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ORIGINAL ARTICLE

Seeing is believing: The colour of silver alloys and the global silver circulation in the Chinese Ming and Qing dynasties

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Abstract

This research investigates the correlation between colour perception and the circulation of silver in China during the Ming (1368–1644 CE) and Qing (1644–1911 CE) dynasties. The primary aim is to deepen our understanding of how silver alloys were perceived and experienced in this historical context while also situating our study within the broader context of the global silver trade. During the Ming and Qing dynasties, silver possessed immense historical significance as a precious commodity. We argue that copper had a more substantial influence on the final colour of silver alloys compared to lead. Furthermore, employing a colourimetric model, our Monte-Carlo simulation demonstrates that over 70% of silver from Mesoamerica to China could be discerned by nonexperts using only their unaided vision, largely due to the elevated copper content. Crucially, our simulation experiment reveals differing effects of copper and lead on the colour of silver alloys. The latter demonstrates minimal change until reaching a threshold of 15%, signifying that lead is a suitable and cost-effective substitute for silver. These findings suggest that the detection of silver purity was less demanding than previously assumed, opening up opportunities for arbitrage.

KEYWORDS

colour, Ming–Qing China, silver, Spanish coins

INTRODUCTION

Silver occurs in various forms, including native silver (relatively pure metallic silver), as a component of electrum (a natural metal containing varying amounts of gold, silver, and copper), as a silver ore (such as argentite Ag_2S or cerargyrite $AgCl$), or as a trace element in other metallic ores (e.g., up to 0.5% in galena PbS). Throughout human history, silver has been widely recognised as one of the most precious metals due to its lustre and other metallic properties. Initially, silver was primarily used for decorative purposes as it was too soft to be made into tools. However, with the development of smelting and refining technologies, which enabled the extraction of silver from ores and galena (Pernicka, 2004), it gradually transitioned from its native or electrum form to smelted silver. This advancement led to the utilisation of silver not only for decorative objects but also as one of the earliest forms of currency in many regions (Cribb, 2003; Eshel et al., 2023; Heymans, 2021).

The objectives of this article are twofold. First, it aims to conduct a series of simulation experiments to explore the intricate relationship between variations in silver colour and the recipes for silver alloys, which include copper and lead. The broader interest in colourimetric analysis, along with the utilisation of silver-based alloys created with information derived from archaeological objects, extends to various disciplines, including archaeometallurgy, technology history, archaeology, art history, decorative art design, and economic history. However, its importance has often been overlooked or disregarded compared to copper alloys, of which the colour variations caused by different alloying recipes have been extensively studied (Fang & McDonnell, 2011; Kuijpers, 2018; Liu & Pollard, 2022; Mecking, 2020; Mödlinger et al., 2017; Radivojević et al., 2018).

Second, the results of these experiments highlight the significance of silver's colour and its relevance to the historical context of silver circulation during the Ming and Qing dynasties. Due to the lack of detailed written records, there is limited information on how silver was examined and imported into China. However, simulation experiments have shown that the addition of varying proportions of copper and lead can cause distinct effects on the final colour of silver. Lead had a negligible impact, whereas the addition of copper was easily distinguishable. This provides a fundamental yet crucial benchmark to assess the potential correlation between silver quality and international trade. Building upon the new colourimetric findings, we develop a Monte Carlo simulation model. The model utilises a random sampling strategy for the kernel distribution of the chemical composition of the actual silver sycees. The colour appearance model is subsequently employed to compare the colours of randomly chosen samples from the New World and Chinese Ming and Qing datasets. The simulation was performed up to 10,000 times, which indicates that more than 70% of the silver imported from the New World to China could be identified by the untrained eye due to colour differences, primarily attributed to higher copper content. This suggests that, alongside the shape and design of New World silver, Chinese officials during the Ming and Qing dynasties were likely aware of the comparatively lower colour of this silver, even without sophisticated assay methods. This simulation fills a gap in the literature regarding the precise process of silver flow into Ming and Qing China.

SILVER AS THE GLOBAL CURRENCY: A HISTORICAL SCENARIO OF THE SILVER COLOUR

Economic history has emphasised the vital role of silver as a worldwide currency. However, silver was not initially recognised as an official means of taxation and bulk commerce in China. It was not until 1581 that the economic policy of the Single Whip reform was introduced, marking China's acceptance of silver as a currency. During the Ming dynasty, trade and exchange flourished, particularly in southeastern China, leading to an unprecedented demand for silver from domestic and international sources. This era coincided with the exploration and expansion of mining activities, especially in Japan and the Americas, along with advancements in mining and smelting technology. These developments opened up excellent trading opportunities for Europeans and other states, facilitating their interaction with China. The most significant event altering the course of silver history was the discovery of vast silver deposits in the Americas by European conquistadors following Columbus' arrival in 1492. This discovery sparked a monumental increase in silver mining, surpassing all previous production levels. Between 1500 and 1800, Bolivia, Peru, and Mexico became significant global hubs for silver production and trade. This surge in silver mining bolstered Spanish influence not only in the New World but also beyond, extending their reach and power. Overall, the discovery of silver in the Americas reshaped the history of this precious metal and had far-reaching consequences, leaving an indelible impact on the world.

Even though there has been a hot debate for many decades regarding the exact amount of silver that flowed into Ming and Qing China from foreign trading, it is evident that a significant portion of this silver relied on overseas supply. As stated by Shi (2016), the four major sources of income for the silver storage of the Qing were land tax, salt tax, customs duty, and miscellaneous. During the Ming and Qing periods, the customs duty varied from 5% to 20%, but it unquestionably fell short of the total amount of silver entering China through unofficial channels like smuggling. Alongside foreign trading, the circulation of silver in the Chinese domestic market was similar, if not more complex. Silver was primarily utilised for taxation, the salaries and expenses of government officials and soldiers, and large transactions. Conversely, daily commercial activities were conducted using copper strings and fragmented silver pieces. There were even instances in which silver bullion had to be debased and transformed into smaller pieces for further circulation. Spanish or British silver coins could also be utilised in Chinese markets during the late Qing dynasty.

