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RESEARCH ARTICLE

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The emotional design of product color: An eye movement and event-related potentials study

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Abstract

It is the key to accurately obtain participants' emotional responses to product color for the product color emotional design. However, traditional research rarely studies participant's internal emotion cognition and changing mechanism. In this article, a color emotional design method based on eye movements and event-related potentials is proposed. Participative behavior experiment, eye movement, and event-related potentials were carried out. Participants evaluated the electric iron pictures with different color layout and color number to obtain participants' participative feelings before eye movement and ERPs experiment. The results showed that three-color samples were more popular than two-color samples, and the participants' emotions were more positive when the color blocks were evenly distributed. The larger the pupil diameter in the eye movement data, the more positive the participants felt. Participants responded quickly to positive and negative stimuli when shown the two-color samples, and the average amplitude of the early components P1 and N2 exhibited significant changes. For the three-color samples, the average amplitude changes of positive and neutral states of participants mainly occurred in N2 and P3 components. However, there were no significant changes in the negative state. The combination of participative and objective methods is expected to offer an important basis for the research of color emotional design method based on color layout and color number, and to provide reliable indicators for the future analysis of physiological data and product color evaluation models.

KEYWORDS

event-related potentials, eye movements, product color emotional design

1 | INTRODUCTION

Color is the first visual feedback signal perceived by participants and plays an important role when people purchase products.[1-3] When participants make purchase decisions, they often attach importance to whether the aesthetics of the product color meets their emotional expectations.[4] If we can accurately describe the participants' aesthetic images and the emotional responses to product colors, the success rate of product design can be significantly improved. Therefore, product color emotional design (PCED) has attracted the attention of enterprises and designers and has become an important aspect of the product value.[5]

In order to evaluate the participant's emotion effectively, it is necessary to quantify the participant's emotion. Previously, interviews, questionnaires, and semantic differences (SD) were used often by researchers to determine the participant's emotion when conducting PCED.[6-8] The participant's color preference in the selection of products was investigated by acquiring the participant's emotional image of product color,[9] and the relationship between the participant's color image and emotional needs was explored.[10-12] Fuzzy analytic hierarchy process,[13] gray relational analysis methods,[14] and other methods were used to establish an optimal color design model and obtain the best color matching scheme to meet the participant's emotional needs. The optimal color scheme improves participant satisfaction. SD and other methods have been successfully used in several previous studies to evaluate product color and participant emotions. They can effectively combine the product color design elements and the participant's image perception of the product color, and has achieved staged results for the development of PCED.

However, the product color elicits a feeling in the participant that is difficult to express in words, and the aesthetic evaluation of product color by participants depends on individual differences and environmental conditions.[15]Color perception of the participant obtained through questionnaire surveys in PCED studies is participative, and it is difficult to capture the emotional state and cognitive mechanism of the participant accurately from a physiological perspective. Therefore, converting the participant's perception of product color design features into product design is becoming more and more important, and has attracted more and more attention from designers and researchers. Physiological measurement methods should also be used in addition to traditional subjective methods to understand the underlying mechanism that causes changes in the participants' emotional states when evaluating product colors. By combining subjective and objective methods, the response modes of participants in different emotional states are captured, and the participants' color perception and emotional needs can be determined, thus improving the accuracy of PCED.

Eye movement measures and event-related potentials (ERPs) have been widely applied in emotional design research because they provide objective, noninvasive measures of the participant experience, while not interfering with the participants completion of the tasks.[16,17] The research in this field mainly focuses on three directions: first, eye movement measures are used to measure the user's emotion,[18] and eye movement indexes such as pupil diameter,[19] the number of fixations, and fixation time[20] are usually used to reflect the user's emotion changes. Among them, when the participant shows a positive emotion to the stimulus, the pupil diameter increases.[21,22] The second is to use ERPs technology to reflect users' emotional cognition. For example, when studying the relationship between stimulation and ERPs components, researchers found that negative stimulation produced more P1 components in the occipital region than positive stimulation and neutral stimulation;[23] However, the P2 and N2 components elicited different responses than the P1 components, and the participants exhibited larger P2 and N2 amplitudes when exposed to positive and negative stimuli than neutral stimuli.[24] ERPs technologies are widely used in the field of industrial design.[25] Researchers use ERPs technology to obtain more accurate perceptual images of users,[26,27] and establish a correlation model between product color and perceptual images of users, so as to generate a product color design scheme that can meet users' emotional cognition. The third method is to combine eye movement and ERPs technology to obtain more reasonable research data. Xue[28] analyzed the cognitive processing of the mental rotation of three-dimensional graphics using eye movement and Electroencephalogram (EEG) measures; a model was established using a data-driven method, providing a new experimental method for research on mental rotation. Winslow[29] investigated visual search tasks by combining ERPs and eye movement measures. Takeda[30] evaluated the attention and workload of drivers by combining ERP and eye-tracking measures. Eye movement and ERP methods have been widely used in research on interface design, product modeling design, product evaluation, and other fields to obtain the internal cognitive mechanism of the participants' emotional needs. The pupil diameter, P1, N2, P300, N400, and other components provide objective information on the participants' emotional state, demonstrating the applicability of physiological measurement methods in emotional design. However, in the research of PCED, the internal cognitive mechanism of participant's emotional changes has not been clearly described. The visual mechanism and brain mechanism of participant's emotional changes caused by different color stimuli have not been fully explained. Therefore, measuring participant's internal cognitive emotions through eye movements and ERPs technology can effectively assist in PCED research.

In this study, we combine subjective and objective methods to determine the internal emotional response mechanism of users to different product colors and the physiological parameters that are strongly related to changes in the emotional state. This study provides experimental support to predict the user's emotional state through physiological parameters, thereby contributing to PCED research.

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-four postgraduate and undergraduate students majoring in industrial design at Hebei University of Technology participated in the study. Sample size was selected to be consistent with previous research[31-33] (Devillez et al, 2019, n = 17; Lee et al, 2019, n = 14; Khushaba et al, 2012, n = 18). The participants were divided into two groups of 12 people each (six males and six females). Due to a lack of eye movement data, two samples of the first set of data were excluded. All participants were between 20 and 30 years old (M = 24.42, SD = 1.53), right-handed, had no history of mental illness, and had normal vision or corrected vision. All participants participated voluntarily in this experiment.

Before the experiment, the participants were fully rested and had washed their scalp with baby shampoo. All experiments were performed in a laboratory without external interference. During the experiment, the participants always maintained a comfortable state, relaxing every once in a while. All participants received written and oral descriptions about the experiment contents and matters needing attention, which were approved by the Ethics Committee of Hebei University of Technology.

2.2 | Stimuli

Researchers have become increasingly aware of the role and influence of the number of color,[7] the layout,[34] color proportions,[35] and decorative patterns[36] in PCED research. However, some of these factors that affect color design have not been investigated and should be integrated into the design process. Therefore, in this study, we used stimulus samples by changing the color layout and the number of colors.

Two independent factors were used in this experiment: (a) color layout (two levels: four-color-layout, six-color-layout) and (b) color number (two levels: two-color, three-color). The photos of stimuli were divided into photos with two colors (180 photos) and three colors (480 photos). The resolution of the images was 1024 × 717 pixels, and the size was about 68 KB.

The photos were obtained from the Internet and other sources and included 147 electric irons, 102 vacuum cleaners, 86 electric kettles, 47 electric rice cookers, and 40 hair dryers. A questionnaire survey was used to eliminate photos with similar colors, leaving 10 to 30 photos for each type of product; 90 photos with different color combinations were retained. It was found that the majority of small household electrical appliances consisted of two colors or three colors, and monochrome images or images with four or more colors were rare. Therefore, we focused on images with two colors and three colors. Fifteen students majoring in industrial design or product design, three professors engaged in industrial design education, and two designers with many years of design experience were invited as members of the expert group. Subsequently, a questionnaire was created for the product images and was distributed to the members of the expert group, who provided information on the participant's perception of color. According to the color of the product picture, the members of the expert group assigned the colors they thought were similar to each other to the same group, which was divided into three to six groups in total. The number of colors in each group was randomly assigned, but it was necessary to ensure that the colors in the group were not repeated and contain all the colors of the picture. At the same time, the frequency of color appearing in the same group was counted, and a similar frequency matrix of 60 × 60 was constructed. The matrix was represented by $\Delta = (xij)$ $(i, j = 1, 2,..., 60)$, as shown in Equation (1). Multidimensional scale analysis was used to determine the fitting degree of the sample, and pressure coefficient was used to determine the size of the fitting degree and the coordinate value of the dimension that could be used. If the coordinate value can be used, the next stage of clustering will be carried out, and if the coordinate value cannot be used, the calculation will be carried out again. Multidimensional scale analysis and clustering analysis were employed to analyze these data. The clustering results showed that six colors (white, blue, red, black, purple, and orange) were the representative colors[7].

