A Cognitive Study of Multicolour Coding for the Head-up Display (HUD) of Fighter Aircraft in Multiple Flight Environments

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Abstract. By analyzing flight environments and HUD key information of fighter combat mission, based on the theory of color psychology and the regulation of the avionics system, this study simplified 10 kinds of typical flight environments and combined with 7 types of key information colors into 70 color schemes. Taking reaction accuracy and reaction time as performance indicators and testing participants' subjective feelings, to evaluate pilots' recognition ability of key information and general information with different color schemes in different flight environments, so as to provide the scientific basis for information coding design of flight HUD. The experimental results showed that the cognitive performance of the bicolor coding is significantly better than that of the monochrome coding by comparing the mean reaction time in various environments, and the cognitive performance of color schemes with the hue of 320 or 340 was better than that of other color schemes in most environments.

1. Introduction
The fighter is mainly aimed at shooting down and expelling the aircraft of the other side. In modern combat mode, fighter aircraft also begin to undertake integrated missions such as reconnaissance, ground attack and electromagnetic suppression, which depends not only on the pilot's first-class combat capability but also on the update and upgrade of modern military equipment. Head-up display (HUD) was created in the aviation sector in the 1950s, is the main flight status display widely used in modern fighter now. HUD mainly projects flight key information and combat control information on the transparent screen directly in front of the pilot, so that the pilot can observe the external environment and internal flight information at the same time. 90% of the flight information obtained by the pilot is through the visual channel, and the color as one of the fastest human visual perception elements, compared with other elements such as shapes, it improves recognizability of flight information \cite{1}, so the color-coding is an important encoding way in HUD visual information display, it helps pilots to achieve a variety of flight information cognition and integration, and improves the pilot's cognitive performance. By detecting the performance of military pilots in simulated combat, Derefeldt \cite{2} et al. found that when using a color-coded symbol system, pilots can fire missiles faster, reducing the possibility of being attacked, proving the practical effect of color-coding.
The HUD display system of many countries mainly adopts the green monochrome coding method (with the wavelength of 555nm). Under the condition of high or low brightness, human eyes respond...
best to green about the comfort level in long-term use, but at the same time, the recognizability and saliency of green are not ideal in some cases [3]. In the actual research, pilots generally reflected that the monochrome display was not conducive to the most effective acquisition of information in many cases. For example, under the condition of high-altitude flight in cloudy weather, the contrast between green HUD information and white flight environment is poor, and the information is less recognizable [4]. The monochrome coded HUD has poor situational awareness, which cannot guarantee the best dynamic and static display effect of information in various complicated flight environments, especially is not conducive to prompt warning, abnormal and key information. So by color-coding to distinguish the key information and general information in the HUD, can help the pilot to keep high efficient and rapid cognitive level, avoid the additional cognitive load in the process of scanning head-up display (HUD) and head-down display (HDD), reduce the error rates in visual information process and fighting process, thereby enhance the overall combat capability.

At present, some countries have applied the multi-color coding method to helmet display (HMD) with a significant effect [5]. At the present stage, the research on multi-color interface coding mainly focuses on civil aircraft and mostly is the color-coding of HDD. There are relatively few studies on the multi-color coding of fighter HUD. Xiong Duanqin et al. [4] used the dynamic simulation flight mode to study the monochrome and multi-color HUD information and found that the combination of green and magenta has the best visual effect. Zhang Lei et al. [6] proposed that the matching of environment -- target color which should be selected according to different mental load levels and task requirements, has a significant impact on the identification of the target. Accordingly, because of fighter special transparent material of HUD, overlapping characters color and environments color is the key factor affecting pilot’s cognitive performance and comfort in a realistic environment. However, few studies involve the matching of multi-color coding and environments color. On this basis, this study designed and conducted cognitive experiment of HUD interface with the bicolor coding to investigate pilots’ recognition ability of key information and general information in different flight environments, compared the cognitive performance of different color schemes to propose the best color scheme and to provide scientific basis for the design of the fighter HUD interface.