Sun et al. (2021) observed significant discrepancies in silver purity between New World coins and Chinese Ming and Qing coins (Figure 1). This raises the question of whether customs officials were aware of these differences rather than solely relying on their sensory perception. Moreover, this relates to the broader issue of economic viability in global trade. Lead and

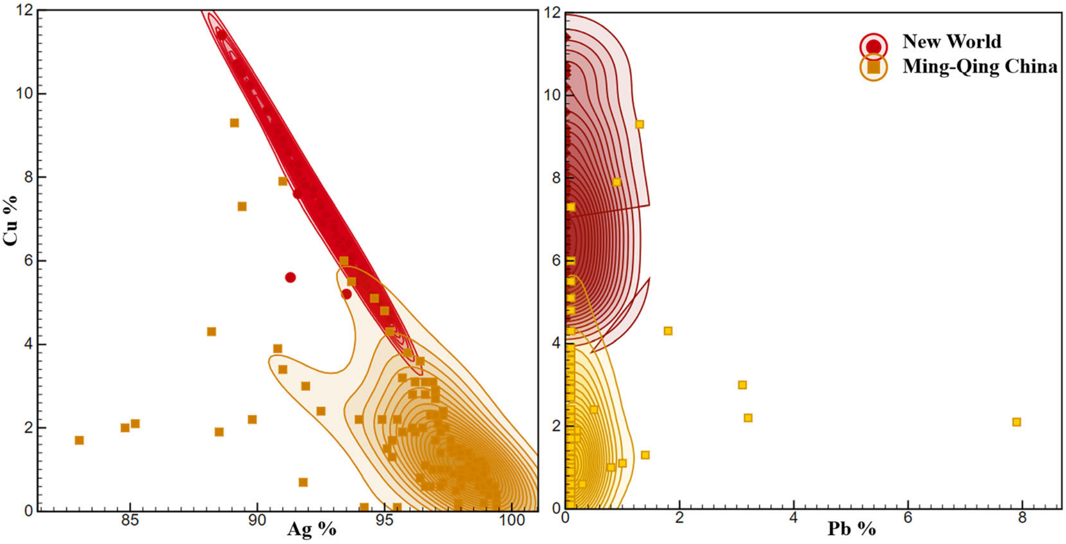


FIGURE 1 The comparison of the kernel density distribution of Cu, Sn and Pb in the silver coinage/bullion between the New World and Ming–Qing China (data from Sun et al., 2021 online supplementary material).

copper are commonly added during the production of silver coins. Because lead is more easily accessible than other precious metals like gold, silver, copper, or tin, it is frequently used as a cost-effective alternative in alloys. Additionally, copper has played a significant role as an alternative alloying element. The practice of adulterating silver coins with lead and copper was not uncommon. Song Yingxing, a Chinese scientist and encyclopedic scholar, documented this practice in his 1637 book, *Tiangong kaiwu*. According to the book, lead and copper were extensively used for adulterating silver coins during that period. Hence, we believe that current casting experiments can provide a valuable reference list of materials to address this matter.

TRADITIONAL METHODS OF SILVER ASSAYING IN CHINA

Although there is a dearth of written records specifically detailing the assaying process for silver circulation during the Ming–Qing period, we can glean some insight by examining historical methods employed in China. Silver as a form of currency in China can be traced back to the Warring States period (475–221 BCE), substantiated by the discovery of silver coins (known as *yin bu bi*) in 1974 (Hao, 1985). Silver may not have been the predominant currency throughout Chinese history, but the refinement of silver remained a crucial technique in Chinese technological advancement. One example is the traditional Chinese cupellation method, *hui chui fa*. This technique was elucidated in the textual record of the Eastern Han period (25–220 CE), the *Catalogue of Mining* (*chu jin kuang tu lu*). The text explains the process of melting silver and lead together, allowing the silver to dissolve within the lead. The silver could be purified by introducing air to oxidise and separate the lead as litharge. As silver gained widespread acceptance and usage as currency across all social strata, the visual properties of silver became increasingly important. This was because the colour of a silver sycee determined its value, making it a critical factor in transactions and assessments of wealth.

This article summarises various physical and chemical methods historically used to identify the colour of silver. These methods are semiquantitative and have been utilised to assess and determine the colour of silver, which was considered a quick way to determine the quality of a silver alloy. In Sima Qian's book, *Records of the Grand Historian* (*shiji*), three types of gold (*jin*) were described: yellow, white, and red, indicating different metal grades. However, in this context, *jin* can be interpreted as copper or copper alloy instead of gold (Liu & Pollard, 2022). As silver became increasingly significant in Chinese currency history, the descriptions of silver colour became more precise during the Ming and Qing dynasties. High-frequency terms, such as *ba cheng* (means 80% of silver content), *jiu cheng* (90%), and *jiuwu cheng* (95%), were used to denote different silver contents in the Chinese language. Place names, such as Shanxi silver, were also used to indicate silver contents, with Shanxi silver referring to silver with a content of 93%.

Furthermore, during the Ming and Qing dynasties, there was a significant emphasis on understanding the intricate relationship between the colour of silver and its surface appearance. This played a crucial role in identifying and evaluating silver during that time. Examples of this emphasis can be found in *The Essential Criteria of Antiques* (*xinzeng gegu yaolun*), written by Cao Zhao in the early Ming dynasty. According to Cao Zhao's writings, certain surface characteristics indicated the presence of various impurities in silver. For example, black marks and a lack of lustre indicated the presence of black lead inside the silver. Silver with around 80% silver content was called dog flea marks (*gou zao ban*). When silver had a 90% silver content, it would turn dead white after being burnt, and the edges would appear grey, resembling a grain-like pattern resembling pine wood, which was known as '*chui song wen*' in Chinese. Silver with a 96% silver content was called snow white (*xuebai*). These descriptions from Cao Zhao's writings provide valuable information on the significance of colour in discerning the quality of silver during this period. Also, it allows us to know that copper and lead were commonly used to dilute the purity of silver.