Similarity matrix of color number is as follows:

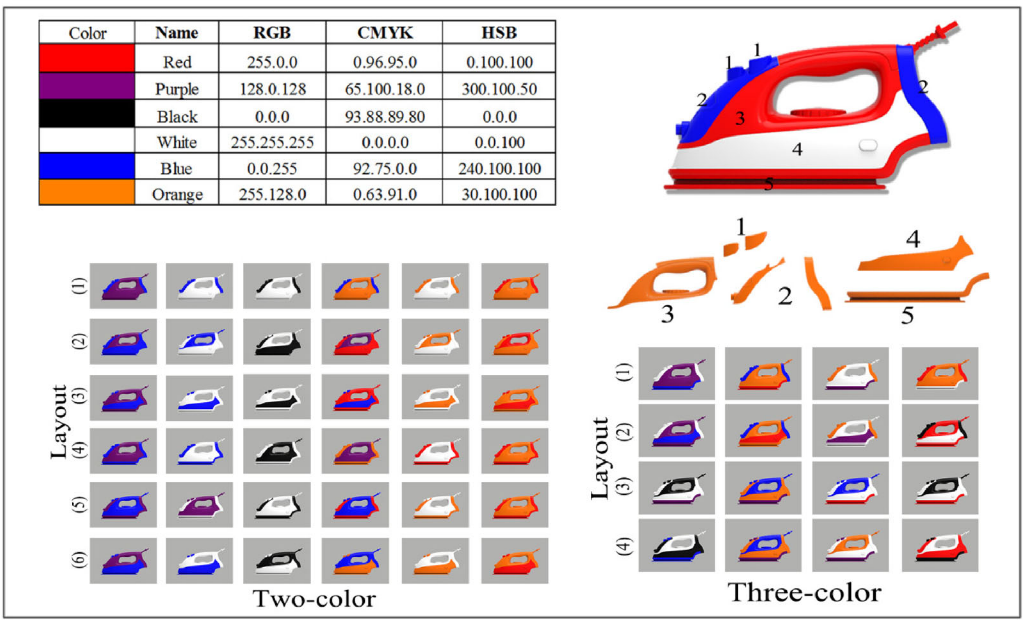
$$\Delta = \begin{bmatrix} x_{1,1} & x_{2,1} & \cdots & x_{i,1} & \cdots & x_{59,1} & x_{60,1} \\ x_{1,2} & x_{2,2} & \cdots & x_{i,2} & \cdots & x_{59,2} & x_{60,2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{1,j} & x_{2,j} & \cdots & x_{i,j} & \cdots & x_{59,j} & x_{60,j} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{1,59} & x_{2,59} & \cdots & x_{i,59} & \cdots & x_{59,59} & x_{60,59} \\ x_{1,60} & x_{2,60} & \cdots & x_{i,60} & \cdots & x_{59,60} & x_{60,60} \end{bmatrix} \tag{1}$$

A total of 147 pictures of electric irons were collected and distributed to six industrial designers with many years of product design experience. Morphological analysis was used by designers to divide the morphological areas of electric irons. According to the on-the-spot product research in the market and the analysis of the color layout of the electric iron, the electric iron was divided into five areas[34]. Section 1 was the button. Section 4 was main body fuselage. Section 5 was bottom plate. The two colors were randomly assigned to five areas, with a total of 20 layouts. And the three colors were randomly assigned to five areas, with a total of 60 layouts. However, according to the characteristics of the electric iron body and market research, six layouts were selected for the two-color images, and four layouts were selected for the three-color images. The final stimulus samples were: six layouts of two-color images (12-345, 13-245, 14-235, 125-34, 134-25, 145-23) arrangement and combination, for a total of 180 images; four layouts of three-color images (and, 12-34-5, 12-35-4, 13-24-5, 15-24-3) permutation and combination, for a total of 480 images. An example of the layout is shown in Figure 1. For example, in a two-color stimulus sample, the design elements included layout, color A, and color B. In these elements, two colors were assigned to six layouts. Colors A and B can be white, blue, red, black, purple, and orange, but the same layout cannot contain only one color. In the first layout (12-345) of the two-color matching experiment, the section 1 and 2 of the electric iron were assigned color A and the section 3, 4, and 5 were assigned color B.

2.3 | Procedure

The experiment was carried out in a quiet room. The laboratory was soundproof and shielded from electromagnetic signals that could interfere with the experiment. After entering the room, the participants sat comfortably in front of the computer screen. They were asked to look at the center of the computer screen. The participants viewed the stimuli from a distance of 65 cm. At the same time, the main test was prepared for the experiment and was ready to finish and start the experiment. The experimental process is shown in Figure 2.

This experiment was divided into two groups. There were 180 trials and six blocks in the first group, and each block included 30 trials. The second group of experiments consisted of 480 trials and four blocks, each of which included 120 trials. After each block, the participants could choose to rest or continue. The EEG signal recorded during the rest was automatically filtered out during data processing. The next stimulus appeared after the participants had pressed the key, and the stimulus materials were randomly presented. Each stimulus material appeared once. Between two stimuli, gray blank pages were presented at an interval of 1 second and fixed pages at an interval of 1 second, as shown in Figure 3. During the experiment, the emotional state of the participants while viewing the product color was recorded. Participants that felt positive feeling while viewing the product color clicked key



Color	Name	RGB	CMYK	HSB
	Red	255.0.0	0.96.95.0	0.100.100
	Purple	128.0.128	65.100.18.0	300.100.50
	Black	0.0.0	93.88.89.80	0.0.0
	White	255.255.255	0.0.0.0	0.0.100
	Blue	0.0.255	92.75.0.0	240.100.100
	Orange	255.128.0	0.63.91.0	30.100.100

FIGURE 1 Examples of the stimuli used for the two-color and three-color images. The rows represent the layout

1. If they felt neutral, they clicked key 2, and if they felt negative, they clicked key 3. In this experiment, the behavioral data, eye movement data, and EEG signals were collected synchronously.

2.4 | Analysis of the behavioral data

The behavioral data were acquired with E-Prime 2.0 software. E-prime 2.0 was installed on a Dell desktop all-in-one computer with a 23.8-in. monitor and a screen resolution of 1920 × 1080 and 60 Hz. All data were analyzed using IBM SPSS 22.0 software. Analysis of variance (ANOVA) procedures was used to assess the impact of the independent variables on the dependent measures. Before performing this analysis, the assumptions associated with the ANOVA procedure were tested by spherical test and variance homogeneity test. The mean reaction times (RT) were compared using a mixed-design repeated-measures one-way ANOVA with the layout *gender factors. An independent samples *t* test was used to determine the differences in the RT between the two-color and three-color images. The emotional states for the different layouts and color numbers were enumerated. A correlation analysis was conducted between the emotional state of the participants and the RT. In this article, we performed data correction. First, it was confirmed that all data meet the normal distribution, and then Mauchly spherical test was carried out. If the test result met the significance >0.05, the data could be used directly. If it was not satisfied, the Greenhouse-Geisser method was used for correction again. A 0.05 level of significance was used for statistical comparisons.

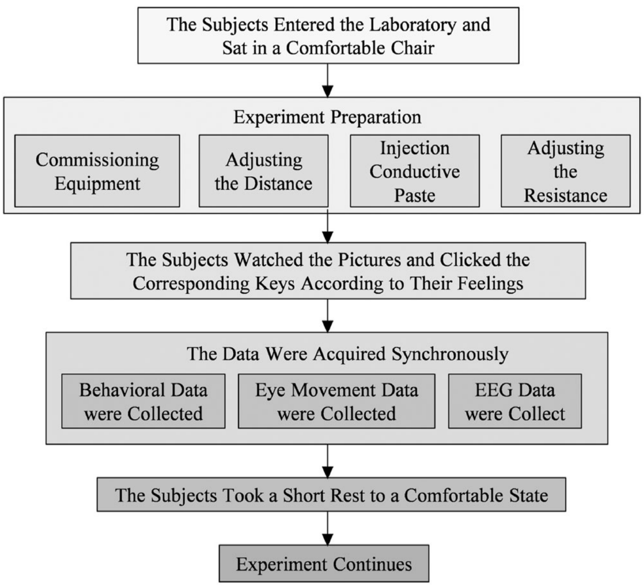


FIGURE 2 Experiment process

2.5 | Analysis of the eye movement data

An external data processing module was attached to detect the eye movement meter on the display screen of the Dell computer equipped with the E-Prime 2.0 software. The participants were about 60 cm away from the screen during data acquisition, allowing for appropriate head movements; an automatic participant's calibration process was performed. Data screening and post-processing were performed using Ergolab software developed by the Jinfa Company (Beijing). The following parameters were separately analyzed using one-way repeated-measures with different layout levels as within-participants factors: the mean saccade duration, average pupil diameter, mean blink duration, mean fixation duration, saccade count, blink rate, fixation rate, saccade rate, total saccade duration, blink count, total blink duration, fixation count, total fixation duration, min and max saccade duration, min and max pupil diameter, min and

