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The Effect of Hue Difference in Vibration Environment on the Searching Performance of Aircraft HUD Interface for Pilots

Junwu Chen, Wenyu Wu, and Jiayu Guo

School of Mechanical Engineering, Southeast University, Nanjing 211189, China

ABSTRACT

In the field of aviation, the color design of the HUD plays a critical role in ensuring flight safety and enhancing operational efficiency. However, the impact of Hue Difference in a vibrating environment on pilots' cognitive performance has not been fully explored. This study selected orange, green, blue, and purple as background colors based on the HSB color model, and for each background color, foreground colors with Hue Difference (HD) of 30°, 45°, 60°, 75°, and 90° were chosen, thereby covering a wide range of color contrast combinations to accurately capture the effect of Hue Difference on cognitive performance. In terms of vibration environment settings, the study considered possible vibration conditions encountered during actual flights, with vibration environments set at frequencies of 5Hz, 10Hz, 15Hz, and 20Hz, as well as a no-vibration condition, simulating various flight scenarios from low-frequency to high-frequency vibrations. During the experiment, participants were tasked with simulating real-world HUD information search tasks, requiring them to make accurate judgments and complete tasks within a specified time frame. Their reaction times and accuracy were recorded as key indicators to assess the impact of Hue Difference on cognitive performance. The experimental results clearly demonstrate significant interactive effects between vibration environment and Hue Difference, as well as between background color and Hue Difference. The change in Hue Difference showed a distinct trend in its effect on reaction time and accuracy across different vibration intensities.

Keywords: Vibration, Hue difference, Head-up display, Visual cognition

INTRODUCTION

Head-Up Display (HUD) is used in aircraft to project critical flight information. The rationality of its color coding directly affects flight safety and mission performance. As aviation technology continues to advance, the vibration environment encountered by aircraft during flight becomes increasingly complex and diverse, posing significant challenges to the visual display performance of HUD. Harding pointed out that the combination of HUD display colors with the surrounding environment may lead to incorrect perception of image information (Harding et al., 2016). Shieh and Chen found that low color contrast severely reduces users' visual search performance (Shieh and Chen, 1997). Niu discovered that, compared to monochrome or tricolor schemes, the use of a two-color coding for HUDs resulted in superior performance (Niu et al., 2022). Puhalla emphasized that the hierarchical perception of colors is crucial for optimizing the human-machine interaction experience (Puhalla, 2008). By applying hierarchical color combinations based on the three-color elements, distinct visual contrasts can be created, effectively guiding users to categorize and identify visual information. Karar confirmed through research that the contrast between symbol color and background color in HUD displays is closely related to attention capture (Kumar et al., 2023). The results indicated that color contrast significantly impacts the effectiveness of flight information capture and recognition. Among the many factors affecting HUD visual performance, Hue Difference, as one of the key color attributes, has not yet been fully understood in terms of its impact on pilots' visual search performance under different vibration frequencies, necessitating further research. Visual search performance plays a crucial role in flight operations, directly determining the speed and accuracy with which pilots acquire and process critical information. Laar conducted visual search experiments using three different color-coding methods, and their results revealed that the visual hierarchical coding method outperformed the other two methods (Van Laar and Deshe, 2007). Besides color, vibration also has a significant impact on visual search. Chen found that low-frequency vibrations, especially in the 4-6Hz range, severely affect visual function, with human tolerance to vibration being lowest in this frequency range (Chen et al., 2017). The longer the vibration duration and the greater its intensity, the more significant the ergonomic effects. Sundström and Khan found that lateral vibration at 5Hz interferes most with visual function (Sundström and Khan, 2008). In a vibrating environment, pilots must quickly identify various flight parameters on the HUD under unstable visual conditions. For example, during critical flight phases such as takeoff and landing, pilots must rapidly and accurately read information such as altitude, speed, and heading. Vibration can cause visual blurring and reduced information recognizability. Therefore, the rational setting of Hue Difference may effectively improve the recognizability of information, mitigating the negative impact of vibration on visual search performance. Although previous studies have acknowledged the importance of color design in HUD interfaces, Hue Difference in vibrating environments has not been systematically and deeply studied.