Once the various colours associated with different levels of silver content have been identified, the next step involves the process of accurately determining and confirming the specific colour of the silver (Yang, 1989; Zhao, 1984). First, one method used for this purpose is the touchstone test, which is a quick and straightforward way to assess the colour of silver. This test involves using a piece of black carbonite as a touchstone, and the colour produced when the silver strikes the touchstone indicates the purity of the silver. The original content of the silver can be determined by comparing the colours of the studied metals with those of standard metals (such as gold/silver base alloys with known formulas) when struck on the touchstone. The touchstone is made from carbon-black stones sourced from the Lan Zhou Yellow River and the Lower reach of E Zhou (Du Wan, 1133). The exact origins of the use of touchstones in China are unclear; Joseph Needham (1974) dates their use back to 1387, but there are records of their use in documents dating back to the pre-Qin period, suggesting that their use may be related to metal grinding stones (Zhang, 1927). For example, yellow silver, derived from the present-day Sichuan region, appears similar to gold in appearance but leaves a white mark on the touchstone (Zhang Shu). Other physical methods for assessing the colour of silver include analysing the sound produced when crushed silver is dropped on a hard surface and measuring its density.

Second, the establishment of professional organisations and individuals in the field has played a significant role. In the aftermath of the Opium War, the creation of the Bureau of Public Valuation aimed to regulate the circulation of silver ingots in the market. This involved a two-step appraisal process: weighing the silver and relying on a professional (known as *kan se ren*) to observe and evaluate its colour. These assessments were conducted through visual and auditory observations without using precise instruments. Despite being based on ancient colour standards passed down through oral tradition, these evaluations are believed to be in line with more complex chemical methods (Liang et al., 2021).

Therefore, the chemical methods used for assaying silver likely originated from early alchemy and metallurgical practices, mainly refining techniques. A straightforward method involves comparing the weight of silver before and after refining, such as cupellation. The development of the Deng scale during the Northern Song dynasty (960–1127 CE) significantly enhanced the accuracy of weighing. This groundbreaking invention allowed measurements as precise as 40 mg, leading to significant advancements in Chinese medical history. Subsequently, the Deng scale was widely adopted in official and commercial activities. It is considered one of the earliest techniques for assaying silver before discovering nitric acid.

SIMULATION EXPERIMENT AND ANALYTICAL METHODS

The simulation experiment

Twenty-five samples were produced based on different recipes (Table 1) to encompass the significant variations of copper and lead in the historical silver currency shown in Figure 1. The silver, lead, and copper used in this study were commercially available and had an initial purity of 99.9%. These elements were weighed to 100 g and thoroughly mixed before being melted and cast. The casting process utilised traditional tools such as small crucibles and clay moulds. Subsequently, the resulting samples were cut into blocks measuring 5 * 5 * 5 cm in size and subjected to further analysis.

Compositional analysis

The Bruker Tracer 5i X-ray Fluorescence (XRF) was used to analyse the samples' composition before and after casting. The analysis was conducted under specific conditions, including an

TABLE 1 Averaged composition and colourimetric data of casting samples (bdl, below detect limit, see Data S2 for raw data).

	Recipe (g)			Composition after casting				Chroma data		
Sample no.	Ag	Cu	Pb	Fe	Cu	Ag	Pb	L	a	b
1	100	0	0	0.9	bdl	99.1	bdl	88.64	−0.21	3.43
2	97	0	3	0.6	bdl	92.8	3.2	90.4	−0.37	2.02
3	94	0	6	0.3	bdl	93.4	6.3	89.42	−0.43	3.04
4	91	0	9	1.2	bdl	81.3	16.6	87.74	−0.37	3.68
5	85	0	15	bdl	bdl	83.8	16.1	87.75	−0.49	3.89
6	97	3	0	bdl	3.2	96.8	bdl	92.39	−0.61	2.66
7	94	3	3	0.1	3.0	93.5	3.4	91.29	−0.77	2.29
8	91	3	6	bdl	3.2	91.0	5.8	90.73	−0.61	3.37
9	88	3	9	bdl	3.3	87.6	9.1	85.19	−0.07	6.58
10	82	3	15	bdl	3.6	82.2	14.2	82.66	−0.07	6.91
11	94	6	0	bdl	6.3	93.7	bdl	89.13	−0.4	5.56
12	91	6	3	bdl	6.4	90.8	2.7	90.84	−0.61	5.22
13	88	6	6	bdl	6.9	86.6	6.5	86.35	−0.28	6.71
14	85	6	9	bdl	6.4	84.9	8.7	84.46	−0.03	7.03
15	79	6	15	bdl	7.2	76.1	16.7	82.4	0.11	6.91
16	91	9	0	0.3	9.6	89.8	0.3	86.89	0.5	7.67
17	88	9	3	bdl	9.4	88.4	2.2	91.26	−0.57	7.06
18	85	9	6	bdl	10.2	83.5	6.3	86.86	−0.34	6.02
19	82	9	9	bdl	10.1	80.4	9.5	83.28	−0.03	6.84
20	76	9	15	bdl	10.6	72.3	17.1	85.27	0.53	7.12
21	85	15	0	bdl	16.6	82.9	0.5	76.98	1.98	13.37
22	82	15	3	bdl	14.2	84.4	1.4	87.92	−0.44	8.33
23	79	15	6	bdl	16.6	78.0	5.5	87.92	0.34	8.3
24	76	15	9	bdl	16.6	74.7	8.8	85.99	0.74	7.42
25	70	15	15	bdl	19.0	65.5	15.5	81.65	1.42	8.66

8 mm detector spot, a voltage 40 Kv, and a current of 40 μA. The analytical time for each sample was set to 30 s using the precious metal mode. To prepare the samples for analysis, they were cut through and then polished to create cross sections. Three points were chosen across each cross section, and the results from these points were averaged to determine the bulk composition. Before each analysis, a calibration was performed using a sterling silver standard with a composition of 95% Ag and 5% Cu (sterling silver). This calibration ensured accurate measurements. The detect limit of the instrument was determined to be 0.1%, meaning that any element present in the sample at concentrations below this limit would not be detected.

Photography

Photos were taken by the HR-2016, AC-2016VD camera lens under the magnification of 20x with the high intensity LED light source (temperature 5700 K), close to day light colour temperature. Subjective to the different shape and surface size of the sample, photos were taken in either single or auto photo stitching capturing mode.