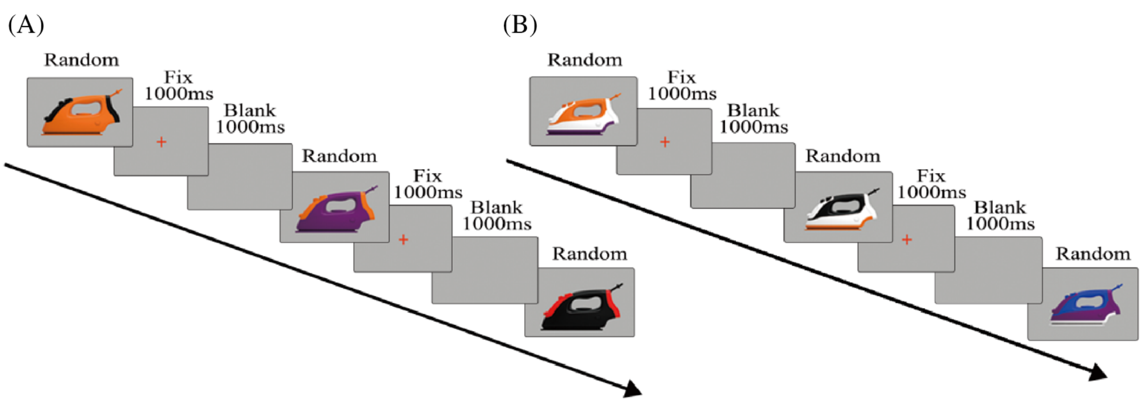


FIGURE 3 Time course of one trial during viewing the two-color (A) and three-color (B) images

max blink duration, and min and max fixation duration. One-way ANOVA was used to determine the differences in the eye movement indices between the two-color and three-color images. The *P*-values were corrected by the Greenhouse-Geisser method. The eye movement components with significant main effects were used for the subsequent correlation analysis with the emotion score, and the eye movement indices related to the emotion score was extracted. Subsequently, the gaze track and eye movement heat maps of the different color schemes were analyzed.

2.6 | Analysis of the EEG recordings

The EEG signals were acquired with a 40-channel NeurOne EEG acquisition system with a sampling rate of 40 000 Hz. All leads were synchronously collected. Figure 4 presented the setup of the experiment. Before the experiment, the impedance was reduced to below 1 kΩ. At the beginning of the experiment, the display on the participants' side presented the experimental instructions. The experiment began after the participants had indicated that he/she understood the experimental procedure. Before EEG data acquisition, a spontaneous EEG signal was recorded for about 15 seconds, and the experiment was started after the waveform was stable. Synchronous acquisition of the eye movement data and EEG signals was ensured by the Ergolab software. The EEG signals were preprocessed and analyzed using EEGLAB, which is an open-source toolbox running on MATLAB. We used EEGLAB to remove the components caused by blinking, glances, or shaking, which can effectively retain EEG signals. The Ground (GND) electrode was set as the ground electrode, and the average value of the bicolor mastoid was used as the reference electrode to reduce the influence of hemispherical asymmetry. The filtering range was 1 to 40 Hz. The analysis signals were 200 ms before stimulation and 1000 ms after stimulation. The human factors related to blinking and side-eye movements were manually excluded. An independent component analysis was conducted to divide the signals into the largest independent component, and the time schedules were averaged for the different experimental conditions. The final superposition times of the experimental conditions were greater than 90% of the total number of conditions.

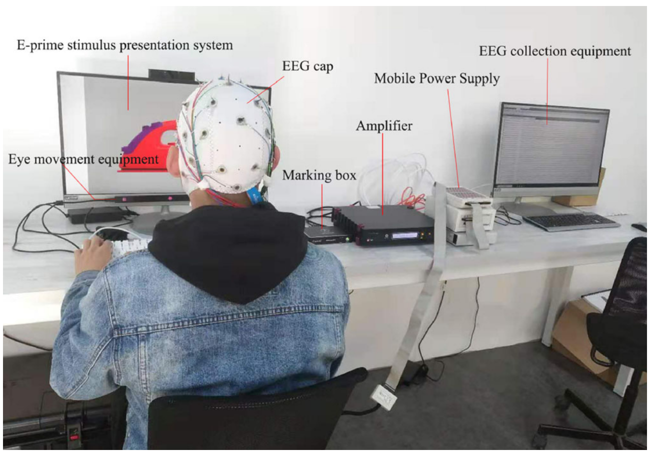


FIGURE 4 The experimental setup utilized in this article

Previous cognitive experiments have shown that ERPs consisted primarily of the early visualization of the exogenous components P1 and N2, the endogenous components P300 and N400, and the late positive potential (LPP). Fourteen conductive electrodes (FP1, FP2, F3, FZ, F4, C3, CZ, C4, P3, PZ, P4, O1, LZ, O2) were selected and divided into three types: left hemisphere (FP1, F3, C3, P3, O1), midline (FZ, CZ, PZ, LZ), and right hemisphere (FP2, F4, C4, P4, O2). In the three-color experiment, the FZ position was excluded due to missing signals. Moreover, the average amplitude and hemispheric effect of ERP of participant emotion caused by layout and color number were analyzed. The *P*-values were corrected with the Greenhouse-Geisser method. Least-significant difference test assuming unequal variance was used for post hoc multiple comparisons and the significance level was set as 0.05.

3 | RESULTS

3.1 | Behavioral performance

In the behavior experiment, the participants expressed his/her emotional state by pressing the keys (1-positive, 2-neutral, and 3-negative). The statistics of the emotional state of the participants for the different color schemes are listed in Figure 5.

As shown in Figure 5A, in the two-color experiment, the sixth layout (145-23) has the highest preference (25.3%), and the first layout (12-345) has the lowest preference (16.1%).

As shown in Figure 5B, the differences in the emotional state of the participants for the different layouts of the three-color samples are not significant, which is attributed to the similarity in the average color block area, the strong visual balance, and the small visual differences in the three-color samples.

The participants' emotional states and average RT to the two-color and three-color samples are shown in Figure 6. The average RT to two-color samples is higher than that of the three-color samples, whereas the average preference of the two-color samples is lower than that of the three-color samples. The three-color images (31.4%) are more popular than the two-color images (21.1%).

Subsequently, we analyzed the correlation between emotional state and the RT. The results of the correlation analysis between the emotional state and the average RT of the two-color and three-color experiments are shown in Table 1. The correlation between the two parameters is statistically significant ($P = .000$).The correlation coefficient shows weak correlation ($\rho = -.262$, $\rho = -.150$). As shown in Figure 6, the average RT for the neutral state is significantly higher than that for the positive and negative states for both the two-color and three-color experiments. Also the RT is shortest for the negative state, which conforms to the objective law that it takes longer for people to make judgments on indecisive things and shorter for people to make judgments on annoying things. In the experiment, the basic colors used in the two-color and three-color experiments are white, blue, red, black, purple, and orange, which is arranged and combined to form color matching samples. Since each color has the same frequency of occurrence, it can effectively avoid the influence of the color itself.

The results of the relationship analysis between the emotional state and the RT of different product layouts are shown in Figure 7. Similarly, the average RT of the participants in the neutral state is the longest, and the average RT of the participants in the negative state is the shortest. Due to a change in the layout, the RT of the participants to the stimulus samples fluctuates. In the experiment, we calculate the average RT of different layouts and control the color variables. Each layout contains the same color combination, thus reducing the influence of color. The results of the repeated-measures ANOVA shows that in the two-color experiment, the main effect of the average RT of the product layout is significant, $F(5, 50) = 3.230$, $P = .013$, indicating that the change in the layout has a significant effect on the RT of the participants.

