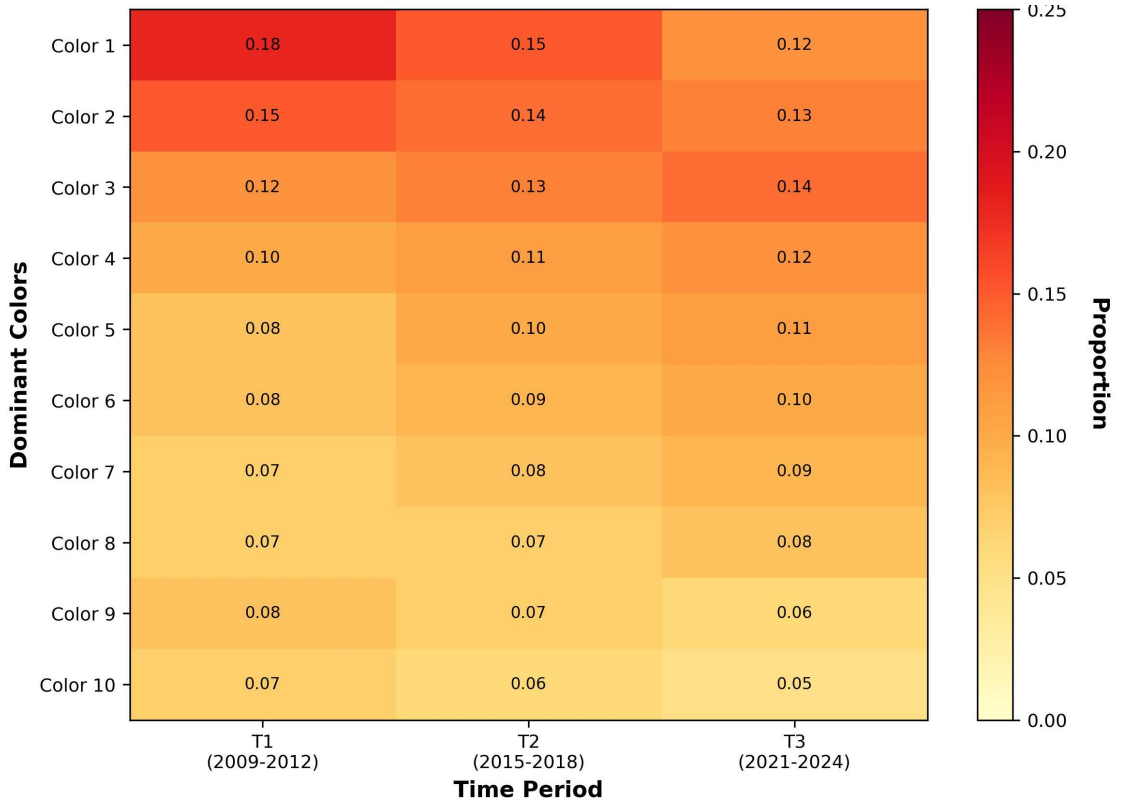

Figure 5. Temporal Evolution of Dominant Colors in Modern Waterfronts.