2. Description of experimental design

2.1. Experimental equipment and environment setting
In this experiment, E-prime2.0 software was used to program the experiment and record the data. After the experiment, EXCEL was used to sort and summarize the experimental data. Finally, by using SPSS to process and analyse the experimental data. The materials of the experiment will be shown in a 15.6 inches Lenovo screen, and all of the experimental images are in 1024 * 768 pixels. The brightness of the control display was 120 cd/ m2 and the indoor illumination was 500 Lux. The whole process of the experiment was completed in the ergonomic laboratory of Southeast University.

2.2. Selection of experimental subjects
The experimental subjects are 20 undergraduates, graduate students and doctoral students (male 16, female 4) from Southeast University who have relevant mechanical knowledge or understanding of aircraft structure, aged between 22 and 27, with normal vision or corrected vision (all above 1.0) and no color blindness or color weakness.

2.3. Design of experimental materials

2.3.1. Selection of HUD flight environment and extraction of environment color. To select HSB Color Space as the color-coding tool for this experiment. First of all, the experiment selected 10 representative fighter environment pictures, followed by (1) mountain scene (high flight altitude) (2) mountain scene (low flight altitude) (3) snow mountain scene (low flight altitude) (4) city scene at night (low flight altitude) (5) desert scene (low flight altitude) (6) plain scene (low flight altitude) (7) sea scene (mid-low flight altitude) (8) cloud scene (high flight altitude) (9) purple sunset scene (low
flight altitude) (10) orange sunset scene (low flight altitude), which covering the current predictable world environments of high and low altitude flight. In order to reduce the distraction of various colors in the flight environments and ensure the reliability of the experiment, these 10 flight environments are purified by ITTI model [7]. Extracting three image features (color, brightness, direction) from images, and then using the center-surround operator to calculate the difference in different scales and normalizing it. The visual significance measurement results of 3 features were combined into a saliency map, and then obtained primary color of the saliency map through mathematical expectation calculation, and 10 pure color images of the environments were labeled as Hn (n=1, 2, 3... 10), as shown in figure 1.

![Figure 1. Flight environments (H) and HUD primary colors (G) with HSB values.](image)

2.3.2. Extraction of HUD primary color. This paper aims at the pilots' recognition ability of key information’s color, so it is necessary to ensure high recognition of HUD primary color in flight environments, which can improve the operability and Scientificity of the whole experiment, and eliminate the possibility that poor readability of the primary color affects the reading of key information. The selection of HUD primary color range is within 120 to 240 degrees and take the integer in a unit of 30 degrees [8]. After the visual acuity measurement [9] and screening, 10 types of HUD primary colors were selected corresponding to 10 types of environment colors, which are labeled as Gn (n=1, 2, 3... 10), as shown in figure 1. The experiment mainly points at the research of hue value in HSB color system, and values of brightness and saturation both are 100%.

2.3.3. Selection of key information colors. Li Weimin [10] proposed that the colors usually selected on the display screen include red, yellow and green, and blue and purple should be used as few as possible because the visual acuity of blue and purple are poor compared with other colors, according to their color psychological characteristics, they are not suitable to be used as colors to provide highlighting. Based on the theory of color design and color psychology, and combining with provisions of color selection in avionics system [11], the paper summarized the color selection basis of different display functions in fighter display system, as shown in table 1.

The table 1 shows that warm colors (centered on orange) stimulate the nerve to excite it and make the person into a state of mental concentration. When multiple colors occur at the same time, the visual perception of warm color is closer than the actual space distance. Hence, it can affect the pilot's vision in the first time enabling to quickly capture and confirm the information. Cool colors (centered on blue) inhibit people's sense of excitement and presents a more contractive vision effect. When multiple colors occur at the same time, the visual perception of cool color is farther than the actual space distance, which is not conducive to the acquisition of visual information. Therefore, the experiment select the warm colors within the range of 300 to 60 degrees on Munsell 12 color ring as the objects of study. Taking 20 degrees as the unit (the brightness and saturation both are 100%) to extract into 7 kinds of colors and labeled as Kn. The HSB values are K1 (300,100,100), K2 (320,100,100), K3 (340,100,100), K4 (0,100,100), K5 (20,100,100), K6 (40,100,100), K7 (60,100,100).
2.3.4. Selection of flight mission. By the analysis of the complexity and difficulty of flight missions, the Air to Air with Long Range Missile interface was finally selected as the stimulation interface. According