Gender as an influencing factor is also considered. There is no interaction between product layout * gender ($F(5, 50) = 0.513$, $P = .765$). The RT of the participants to the stimulus is not affected by gender. Similarly, in the three-color experiment, the main effect of the average RT of the product layout is significant, $F(3, 30) = 6.625$, $P = .001$. Subsequently, the difference in the RTs for the different color combinations (two-color and three-color experiment) is analyzed. The independent sample t test shows that $P = .131$, indicating that there is no significant difference between the average RT of the two-color and three-color experiments. In summary, the effect of the

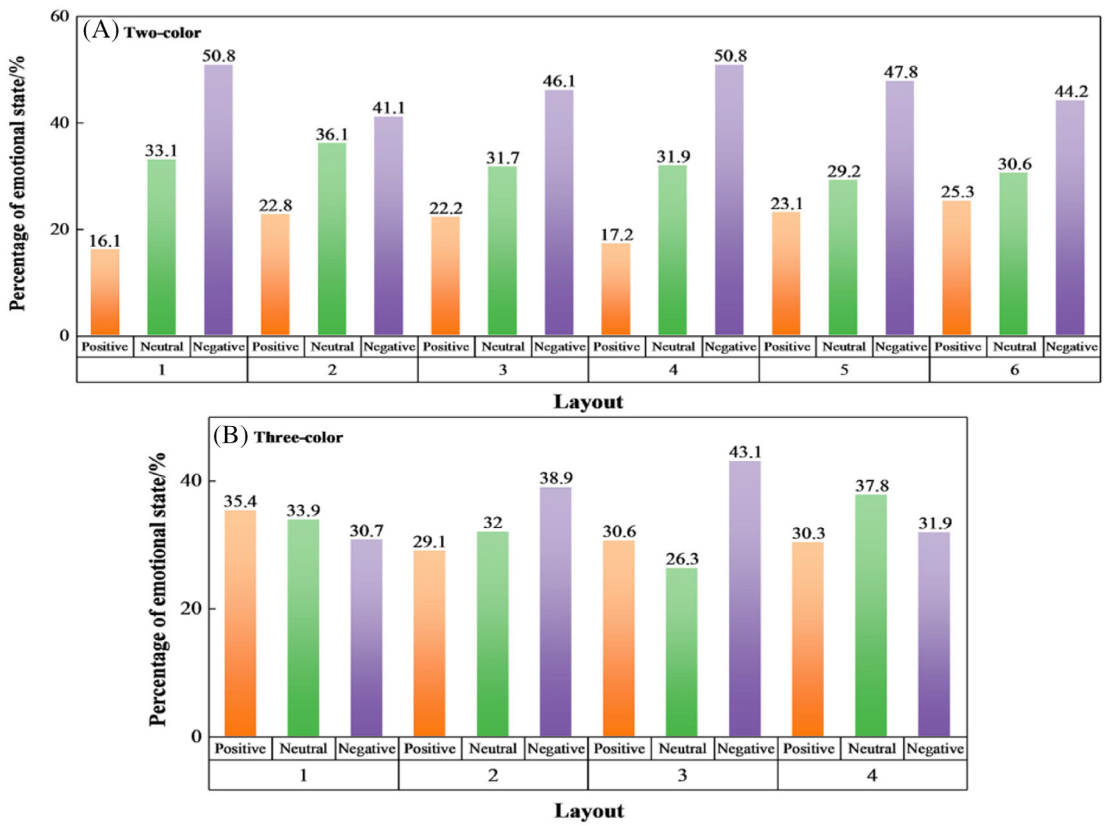


FIGURE 5 Emotional states of the participants for different layouts

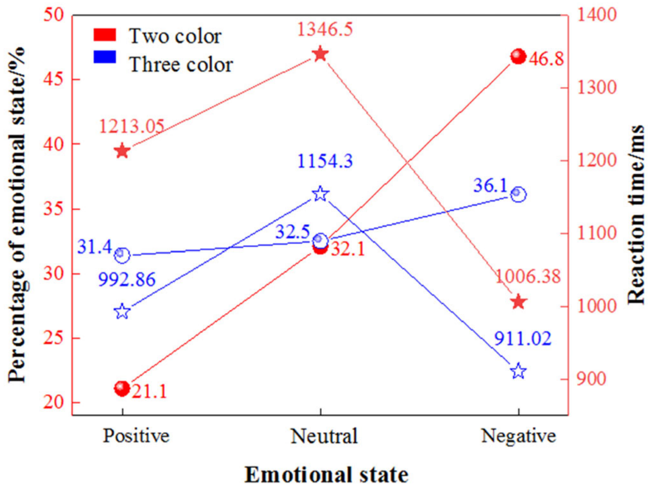


FIGURE 6 The relationship between the emotional state and the reaction time for different color combinations

TABLE 1 Results of the correlation analysis between the emotional state and reaction time

	Spearman correlation	Sig. (double tails)
Two-color	−.262	.000
Three-color	−.150	.000

number of colors and gender on the RT of the participants is relatively small compared to the effects of the product layout. Therefore, the analysis of the eye movement data primarily focuses on the product layout to extract the eye movement indicators.

3.2 | Eye movement

The frequency percentages of the emotional states (positive, neutral, and negative) corresponding to the different color images are converted into emotional state scores (percentile system) to determine the changes in the eye movement indices resulting from different color layouts. The total score of the three emotional states is 100 points, and each emotional state comprises one-third of the total. The negative state has a range of 0 to 33.33 points, the neutral state has a range of 33.34 to 66.66 points, and the positive state has a range of 66.67 to 100 points. For example, if a participant expresses positive feelings when viewing five pictures, neutral feelings for 11 pictures, and negative feelings for 14 pictures of 30 pictures of the first layout in the two-color experiment, then the final emotional score of the participants is 5/30 * 100 + 11/30 * 50 + 14/30 * 0 = 35 points. Therefore, the participant exhibits a neutral state overall for the first layout of the two-color experiment. Each participant's responses on the Likert Scale were subjected to statistical analysis.

The results of variance analysis of repeated measurements were shown in Table 2. The results show that in the two-color layout, the mean saccade duration (F(5, 35) = 4.275, P = .004), average pupil diameter (F(1.923, 13.461) = 5.647, P = .017), saccade rate (F(5, 35) = 4.338, P = .004), fixation count (F(5, 35) = 3.736, P = .008), and total fixation duration (F(5, 35) = 8.283, P = .000) have significant main effects. The max pupil diameter (F(1.636, 11.449) = 4.015, P = .054) is significant. In the three-color layout, the average pupil diameter (F(1.403, 15.433) = 5.798, P = .021), mean blink duration (F(3, 33) = 4.978, P = .006), mean fixation duration (F(1.839, 20.224) = 6.648, P = .007), blink rate (F(3, 33) = 5.271, P = .004), fixation count (F(1.463, 16.095) = 6.722, P = .012), fixation rate (F(3, 33) = 13.900, P = .000), total fixation duration (F(1.514, 16.657) = 12.613, P = .001), max pupil diameter (F(1.845, 20.291) = 3.631, P = .048), and min pupil diameter (F(3, 33) = 2.931, P = .048) have significant main effects.

We extracted the eye movement indicators that were significantly related to the emotional state and performed a correlation analysis between the eye movement indicators with significant main effects and the emotion scores, as shown in Table 3. The results show that the average pupil diameter (P = .025) of the two-color layout is correlated with the emotional score. The mean blink duration (P = .005), blink rate (P = .005), and mean fixation duration (P = .006) of the three-color layout is significantly correlated with the emotional score, and the average pupil diameter (P = .066) has a low correlation with the emotional score. Detailed data are shown in Table 4.

The scanning paths and hot spot maps of the two-color and three-color experiments for different layouts are shown in Figures 8 and 9. A to F represents the six regions of the two-color samples, and G to J represents the four regions of the three-color samples. As shown in Figure 8, although there are only two colors, the average number of fixation points is 7 to 8, and the scanning path is complex. However, there are only 3 to 4 fixation points in the three-color experiment, and the scanning path is short.

The color of the hot spot map reflects the gaze duration and attention of the participant. Red represents a long duration and concentrated gazing, while yellow and green mean indicate less duration. The 2D and 3D hotspot maps for the different color layouts are shown in Figure 9. The fixation points of the two-color and three-color layouts are located in area 3 and a small part of area 4 of the electric iron. The hot spots are scattered, the thermal value of the fixation point is higher, and the participant's residence time is longer in the two-color layout

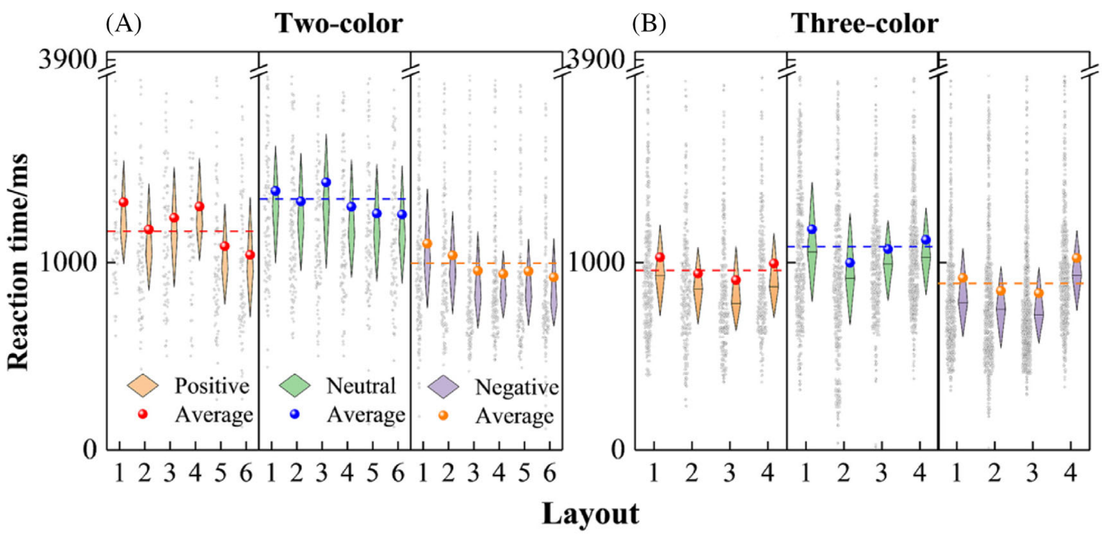


FIGURE 7 The relationship between the reaction time and the emotional state for different product numbers

