

Research on Visual Fatigue Caused by Color Combinations in Civil Aircraft Cockpit Display Interfaces

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Abstract. In order to analyze the visual fatigue degree of the foreground and background color combination of the display of civil aircraft cockpit, the visual afterimage experimental paradigm is used in the present study. Objective eye movement data and subjective reported visual afterimage color were collected. The difference of pupil diameter under different color combinations showed that background color had a significant effect on visual fatigue. In addition, black background color can lead to the lowest degree of visual fatigue, followed by brown background color. Moreover, blue background color was the most likely to cause visual fatigue. The subjective report data showed that the visual afterimage color was related to the foreground and background color combination. In the combination of background color and foreground color, the ratio of visual afterimage color and background color is the highest, followed by the foreground color, and the complementary color of foreground color or background color. Based on the above results, the color design suggestions of civil aircraft cockpit interface are proposed in this work.

Keywords: Civil aircraft cockpit; display interface; color combination; visual fatigue; afterimage

1. Introduction

The cockpit display interface in civil aircraft is a crucial human-machine interaction interface that provides flight information. Pilots primarily rely on visual channels for obtaining information to carry out flight instructions [1]. Visual fatigue stands as one of the key factors affecting pilot interface cognition. The National Transportation Safety Board of the United States has pointed out that visual limitations caused by visual fatigue have become a primary cause of numerous incidents involving civil aircraft, as indicated by multiple accidents [2].

Interface color is a significant facet of visual ergonomics research, with attributes such as hue, brightness, saturation, and contrast playing a crucial role in visual fatigue. Appropriate color matching of information can enhance user discernment efficiency and reduce visual fatigue. Existing research indicates that color combinations of foreground and background hues impact the visual search efficiency of driving interfaces. Zhang Lei et al. [3] indicated that task performance and preferences regarding different color matches in flight information display interfaces are not entirely consistent. Guo Zizheng et al. [4] noted that distinct foreground-background color matches in train control interfaces influence the visual recognition efficiency of drivers. Huang [5] discovered that the contrast between the foreground and background colors of images affects visual search, with higher contrast images being more easily detectable through visual search.

Currently, further in-depth research is needed concerning the impact of foreground and background color combinations on visual fatigue in civil aircraft cockpit interfaces. This study combines quantitative data on pupil accommodation speed and qualitative data on visual afterimage colors to investigate the issue of visual fatigue related to color combinations in civil aircraft cockpit interfaces. The study aims to propose design recommendations for the color scheme of civil aircraft cockpit display interfaces.

2. Research on Visual Fatigue in Display Interfaces

The study of visual fatigue in display interfaces employs three main research methods: subjective, objective, and a combination of both. Subjective research methods involve quantitatively analyzing the degree of visual fatigue experienced by subjects through scales and questionnaires. This approach is typically carried out through post-experiment verbal recall by subjects, yielding qualitative data. However, it cannot dynamically monitor changes in visual fatigue during task execution. Objective research methods primarily employ external devices such as electroencephalography (EEG) and eye-tracking to collect physiological indicators from subjects for quantifying visual fatigue. Chen Yujia et al. [8] proposed that the speed of pupil accommodation serves as a good representation of visual fatigue, where slower pupil accommodation indicates higher visual fatigue, and vice versa. The combination of subjective and objective methods integrates the two aforementioned approaches to provide a more comprehensive analysis of fatigue. This has become a prominent path in recent research on visual fatigue. Park [6] et al. compared the effects of different interface curvatures on visual fatigue using subjective ratings and Critical Fusion Frequency (CFF) measurements. Xie [7] et al., on the other hand, investigated the impact of display interface color patterns and screen brightness on visual fatigue through a combination of eye-tracking data and subjective questionnaires.

