Wooden Furniture Design Based on Physiological-Psychological Measurement Technology and Kansei Engineering: Taking Ming-style Chair as an Example

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Psychological and physiological cognitive measurements were combined with Kansei engineering theory to study the shape of the traditional Chinese official-hat chair, a kind of Ming-style chairs, while investigating people's perceptual cognitive process. This work employed focus groups to obtain 5 groups of representative words and 22 typical samples for evaluation experiments. After data preprocessing, principal component analysis (PCA) was used to extract three main components: "Concise-Ornate", "Soft-Strong", and "Elegant-Vulgar". In terms of component weight calculation, the analytic hierarchy process (AHP) was initially used to calculate the subjective cognitive weight of different components, and then eye-tracking technology was used to assist in calculating the physiological cognitive weight. Finally, combining the subjective and objective weights, the weights of the components were determined as: backrest (41.02%) > stretcher (18.29%) > handrail (11.64%) > top rail (11.14%) > outside stick (8.64%) > inside stick (5.32%) > foot rail (3.95%). The four main components—backrest, stretcher, handrail, and top rail—along with perceptual image evaluations, were selected to establish a multivariate linear regression equation, thereby constructing a mathematical mapping relationship between perceptual image and main design elements. This provides theoretical support for designers in creating different perceptual images.

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Keywords: Wooden furniture; Kansei engineering; Eye tracking technology; Analytic hierarchy process (AHP); Ming-style furniture

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INTRODUCTION

The history of human interaction with wood predates the Stone Age. The use of wood in China has a history of thousands of years. Wood products not only provide the material basis for daily life but also carry the spirit and aesthetic ideas formed through societal labor. Through the long history of human interaction with wood, a distinct culture of wood gradually emerged. As a unique symbol within the Chinese cultural system, Chinese wood culture holds significant value. Wood and its exquisite crafts serve as vital carriers and media for disseminating and advancing wood culture, imbued with profound cultural significance and artistic value (Xue and Chen 2024).

In Chinese traditional wood products, furniture—being closely related to human life—embodies the philosophy of Chinese life. The unique craftsmanship of Chinese classical furniture reflects a respect for wood and a reverence for nature. The design and application of these forms possess high artistic and aesthetic value. Ming-style furniture emerged during the development of Chinese furniture, attracting worldwide attention. Gustav Ecke (1896 to 1971), a pioneering scholar in the study of Ming-style furniture, published the first known work on Ming-style furniture, *Chinese Domestic Furniture*, in 1944. This pioneering work on Ming-style furniture significantly influenced subsequent furniture studies. Ming-style chairs can be categorized by form, such as the official-hat chair, circle chair, and rose chair. Even today, Ming-style furniture occupies a significant position in the Chinese solid wood furniture market.

As a wooden product, the appearance of Ming-style furniture affects consumers' purchasing decisions. With increasingly diversified and personalized consumer demand, high-end consumer groups tend to customize products according to personal preferences, yet most traditional furniture markets rarely consider these personalized needs. Therefore, it is crucial to design products that conform to consumers' image preferences (Xiong *et al*. 2016). In recent years, to explore consumers' imagery preferences, many designers have employed methods such as the Semantic Differential (SD) method and Analytic Hierarchy Process (AHP) to quantify cognitive data and obtain optimal solutions. However, as mental decision-making involves complex brain processes, the results are not always precise. With technological progress, physiological cognitive measurement technology has become capable of capturing consumer behavior data with high precision. To more intuitively reflect consumers' implicit behavior, researchers can analyze their cognitive behavior process, aiding the study of decision-making and judgment (Lim *et al*. 2020). Many scholars have used EEG (electroencephalogram), eye tracking technology, and SCL (skin conductance level) to conduct research on individuals' physiological signals. Measuring consumers' physiological data has become central to cognitive research.

Therefore, this paper employs a combination of psychometric and physiological measurements to investigate the psychological and behavioral processes of consumers, and to develop new methodologies for wooden furniture design. By translating consumers' imagery preferences, this study provides a method for achieving personalized design and addressing the issue of product stacking under the mass production model of traditional furniture enterprises. This approach saves materials and lays the foundation for shortening the new product development cycle, reducing costs, and achieving green, intelligent manufacturing and sustainable development.

LITERATURE REVIEW

Kansei Engineering and Wooden Furniture

The word "Kansei" is derived from the Japanese word for "people's emotional, perceptual, and sensory responses." The concept of Kansei Engineering was first proposed by Kenichi Yamamoto in Japan. It is a systematic research method that integrates the emotional and psychological aspects of users into product design and development. It combines the rational analysis of human emotion and engineering to explore the relationship between human perception and object design characteristics. The product image reflects consumers' cognition of product form, and understanding how consumers evaluate product image shape can better inform design to meet consumer preferences.

Regarding Kansei Engineering, in the context of the side view of a car, Kang and Wang (2022) utilized neural networks, the entropy method, Quality Function Development (QFD), and other techniques to construct a relationship matrix between customers' aesthetic preferences and products characteristics. Guo *et al.* (2023) built a model representing the relationship between user perception and interface attributes for individual users. Taking the electric recliner as an example, Zhou *et al.* (2023) used Kansei Engineering and Grey Relational Analysis (GRA) to explore the image modeling optimization design process based on users' perceptual preferences. By integrating Kansei Engineering with other methodologies to analyze target products, they have effectively met user needs and achieved successful imagery alignment.

In terms of wooden furniture, An *et al.* (2022) used the method of Kansei Engineering to study traditional Chinese wooden screens, and applied Quantification Theory Type I for quantitative analysis. Xu and Pan (2023) analyzed and discussed solid wood chairs using Kansei Engineering concluding that this process scientifically and effectively reflects consumers' potential perceptual needs for the form images of solid wood chairs, thereby improving design efficiency in furniture product development. Zuo *et al.* (2023) combined perceptual engineering, AHP, and QFD to study the Ming-style chair, resulting in a design solution that satisfies users' perceptual needs. Lin *et al.* (2024) used Kansei Engineering to conduct perceptual semantic experiments on Ming-style, Qing-style, and modern Chinese-style furniture, and established mapping models using Quantification Theory Type I.

Currently, few studies have focused on consumers' perceptual imagery in classical furniture. Literature indicates that studies on Ming-style chairs primarily employ subjective evaluation methods to gather relevant data in the initial stages, followed by model construction for subsequent analysis. These studies lack consideration of consumers' implicit physiological behaviors and fail to collect objective data for judgment and comprehensive analysis during preliminary data collection.