TABLE 2 Results of repeated measurement analysis of variance for eye movement data

	Two-color			Three-color		
Source	**df**	***F***	**Sig.**	**df**	***F***	**Sig.**
Average pupil diameter	1.923	5.647	.017	1.403	5.798	.021
Mean blink duration	N	N	N	3	4.978	.006
Mean fixation duration	N	N	N	1.839	6.648	.007
Mean saccades duration	5	4.275	.004	N	N	N
Blink rate	N	N	N	3	5.271	.004
Saccades rate	5	4338	.004	N	N	N
Fixation count	5	3.736	.008	1.463	6.722	.012
Fixation rate	N	N	N	3	13.900	.000
Total fixation duration	5	8.283	.000	1.514	12.613	.001
Max pupil diameter	1.636	4.015	.054	1.845	3.631	.048
Min pupil diameter	N	N	N	3	2.931	.048

than the three-color layout. However, the hot spots in the three-color layout are concentrated, the thermal value is small, and the duration is short, which is consistent with the result of the scanning path.

3.3 | ERPs results

The ERP signals of the two-color and three-color samples for the three emotional states are shown in Figures 10 and 11.

3.3.1 | P1 component results

The average amplitude of the P1 component of the ERP in the two-color experiment is shown in Figure 12A. The results of variance analysis of repeated measurements are shown in Table 5. The statistical analysis results show that the main effect of the average amplitude of P1 is significant for the different emotional states, $F(2, 228) = 3.366$, $P = .036$. The paired comparison shows that the average amplitudes of the P1 component for the positive and negative states are statistically significant, $P = .011$. However, the average amplitudes are not statistically significant for positive and neutral states ($P = .263$) or the neutral and negative states ($P = .132$). The main effect of the interaction of the emotional state * hemisphere is significant, $F(4, 228) = 2.636$, $P = .035$. It is found (Figures 10 and 12) that the average amplitude of P1 is the largest in the right hemisphere, and the average amplitude of P1 in the left hemisphere exhibits the largest changes with the emotional state.

TABLE 3 Correlation analysis between the eye movement indices and the emotional score

	Two-color		Three-color	
	Spearman correlation	**Sig.**	**Spearman correlation**	**Sig.**
Average pupil diameter	−0.323	0.025	0.267	0.066
Mean blink duration	N	N	0.397	0.005
Mean fixation duration	N	N	0.394	0.006
Blink rate	N	N	−0.396	0.005

TABLE 4 Correlation between the eye movement indices and the emotional score

	Two-color						Three-color			
	1	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**
Average pupil diameter	3.38	3.32	3.32	3.20	3.21	3.25	3.58	3.42	3.39	3.40
Mean blink duration	N	N	N	N	N	N	0.20	0.19	0.19	0.18
Blink rate	N	N	N	N	N	N	5.07	5.30	5.36	5.68
Mean fixation duration	N	N	N	N	N	N	0.25	0.22	0.21	0.21
Emotional score	29.10	38.18	36.13	33.43	36.35	37.60	44.79	39.20	37.94	37.99

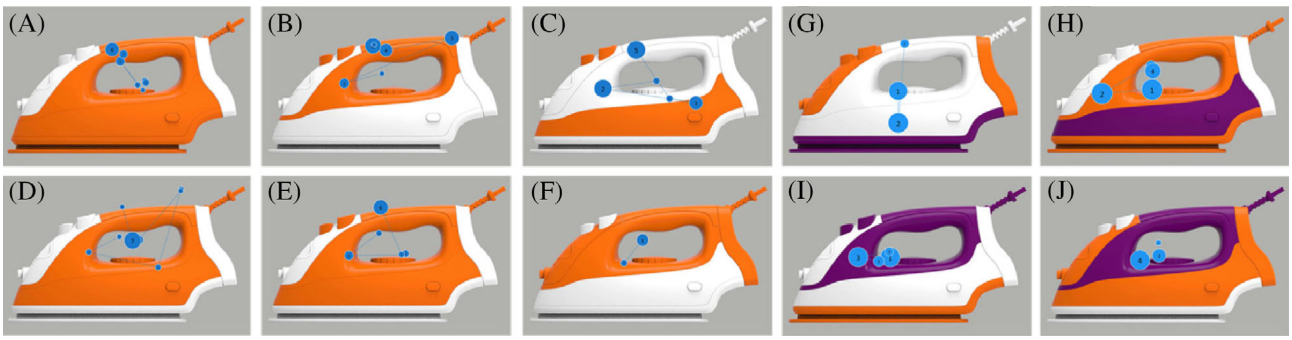


FIGURE 8 Eye movement track map

The participants exhibit an incremental change in the average amplitude from the positive to the negative emotional state. That is, the left hemisphere is affected by the emotional state, which stimulates the average amplitude of P1 in the left hemisphere and produces a high cognitive load.

The average amplitudes of the different brain electrodes (frontal region [FP1, FP2, F3, FZ, F4, C3, CZ, C4], parietal region [P3, PZ, P4], and occipital region [O1, LZ, O2]) show that the main effect of the emotional state is only significant at F3 ($F(2, 24) = 5.195$, $P = .013$) and C3 ($F(2, 24) = 8.192$, $P = .002$) in the frontal region of the left hemisphere and O1 ($F(2, 24) = 5.101$, $P = .014$) in the occipital region of the left hemisphere. In the three-color experiment, the mean amplitude of P1 is analyzed using repeated-measures ANOVA of the emotional state * hemisphere, as shown in Table 5. The main effect of the mean amplitude of P1 for the different emotional states is not significant, $F(1.518, 141.178) = 1.136$, $P = .312$. There is no significant interaction between emotional state * hemispheres, $F(3.036, 141.178) = 0.325$, $P = .810$.

3.3.2 | N2 component results

The average amplitude of the N2 component of the ERP in the two-color experiment is shown in Figure 12B. The results of variance analysis of repeated measurements are shown in Table 5. The average amplitude of N2 is analyzed using repeated-measures ANOVA of the emotional state * hemisphere. The results show that the main effect of the average amplitude of N2 in the different emotional states is significant, $F(1.429, 125.737) = 11.855$, $P = .000$. A paired comparison shows that the difference is

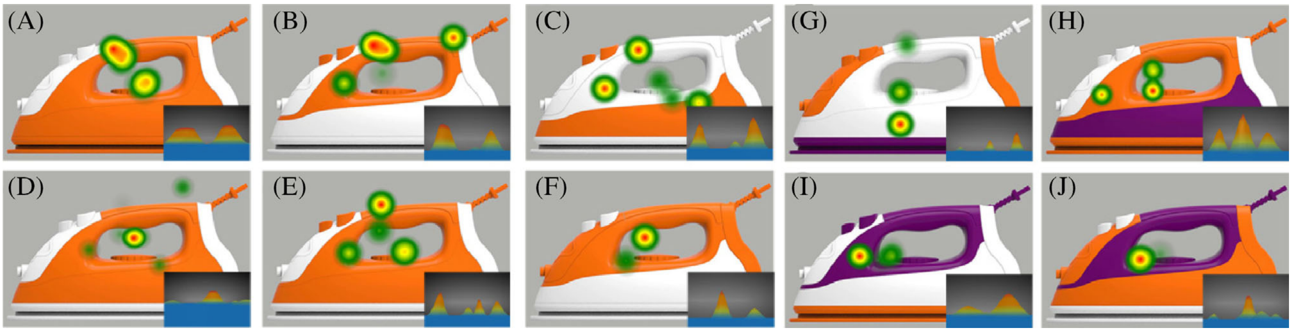


FIGURE 9 2D and 3D maps of the eye movements

attributed to the difference in the average amplitudes between the positive and negative states (P = .000), as well as the positive and neutral states (P = .001), and there is no statistical difference in the average amplitudes between the neutral and negative states (P = .439). There is no interaction between the emotional state and the hemisphere, F(2.858, 125.737) = 0.718, P = .537.

The statistical analysis of the average amplitude of the electrodes in different brain regions shows that the main effects of the emotional state on the average amplitude of the left hemisphere frontal region C3 (F(2, 24) = 3.867, P = .035), the left hemisphere parietal region P3 (F(1.231, 14.775) = 5.381, P = .02), the left hemisphere occipital region O1 (F(2, 24) = 6.712, P = .005), and the midline parietal region PZ (F(1.396, 16.755) = 4.662, P = .035) are significant.