Visual afterimage refers to the opposite or complementary colors perceived by the visual organ when a brightly colored stimulus is visually adapted and removed [8]. It is a common visual physiological phenomenon and a characteristic manifestation of visual fatigue. Garai et al. [9] conducted experiments using different highly saturated color contrast groups, demonstrating that the intensity and duration of visual afterimages differ based on various color combinations. The appearance of visual afterimages can affect visual attention, search efficiency, and color perception. Theeuwes et al. [10], through masked and unmasked contrast experiments, indicated that visual afterimages, acting as a "pop-out phenomenon," attract attention and thus influence visual search. Chen Yujia et al. [8], by combining the Lier afterimage and visual search paradigm, compared search efficiency and validated a noticeable reduction in visual search efficiency when visual afterimages are present. Both domestic and international research on visual afterimages primarily focuses on three aspects: the influencing factors of visual afterimages, the impact of visual afterimages on cognitive performance, and the effects of different stimuli on visual afterimage outcomes. Research methodologies predominantly include subjective research methods, utilizing tools such as scales, questionnaires, and verbal inquiries.

In summary, the integration of qualitative and quantitative data can provide a more comprehensive analysis of the extent of visual fatigue caused by color combinations. The speed of pupil diameter adjustment serves as a suitable quantitative indicator for assessing visual fatigue. Visual afterimages are a valuable qualitative indicator for evaluating visual fatigue. Analyzing the colors of visual afterimages after task completion can guide the selection of colors for subsequent task-related information.

3. Experiment

3.1 Selection of Experimental Colors

The primary background colors chosen for the experimental civil aircraft cockpit display interface are: black, blue, and brown. The color codes for these three background colors are provided in Table 1. The main foreground colors selected for the experimental civil aircraft cockpit display interface include: red, amber, green, white, cyan, magenta, light gray, and medium gray. The color codes for these eight foreground colors are listed in Table 2.

Table 1. Primary Background Colors for Civil Aircraft Display Interfaces

Background Color	Color Identifier	Color Code
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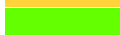





	b01-Black	#000000
	b02-Blue	#0066aa
	b03-Brown	#5f2a05

Table 2. Primary Foreground Colors for Civil Aircraft Display Interfaces

Foreground Color	Color Identifier	Color Code
	f01-Red	#ff1e14
	f02-Amber	#ffd339
	f03-Green	#64ff00
	f04-White	#ffffff
	f05-Cyan	#32ffff
	f06- Magenta	#ff32ff
	f07-Light Gray	#bfbfbf
	f08-Medium Gray	#7f7f7f

3.2 Experimental interface Design

The experiment adopted the Garai visual afterimage experimental paradigm [9], utilizing circular target materials filled with pure colors. Subjects fixated on the target materials for a predetermined duration and then perceived visual afterimage phenomena on an interface with only the background color. They subsequently described the colors of the visual afterimages. A 3 (three background colors) × 8 (eight foreground colors) within-subject experimental design was used in the study. The dimensions of the experimental interface were 1980×1024 pixels, as shown in Figure 1.

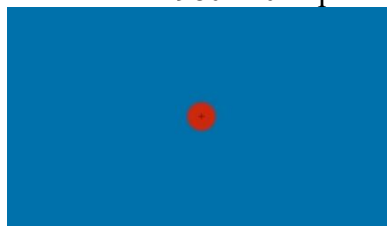


Fig. 1 Illustration of Experimental Interface Design (The combination of Red and Blue)

3.3 Experimental Procedure and Environment

The experiment was divided into three sessions based on background colors. Each session consisted of 8 trials, totaling 24 trials. Each trial included a visual concentration phase (1 second), an induction phase (5 seconds), a response phase (unlimited time), and a rest phase (20 seconds). During the rest phase, participants were asked to verbally report the colors of the visual afterimages they experienced. Eye movement data from participants were recorded using the Tobii Glass2 Pro eye tracker.

Before beginning the experiment, each participant received an explanation of the visual afterimage phenomenon and instructions for the experiment. In each trial, a cross symbol was presented on the screen as a fixation point for a duration of 1000 ms. Then a circular induced stimulus pattern appeared in the center of the interface, which lasts for 5000 ms and disappeared, leaving only the background color and the "+" used for visual concentration. Participants were then required to verbally report whether they experienced a visual afterimage and the color of the visual afterimage. When the visual afterimage disappeared or was not present, participants pressed the "0" key. Subsequently, a pure black rest screen appeared for 20000 ms. After the rest period, the next trial commenced. The experimental procedure is illustrated in Figure 2.