Colourimetric analysis

Although describing colour may seem standard in everyday life, it is an incredibly challenging task in the realm of science. This is because the perception of colour is influenced by numerous factors, including the electromagnetic wavelength of the light source, the object itself, the surrounding physical environment, and even the sociocultural background of the viewers. It was not until 1931 that the Commission Internationale de l'Éclairage (CIE) recommended the widely used colour measurement model, CIE-XYZ, which assumes that all colours can be mixed and reproduced using red, green, and blue. However, this model fails to objectively assess the differences between types of colours. To address this limitation, CIE-Lab was developed, which incorporates the brightness value and calculates three new parameters (L, a, b) from the XYZ values. This allows for the measurement of colour differences under standard viewing conditions. The L value represents the brightness, with 100 indicating white and 0 indicating black. A value represents the proportion of green and red, with positive values indicating red and negative values indicating green. The b value represents the proportion of yellow to blue, with positive values indicating yellow and negative values indicating blue. The following equations can be used to calculate the distance (△E) between two colours or two sets of Lab values: $\triangle E = [(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2]^1/^2$, where subscripts 1 and 2 denote different sets of Lab values derived from the colours of the two objects being examined.

Table 2 provides a summary of the relationship between different △E values and the perception of colour differences, with more details available in Fairchild (2005). For this particular study, chromaticity analysis was conducted using a portable X-rite SP64 Portable Sphere Spectrophotometer equipped with a pulsed tungsten lamp light source positioned vertically at 90° to the cross section of the sample. Three consecutive measurements were taken, and the average value for each sample is presented in Table 1. All raw data can be found in Data S2. The measurements were taken within a sphere measurement area with a diameter of 1 cm.

RESULTS AND DISCUSSION

Eye perception of colour differences

Even when observed without the aid of sophisticated equipment, it is evident that there is no simple or linear relationship between the alloying recipes used and the resulting colour of the samples. As copper and lead are added to the alloy, the brightness of the sample decreases, resulting in more prominent dark yellow dots or larger yellowish areas. Interestingly, the first five samples, which contain no copper but increasing amounts of lead up to 15%, show almost no difference in colour. In sharp contrast, the addition of copper has a noticeable impact on colour variation. This is demonstrated by the samples that contain no lead but steadily increasing levels of copper (samples #1, #6, #11, #16, #21), where there seems to be no significant colour change in silver with copper content below 6%. However, there is a clear colour variation

TABLE 2 Colour difference described by △E (terms in bold correspond to the legends in Figure 6).

△E	Perception of difference
<1	**No** colour **difference**
[1, 2]	The colour **difference** is only **discernible** by **expert** (a **trained observer**)
[2, 3.5]	Colour **difference perceived** by any **nonexpert**
[3.5, 5]	The **clear difference** between the two colours under investigation
>5	Perceived as two completely **different colours**

observed from samples with 9% copper and beyond, with a distinction between bright and grey shades becoming apparent. When the copper content reaches 15%, the silver exhibits not only brightness variations but also red-yellowish dots or smaller areas. The same pattern is observed in the samples containing lead and copper. For example, samples #6–9, which contain 3% copper but varying amounts of lead from 0% to 9%, exhibit the same colour until Sample #10 with 15% lead (still 3% copper), which displays a grey-dark colour. Samples with 6% copper (#11–15) exhibit yellow, dark dots if the lead content exceeds 9% (#14–15), whereas the rest show similar colours. The majority of samples with 9% and 15% copper, regardless of their varying levels of lead, show significant variations in brightness and yellow or dark yellow patterns, making them noticeably different from the pure silver sample (#1) and those with lower levels of copper and lead (except #18) (Figure 2).

Colour difference by CIE-Lab

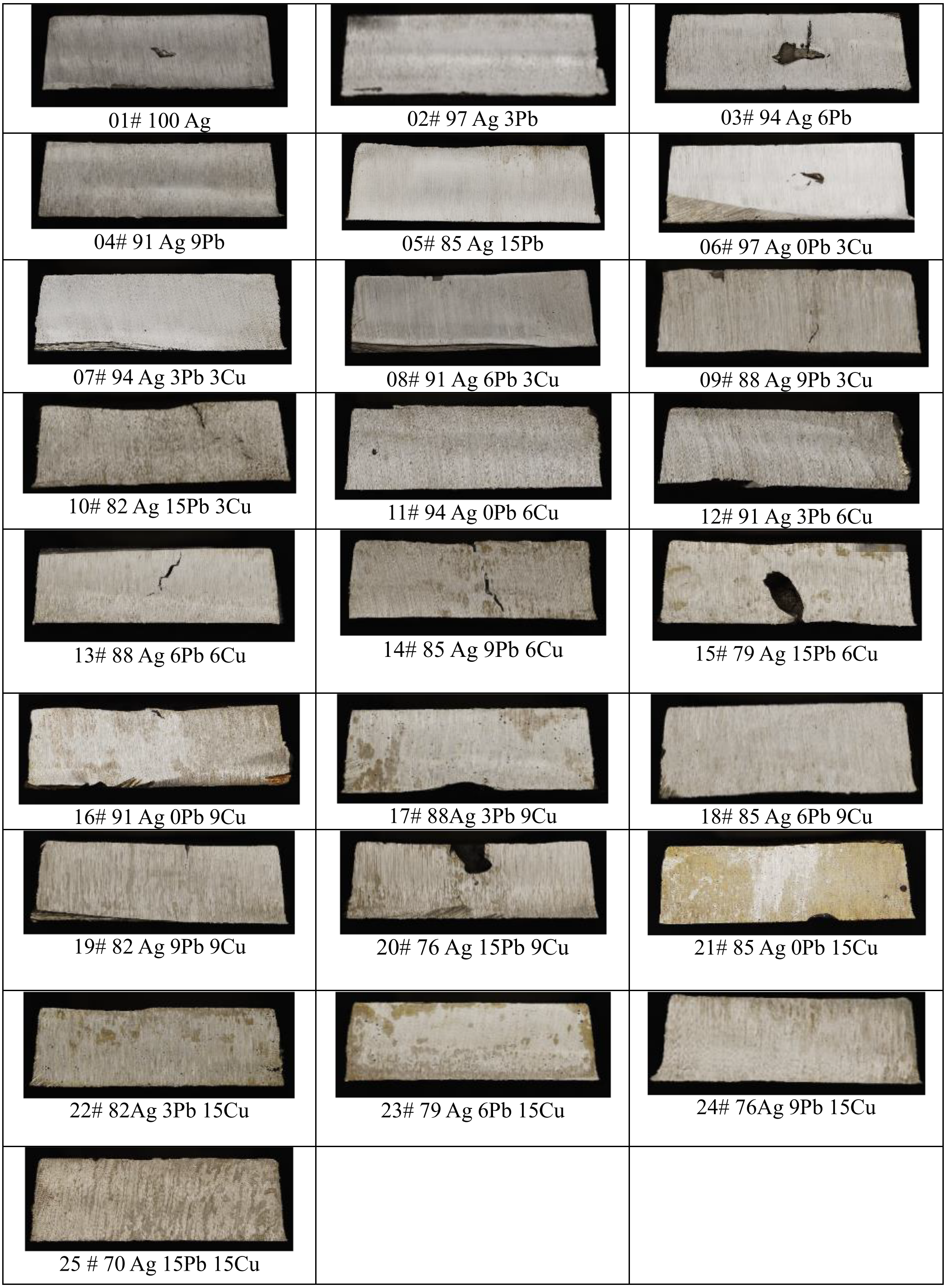
Colourimetric data provided further objective assessment and confirmed the previously mentioned observations. In general, both lead and copper consistently had a negative impact on colour brightness (Figures 3a–c, 4a–e), and an increase in the total amount of alloys (Cu + Pb) resulted in a noticeable decline in the values of L (Figure 4f). Although it may be tempting to suggest that copper plays a more dominant role in the decline of brightness, for example, Sample #21, which has the lowest L value despite not containing any lead in its alloying recipe but up to 15% copper, Figure 4a–e shows that, in general, if lead is kept constant, the addition of copper does decrease brightness, but this is not always the case. Sample #20 and #24 become brighter with more lead than those #15 and #19, respectively.