Physiological and Psychological Measurement Technology

People have corresponding psychological and physiological reactions to stimuli, which can reflect people's perceptual cognition and preferences to a certain extent.

Psychological measurement technology

In design, subjective measures are based on relevant psychological theories, such as interviews, Semantic Differential (SD), focus groups, Analytic Hierarchy Process (AHP), and other methods that are used to quantify and analyze people's psychological characteristics and decisions. The psychological cognitive measurement method is a subjective measurement method, which is common in the use of design science. In this study, the SD method and AHP are primarily used to measure psychological cognition. Cui *et al.* (2022) adopted the Comprehensive Evaluation (CE) method, establishing a ladder fuzzy AHP, and proposing a CE model to evaluate the performance of products. Chen and Sun (2023) explored Research and Development (R&D) strategies for custom kitchen cabinets made from these panels by integrating QFD and AHP methods. Based on the AHP, Liu *et al.* (2023) made a quantitative analysis of the user needs of dining chairs by combining qualitative and quantitative methods. Miao *et al.* (2024) adopted AHP, morphological analysis, and QCA methods to study the preference of children's desk users.

Physiological measurement technology——Eye tracking technology

With advancements in science and technology, individuals can utilize various physiological measurement tools to gather data on subjects' physiological responses. Through collecting physiological data, one can delineate the progression of a user's psychological state during the judgment process through objective physiological changes.

Advancements in physiological measurement technology have led to various methods, such as eye tracking, event-related potentials (ERP), skin conductance level (SCL), and facial recognition, which can capture and interpret subjects' physiological indicators, facilitating data analysis. According to literature, there is a growing trend in the field of consumer psychology to explore the underlying cognitive processes behind users' objective behaviors using physiological measurement techniques like EEG and eye tracking (Zhu and Lv 2023).

Eye movement data most intuitively reflects the user's visual cognitive behavior. Hsu *et al.* (2017) conducted eight perceptual evaluations of 16 chairs while tracking their eye movements. Two main factors, valence and arousal, were extracted from the eight perceptual scales, forming a perceptual plane compatible with Russell's affective ring model. Zhagn and Xu (2020) used the chair of the Tang Dynasty as an example, combining the eye tracking and perceptual evaluation methods to evaluate the semantic acceptability of the chair of the Tang Dynasty, and determined that the backrest, handrail, and chair legs are the most important morphological features in the design of the chair in the Tang Dynasty. Yu *et al.* (2021) used a combination of eye tracking techniques and subjective assessment to study individual aesthetic preferences in wood color. Li *et al.* (2022) studied robots with moderate anthropomorphic features, aiming to provide a basis for the objective evaluation of affective impressions. The frequency and duration of gazes can differentiate positive impressions of the appearance of a humanoid robot. Ilhan and Togay (2023) assert that eye tracking technology can serve as a tool to gather implicit aesthetic information from users. Their research on modern sofas aims to ascertain the influence of various product details on user appreciation, which can be interpreted by specific gaze metrics. Miao *et al.* (2024) employed AHP to analyze behavioral demands and compared hot spot map, track maps, and other data collected during eye movement experiments as children observed different lockers.

In summary, the current application of physiological cognitive measurement has reached a relatively mature stage and has demonstrated effectiveness in the process of product design decision-making, suggesting that physiological cognitive measurement technology is both reliable and feasible. Commonly used indicators of eye tracking technology include the first fixation time, the number of fixations, and the duration of fixations. However, eye movement technology is still less utilized in traditional wooden furniture design. Furthermore, it has not been considered in design weighting for quantitative research. Compared to psychometric technology, using eye-tracking technology to capture subjects' eye movement behavior is more objective and can assist in psychometric analysis and judgment. Through quantitative analysis and calculation, it can indicate which design components are more important, providing theoretical guidance for subsequent design.

EXPERIMENTAL

Research Framework and Object

This paper used the traditional Chinese classic seat known as the "official-hat chair" as a case study. The official-hat chair is a type of Ming-style chair. The name "official-hat chair" originates from its resemblance to the hats worn by ancient Chinese officials. The technical roadmap is outlined in Fig. 1. The chair's shape and corresponding name are illustrated in Fig. 2. In terms of furniture modeling classification, the "official-hat chair" falls under the category of "armchair," which were highly popular during the Ming Dynasty. Therefore, the subsequent discussion will refer directly to "armchair."

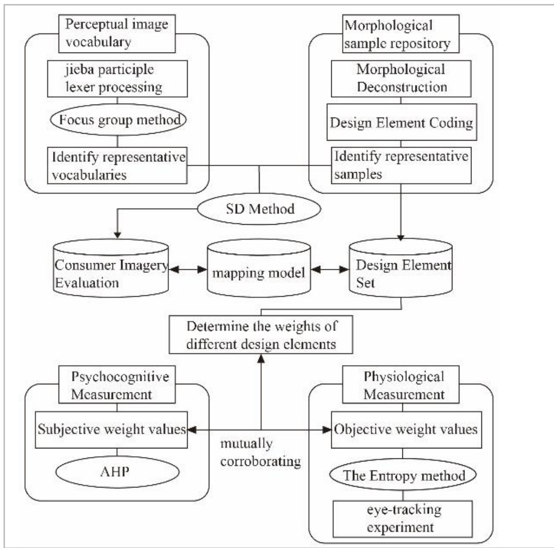


Fig. 1. Research framework

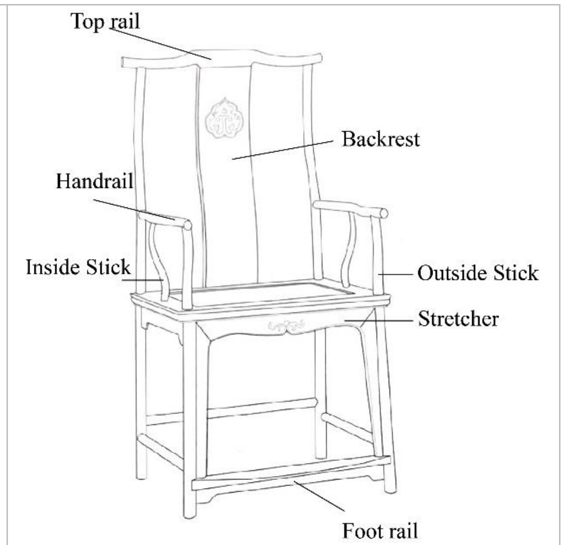


Fig. 2. Research Object

Research Method

AHP

The AHP is a hierarchical weight decision analysis method. A scale method ranging from 1 to 9 points is typically employed for scoring, as demonstrated in Table 1, to assess the relative importance of the two indicators.