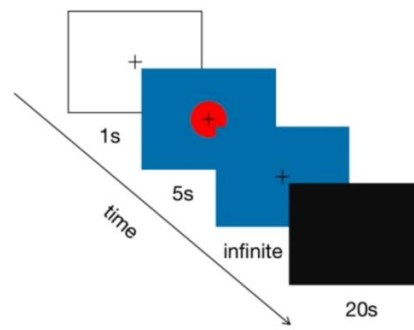


Fig. 2 Experimental Procedure in Each Trial

The experimental procedure was developed using E-Prime 3.0 and presented on a full-screen 13.3-inch ThinkPadX395 display, with no other disturbances on the screen. The display monitor had a resolution of 1980×1024 pixels and a refresh rate of 60Hz. The experiment was conducted in a disturbance-free laboratory environment. Participants maintained a fixed sitting position with their heads approximately 700 mm away from the screen, and the visual angle of the stimuli was approximately 30 degrees, as shown in Figure 3. The SPIC series spectral color illuminance meter was used to collect environmental light data. The illuminance level of the control panel and dashboard of the cockpit of a civil aircraft should be controlled between 65 lx and 194 lx [11]. The actual illuminance level in the experiment maintained between 80 lx and 110 lx.

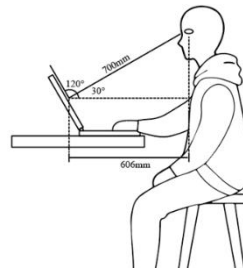


Fig. 3 Experimental Setup

3.4 Experimental Subjects

The experiment randomly selected 30 university students (9 males and 20 females) as participants. The average age was 22.43 years ($SD = 11.12$). All participants had normal or corrected visual acuity, and no color blindness or color weakness (determined through a vision test). Before the experiment, participants had adequate rest, refrained from alcohol consumption and stimulant beverages like coffee. All participants received written informed consent prior to participation and had no prior exposure to similar experiments.

4. Data Analysis and Results

In the experiment, all 30 participants completed the tasks as instructed. Due to the instability of the eye-tracking equipment, the eye-tracking data of 10 participants were retained for further analysis.

4.1 Eye Movement Pupil Diameter Analysis

The speed of pupil accommodation can be indicated by the variance of pupil diameter, with a higher variance indicating a more active state of pupil response. The calculation process for pupil diameter variance is as follows: Group the experimental trials based on background and foreground colors, calculate the average pupil diameter for each group, and compute the variance to compare the relative levels of visual fatigue between different color combinations.

The effect of the three background colors and the different foreground colors under each background on the average pupil diameter change was analyzed using a related samples

non-parametric test (Friedman test). The results indicated that all three background colors had a significant effect on the change in pupil diameter for both left and right eyes (Left: $\chi^2 = 102.037, p < .001$, Right: $\chi^2 = 89.825, p < .001$). However, the different foreground colors showed no significant impact on the change in pupil diameter for both left and right eyes.

The statistical data for the mean and variance of the average pupil diameter for both left and right eyes under the three background colors are presented in Table 3. The mean pupil diameter was found to be the highest under the black background color, followed by brown and blue, as depicted in Figure 4. This suggests that participants exhibited a more active state of pupil response under the black background color, indicating relatively weaker fatigue levels. While, under the blue background color, participants had a less active state of pupil response, indicating relatively stronger fatigue levels.

Table 3. Mean and Variance of Pupil Diameter under Different Background Colors

Pupil Diameter		Background Color		
		Black	Brown	Blue
Mean	Left	5.092	4.773	4.076
	Right	5.144	4.836	4.050
Variance	Left	0.876	0.425	0.407
	Right	0.937	0.464	0.435