Copper and lead have a similar effect on the values of a. Figure 3d–f indicate a positive relationship between the level of copper/lead and values, demonstrating that a higher addition of either copper or lead creates more positive values of a, resulting in a more significant proportion of red in the samples. This relationship is further supported by the combined effects of copper and lead, which show a clear positive trend with a (Figure 4f). It is important to note that there is no consistent pattern between a specific element and changes in values when the other alloying element is held constant. For example, when Cu = 3%, comparing the values of Sample #11–16 with varying levels of lead (0%–15%, Table 1), there is no discernible pattern. However, Sample #21 stands out as an outlier with no lead but the highest copper (15%), presenting the highest value of a (1.98). This suggests that copper may significantly contribute to the proportion of red in this case.

The most noticeable pattern can be observed in the values of b. Although there is no clear relationship between b and the percentages of lead, it is apparent that there is an increase in b values when copper is added (Figure 3i). Higher values of b indicate a greater proportion of yellow in the samples, which aligns with those containing higher amounts of copper (e.g., #21). Additionally, the addition of lead seems to mitigate the yellow effect caused by copper. The values of b show a significant increase from 3.43 to 13.37 in Samples #1, 6, 11, 16, and 21, all of which do not contain lead (Table 1, Figure 4a). This significant change is not observed in other groups of samples with varying percentages of lead (Figure 4b–e).

Colour by $\triangle$E

The 25 alloying recipes and colourimetric results of L, a, b divide the entire alloying of interest into 16 different areas (Figure 5), all irregular rectangles due to the variation between the designed and measured alloying compositions. Two algorithms are designed using Python (version 3.11), which automatically applies a random sampling strategy to the sample distribution and calculate the colour difference (Figure 1, Data S1).



01# 100 Ag

02# 97 Ag 3Pb

03# 94 Ag 6Pb

04# 91 Ag 9Pb

05# 85 Ag 15Pb

06# 97 Ag 0Pb 3Cu

07# 94 Ag 3Pb 3Cu

08# 91 Ag 6Pb 3Cu

09# 88 Ag 9Pb 3Cu

10# 82 Ag 15Pb 3Cu

11# 94 Ag 0Pb 6Cu

12# 91 Ag 3Pb 6Cu

13# 88 Ag 6Pb 6Cu

14# 85 Ag 9Pb 6Cu

15# 79 Ag 15Pb 6Cu

16# 91 Ag 0Pb 9Cu

17# 88Ag 3Pb 9Cu

18# 85 Ag 6Pb 9Cu

19# 82 Ag 9Pb 9Cu

20# 76 Ag 15Pb 9Cu

21# 85 Ag 0Pb 15Cu

22# 82Ag 3Pb 15Cu

23# 79 Ag 6Pb 15Cu

24# 76Ag 9Pb 15Cu

25 # 70 Ag 15Pb 15Cu

FIGURE 2 Images of the silver alloys with designed recipes.

Given the admittedly small set of data, we argue that it is safer to use both the discontinuous distribution reflected by the scattered concentrations of copper and lead as well as the underlying kernel density distribution for random sampling. Although kernel density estimation (KDE)