Table 1. Scale Method of 1 to 9 Points

Scale of Relative Importance	Linguistic Variable
1	Equally important
3	Slightly important
5	Obvious importance
7	Strongly important
9	Extremely important
2/4/6/8	The median of the two adjacent judgments above
Reciprocal	If the judgment b_{ij} is compared between factor *i* and *j*, then the judgment b_{ji} =1/b_{ij}

Steps of the Analytic Hierarchy Process:

Step 1: Establish a judgment matrix by inviting professors and experts in the field of furniture to provide scores. The parameters *i* and *j* are compared pairwise using the 1 to 9 scale method. Each judgment was recorded in the form of a pairwise comparison matrix A of dimension $n \times n$, parameter b_{ij} was the result of comparing the contribution of parameter b_i and parameter b_j to the previous level. Equation 1 represents the pair-wise comparison matrix denoted as A,

$$A = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \quad (1)$$

where n was the number of parameters to be compared.

Step 2: Normalize the judgment matrix and calculate the weight values of each item, as shown in Eqs. 2 and 3,

$$\overline{b_{ij}} = \frac{b_{ij}}{\sum_{j=1}^{n} b_{ij}} (i, j = 1,2, \dots, n) \quad (2)$$

$$W_i = \sum_{j=1}^{n} \frac{\overline{b_{ij}}}{n} (i, j = 1,2, \dots, n) \quad (3)$$

where W_i is the weight of the i indicator.

To judge the rationality of the weight value, it is necessary to conduct a consistency test on the judgment matrix.

Step 3: Calculate the maximum characteristic root value of the matrix, and the calculation Eq. 4 is shown as follows:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{[AW]_i}{nW_i} \quad (4)$$

Step 4: The consistency index (CI) is calculated by combining λ_{max} with the Eq. 5:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

Step 5: The consistency ratio (CR) is calculated by Eq. 6, in which the random index (RI) is shown in Table 2. If CR < 0.1, it means that the evaluation matrix consistency test is passed, and the smaller the CR value, the better the matrix consistency.

$$CR = \frac{CI}{RI} \quad (6)$$

Table 2. RI Indicators of Judgment Matrix

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46

The entropy method

The entropy method is a weight allocation technique based on the concept of entropy from information theory, and it is an objective weight calculation method. It calculates the weight of each index based on the amount of information it carries and its degree of variation.

Step 1: Determine whether the data represents positive or negative attributes, and then standardize the data to remove dimensional differences, compressing each indicator to a range between 0 and 1. Positive attribute indicators are normalized according to Eq. 7, while negative attribute indicators are normalized according to Eq. 8,

$$Positive: \; X'_{ij} = \frac{X_{ij} - X_{j(min)}}{X_{j(max)} - X_{j(min)}} \quad (7)$$

$$Negative: X'_{ij} = \frac{X_{j(max)} - X_{ij}}{X_{j(max)} - X_{j(min)}} \tag{8}$$

where X'_{ij} represents the standardized value, X_{ij} represents the raw data of the j index of the i component, $X_{j(\max)}$ represents the maximum value in index j, and $X_{j(min)}$ represents the minimum value in index j.

Step 2: To ensure the normal operation of subsequent logarithm calculation, a "translation value" is uniformly added to all indicator data, so that the data of this indicator is non-negative. This value is positioned 0.001 in this paper as shown in Eq. 9:

$$X''_{ij} = X'_{ij} + 0.001 \tag{9}$$

Step 3: Calculate the proportion of the *j* sample value of item *i* according to Eq. 10:

$$P_{ij} = \frac{X''_{ij}}{\sum_{i=1}^{m} X''_{ij}} (i = 1,2, \dots, m; j = 1,2, \dots, n) \tag{10}$$

Step 4: Calculate the information entropy of each index according to Eq. 11,

$$e_j = -K \sum_{i=1}^{m} \left(P_{ij} \ln\left(P_{ij}\right)\right) \tag{11}$$

where K = 1/ln(n).

Step 5: Information utility value d_j according to Eq. 12:

$$d_j = 1 - e_j (j = 1,2, \dots, n) \tag{12}$$

Step 6: Weight coefficient value ω_j according to Eq. 13:

$$\omega_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{13}$$

Step 7: Comprehensive evaluation of the evaluation object according to Eq. 14:

$$Z_i = \sum_{j=1}^{n} \omega_j X''_{ij} \tag{14}$$

Quantification theory type I

Quantification Theory Type I employs multiple linear regression analysis to establish a mathematical model. In this context, the perceptual image evaluation serves as the dependent variable, a quantitative variable. The decomposition of furniture styling design elements constitutes the independent variables, which are qualitative variables. Through the analysis of Quantification Theory Type I, the correspondence between user affective needs and design elements is explored, yielding standardized coefficients and determination coefficients for each category of styling design elements. The standardized coefficients of styling design elements further elucidate the impact of each element within the design on affective imagery, while the determination coefficient indicates the precision of the model.

$$\delta_i(j,k) = \begin{cases} 1, \text{the } i\text{-th sample possesses the } j\text{-th styling element of the } k\text{-th category.} \\ 0, \text{None} \end{cases}$$

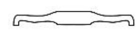
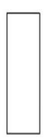
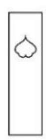
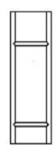
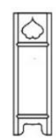
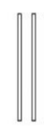
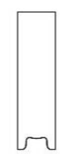
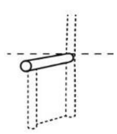
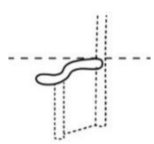
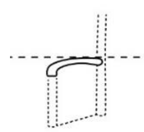
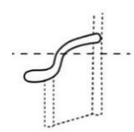
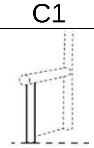
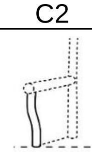
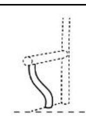
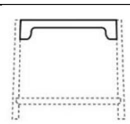
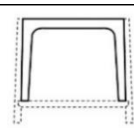
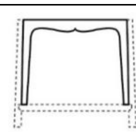
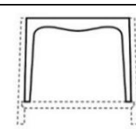
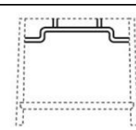
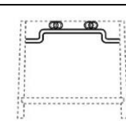
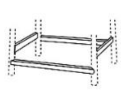
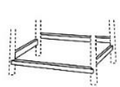
$$y_i = \sum_{j=1}^{m} \sum_{k=1}^{r_j} \delta_i(j,k) b_{j,k} + \varepsilon_i \tag{15}$$

where $b_{j,k}$ is a constant, whose magnitude is determined by the constant of the *j*-th styling element in the *k*-th category, ε_i represents the error generated when investigating the imagery value of the *i*-th sample, k=1, 2, …, r_j.