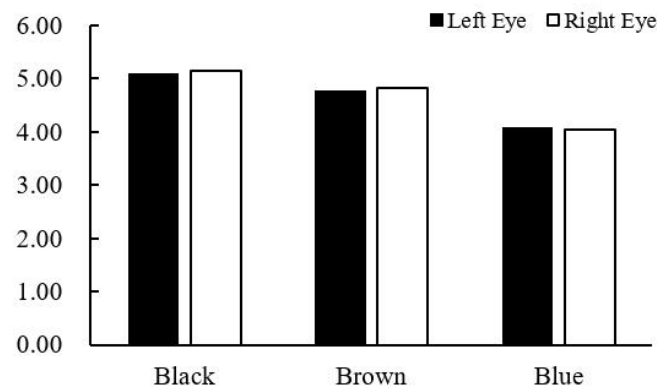


Fig. 4 The mean pupil diameter

4.2 Visual Afterimage Color Statistics

Based on whether visual afterimages were perceived and the reported colors of these afterimages, the types of reports given by participants were categorized. The statistics include the count of trials where no visual afterimage was reported, the colors of reported visual afterimages, and their frequencies. A total of 30 sets of statistics were collected for each combination of foreground and background colors, and a cumulative count of the top three reported types for each color combination were summarized in Table 4.

Among the three background colors, black had the highest proportion of trials with no reported visual afterimages, averaging 55.42%. The average proportions for the other background colors with no reported visual afterimages ranked from high to low were: brown (42.92%) and blue (38.75%). Under the blue background color, the reported colors of visual afterimages were mostly blue, with a few being complementary colors of the foreground. Under brown and black background colors, the reported colors of visual afterimages were primarily the same as the background color.






Among the eight foreground colors, medium gray had the highest average proportion of trials with no reported visual afterimages (72.22%). The proportions for other foreground colors with no reported visual afterimages ranked from high to low were: light gray (52.22%), amber (44.44%), white (42.22%), cyan (41.11%), green (41.11%), red (36.67%), and magenta (35.56%).

The reported colors of visual afterimages were closely related to the background color. Under black, brown, and blue background colors, the reported colors of visual afterimages were most

frequently the same as the background color. Specifically, for black background color, the reported afterimage color was black in 19.58% of the cases. For brown background color, the reported afterimage color was brown in 26.67% of the cases. For blue background color, the reported afterimage color was blue in 25.42% of the cases.

For most foreground-background color combinations, the proportion of trials with no reported visual afterimages exceeded the proportion of trials with reported visual afterimages. Only for red and magenta foreground colors on a blue background, and white foreground color on a brown background, did the proportion of trials with reported visual afterimages exceed the proportion of trials with no reported visual afterimages. Magenta was the color that produced the most frequent visual afterimages on a blue background, with a reported afterimage proportion of 70%. Among them, green had the highest reported afterimage proportion (43.33%), followed by blue (26.67%). On a blue background, red had the highest reported afterimage proportion (33.33%), while magenta had the highest reported afterimage proportion (30%) on a blue background and white had the highest reported afterimage proportion (30%) on a brown background.

Table 4. Self-reported Afterimage Color Statistical Table

	Background Color: Black	Afterimage Color (Times)	Background Color: Blue	Afterimage Color (Times)	Background Color: Brown	Afterimage Color (Times)
Foreground Color: Red		1.None (12) 2.Red (7) 3. Black (6)		1.Blue (10) 2.None (9) 3.White (3)		1.None (12) 2.Brown (10) 3.Black (5)
Foreground Color: Amber		1.None (17) 2.Black (5) 3.White (3)		1.None (10) 2.Blue (9) 3.Yellow (4)		1.None (13) 2.Brown (8) 3.Yellow (3)
Foreground Color: Green		1.None (15) 2.Black (7) 3.White (3)		1.None (10) 2.Blue (5) 3.Green (4)		1.None (12) 2.Brown (8) 3.Orange (4)
Foreground Color: Cyan		1.None (16) 2.Black (8) 3.Blue (3)		1.None (11) 2.Blue (8) 3.White (3)		1.None (10) 2.Brown (8) 3.Orange (3)
Foreground Color: Magenta		1.None (12) 2.Black (4) 3.Green (3)		1.Green (13) 2.Blue (8) 3.None (5)		1.None (15) 2.Brown (6) 3.Pink (2)
Foreground Color: Light Gray		1.None (18) 2.Black (7) 3.White (2)		1.None (17) 2.Blue (8) 3.White (2)		1.None (12) 2.Brown (10) 3.Yellow (2)
Foreground Color: Medium Gray		1.None (23) 2.Black (6) 3.Red (1)		1.None (21) 2.Blue (3) 3.Gray (3)		1.None (21) 2.Brown (4) 3.White (1)
Foreground Color: White		1.None (20) 2.White (4) 3.Black (4)		1.None (10) 2.Blue (10) 3.White (6)		1.Brown(10) 2.None (8) 3.Orange (3)