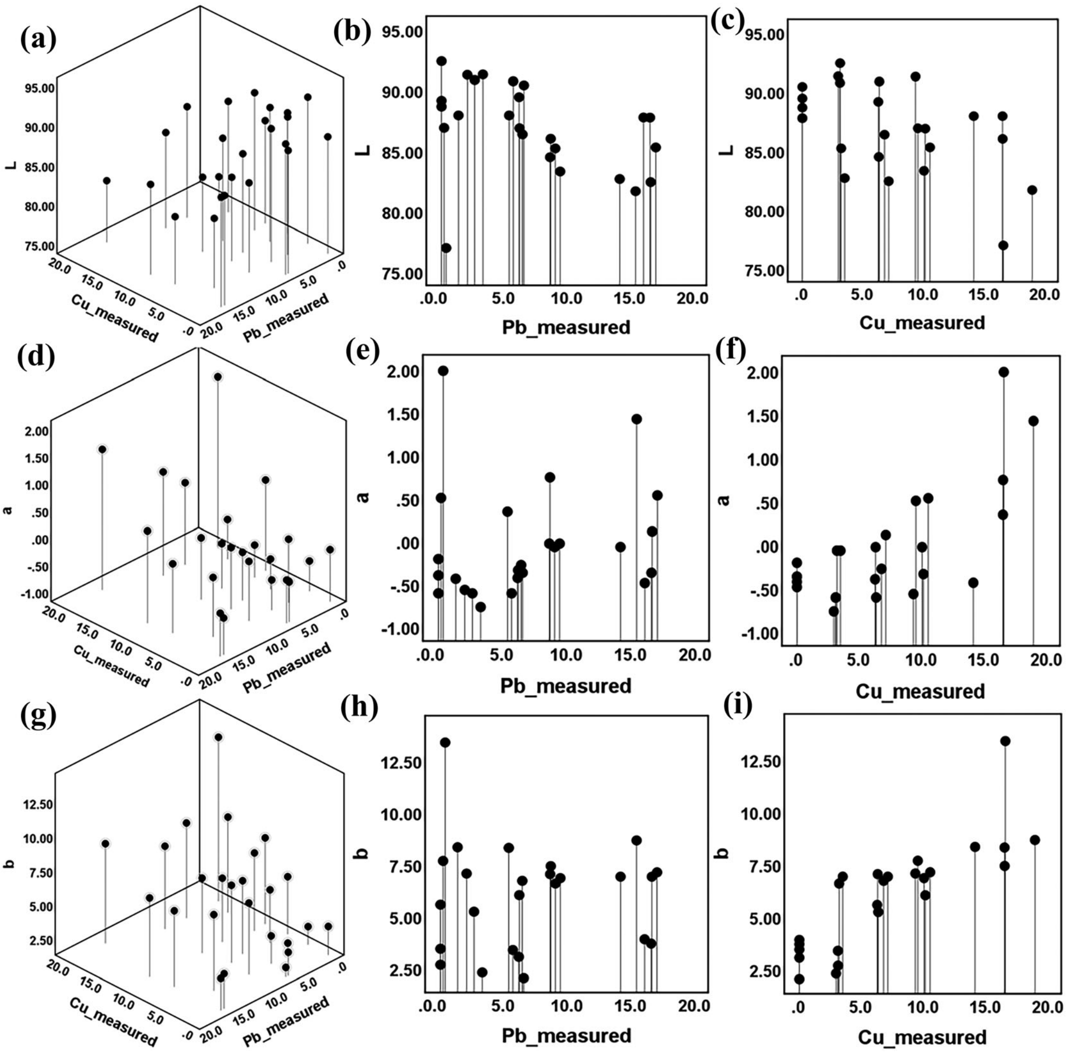


FIGURE 3 Changes in L, a, b in different silver alloyed samples.

in theory better reflects the probability density distribution, it is still likely to put too much emphasis on high density areas and ignore the outliers. As shown in Figure 6, two types of distributions have led to rather similar results.

Due to the irregular rectangles, we calculate the relative positions between the randomly selected sample and the linear regression of any two of the four corner points in each area of Figure 5 (see Def Region in Python code, Data S1). The L, a, and b values of this sample are assigned the average values of L, a, and b of the four corner points that it falls into, assuming that the variation of the colour within each area in Figure 5 is relatively small. The subsequent algorithm follows the colour appearance model to calculate the colour difference that can be appreciated with different levels of expertise (Table 2). A loop is imposed onto the entire process to compare any randomly selected samples from Ming–Qing China and America using △E.

Figure 6 summarises the simulation results of the colour comparison. For instance, two random samples are picked up from the kernel density distributions defined by the percentages of

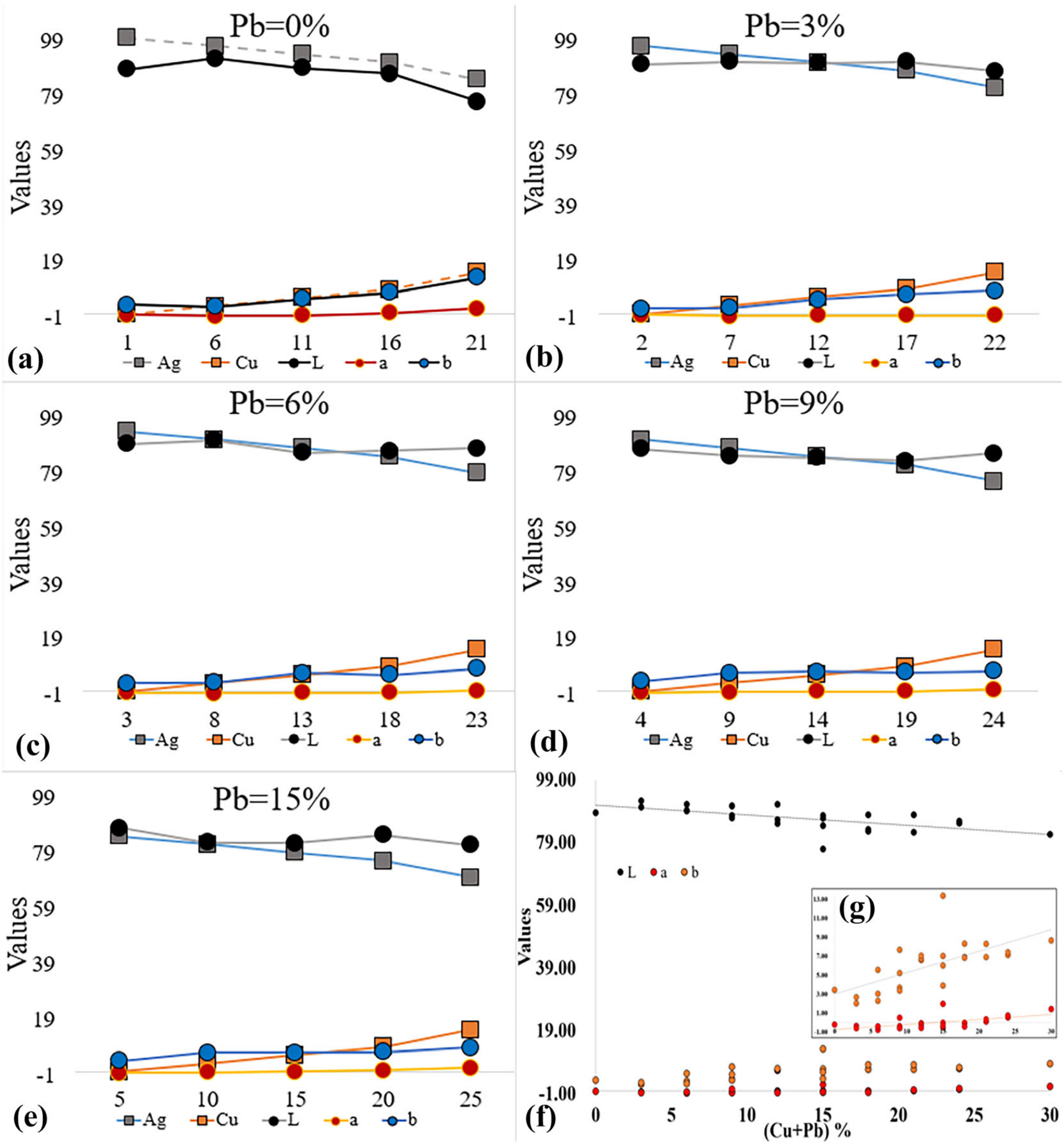


FIGURE 4 Variation of L, a, b in samples [samples grouped with the same percentage of lead (a–e); (f) the correlations between L, a, b and the total amount of copper and lead; (g) the enlarged area of a and b in (f)].