| Table 1. Optional colors with display function in avionics system. |
|------------------------|-------------------|-----------------|-----------------------------|
| Color     | Display Function                          | Emotional Response | Physiological Response                  | Sense of Advance and Recede |
|-----------|-------------------------------------------|--------------------|----------------------------------------|-----------------------------|
| Red       | Warning, prohibition, activation, limit    | Excited, nervous   | Sense of impending, visual fatigue;    | Advancing color             |
|           | state                                      |                    | Stimulate nervous excitement, improve  |                              |
|           |                                           |                    | work efficiency                        |                              |
| Orange    | Prompt, caution, alarm                     | Excited, restless  | Blood circulation increases;           | Advancing color             |
|           |                                           |                    | Relieve fatigue                        |                              |
| Yellow    | Abnormal/critical alarm, attention,        | Optimism, inspiration | Activate memory and active thinking   | Advancing color             |
|           | status notification                        |                    |                                        |                              |
| Green     | Start up, normal operation, standard mode  | Harmony, self-      | Facilitates concentration of thought;  | Normal Color                |
|           |                                           | discipline, peace  | Lower blood pressure                   |                              |
| Blue      | Sky background, notification               | Calm, trust, fresh,| Lower blood pressure;                  | Receding Color              |
|           |                                           | fresh, profound    | Balance metabolism                     |                              |
| Mauves    | Less use, radioactive, corrosive           | Mysterious and dreary | Depresses motor nerve, lymphatic and  | Receding Color              |
|           |                                           |                    | cardiac pulse system; hypnosis         |                              |
| Magenta   | caution                                   | Relaxing, soothing,| Decreases adrenalin production;        | Advancing color             |
|           |                                           | gentle, romantic   | Promotes action and relaxes muscles;   |                              |
|           |                                           | Stability, comfort  | Stable mood                            |                              |
| White     | Scale and related figures                  | Stability, comfort  | Keep blood pressure normal, keep       | Advancing color             |
|           |                                           | and monotony       | actions simple and clear                |                              |

Table 1 to the research on general display information and priority of the fighter cockpit [12], the target box and aiming circle as the key information are the color-coding objects of this study.

In the experiment, experimental samples total 10 (HUD primary colors) × 7 (HUD key information colors) + 10 (monochrome HUD samples) = 80. The monochrome HUD interface is set as a control group to verify that the bicolor coding is superior to the monochrome one. The specific experimental materials as shown in figure 2.

**Figure 2.** HUD Color schemes in H1 flight environment (a) G1 (b) K1+G1 (c) K2+G1 (d) K3+G1 (e) K4+G1 (f) K5+G1 (g) K6+G1 (h) K7+G1.
3. Experimental methods and process
The whole experiment is divided into two parts. The first part is the objective experiment, including the practice and the formal experiment. The formal experiment includes 2 tasks, first, subjects are required to judge whether the target enters the aiming circle, Press the keyboard "1" for "yes" (entered the aiming circle) and "2" for "no" (not entered the aiming circle), then determine whether the target designator box is on the same side of waterline as velocity vector, press the keyboard "1" for "yes" (on the same side) and "2" for "no" (not on the same side). The second part is the subjective evaluation, which requires the subjects to evaluate the information accessibility and color harmony of different color schemes.
First, the subject reads the experimental instructions and enters the practice phase by pressing the space bar. The practice operation is consistent with the formal experiment so that the subject can be familiar with the experiment. After the practice phase, the formal experiment is conducted, and the experimental program records the response time and accuracy of 2 tasks. The experimental samples appear randomly in order to obtain the most natural response data of the subjects. The experiment is repeated twice. In order to prevent visual fatigue from affecting the experimental results, subject is allowed to rest three times (30s/Time) during the formal experiment, and it will take about 25min for each subject to complete the experiment. The experimental process is shown in figure 3.

Figure 3. Experimental flow chart.