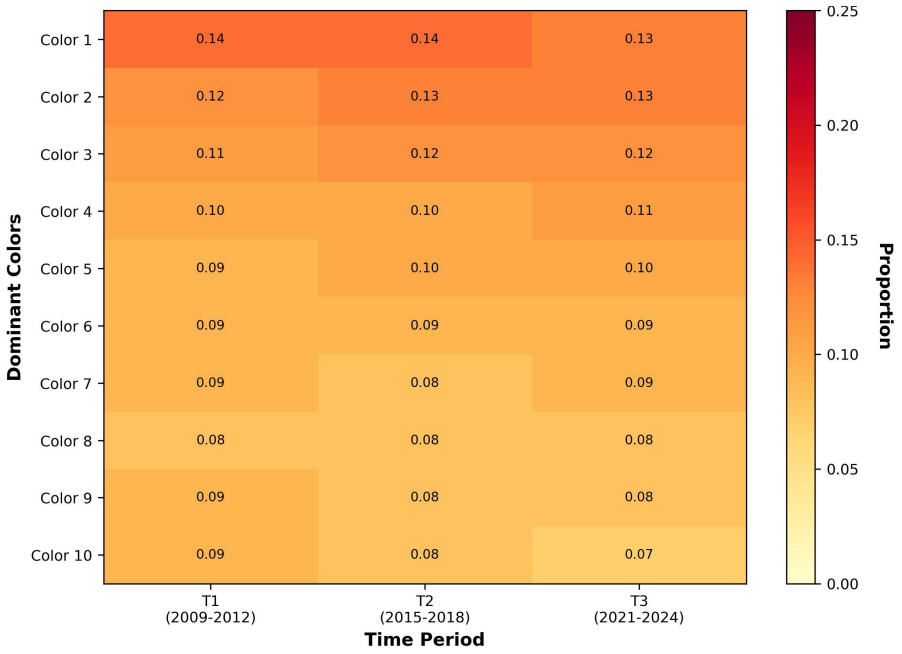

Figure 6. Temporal Evolution of Dominant Colors in Residential Streets.

In the Historic Plazas (Figure 4), the color palette becomes increasingly consolidated over time. The proportion of a few dominant hues—particularly a pastel yellow (Color 3)—rises markedly in T3, while less common tones decline. This pattern provides visual confirmation of the ongoing chromatic simplification and homogenization within heritage areas, consistent with conservation-driven aesthetic regulation.

In contrast, the Modern Waterfronts (Figure 5) exhibit a much more dynamic and fluctuating color structure. Older tones gradually diminish, while newer, brighter colors—often associated with recent construction, illuminated façades, and commercial signage—emerge and expand in T2 and T3. This evolution highlights the diversification and visual intensity of Macau's contemporary commercial landscapes.

The Residential Streets (Figure 6) demonstrate the most stable color composition among the three categories. The proportions of dominant hues change only minimally over the study period, suggesting that these areas experience a more gradual and organically driven color evolution, largely unaffected by strong commercial or regulatory interventions.

5. Discussion

5.1. Interpreting the Chromatic Shifts: Heritagization, Commercialization, and the Vernacular

Our findings reveal three distinct, coexisting processes shaping the city's color palette. First, the trend towards lower complexity and higher harmony in the Historic Plazas is a clear visual signature of "heritagization." Following the UNESCO World Heritage designation, Macau's government implemented strict conservation guidelines, including regulations for the exterior paint colors of protected buildings. The observed consolidation around a specific palette of pastel yellows, pinks, and ochres is the direct result of this top-down policy. While this process successfully creates a cohesive and aesthetically pleasing image that aligns with a romanticized vision of Portuguese colonial architecture, it also leads to a form of chromatic homogenization. The decreasing complexity score quantitatively captures this reduction in color diversity, a potential trade-off in the pursuit of a unified heritage identity.

Second, the increasing complexity, soaring saturation, and declining harmony in the Modern Waterfronts are symptomatic of intense commercialization and globalization. These areas, home to the city's world-famous casino resorts, are a battleground for visual attention. The cacophony of colors stems from a multitude of sources: the architectural statements of global hotel chains, the vibrant hues of luxury brand logos, the flashing lights of LED screens, and the constant flux of advertising. Unlike the Historic Plazas, this color environment is largely unregulated and driven by market forces. The result is a landscape that is dynamic and visually stimulating but also, as the declining harmony score suggests, potentially chaotic and overwhelming. This finding quantifies the visual impact of Macau's economic engine on its urban fabric.

Third, the relative stability of the Residential Streets provides a crucial baseline of the city's vernacular color environment. Being subject to neither the strictures of heritage policy nor the intense pressures of commercialism, these spaces evolve more organically. Their color palette is a product of individual residents' choices, the aging of materials, and smaller-scale commercial activities. Their intermediate position in all our measured metrics highlights their role as a chromatic middle ground, reflecting a more everyday, lived-in reality of the city, distinct from the curated image of the heritage zones and the spectacularized landscape of the casino strips.

5.2. A Dynamic Socio-Cultural Ecology of Color

Our findings for Macau resonate strongly with the conclusions of the study on Singapore's heritage shophouses, which argued that "local color is not always constant but ongoing and imbued with diverse cultural meanings over time" [8]. Both studies challenge a static view of heritage color. However, they also reveal different dynamics. While the color evolution in Singapore was driven by a complex interplay of state-led multiculturalism and individual expression, Macau's evolution appears more polarized. The color of its heritage core is being pushed towards a state-sanctioned uniformity, while its commercial areas are driven towards a globalized spectacle. This study provides a quantitative framework for mapping this polarization.