copper and lead of the actual Ming–Qing sycees and the New World silver (Figure 1), respectively, therefore with known alloying compositions. This allows reconstruction of their original colours described by L, a and b, based on the level of copper and lead (Table 1, Figure 5), their colour difference △E, and the degree of expertise needed for detection of the colour difference (Table 2). Here, given the tremendous volume of silver flow from the New World to Ming–Qing China, 5000, 10,000, and 100,000 simulations as such have been conducted to determine how frequently randomly selected samples were perceived as having different or the same colours and by what level of expertise. To illustrate, if the simulation was conducted, for example, 5000 times and in 600 instances there turn out be no colour difference observed, the percentage of no colour difference would be 12% (= 600/5000). As shown in Figure 6, regardless the number of

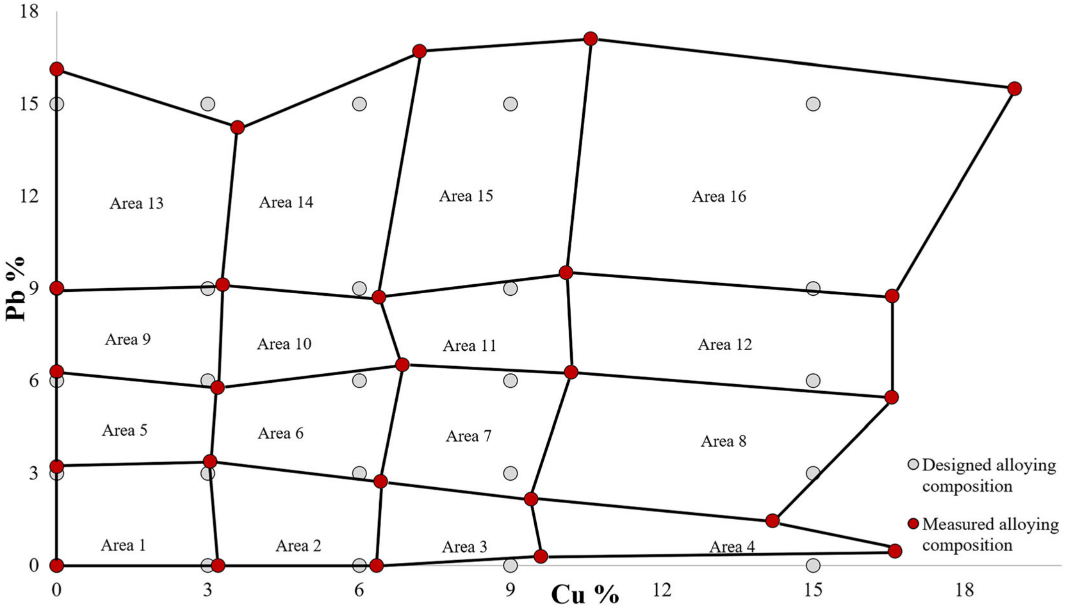


FIGURE 5 Distribution of simulated casting results.

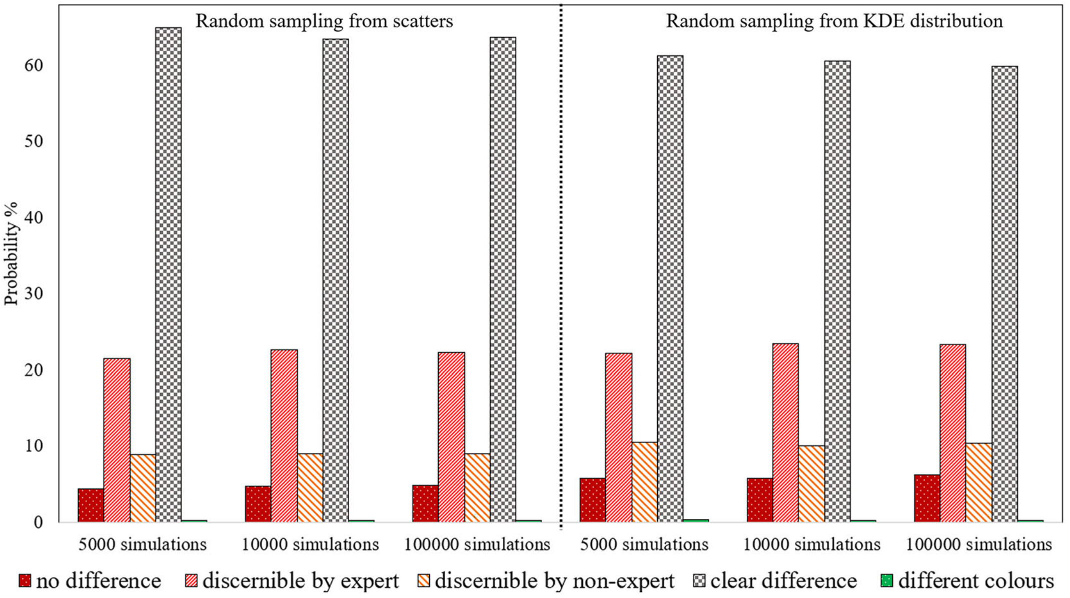


FIGURE 6 Summary of Monte-Carlo simulation for the silver colour difference between Ming–Qing China and the New World (criteria follow Table 2). KDE, kernel density estimation.

simulations, over 60% of the silver can be discerned by untrained observers with the naked eye (labelled 'clear difference'). This percentage increases to nearly 90% when trained observers account for an additional 30% ('discernible by expert' + 'discernible by non-expert'). In summary, it is evident that the silver fineness between Ming–Qing China and the New World can be distinguished simply by colour.