The Establishment of Perceptual Image Vocabulary Database

Through extensive collection of furniture literature from books, magazines, and online sources, this study employs *Jieba* segmentation to extract adjectives and determine the frequency of emotional image words. Among which, the 40 most frequent emotion-related words were selected. To mitigate participant fatigue during the test, the Focus Group method was employed to categorize and refine the collected words. This qualitative research approach enables the exploration of individuals' attitudes, perceptions and opinions by facilitating open discussions among a group of respondents. Eight focus group members, including furniture experts, designers, and graduate students, were assembled to categorize similar words. After classification, the eight group members selected the perceptual words most suitable for the official-hat chair. Ultimately, five words were identified, and antonyms were found to form the group of perceptual image words: "Concise-Ornate", "Soft-Strong", "Ethereal-Thick", "Smooth-Stagnant", and "Elegant-Vulgar".

Table 3. The Form Decomposition of Armchair

Code	Category	1	2	3	4	5	6	7
A	Top rail							
		A1	A2	A3	A4	A5	A6	
B	Backrest							
		B1	B2	B3	B4	B5	B6	B7
C	Handrail							
		C1	C2	C3	C4			
D	Outside Stick							
		D1	D2	D3				
E	Inside Stick							
		E1	E2	E3	E4	E5		
F	Stretcher							
		F1	F2	F3	F4	F5	F6	
G	Foot rail				Other form			
		G1	G2	G3	G4			

The Establishment of Object Sample Repository

A total of 215 armchair samples were collected for this study, and the modeling elements of the armchairs were deconstructed using morphological analysis. Morphological analysis, a non-quantitative research method proposed by Professor Fritz Zwicky, an astrophysicist at the California Institute of Technology, applies morphological theory to guide innovative design. The overall external form of a product is constructed from various product modeling design elements. In this study, all samples were decomposed and classified by morphological elements, and the most representative pattern in each category was selected for the extraction of morphological lines. The form decomposition is illustrated in Table 3. In the subsequent product form description, the codes of form elements will be used.

To obtain typical experimental samples and include as many morphological elements as possible, a total of 22 representative samples were selected for subsequent experiments. All images were desaturated using Adobe Photoshop, an image processing software, to minimize the influence of material and color on shape perception, and convert into images with dimensions of 1680 mm × 1050 mm, with a uniform resolution of 300 dpi. The viewing angle of the armchair sample images was primarily set at 45° to display as many details as possible for the subjects.

Questionnaire Data Collection

An online survey was used to administer the questionnaire, requiring participants to complete it carefully in a quiet and uninterrupted environment. The questionnaire utilized a seven-point Likert scale, where “1” indicates strong agreement with the left perceptual vocabulary, “7” indicates strong agreement with the right perceptual vocabulary, and “4” represents neutrality. In total, 64 questionnaires were collected, and 4 invalid questionnaires were excluded.

To eliminate the impact of differences in the dimensions of various indicators, it is necessary to normalize each indicator’s data by mapping all values to the range [0,1]. The normalization calculation Eq. 16 is as follows,

$$R = \frac{r - \min\{r\}}{\max\{r\} - \min\{r\}} \quad (16)$$

where R is the data after standardized processing, and r is the original indicator data.

After analyzing the processed data, the values of each sample for different perceptual words were averaged to obtain the mean value of perceptual image evaluation, as shown in Table 4.

The software SPSS27 was used to perform principal component analysis (PCA) on the data, a statistical method that reduces multiple variables into a small number of principal components that capture most of the information from the original variables. First, the Bartlett sphericity test and the Kaiser-Meyer-Olkin (KMO) test were performed to evaluate the significance and adequacy of the data for factor analysis. The KMO value of the questionnaire data was 0.614, which was greater than the critical value of 0.6, and the Bartlett sphericity test results showed that the P-value was 0.000, which was less than 0.05, indicating a significant difference. Therefore, the data are suitable for PCA.

Table 4. Average Scores of Each Sample Under Different Perceptual Words

Sample	Concise-Ornate	Soft-Strong	Ethereal-Thick	Smooth-Stagnant	Elegant-Vulgar
1	0.20	0.75	0.36	0.17	0.20
2	0.40	0.45	0.63	0.50	0.51
3	0.71	0.59	0.64	0.53	0.50
4	0.19	0.33	0.29	0.24	0.32
5	0.66	0.58	0.54	0.46	0.36
6	0.36	0.57	0.54	0.34	0.42
7	0.11	0.92	0.24	0.28	0.37
8	0.95	0.51	0.76	0.69	0.66
9	0.12	0.43	0.31	0.25	0.36
10	0.46	0.40	0.58	0.43	0.58
11	0.63	0.38	0.43	0.51	0.38
12	0.32	0.37	0.35	0.24	0.26
13	0.22	0.58	0.29	0.39	0.47
14	0.36	0.66	0.45	0.43	0.44
15	0.42	0.52	0.70	0.49	0.56
16	0.10	0.68	0.27	0.24	0.32
17	0.27	0.69	0.34	0.29	0.39
18	0.28	0.69	0.44	0.47	0.58
19	0.50	0.40	0.52	0.46	0.40
20	0.64	0.33	0.52	0.25	0.30
21	0.47	0.33	0.41	0.29	0.29
22	0.32	0.39	0.38	0.30	0.26

The eigenvalues and variance contribution rates of each factor were obtained through PCA using SPSS. Table 5 shows that the first three common factors explained 94.973% of the total variance, indicating they represented 94.973% of the original five indicators measuring perceptual image, implying minimal data loss and effective interpretation of the initial data. Factor rotation was performed using the varimax method; factors with absolute values less than 0.05 are represented by blank spaces, and negative values indicate negative correlations between indicators, as shown in Table 6.