The average amplitude of the N2 component of ERP in the three-color experiment is shown in Figure 12C. The results of variance analysis of repeated measurements are shown in Table 5. The statistical results show that the main effect of the average amplitude of N2 for the different emotional states is significant, F(1.898, 290.387) = 3.138, and P = .047. A paired comparison results show that the average amplitude in the positive and negative states (P = .033) and the positive and neutral states (P = .048) is statistically significant, while the average amplitude in neutral and negative states (P = .977) is not statistically significant. The main effect of the interaction of the emotional state * hemisphere is not significant, F(3.796, 290.387) = 0.582, P = .667. The differences in the average amplitude between the left and midline hemispheres (P = .546), the left and right hemispheres (P = .083), and the midline and right hemispheres (P = .348) are not statistically significant.

The statistical analysis of the average amplitude of the electrodes in different brain regions shows that the main effects of the emotional state on the average amplitude of the left hemisphere frontal area C3 (F(1.354, 14.896) = 5.874, P = .021) and the right hemisphere frontal area C4 (F(2, 22) = 5.806, P = .009) are significant, whereas the main effect of N2 on the average amplitude of the other electrodes is not significant.

3.3.3 | P3 component results

The average amplitude of the P3 component of the ERP in the two-color experiment is shown in Figure 12D. The results of variance analysis of repeated measurements are shown in Table 5. The results of the repeated-measures ANOVA show that the average amplitude of P3 in the different emotional states (F(1.428, 255.567) = 4.264, P = .026) has a significant main effect. A paired comparison shows that the difference is caused by the difference between the neutral and negative states (P = .003) and the difference between the positive and neutral states (P = .022), while the difference between the positive and negative states (P = .384) is not statistically significant. The interaction between emotional state * hemisphere is not significant, F(2.855, 255.567) = 2.004, P = .117. The difference in the average amplitudes of the left and right hemispheres (P = .036) is statistically significant. The difference in the average amplitudes of the left and midline hemispheres (P = .552) and those of the midline and right hemispheres (P = .166) are not statistically significant.

The statistical analysis of the average amplitude of the electrodes in different brain regions shows that the main effect of the emotional state on the average amplitude of F3 (F(2, 24) = 3.517, P = .046) in the left hemisphere frontal region is significant, and that of C3 (F(2, 24) = 2.720, P = .086) in the left hemisphere frontal region is marginally significant, while the main effect on the average amplitude of P3 in the other electrode positions is not significant.

The average amplitude of the P3 component of ERP in the three-color experiment is shown in Figure 12E. The results of variance analysis of repeated measurements are shown in Table 5. The repeated-measures ANOVA of the emotional state x hemisphere on the average amplitude of P3 shows that the main effect of the P3 average amplitude in different emotional states is

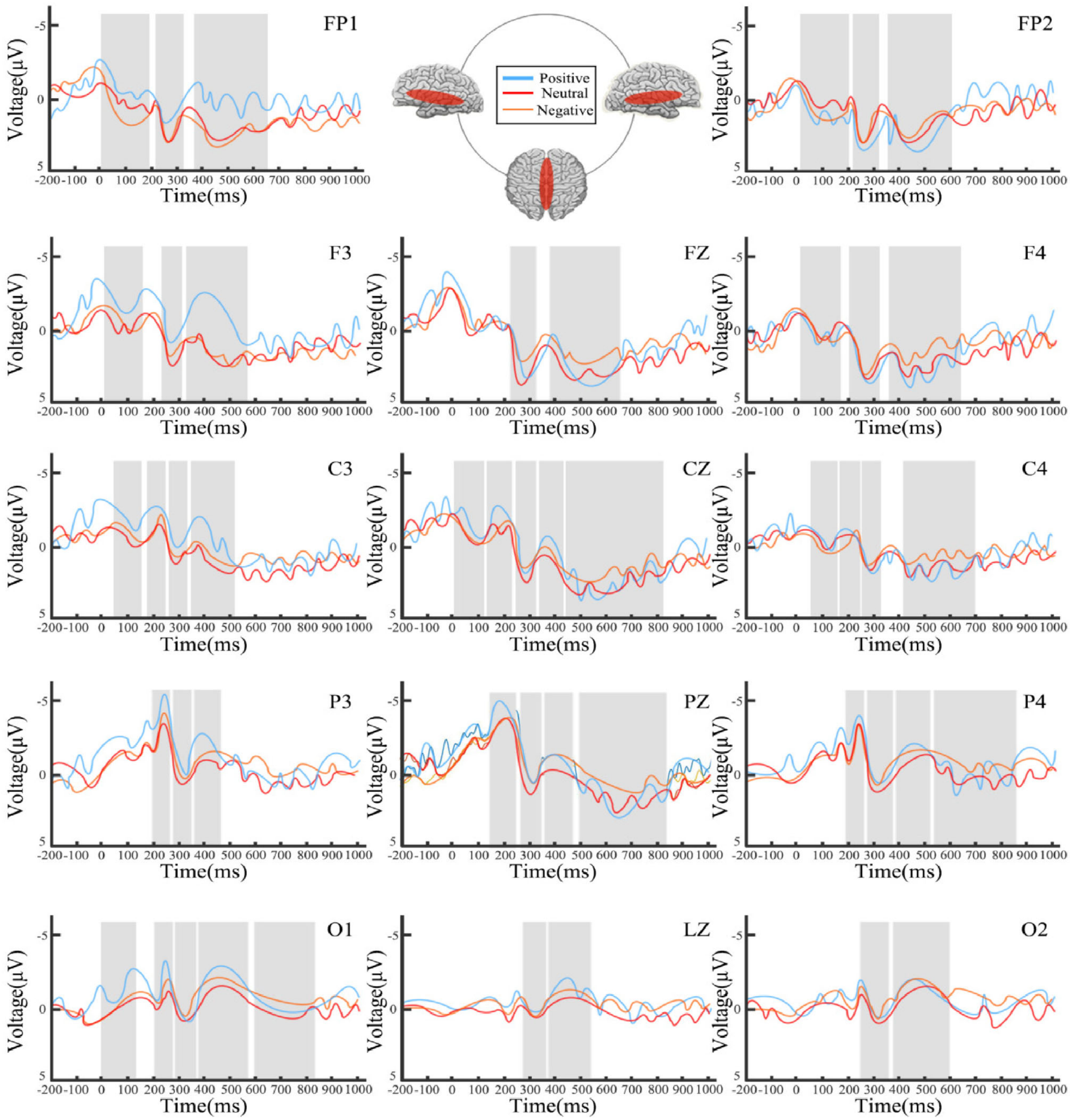


FIGURE 10 Event-related potentials for the positive, neutral, and negative states for the two-color layout. The sites are the left hemisphere (FP1, F3, C3, P3, O1), midline (FZ, CZ, PZ, LZ), and right hemisphere (FP2, F4, C4, P4, O2)

significant, $F(1.580, 241.732 = 4.917, P = .013)$. A paired comparison indicates that the differences in the average amplitudes of the positive and negative states ($P = .016$) and the positive and neutral states ($P = .017$) are statistically significant, while those of the neutral and negative states ($P = .818$) are not statistically significant. The main effect of emotional state * hemisphere is not significant, $F(3.160, 241.732) = 1.623$, $P = .182$. The main effect is not significant among different hemispheres, and the differences in the average amplitude between the left hemisphere and midline ($P = .586$), left hemisphere and right hemisphere ($P = .736$), and the midline and right hemisphere ($P = .403$) are not statistically significant. The main effect of the emotional state on the average amplitude of C4 ($F(2, 22) = 3.555$, $P = .046$) and F4 ($F(2, 22) = 4.203$, $P = .028$) in the frontal region of the right hemisphere are significant, while that of the other electrodes is not significant.