STUDY PURPOSE

While some studies have examined the impact of color coding on information display, there is still a gap in research regarding how Hue Difference specifically affects visual search performance under different vibration frequencies, and the cognitive mechanisms behind this (Ojanpää and Näsänen, 2003; Ou et al., 2015). This experiment aims to investigate the impact of different Hue Difference combinations on pilots' cognitive performance within the HUD system under vibrating conditions. Specifically, the study simulates HUD information search tasks to analyze how various Hue Difference combinations affect pilots' ability to recognize information and search efficiency under different vibration frequencies. Through these analyses, the experiment aims to determine the most suitable foreground/background Hue Difference matching values for different vibration environments, providing both theoretical support and practical guidance for the color coding design of aircraft HUD interfaces.

METHOD

Participants

A total of 20 participants were selected for the experiment, consisting of 10 females and 10 males from Southeast University. All participants had not previously participated in similar experiments, with ages ranging from 21 to 27 years. None of the participants had color blindness or color weakness, and their corrected vision was above 1.0, ensuring they had normal visual perception abilities to guarantee the validity and reliability of the experimental data. Prior to the experiment, all participants signed an informed consent form, understanding the purpose, procedure, and any potential risks involved. During the experiment, participants' personal information will be kept strictly confidential, and only anonymized data will be used for analysis to protect their privacy. Participants have the right to withdraw from the experiment at any stage, and withdrawal will not have any negative consequences.

Experimental Equipment

The experimental process used the psychology experiment development software E-prime 3.0 to write the vibration environment program and present stimulus pictures as well as real-time recording of performance data. The experiment used a 23-inch Dell display with a resolution of 2560*1440 pixels, connected to a host computer with a screen refresh rate of 60Hz, and controlled the brightness of the screen to 130cd/m^2 to ensure the clarity and accuracy of the experimental stimuli. The distance between the subject and the center of the screen was 550-600mm, and the room was illuminated normally with two 40W OPPLE LED lamps.

Experimental Preparation

In the experiment, participants performed a target search task. To ensure accuracy, the target materials were strictly controlled, using the capital letters showed in Fig. 1, "R", "G", "P", "Q", and "B" in PingFang SC font. These letters contain both straight lines and curves, with similar visual complexity, and were randomly arranged to minimize interference from target differences. A pilot experiment was conducted with the same task but desaturated images, with a white background and black letters as the target. Participants identified the target location and provided feedback, with reaction times recorded. The pilot experiment showed a flat reaction time curve, confirming that the letter combinations effectively reduced data variability.

PGQ	PRQ	PGB	PRB	PRG
GPB	GPR	GQB	GQR	GBR
GBP	GRP	GBQ	GRQ	GRB
RGQ	RGB	RPQ	RPB	RQB
RQG	RBG	RQP	RBP	RBQ

Figure 1: Target search materials.

Based on the sensitivity of the human eye to vibration and related aircraft vibration studies, the impact of aircraft vibration on visual function and task performance primarily occurs within the 2-20Hz low-frequency range, with a 1.6mm amplitude confirmed as the sensitivity threshold. This experiment selects 5Hz, 10Hz, 15Hz, and 20Hz as core variables, with an amplitude of 1.6mm to simulate real aircraft vibration environments. A no-vibration condition is set as the control group, with vibration frequencies arranged from high to low. The vibration direction follows a cycle of left-right and then up-down, aiming to comprehensively reveal the impact of vibration on visual function and ensure the reliability of the results.

This study used the HSB color model, as it allowed for intuitive adjustment of hue, making it especially effective for precise color control in specific applications (Yang et al., 2010). The experiment selected four basic hues (orange, green, blue, and purple) from the HSB system as background colors, with a 90-degree interval between each pair and a brightness and saturation of 70%. For foreground colors, hues with hue differences of 30°, 45°, 60°, 75°, and 90° were selected based on each background color. Due to the properties of the hue circle, each background color corresponded to 10 foreground colors. This selection of color combinations helped explore the impact of hue difference on visual cognition under vibration conditions.

Experimental Procedure

The experiment designed 40 (4 background colors × 10 hue difference combinations) × 5 (5 vibration environments) = 200 experimental combinations, conducted in 5 groups, with an estimated total duration of 45 minutes. The main measurements were reaction time, accuracy, and completion rate, where shorter reaction times and higher accuracy and completion rates indicated better visual search performance due to hue difference combinations.