Table 5. Results of PCA

Component	Initial Eigenvalues		
	Eigenvalues	Contribution Rate	Cumulative Contribution Value (%)
Soft-Strong	3.166	63.314	63.314
Elegant-Vulgar	1.166	23.327	86.642
Concise-Ornate	0.417	8.332	94.973
Smooth-Stagnant	0.188	3.770	98.743
Ethereal-Thick	0.063	1.257	100.000

Table 6. Rotated Component Matrix

Intentional Vocabulary Group	Composition Coefficient Matrix		
	1	2	3
Concise-Ornate	**0.938**	0.220	-0.200
Ethereal-Thick	0.750	0.541	-0.150
Elegant-Vulgar	0.223	**0.962**	
Smooth-Stagnant	0.597	0.751	
Soft-Strong	-0.166		**0.984**

Three factors were obtained by PCA using SPSS, and the words with the highest loadings for each component were selected for subsequent research: "Concise-Ornate", "Soft-Strong", and "Elegant-Vulgar", representing the decorative factors (Y1), linear factors (Y2), and style factors (Y3) of the armchair.

Psychological Evaluation Weight Calculation

The hierarchical structure model of the armchair was established, and the user judgment matrix was constructed using the Analytic Hierarchy Process (AHP) for the design elements in the middle layer, as shown in Fig. 3. Five experts were invited to score seven indicators in the AHP hierarchy using the 1 to 9 scale method. Then, the geometric mean method was used to aggregate the scores of the five experts into a table, followed by subsequent calculations, as shown in Table 7.

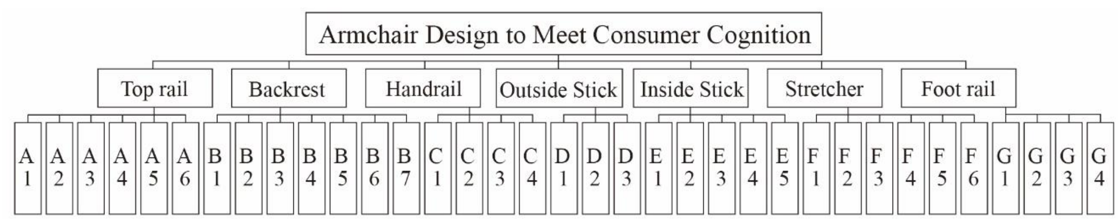


Fig. 3. Hierarchical structure model of the armchair

Table 7. Comprehensive Value of AHP Scores of 5 Experts

	Top rail	Backrest	Handrail	Outside Stick	Inside Stick	Stretcher	Foot rail	Weight
Top rail	1.000	0.240	1.552	4.359	3.064	0.437	1.285	**0.1351**
Backrest	4.169	1.000	3.393	5.008	4.478	1.888	4.521	**0.3463**
Handrail	0.644	0.295	1.000	2.551	1.644	0.384	1.974	**0.1047**
Outside Stick	0.229	0.200	0.392	1.000	0.608	0.223	0.530	**0.0446**
Inside Stick	0.326	0.223	0.608	1.644	1.000	0.284	0.871	**0.0638**
Stretcher	2.287	0.530	2.605	4.478	3.519	1.000	3.681	**0.2324**
Foot rail	0.778	0.221	0.506	1.888	1.149	0.272	1.000	**0.0731**

Table 8. Consistency Test Value

λ_{max}	*CI*	*RI*	*CR*
7.182	0.030	1.360	0.022

The eigenvector and weight were calculated according to Eqs. 2 and 3, and then the consistency test of the scoring matrix was performed. The maximum characteristic root value was calculated according to Eq. 4, the *CI* value was obtained according to Eq. 5, and the *CR* value was calculated according to Eq. 6. With $CR = 0.022 < 0.1$, the consistency test results, shown in Table 8, indicate that the consistency test was passed. The weight value obtained was used as the subjective evaluation weight of each component. From this, the mutual importance of each part can be evaluated: Backrest > Stretcher > Top rail >

Handrail > Foot rail > Inside Stick > Outside Stick. Among them, the weight of backrest modeling accounted for 34.63%, the highest proportion, indicating that people consider the backrest modeling to be the most important in the cognitive process. The second most important parts are the stretcher and top rail, accounting for 23.24% and 13.51%, respectively, indicating that people also consider these two parts important in the cognitive process. Then came the handrail, foot rail, inside stick, and outside stick, accounting for 10.47%, 7.31%, 6.38%, and 4.46%, respectively.

Physiological Cognitive Experiment

AHP is merely a subjective scoring method for experts to determine the weight of different components, and the selection results do not truly reflect the decisions and feelings of target users. For objective evaluation, physiological indicators, such as eye tracking, can assist in judgment. By analyzing product visual recognition, the weight differences of factors affecting product visual recognition features can be better understood, which is more intuitive than subjective scoring. Additionally, implicit psychological and behavioral information can be inferred from the subjects' cognitive processes.

Experimental purpose

The eye movement experiment helps to identify which parts the subjects focus on when judging the perceptual image words and which parts are important in the cognitive process of this perceptual phrase.

Experimental materials and procedures

In this experiment, an eye tracker with a sampling rate of 250 Hz and ErgoLAB 3.17.8 were used to collect eye movement data. The experiment was divided into three groups based on the three sets of perceptual words obtained, with a total of six stimuli in each group. The images of each stimulus were arranged in a 2 × 2 layout, and the stimulus contents of each group were used as experimental materials, comprising 22 chair pictures and two spare chair pictures in the questionnaire survey. There was a 1-second gray screen rest time between the stimulus images to allow the eyes to refocus. To facilitate subsequent result processing and analysis, areas of interest (AOIs) were marked for different parts of each chair, and all similar parts were grouped together.

Experimental subjects

In this experiment, 18 graduate students majoring in furniture design, industrial design, or product design were recruited as subjects. All participants had binocular visual acuity or corrected visual acuity above 1.0, and all were right-handed.

Experimental process

Before the experiment, the equipment was adjusted. Each participant sat upright, holding the mouse in their right hand, with the distance between their eyes and the screen being 60 to 65 cm. The sight calibration task was completed before the experiment.