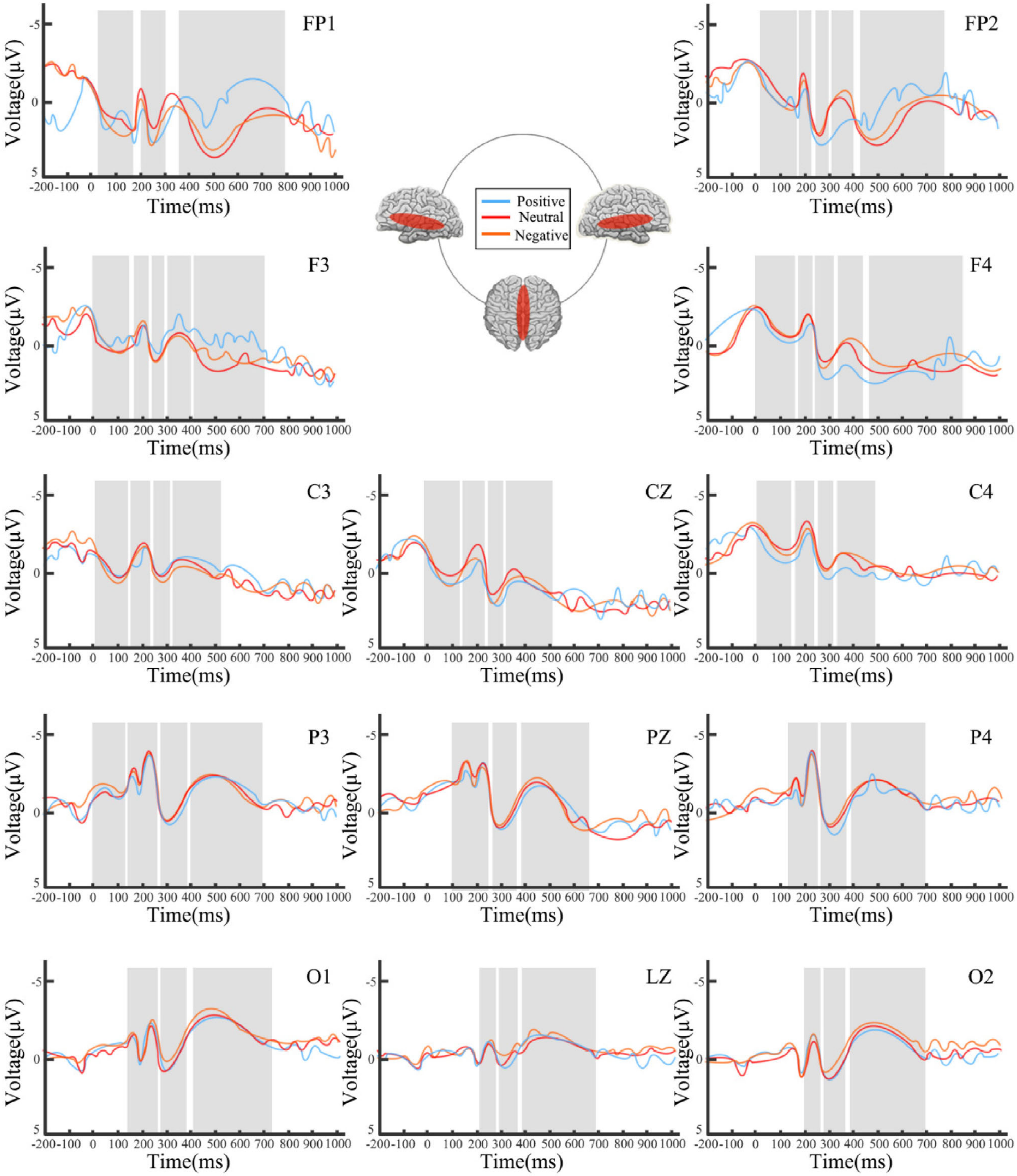


FIGURE 11 Event-related potentials for the positive, neutral, and negative states in the three-color experiments. The sites are the left hemisphere (FP1, F3, C3, P3, O1), midline (CZ, PZ, LZ), and right hemisphere (FP2, F4, C4, P4, O2)

3.3.4 | N400 component analysis

The average amplitude of the N400 component of ERP in the two-color experiment is shown in Figure 12F. The results of variance analysis of repeated measurements are shown in Table 5. The average amplitude of N400 in the different emotional states is marginally significant, $F(1.358, 137.163) = 3.402$, $P = .054$. The differences in the average amplitude of the positive and neutral states ($P = .051$) and neutral and negative states ($P = .006$) are

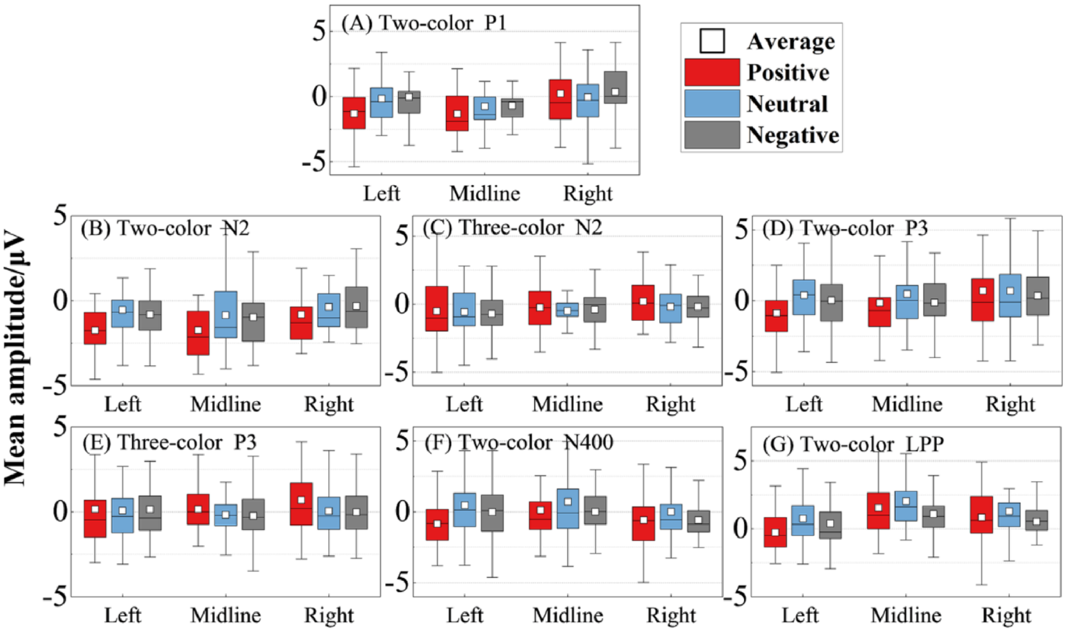


FIGURE 12 The average amplitude of the event-related potentials

TABLE 5 Results of repeated measurement analysis of variance for event-related potential signals

	Two-color			Three-color		
	df	***F***	***P***	**df**	***F***	***P***
P1	2	3.366	0.036	1.518	1.136	0.312
N2	1.429	11.855	0.000	1.898	3.138	0.047
P3	1.428	4.264	0.026	1.580	4.917	0.013
N400	1.358	3.402	0.054	1.556	2.171	0.128
LPP	1.607	10.204	0.000	1.190	2.947	0.085

statistically significant, while those of the positive and negative states (P = .495) are not statistically significant. The interaction between emotional state * hemisphere is not significant, F(2.716, 137.163) = 0.756, P = .509. The average amplitude difference between the different hemispheres is not statistically significant in the left and midline hemispheres (P = .275), the left and right hemispheres (P = .308), and the midline and right hemispheres (P = .086). The main effect of the average amplitude of N400 in the different emotional states is only significant in F3 (F(1.137, 13.639) = 4.505, P = .049) in the frontal region of the left hemisphere.

The main effect of the average amplitude of N400 in the three-color experiment is not significant F(1.556, 219.414) = 2.171, P = .128. However, the interaction between emotional state * hemisphere is significant, F(3.112, 219.414) = 3.910, P = .009. The average amplitude of N400 is the largest in the right hemisphere and exhibits the most changes.

3.3.5 | LPP component results

The average amplitude of the LPP component of ERP in the two-color experiment is shown in Figure 12G. The results of variance analysis of repeated measurements are shown in Table 5. The main effect of the average amplitude of LPP in the different emotional states is significant, F(1.607, 183.233) = 10.204, P = .000. A paired comparison shows that the differences in the average amplitude between the positive and neutral states (P = .004) and the neutral and negative states (P = .000) are statistically significant, while that of the positive and negative states (P = .571) is not statistically significant. There are no significant differences in the emotional states between the different hemispheres, F(3.215, 183.233) = 2.377, P = .067. The differences in the average amplitude between the left hemisphere and the midline (P = .001) and the midline and the right hemisphere (P = .040) are statistically significant, while that of the left hemisphere and the right hemisphere (P = .139) is not statistically significant. The main effects of the emotional state on the average amplitude of FP1 (F(2, 24) = 6.048, P = .007) in the frontal region of the left hemisphere and P4 (F(2, 24) = 3.373, P = .051) in the parietal region of the right hemisphere are significant.

The difference in the average amplitude in the three-color experiment between the different emotional states is not statistically significant, F(1.190, 54.747) = 2.947, P = .085. There is no interaction between the emotional state and the hemisphere, F(1.190, 4.747) = 1.968,

P = .164. There is no significant difference in the average amplitude between the different hemispheres.

4 | DISCUSSION

In the present study, the participants were divided into two groups, that is, the two-color and three-color experiments. In the two-color experiment, the stimulus was divided into six layouts. In the three-color experiment, the stimulus was divided into four layouts. The purpose was to assess the physiological mechanism of the participants' emotional changes caused by the different colors of the products. The emotional state of the participants is determined using behavioral data. The internal causes of the emotional changes of the participants are investigated using eye movement measurements and ERPs signals. The eye movement indices and ERPs signals related to the emotional state are extracted, which provides theoretical support for PCED.