4. Experiment results and analysis
4.1. Cognitive performance results and analysis
In 10 kinds of flight environments, the distribution of average reaction time about subjects' recognition of HUD information under 8 types of color-coding is shown in figure 4. The accuracy of this experiment is not in high reference to reveal the relationship between the variables, however, reaction time can quantitatively reflect the relations and significant differences among various variables. Therefore, the analysis of this experimental conclusion mainly based on the reaction time and supplemented by the accuracy. First, it can be seen from figure 4 that reaction time intervals in some environments are significantly lower than that in other environments. For example, the intervals in H5 and H8 environments are at a low level, indicating that the difference in environment does have an impact on information identifiability. Second, under some conditions, the reaction time intervals present a minor differences. For example, the intervals in H1, H4 and H10 environments are small, which means the flight environment with low Brightness, such as mountain scene (high flight altitude), city scene at night and sunset scene, which are close to the dark environment, have less interference to identifying information, so the differences of reaction time is not large.
In figure 4, the point at the lowest position in the ordinate represents this point with the minimum average reaction time, which indicates that the pilot has the highest cognitive performance at this point. Thus, color scheme Gn + Kn, corresponding to the point, can be used as the best color scheme in the environment represented by the abscissa of that point. The color scheme with the best reaction accuracy and reaction time are: G1+K2 in H1; G2+K2 in H2; G3+K1 in H3; G4+K3 in H4; G5+K2 in H5; G6+K3 in H6; G7+K6 in H7; G8+K3 in H8; G9+K7 in H9 and G10+K3 in H10. Based on the above objective experimental results, it can be seen that the bicolor coding has relative advantages in accuracy and reaction time of identifying key, abnormal and attention information compared with the monochrome coding.
In order to further discuss the double-effect results of color schemes and flight environments, the experimental data were imported into IBM SPSS software for processing, and significance test of difference was performed by using one-way ANOVA. The analysis result is shown in table 2. F represents difference level, P represents the significance level (significant difference: P < 0.05). The table 2 shows that different color schemes have a significant influence on reaction time (F = 2.449, P = 0.028 < 0.05). Different flight environments also have a significant effect on reaction time (F = 2.062, P = 0.047 < 0.05), and P values is near to the critical value 0.05, suggesting that the influence of environment on the reaction time is significantly lower than that of color schemes. Thus it has statistical significance to study the color-coding of HUD in different flight environments.

| Source       | Type III sum of squares | df  | Mean square | F      | Sig. |
|--------------|-------------------------|-----|-------------|--------|------|
| Corrected Model | 3053763.916a           | 16  | 190860.245  | 2.231  | 0.013|
| Intercept    | 763932784.221           | 1   | 763932784.221 | 8930.339 | 0.000 |
| Environments | 1587335.490            | 9   | 176370.610  | 2.062  | 0.047|
| Color schemes | 1466428.425            | 7   | 209489.775  | 2.449  | 0.028|
| Error        | 5389242.633            | 63  | 85543.534   |        |      |
| Total        | 772375790.770          | 80  |             |        |      |
| Corrected Total | 8443006.549          | 79  |             |        |      |

4.2. Subjective evaluation results and analysis
After the experiment, subjects were asked to select the optimal HUD interface in terms of information availability and color harmony, and the population distribution is shown in figure 5 and figure 6. In this experiment, information availability refers to the identifiability or visual salience. In figure 5, Gn+K7 is rated as the color scheme with the highest information availability in 70% of the flight environments. Locally, there is an obvious tendency of population dominated by Gn+K7 in H4 and H9, with the proportion remaining at around 75%. Color harmony in this experiment refers to the color comfort of the display interface. In figure 6, Gn+K7 is evaluated as the best color scheme with high color harmony in 60% of flight environments. Locally, the proportion of Gn+K7 is slightly higher than that of other color schemes in H1, H2, H5, H7, H9, and H10, accounting for about 45%, especially up to 60% in the H1.
5. Discussion

10 kinds of flight environments, including different samples of topography, climate, height and time, were used as the dividing basis to judge the effectiveness and differences of HUD color-coding in the actual flight environment at present. Overall, there are significant differences in the identifiability of HUD information under the same color-coding in different environments, and there are also significant differences in the identifiability of HUD information under the different color-coding in the same environment. HUD interfaces with any color schemes in dark environment have obvious advantages compared with those in bright environment, which is because the dark environment has less interference with the pilot's recognition ability. The result shows that the cognitive performance of bicolor coding is better than that of monochrome coding. According to the average reaction time, the cognitive performance of color schemes with the hue of 320 or 340 is better than that of other color schemes in various environments.