During the experiment, the Concurrent Think Aloud method was adopted. The subjects were asked to judge which of the four chairs in each stimulus was most consistent with the cue word of the perceptual word, and sufficient thinking time (30 s) was provided for each stimulus. After making their judgment, they informed the nearby recorder, then clicked the mouse with their right hand to continue. Then, they moved on to the next stimulus picture and repeated the process until the end of the three sets of experiments, as shown in Fig. 4.

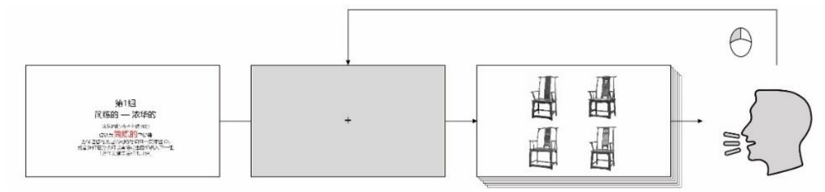


Fig. 4. A set of experimental flow diagrams

RESULTS

Physiological Cognitive Weight Calculation

Eye movement data collection includes numerous indicators. During the judgment process, subjects compare different areas of interest. Therefore, the eye movement indicators shown in Table 9 were selected for subsequent analysis.

Table 9. Meaning of Eye Tracking Indicators

Index Name	Indicator Meaning	Significance
AOI First Fixation Time (s) / FFT	Count the time (s) from the start of the stimulus or segment to the subject's first gaze at the AOI.	Indicates the subjects' attention tendency during the initial processing.
AOI First Fixation Duration (s) / FFD	The duration (s) from the beginning of the stimulus to the first time the subject looked at the fixation point of the AOI was measured.	Indicates the initial degree of attraction of the area of interest to the subject.
AOI Visit Count (n) / VC	A visit is counted between the time the fixation point enters the AOI and the time the fixation point leaves the AOI. Total number of visits to AOI (n).	Indicates the significance of various areas of interest in the decision-making process.
AOI Total Visit Duration (s) / TVD	The total duration of the visit to the interest area (s).	Indicates the importance subjects assign to this area of interest during the decision-making process.
Number of Visitors (n) / NV	Number of people who have visited the area of interest (n).	Shows which areas of interest subjects focus on during the decision-making process.

In this experiment, the visit counts and the duration of visits are meaningful for understanding the participants' preferences for different parts of the armchair. Table 10 displays the proportion of visits to different parts across three sets of affective vocabulary. According to the results of this experiment, for the "Concise-Ornate" pair, participants paid more attention to the backrest and stretcher, as these are the parts of the armchair that are most easily decorated—the less decorated, the more concise. For the "Soft-Strong" pair, participants focused more on the top rail, handrail, and outside stick, as the curves and trajectories of these parts influence people's judgments of this affective pair. In judging the "Elegant-Vulgar" pair, besides placing more emphasis on the inside stick, other parts were relatively less prominent, indicating a consideration of the overall style. The results of the visit frequency also effectively elucidated the three factors derived from the principal component analysis: the decoration factor, the linear factor, and the style factor. Overall, based on the count of visits, the preference order is Backrest > Stretcher > Outside Stick > Handrail > Top rail > Inside Stick > Foot rail.

Subsequently, the eye-tracking data for each set of vocabulary was processed to obtain the mean values. The data from the three sets were then averaged, resulting in the values presented in Table 11.

Table 10. The Proportion of the VC

Perceptual Vocabulary	Top Rail	Backrest	Handrail	Stretcher	Outside Stick	Inside Stick	Foot Rail
Concise-Ornate	5.11%	**56.43%**	6.70%	**15.33%**	10.54%	3.53%	2.35%
Soft-Strong	**7.22%**	54.01%	**11.54%**	11.31%	**11.65%**	3.27%	1.00%
Elegant-Vulgar	6.02%	54.56%	10.09%	12.32%	**11.65%**	**4.63%**	0.74%
Average	6.12%	55.00%	9.44%	12.98%	11.28%	3.81%	1.36%

Table 11. Mean Eye-tracking Metrics for AOIs Across Three Sets of Vocabulary

Metrics	Top Rail	Backrest	Handrail	Stretcher	Outside Stick	Inside Stick	Foot Rail
FFT	3.37	0.49	3.19	3.04	2.86	4.22	3.99
FFD	0.23	0.23	0.26	0.23	0.24	0.22	0.18
VC	8.17	71.89	12.67	17.33	14.78	4.94	1.78
TVD/ VC	0.25	0.92	0.28	0.28	0.26	0.23	0.19
NV	6.39/18	17.94/18	8.17/18	9.83/18	8.67/18	3.89/18	1.67/18

In terms of first fixation duration, the backrest, outside stick, and handrail were the three components noticed first, followed by the stretcher and top rail, and finally the inside stick and foot rail. Regarding the duration of the first fixation, the differences were not significant, with the longest initial viewing time on the handrail. The backrest stood out with the highest number of visits, and it also had the longest average visit duration, indicating that the backrest played a crucial role in participants' affective cognitive judgments, followed by the stretcher. Almost everyone noticed the backrest, indicating its critical role in determining affective imagery.

Due to the varying correlations of eye-tracking metrics with evaluation results and the significant differences in data dimensions, the entropy method was employed to assign values to each metric. First, each metric was standardized: FFD, VC, TVD, and NV were positive indicators, processed using Eq. 7, while FFT is a negative indicator, processed using Eq. 8. Then, information entropy (e_j) was calculated using Eqs. 9, 10, and 11, and the information utility value (d_j) was determined using Eq. 12. Finally, the weight of each metric (ω_j) was calculated using Eq. 13. The calculation results are shown in Table 12.

Table 12. Calculated Value Based on the Entropy Method

Metrics	e_j	d_j	ω_j
FFT	0.7835	0.2165	17.92%
FFD	0.9090	0.0910	7.53%
VC	0.6676	0.3324	27.50%
TVD	0.5903	0.4097	33.90%
NV	0.8410	0.1590	13.16%

Finally, the overall score for each area of interest was computed using Eq. 14. Subsequently, the proportion of each overall score was determined to derive the weights and rankings of the different components. From Table 13, it is evident that the backrest had the highest weight at 47.42%, followed by the stretcher at 13.33%. In the objective weights, the most important components were the backrest and stretcher, consistent with the subjective ranking. In the physiological cognitive process, the handrail and outside stick each accounted for 12.81%, higher than the top rail's 8.77%. The inside stick accounted for 4.27%, which was higher than the Foot rail's 0.59%. This indicates differences between people's subjective perceptions and their visual behavior.