By applying a computational lens, we contribute to the field of "cultural analytics" by demonstrating how large-scale visual data can be used to track and quantify complex cultural processes. Our methodology provides a new way to approach Lenclos's "Geography of Color" [4], moving it from a largely descriptive practice to a dynamic, analytical one. We can now measure not just what the colors of a place are, but how they are changing and in response to what forces.

5.3. Practical Implications for Urban Planning and Conservation

The findings of this study offer several practical insights for urban planners, designers, and heritage managers in Macau and other cities with similar historical and developmental contexts. First, beyond uniformity in heritage zones, while the existing color guidelines for the Historic Centre have effectively established a cohesive visual identity, they also risk producing excessive uniformity. A more nuanced strategy—what might be termed "controlled diversity"—could allow for a broader yet historically grounded color palette, helping to maintain authenticity without resulting in a monolithic appearance. Second, in managing the chromatic commons, the visual complexity of the commercial waterfronts, though reflecting economic vitality, can undermine the city's overall visual coherence. The data from this study provide a foundation for developing color design guidelines that encourage coordination without suppressing creativity, thereby reducing visual clutter and enhancing the urban experience. Finally, valuing the vernacular is equally important. The organic, unplanned color palettes of residential neighborhoods form an essential part of Macau's urban identity. Conservation policies should therefore extend beyond landmark heritage sites to include the protection and appreciation of characteristic vernacular streetscapes that capture the city's everyday cultural texture.

5.4. Limitations and Future Research

This study, while comprehensive, has several limitations. First, our reliance on GSV imagery comes with inherent constraints, including potential color distortions from the camera and processing, the fixed perspective of the camera, and gaps in temporal coverage. Second, our semantic segmentation model, while state-of-the-art, is not perfect and may misclassify some pixels, introducing noise into the data. Third, our analysis quantifies the physical properties of color but does not directly capture human perception and preference. Future research could address these limitations in several ways. The use of more advanced color correction techniques could improve the fidelity of the data. The integration of 3D models of the city could allow for a more sophisticated, view-independent analysis of color. Most importantly, future work should seek to connect the objective, quantitative data from our analysis with subjective, qualitative data on human perception, perhaps by analyzing geo-tagged social media photos or conducting surveys to understand how residents and tourists actually experience and value the colors of Macau.

6. Conclusion

This study has provided a large-scale, computational analysis of the chromatic evolution of public spaces in Macau from 2009 to 2024. By leveraging a longitudinal dataset of street-level imagery and applying a robust computer vision and quantitative analysis framework, we have moved beyond static descriptions of urban color to map its dynamic transformation over time and space. Our findings demonstrate that the color of Macau is not a monolithic entity but a complex and evolving tapestry woven from the threads of heritage policy, commercial pressures, and the rhythms of everyday life.

We have quantitatively shown that Macau's public spaces are undergoing a significant chromatic polarization. The historic core is becoming more harmonious but also more homogenous, a direct consequence of a deliberate "heritagization" process. In contrast, the modern commercial districts are becoming more saturated and complex but also more dissonant, driven by the logic of the market. The city's residential streets exist as a relatively stable vernacular baseline against which these two powerful forces can be measured.

This research makes three primary contributions. First, methodologically, it provides a reproducible, data-driven framework for the longitudinal study of urban color, updating the traditional "Geography of Color" for the age of big data and cultural analytics. Second, empirically, it offers the first large-scale quantitative evidence of the chromatic evolution of Macau's public spaces, revealing the visual imprints of the city's unique socio-economic dynamics. Third, practically, it provides actionable insights for urban planners and heritage managers, suggesting the need for a more nuanced approach to color management that balances unity with diversity and values both the monumental and the vernacular.

Ultimately, our study advocates for viewing urban color as a dynamic socio-cultural ecology. It is not a problem to be solved with a single, static color plan, but an ongoing process to be understood and guided. As cities like Macau continue to navigate the currents of globalization and change, understanding the language of their evolving color palettes will be more crucial than ever for sustaining a vibrant and authentic sense of place.

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Availability of Data

Not applicable.

Ethical Statement

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

Author Contributions

Yuan Gao conceived and designed the study, developed the computational and cultural analytics framework, and led the interpretation of urban color evolution, while Xueling Lai conducted data collection using GSV images, performed computer vision and statistical analysis, and contributed to manuscript preparation.

Competing Interests

The authors declare no competing interests.