4. Design Recommendations for Civil Aircraft Cockpit Interface Colors

(1) For the color combination design of two consecutive tasks, avoid decreased efficiency in subsequent tasks due to visual afterimages. Since the color of visual afterimages can impact subsequent tasks involving related colors [8], after tasks that are prone to generate visual afterimages (such as the Primary Flight Display - PFD fixation task), colors like blue or brown that

tend to produce blue or brown visual afterimages should be avoided in the design of interface elements for subsequent tasks, such as using similar colors like cyan or brown.

(2) For visual elements that require prolonged fixation, avoid using foreground and background color combinations that tend to produce visual afterimages. Avoid using foreground-background color combinations that are likely to generate visual afterimages. For example, under a blue background, it's recommended to avoid using magenta or red visual elements, and under a brown background, it's advised to avoid using white visual elements. For visual elements requiring prolonged fixation under normal circumstances, colors with fewer reports of visual afterimages, like medium gray or light gray, are recommended.

5. Conclusion

This study explored the issue of visual fatigue in the color combinations of civil aircraft cockpit display interfaces. Experiments were conducted using the primary background and foreground colors of the cockpit display interface, collecting pupil diameter data and verbally reported visual afterimage colors for statistical analysis. The results indicated that the background color significantly affects visual fatigue, while there is currently no distinct difference observed among different foreground colors. Black background color had the lowest impact on visual fatigue, whereas blue background color had the highest impact. The color of visual afterimages is influenced not only by the stimulus color itself but also by the color combination. In most cases, the reported color of visual afterimages was identical with the background color. Design recommendations for civil aircraft cockpit interface colors were proposed based on the findings of this study.

References

- [1] Strickland D, Pioro B, Ntuen C. The impact of cockpit instruments on pilot exhaustion[J]. Computers & Industrial Engineering, 1996, 31(1-2): 483-486.
- [2] Liu, Y. X., & Hou, L. N. (2018). Statistical Analysis of Civil Aviation Accidents in Recent Years. Information Recording Materials, 019(009), 245-246.
- [3] Zhang, L., Zhuang, D. M., & Yan, Y. X. (2009). Encoding Method of Aircraft Cockpit Display Interface. Journal of Nanjing University of Aeronautics & Astronautics, 41(4), 466-469.
- [4] Guo, Z. Z., Li, Y. J., Ma, G. Z., et al. (2012). Impact of Color Matching of EMU Control Interface on Recognition Efficiency. Journal of the China Railway Society, 34(2), 27-31.
- [5] HUANG K C. Effects of computer icons and figure background area ratios and color combinations on visual search performance on an LCD monitor[J]. Displays, 2008, 29(3): 237-242.
- [6] Park S, Choi D, Yi J, et al. Effect of display curvature, display zone, and task duration on legibility and visual fatigue during visual search task[J]. Applied Ergonomics, 2017, 60: 183-193.
- [7] Xie X, Song F, Liu Y, et al. Study on the effects of display color mode and luminance contrast on visual fatigue[J]. IEEE Access, 2021, PP (99): 1-1.
- [8] Chen, Y. J., Yan, Z. Y., Yu, Z., & Chang, M. (2020). Interference Effects of Visual Negative Afterimages on Visual Search Efficiency. Psychological Science, 43(02), 272-279.
- [9] Garai L, Horvath A. Measuring colour afterimage perception, 2020 11th IEEE International Conference on Cognitive Infocommunications (CogInfoCom), Mariehamn, Finland, 2020, pp. 000191-000196.
- [10] Theeuwes J, Lucassen M P. An adaptation-induced pop-out in visual search[J]. Vision Research, 1993, 33(16): 2353-7.
- [11] Zhao Chunling, Fan Ruijie, Zhu Zhisheng, Liu Hongtao. Design, Integration and Certification of Civil Aircraft Flightdeck [M]. Shanghai Jiao Tong University Press, 2019