Table 13. Overall Score, Weight Conversion and Ranking of Categories

Category	Z_i	Weight	Ranking
Top rail	0.18	8.77%	4
Backrest	0.973	47.42%	1
Handrail	0.263	12.81%	3
Stretcher	0.273	13.33%	2
Outside Stick	0.263	12.81%	3
Inside Stick	0.088	4.27%	5
Foot rail	0.012	0.59%	6

The Comprehensive Weights Calculation

The physiological indexes, psychological indexes, and comprehensive weights and rankings of different categories are presented in Table 14. Comparing subjective and objective results, the importance of the backrest and stretcher is undeniable. Psychologically, people place more emphasis on the top rail, however, according to eye-tracking experiment results, individuals are more attracted to the central parts of the chair, thus paying more attention to the outside stick and handrail, with almost no attention to the foot rail. Through combining subjective psychological ratings with objective physiological ratings, the weights from both aspects were averaged, resulting in the final weighted ranking: Backrest > Stretcher > Handrail > Top rail > Outside Stick > Inside Stick > Foot rail.

Table 14. Comprehensive Weight and Ranking

Category	Psychological Index Weight	Ranking	Physiological Index Weight	Ranking	Comprehensive Weight	Ranking
Top rail	13.51%	3	8.77%	4	11.14%	4
Backrest	34.63%	1	47.42%	1	41.02%	1
Handrail	10.47%	4	12.81%	3	11.64%	3
Stretcher	23.24%	2	13.33%	2	18.29%	2
Outside Stick	4.46%	5	12.81%	3	8.64%	5
Inside Stick	6.38%	7	4.27%	5	5.32%	6
Foot rail	7.31%	6	0.59%	6	3.95%	7

Construct Multiple Linear Regression Equation

Using Quantification Theory Type I, a multiple linear regression equation was constructed, referencing Eq. 15, to transform the results of morphological analysis into binary data, "0" and "1". This transformation facilitated the quantification of the mapping relationship between the design elements of armchairs and the evaluation values of various dimensions of affective imagery, thereby establishing a mapping model between design elements and affective imagery.

In SPSS 27.0, the method of least squares was employed to determine the categorical scores of each component corresponding to various affective vocabulary, as well as the multiple correlation coefficient (R), the coefficient of determination (R^2), the adjusted R^2, and the constant term (C). Mapping models were established between the four critical components with weights greater than 10% and the three sets of affective vocabulary, as shown in Table 15.

Table 15. Categorical Scores

Category	Concise-Ornate	Soft-Strong	Elegant-Vulgar
A1	0.167	-0.221	0.060
A2	0	0	0
A3	0.447	-0.194	0.299
A4	0.247	0.070	-0.093
A5	0	0	0
A6	0.242	-0.096	0.062
B1	0	0	0
B2	0.055	-0.161	-0.030
B3	0.407	0.052	-0.031
B4	0.106	-0.321	-0.153
B5	0.089	-0.070	0.024
B6	-0.325	-0.067	-0.118
B7	0.023	-0.005	0.115
C1	-0.07	0.146	0.007
C2	0	0	0
C3	0.242	-0.022	0.075
C4	-0.194	-0.385	-0.093
F1	0.457	0.114	0.045
F2	0.159	0.062	0.086
F3	0	0	0
F4	0.077	0.026	0.210
F5	0.227	0.089	0.067
F6	0.606	0.380	0.392
C	-0.043	0.681	0.294
R	0.983	0.991	0.966
R^2	0.967	0.982	0.933
Adjusted R^2	0.769	0.877	0.534

Based on the categorical scores in the table, the mapping relationship expression can be formulated as follows:

$Y_{Concise\text{-}Ornate}$=-0.043+0.167 A1+0.447 A3+0.247 A4+0.242 A6 +0.055 B2+0.407 B3+0.106 B4+0.089 B5-0.325 B6+0.023 B7 -0.07 C1+0.242 C3-0.194 C4 +0.457 F1+0.159 F2+0.077 F4+0.227 F5+0.606 F6

$Y_{Soft\text{-}Strong}$=0.681-0.221 A1-0.194 A3+0.07 A4-0.096 A6-0.161 B2+0.052 B3-0.321 B4-0.07 B5-0.067 B6-0.005 B7+0.146 C1-0.022 C3-0.385 C4 +0.114 F1+0.062 F2+0.026 F4+0.089 F5+0.38 F6

$Y_{Elegant\text{-}Vulgar}$=0.294+0.06 A1+0.299 A3-0.93 A4+0.062 A6-0.03 B2-0.031 B3-0.153 B4+0.024 B5-0.118 B6+0.115 B7+0.007 C1+0.075 C3-0.093 C4+0.045 F1+0.086 F2+0.21 F4+0.067 F5+0.392 F6

The results of the range and contribution rate calculations for each group of components are presented in Table 16.

Table 16. The Range and Contribution

	Concise-Ornate		Soft-Strong		Elegant-Vulgar	
	Range	Contribution rate	Range	Contribution rate	Range	Contribution rate
A	0.447	21.57%	0.415	24.43%	0.392	**34.72%**
B	0.732	**35.33%**	0.373	21.95%	0.177	15.68%
C	0.436	21.04%	0.531	**31.25%**	0.168	14.88%
F	0.457	22.06%	0.380	22.37%	0.392	**34.72%**

DISCUSSION

As shown in Table 15, the multiple correlation coefficient R and the coefficient of determination R^2 can indicate the degree to which the predictive model explains the scores of sample design elements and affective vocabulary. A larger value indicates a better fit. As shown in the table, the coefficients of determination R^2 were 0.967, 0.982, and 0.933, respectively, while the adjusted R^2 values were 0.769, 0.877, and 0.534, all exceeding 0.5. This indicates that the degree of fitting was good, meeting the requirements of this study.

The category range is obtained by subtracting the minimum value from the maximum value of the category scores. This value is referred to as the range. The proportion of each range to the total range is termed as the contribution rate. The contribution rate represents the degree of influence of the category on affective vocabulary, with a higher contribution rate indicating greater importance within that imagery. For the “Concise-Ornate” word group, the influence levels were as follows: B > F > A > C. The backrest (B) had the largest numerical range and the highest contribution rate. Therefore, the style of the backrest was the component that most influences people’s affective judgments regarding “Concise-Ornate.” Similarly, for the “Soft-Strong” word group, the handrail (C) had the highest influence level. For the “Elegant-Vulgar” word group, the stretcher (F) and top rail (A) had the highest influence levels.