4.1 | Behavioral data

The results of the behavioral experiments show that gender has no significant influence on the emotional state of participants in the color experiment. The participants prefer a balanced color distribution. If the colors in the block are connected, the participants' performance for the stimulus is very low. The reason may be that the more balanced the color distribution of the blocks, the better the sense of visual balance is, and, therefore, the higher the degree of the performance is. The experiment shows that neutral colors are preferred, while cold colors are the least popular, which provides a design direction for the color of small household appliances. The statistical results show that the average RT of the participants in the different emotional states is higher for the two-color samples than the three-color samples. This result indicates that the participants' cognitive resources and RT are greater in the two-color experiments than the three-color experiments. The average RT is the longest in the neutral state and the shortest in the negative state. This result demonstrates that the participants tend to deal with negative events, and often think for a longer time when they are neutral or positive. This finding is also in line with the result that the average preference of the three-color experiment is higher than that of the two-color experiment. Bai obtained similar results in a study on the number of color combinations in clothing.[37] Therefore, in the color design of small household appliance products, three colors should be used.

4.2 | Eye movement

On the basis of the results of behavioral experiments, eye movement and ERP experiments were carried out. The average pupil diameter of the participants in the experiments with different numbers of color combinations is correlated with the emotional score. In the two-color experiment, the average pupil diameter shows a decreasing trend, with a slight increase in the sixth layout. The emotional scores and pupil diameters of the six layouts show similar trends, but there is a low correlation in the first layout. However, in the three-color experiment, the average pupil diameter and the emotional score show similar rules. The higher the emotional score of the participants, the larger the average pupil diameter is, indicating that the pupil diameter increases when the participants have positive feelings about the stimulation pictures, which is consistent with the findings of David and Antonio.[16,21-22] The correlation analysis of the emotional state scores and the eye movement parameters show that the blink rate, mean blink duration, mean fixation duration, and average pupil diameter are significantly correlated with the emotional state; therefore, these four eye movement indices are crucial factors in PCED. The eye movement trajectory shows that there are fewer fixation points for the three-color samples than the two-color samples. The scanning path and the time required for the participant to make decisions are shorter for the three-color samples than the two-color samples, which is consistent with the RT result. The hot spot maps show that the participants' area of interest area for the small household appliances is located in the central area of the products, whereas less attention is focused on the details.

4.3 | ERPs components

In the different emotional states, F3 and C3 in the left hemisphere frontal region, P3 in the left hemisphere parietal region, O1 in the left hemisphere occipital region, PZ in the midline parietal region, and C4 and F4 in the right hemisphere frontal region are the active positions; the components P1, N2, P3, N4, and LPP are significant indicators.

4.3.1 | Two-color

In the two-color experiment, P1 component reflects the participant's emotional perception. The active positions of the brain regions are the frontal region and occipital region of the left hemisphere. This shows that P1 amplitude of different emotional states has hemispheric effect.

There is a significant interaction between the emotional state and the hemispheres. The left hemisphere generates a higher cognitive load resulting from the emotional state of the participants, indicating that the aesthetic experience results in hemispheric asymmetry, and the brain processing tends to be lateralized.[38] The amplitude of P1 is the largest when participants show negative feelings toward stimulation, and the amplitude of P1 is the smallest when participants show positive feelings. The results of the P1 average amplitude are consistent with the results of Olofsson, who found that the average amplitude of P1 in the negative state was larger than that in the positive state in the O1 position of the occipital region.[23] This result shows that the energy invested by the participants in the two-color experiment is directly related to their emotional state. Negative stimuli unconsciously mobilize more attention resources. Participants consume the most energy when they are in a negative state and the least energy when they are in a positive state. The two-color sample attracted the participant's attention at an early stage and elicited a positive or negative emotional state.

There were also significant differences in N2 average amplitudes among different emotional states. The N2 average amplitude was the largest when the participants were in a negative state, which is consistent with that of previous studies that found that terrorist stimulation induced larger N2 average amplitude than neutral stimulation.[39,40] This result indicated that the color sample was not in agreement with the color that the participants expected for small household appliances. In addition, in the Patrick et al[41] study, it was shown that the N2 component increased when participants made decisions.

P3 component reflects the cognitive process related to task decision-making.[42] The average P3 amplitude in the neutral state is significantly enhanced. At this time, the participant requires significant cognitive resources when processing the neutral sample, which indicates the lack of a match between the sample stimulation and the participants' psychological cognition; therefore, it is difficult for the participant to make a decision.

A significant N400[43] component is observed at F3 in the forehead area, indicating that the participants are comparing, selecting, and evaluating the colors of the product. Similar to the P300 component, the average amplitude of N400 is the largest in the neutral emotional state. The participants need more time to make decisions, which is consistent with the results of Chen.[44] Our results indicate that the middle-late component tends to appear when the participants are in the neutral state, which explains why participants require longer response times when making neutral choices.

In the two-color experiment, the FP1 and P4 positions induced significant LPP components. At this time, the positive product color matching resulted in larger average LPP amplitude,[45] which indicates that positive stimuli can attract sustained attention.

4.3.2 | Three-color

In the three-color experiment, only N2 and P3 components showed significant differences. The three-color experiment also shows a significant N2 component at C3 in the left and C4 in the right hemispheres. The average amplitude of N2 is the largest in the positive state and smallest in the neutral state. This result indicates that in the early stage, a positive or negative stimulus is more likely to attract attention than a neutral stimulus, which is consistent with previous research results.[46,47] However, there is no interaction between the emotional state and the hemisphere, and there is no lateralization trend of brain processing.

Similarly, the trends of the P3 component are significantly different for the C4 and F4 positions in the frontal region. The average amplitudes of P3 for the participants in the positive, neutral, and negative states shows a decreasing trend, indicating a good match between the stimulation sample and the psychological cognition of the participants; therefore, the participants make rapid decisions. This result also explains why the average preference of the three-color samples is higher than that of the two-color samples. There is no significant interaction between the hemisphere and the emotional state, indicating that there is no lateralization of brain processing in the average P3 amplitude. At this time, the participants have analyzed the information that affects their emotion, and other external factors are also considered.[48] Therefore, the P3 component can be used as an evaluation index to predict the emotional state of participants in the middle and late stages.

5 | CONCLUSION

In conclusion, this study examined the internal cognitive mechanism of the participants' emotional changes when observing color schemes with different color layouts and color numbers using the PCED method based on eye movement measurements and ERPs. The main conclusions of this study are as follows:

1. The more balanced the color block area was in the color layout, the higher the participants' preferences

were. When neutral colors were used, it can significantly improve the participant's preference. The three-color samples were more popular than the two-color samples.
2. The behavioral data showed that the RT of the participants was the longest for the neutral state and the shortest for the negative state. There was no interaction between the RT of different genders. This showed that participants required more time when dealing with uncertainty.
3. The mean blink duration, blink rate, and average pupil diameter were significantly correlated with the emotional score; the larger the average pupil diameter, the higher the participants's score of the color sample was. The eye movement trajectory and hot spot maps showed that the participants' interest in the products was focused on the main area and less on the details.
4. Brain mechanism studies have shown that the ERP components that are related to emotional states are mainly concentrated in the frontal area, and the occipital and parietal areas have few components. We observed no significant hemisphere effects for the different emotional states.
5. In the two-color experiment, the average amplitude was significantly different for the early components (P1, N2) between the positive state and the negative state and for the middle and late components (P3, N4) in the neutral state. However, the range in which the average amplitude was significantly different for the different emotional states in the three-color samples was only 100 to 350 ms (N2, P3), resulting in significantly lower response time than for the two-color samples.
6. The P1 component induced by the F3, C3, and O1 positions, the N2 component induced by the C3, P3, PZ, and O1 positions, the P3 component induced by the C3 and F3 positions, the N400 component induced by the F3 position, the LPP component induced by the FP1 and P4 positions in the two-color experiment, and the N2 component induced by the C3 and C4 positions and the P3 component induced by the C4 and F4 positions in the three-color experiment were suitable as evaluation criteria for the emotional state. These results provide a reference for the future development of product colors based on physiological data.

Never the less, there are still many limitations in this study. The proposed method used ERPs to compensate for the lack of the participant's inherent cognitive processing mechanism in eye movement measurements. However, due to the limitation of the low spatial resolution of the ERPs, the spatial location of the brain function of the emotion processing could not be accurately obtained. Methods such as Functional Magnetic Resonance Imaging (FMRI) and positron emission imaging have high spatial resolution; therefore, in future research, we will use FMRI combined with eye movements and ERPs to investigate the brain mechanism of changes in the participant's emotional state. In addition, the current research is limited to the visual perception of product colors, and a larger design study should be conducted in the future. The product color emotion model based on physiological data should be further established, and attention should be paid to the multimodal interaction of products.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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