TABLE 3 Weight difference between recipes listed in Table 1 (expressed in percentage and absolute differences between two recipes, all assuming a volume of 120 cm^3, detailed calculation on Data S2).

Alloying recipe	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0.00																								
2	0.25	0.00																							
3	0.49	0.25	0.00																						
4	0.74	0.49	0.24	0.00																					
5	1.23	0.98	0.73	0.49	0.00																				
6	0.44	0.68	0.92	1.17	1.65	0.00																			
7	0.19	0.44	0.68	0.92	1.40	0.25	0.00																		
8	0.05	0.19	0.44	0.68	1.16	0.49	0.25	0.00																	
9	0.30	0.05	0.19	0.43	0.92	0.74	0.49	0.25	0.00																
10	0.79	0.54	0.30	0.05	0.43	1.24	0.99	0.74	0.49	0.00															
11	0.88	1.12	1.36	1.60	2.08	0.44	0.68	0.93	1.17	1.65	0.00														
12	0.63	0.87	1.12	1.36	1.84	0.19	0.44	0.68	0.93	1.41	0.25	0.00													
13	0.38	0.63	0.87	1.11	1.59	0.05	0.19	0.44	0.68	1.17	0.50	0.25	0.00												
14	0.14	0.38	0.63	0.87	1.35	0.30	0.05	0.19	0.44	0.92	0.74	0.50	0.25	0.00											
15	0.35	0.11	0.14	0.38	0.86	0.80	0.55	0.30	0.05	0.43	1.24	0.99	0.74	0.49	0.00										
16	1.31	1.55	1.80	2.04	2.51	0.88	1.12	1.37	1.61	2.09	0.44	0.69	0.93	1.18	1.66	0.00									
17	1.07	1.31	1.55	1.79	2.27	0.63	0.88	1.12	1.36	1.84	0.19	0.44	0.69	0.93	1.42	0.25	0.00								
18	0.82	1.06	1.31	1.55	2.03	0.38	0.63	0.87	1.12	1.60	0.05	0.19	0.44	0.68	1.17	0.50	0.25	0.00							
19	0.57	0.82	1.06	1.30	1.78	0.14	0.38	0.63	0.87	1.36	0.30	0.05	0.19	0.44	0.93	0.75	0.50	0.25	0.00						
20	0.08	0.33	0.57	0.81	1.30	0.36	0.11	0.14	0.38	0.87	0.80	0.55	0.30	0.05	0.44	1.25	0.99	0.74	0.49	0.00					
21	2.19	2.43	2.67	2.90	3.38	1.76	2.00	2.24	2.48	2.96	1.32	1.57	1.81	2.05	2.53	0.89	1.13	1.38	1.62	2.11	0.00				
22	1.94	2.18	2.42	2.66	3.13	1.51	1.75	2.00	2.24	2.71	1.08	1.32	1.56	1.81	2.29	0.64	0.88	1.13	1.37	1.86	0.25	0.00			
23	1.70	1.94	2.18	2.42	2.89	1.26	1.51	1.75	1.99	2.47	0.83	1.07	1.32	1.56	2.04	0.39	0.64	0.88	1.13	1.61	0.50	0.25	0.00		
24	1.45	1.69	1.93	2.17	2.65	1.02	1.26	1.50	1.74	2.22	0.58	0.83	1.07	1.31	1.80	0.14	0.39	0.63	0.88	1.37	0.75	0.50	0.25	0.00	
25	0.96	1.20	1.44	1.68	2.16	0.52	0.77	1.01	1.25	1.74	0.08	0.33	0.58	0.82	1.31	0.36	0.11	0.14	0.39	0.88	1.26	1.00	0.75	0.50	0.00

In addition to colour, it is also reasonable to assume weight/density of sycees as the quality proxy in international and domestic transactions. In the Ming–Qing context, weighing apparatus were of course widely available, but the actual weight provides little direct measure of the fineness of silver compared to density. The latter is pragmatically more difficult to monitor by human perception. The immediate parameter humans can sense with no aid is still weight, but foreign silver flooded into China in various forms, and daily transaction involved silver was often through amorphous fragments of silver (sui yin zi). Converting weight into density requests more complicated steps in practice. Combined psychophysics, a subfield of cognitive psychology that connects the human perception and the external physical stimuli, such as weight, we performed another simulation, demonstrating no obvious difference in weight can be detected by unaided human perception among the different types of silver alloys. Psychophysics shows that any weight difference that can be detected by human perception has to be beyond the statistical threshold of 10% (the Weber fraction, Kuijpers & Popa, 2021). If one compares the weight difference as a result of the alloying recipes listed in Table 1, assuming that all the samples are made in the same volume (standardised shapes, e.g., 10 cm * 3 cm * 4 cm), none of any two recipes show weight difference beyond this threshold (Table 3). The same result is also found in the volume between 50 cm^3–1000 cm^3, corresponding to the variation of the sizes for most types of sycees in Ming–Qing China. It is therefore suggestive that weight/density appear little use to detect the fineness of silver without other types of aid.

CONCLUSION AND FUTURE WORKS

The importance of the colour of silver plays a significant role in the social and economic aspects of human society, particularly after the 14th century when China started using silver for taxation and new silver deposits were discovered worldwide. Our simulation experiments demonstrate the varying shades of silver alloys and how they align with ancient recipes. These experiments also highlight the distinct effects of copper and lead on the colour of silver alloys. Intriguingly, lead only caused a negligible change in colour until reaching a concentration of 15%, which makes it a viable and cost-effective substitute for silver. Conversely, copper had a more prominent impact on the colour transformation of silver alloys. Although this observation can be applied to numerous archaeological and historical situations, our research focuses on contextualising the colour of silver within the global flow of silver between Ming–Qing China and the New World. Although detailed technical records on how the foreign silver was assayed and recast by Chinese craftsmen are scarce, it was common knowledge that the lower purity of New World silver coins led to a more yellow and red hue due to their higher copper content. This discovery establishes a foundation for future studies, enabling deeper chemical and isotopic analyses of silver circulation among China, Southeast Asia, the New World, Europe, and Japan during this era.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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