Furthermore, the results of this model can be cross-validated with the eye-tracking experiment results. In the proportion of visit frequency in the eye-tracking experiment (as shown in Table 10), for the “Concise-Ornate” word group, people pay more attention to the backrest and stretcher, which aligns with their contribution levels in the “Concise-Ornate” group (as shown in Table 16), where the backrest (B) and stretcher (F) had the highest contribution rates. This is because there are numerous decorative elements on the backrest and stretcher. This finding is consistent with the conclusion in the study by Zhagn and Xu (2020), who reported that if the decorative pattern is complex, people need to pay more attention to the relationship between the decorative pattern and other parts. This finding is also consistent with the conclusion of Liu *et al.* (2017) in the eye movement experiment on the southern official-hat chair, which determined that the backrest is the most important component. Similarly, in the eye-tracking results for the “Soft-Strong” group, relatively higher proportions are observed for the handrail (C) and top rail (A), which correspond to the handrail and top rail having the highest contribution rates. For the

"Elegant-Vulgar" group, as only four relatively important components are retained, apart from the backrest (B), the stretcher (F) is the next most influential. Through comparative analysis with eye-tracking experiment results, it further demonstrates the scientific validity of this model. Additionally, it further elucidates that the imagery of "Concise-Ornate" places more emphasis on easily decorated components, while the imagery of "Soft-Strong" focuses more on components related to linearity, aligning with the results of the previous factor extraction.

In the category scores, positive values indicate a preference towards the right-side affective vocabulary, while negative values indicate a preference towards the left-side affective vocabulary. Under the "Concise-Ornate" word group, taking the backrest (B) as an example, the category score for B6, which represents straight splats, was -0.325. Therefore, the use of B6 component can make the armchair appear more concise. The rankings of other components in category B were as follows: B3(0.407) > B4(0.106) > B5 (0.089) > B2(0.055) > B7(0.023) > B1(0). The score for B3, representing triple-splat backrest, was 0.407, which was the highest positive score, indicating that the triple-splat backrest will make the armchair appear more ornate. Under the "Soft-Strong" word group, regarding the handrail, the inclined type C4 will make the armchair appear more graceful, while the straight type C1 will make it appear sturdier. In terms of the top rail (A), the perceived gracefulness levels were A1 > A3 > A6. These three components are all curved, giving the chair a more graceful appearance, while A4 will give a sturdier appearance. Under the "Elegant-Vulgar" word group, except for F3, which does not make the armchair more vulgar, the rest will make the armchair appear more tasteless, especially the use of F6, which will lean the armchair towards tacky. In terms of the top rail, the design of A4, featuring a rounded straight line, will make the armchair's design more elegant.

However, this study has limitations in the selection of participants, which may be somewhat restrictive. Subsequent research could categorize and discuss individuals from different age groups and cultural backgrounds. In terms of physiological measurements, this study only explored eye-tracking technology. In the future, a multimodal fusion strategy, combining techniques, such as EEG, ERP, and SCL, could be employed to analyze the physiological cognitive processes of products. This would help enhance the accuracy of cognitive research and guide design practices.

CONCLUSIONS

1. According to the experimental data, differences exist between psychological and physiological cognition. This research adopted a combined subjective-objective evaluation approach, using physiological indicators as a supplement, to provide objective data from different perspectives. This approach offers more evidence for analyzing the complex "psychological-physiological" mechanisms of subjects. Moreover, through this combined approach, the importance of components was ranked as follows: Backrest > Stretcher > Handrail > Top rail > Outside Stick > Inside Stick > Foot rail.
2. Selected components with higher weights were used to establish multiple linear regression equations with affective vocabulary, revealing the mapping relationship between design elements and affective cognition, with a good fit. The quantified design element scores can provide theoretical guidance for subsequent design. The backrest

has the most significant impact on people's affective judgments of "Concise-Ornate", while the handrail has the most significant impact on people's judgments of "Soft-Strong". Specifically, A2, A5, B1, C2, and F3 show no difference in their impact on affective cognition. B6 and C4 can make the handrail appear more concise, while A1, A3, A6, C3, and C4 will make the armchair appear more graceful. A4, B2, B3, B4, B6, and C4 will make the armchair appear more elegant. Additionally, the contribution of design elements is consistent with the conclusions of principal component analysis and eye-tracking results.

3. This model establishes a mapping relationship between key styling design elements of armchairs and affective vocabulary, quantifying the influence of different components. It provides insights into which types of components have a greater impact on specific imagery aspects. The establishment of this model can provide designers with theoretical foundations for design and prepare for pre-design for product personalization.

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APPENDIX
Supplementary Information

Table S1. Perceptual Image Vocabulary Database

Graceful	Neat	Soft	Smooth	Concise	Vigorous	Ethereal	Handsome
Gentle	Implicit	Beautiful	Snappy	Generous	Mellow	Dignified	Vivid
Thick	Stretch	Round	Elegant	Tender	Smart	Huge	Bountiful
Simple	Powerful	Delicate	Luxuriant	Ostentatious	Tasteful	Tall	Fine
Harmonious	Majestic	Dynamic	Flexible	Refined	Excellent	Mild	Lustrous

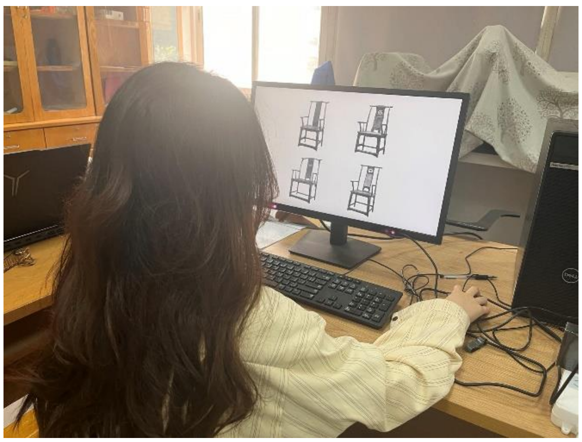

Fig. S1. Eye movement experiment