5.1. Topographic conditions

According to topography, in the environment, such as a mountain scene or a plain scene, where the main color is green and the brightness is low (about 30%~40%), the display effect of key information color with the hue of 320 or 340 is better than that of other colors; in a snow mountain scene or a cloud scene where the main color is white and the brightness is high (about 70%~100%), the display effect of key information color with the hue of 300 or 340 is better than that of other colors; in the environment with cool color and moderate brightness (about 40%~70%), such as a sea or purple sunset scene, the display effect of color with the hue of 40 or 60 is better than that of other colors. In a desert scene, the display effect of color with the hue of 320 is better than that of other colors.

5.2. Climatic conditions

According to climate, in the polar climate, the color with the hue of 300 is better than other colors. In the desert climate, the color with the hue of 320 is better than other colors. In the continental climate and rainforest climate, the display effect of the color with the hue of 320 and 340 are better than that of other colors. In the marine climate, the display effect of the color with the hue of 40 is superior to that of other colors.

5.3. Altitude conditions

According to the flight height, in the high-altitude flight condition, the environment is mainly land, marine or cloud, and it can be obtained from the above analysis that the display effect of color with the hue of 320 or 340 is better than that of other colors. Environment colors are more complicated when flying at low altitude, but in most cases, the color with the hue of 320 or 340 is better than other colors. From the overall analysis, the flight height has little impact on display effect. Regardless of the high, medium and low altitude conditions, the color schemes with the best overall effect are Gn+K2 and Gn+K3.
5.4. Day-night time conditions
According to the time, the cognitive performance of flying at night is relatively high. In the near-night environment with low brightness (about 20%~40%), such as nightfall and dusk in the city, the display effect of color with the hue of 340 is better than that of other colors. During the daytime, cognitive performance has quite differences from the change of the environments, the cognitive performance in the environment with high brightness (about 70%~100%) is significantly higher than that in other conditions, and the color scheme has a strong contrast with environment colors, therefore the hue value between 300 and 0 is significantly better than that between 20 and 60. While in the environment with 40%~70% brightness and saturation, the contrast between the color schemes and environment colors is not strong enough to enable human eyes to achieve the best cognitive state, so the hue value between 20 and 60 is significantly better than that between 300 and 0.

5.5. Subjective evaluation
From the subjective analysis, in the environment with high brightness (about 70%~100%), the highest evaluation score of information availability is the color with the hue of 320 and 20, and in other environments, the color with the hue of 60 gets the highest score. In the environment with low brightness (about 20%~40%), the highest evaluation score of color harmony is the color with the hue of 40, and in other environments, the color with the hue of 60 gets the highest score. On the whole, the color with the hue of 60 gets the highest score both of information availability and color harmony in most of the environments. However, the materials presented in the experiment are images instead of real-time flight pictures. Considering the physiological and psychological effects of long-term flight on human beings, it is necessary to design a further experiment to judge the reliability of such subjective evaluation.

6 Conclusion
Some conclusions about ergonomic design of HUD color-coding are drawn: the cognitive performance of bicolor coding is significantly better than that of monochrome coding, and the cognitive performance of color schemes with the hue of 320 and 340 were better than that of other color schemes in different environments. In the subjective evaluation, subjects prefer yellow (the hue of 60) to be the color of key information in most environments. The results not only further develop HUD design of color-coding about the key, warning, and abnormal information, but also have a preliminary study on the classification of flight environment. It provides a preliminary experimental basis for the information coding design of HUD based on different environments. In order to obtain reliable and usable experimental basis, dynamic HUD display system should be adopted for experimental verification in the future.

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