Before the experiment, participants were given sufficient rest to ensure they were in a good mental state. After reading and understanding the task and procedure, they filled out personal information (name, gender, age). Before the formal experiment, participants underwent a practice phase, identical to the main experiment, with 7 practice trials to familiarize them with the task, especially adapting to visual search under different vibration conditions.

The formal experiment used a within-subject design, divided into 5 groups, each with 40 trials, totalling 200 trials and estimated to take 40 minutes. Each trial included three pages: first, a black background page (3 seconds), with the target material in the center. After confirmation, participants pressed the spacebar to proceed to the next page. Then, a fixation point page (centered "+", lasting 3 seconds) followed by an automatic transition to the target search page (15 seconds). This page was divided into four modules (top-left, top-right, bottom-left, bottom-right), where participants needed to find the target material and identify its location by pressing the corresponding key (Q for top-left, P for top-right, Z for bottom-left, M for bottom-right). To avoid feedback errors from individual habits, participants were instructed to place both hands evenly on the keyboard. Throughout the experiment, the order of trials and batches within each group was randomly set without repetition to ensure randomness and scientific rigor. The overall experimental procedure is illustrated in Figure 2.

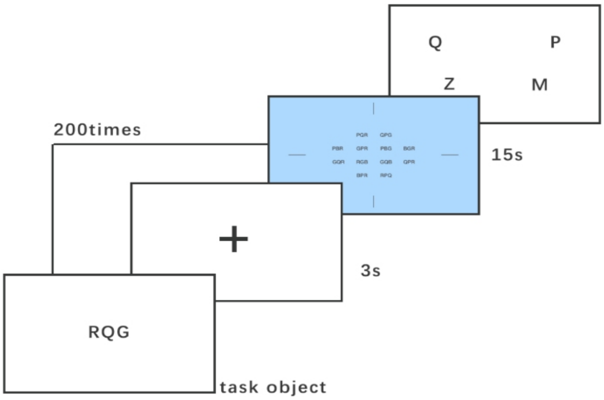

Figure 2: Experimental procedure.

DATA ANALYSIS

The raw data was thoroughly processed and checked to ensure accuracy and completeness, providing a reliable foundation for subsequent analysis. Then, a three-way ANOVA was used to assess the effects of hue difference, vibration environment, and background hue on participants' accuracy and reaction times in the visual information search task, with accuracy and reaction time as the dependent variables and hue difference, vibration environment, and background hue as the independent variables. The analysis aimed to determine the main effects of each factor and their interactions, including two-way interactions (hue difference * vibration environment, hue difference * background hue, vibration environment * background hue) and a three-way interaction (hue difference * vibration environment * background hue). For significant interaction effects, simple effect analyses were conducted. Finally, for factors with significant main effects or interactions, post hoc multiple comparisons were performed to clarify the specific differences between levels of each factor.

In this experiment, the analysis of overall accuracy revealed the participants' performance in the visual information search task. After data processing and statistical analysis, the overall accuracy remained above 88%, indicating that most participants understood the task and performed it attentively. However, despite the high overall accuracy, certain tasks exhibited varying levels of difficulty, leading to an overall accuracy that did not exceed the ideal 95% level (see Figure 3). This may be attributed to the different impacts of Hue Difference combinations, vibration frequencies, or background hues on the participants' cognitive load. Particularly in stronger vibration environments, the complexity of the task and cognitive burden may have increased, thus affecting the participants' accuracy performance.

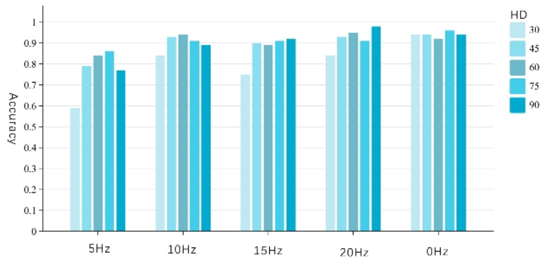

Figure 3: Accuracy of different vibration environment.

The reaction times of 20 participants completing the visual information search task were analyzed using a three-way ANOVA, as shown in Table 1.

Table 1. Within-subjects effects test for reaction time in vibration environment, Hue Difference, and background Hue Difference.

Source	Type III Sum of Squares	df	Mean Square	F	Significance	Partial Eta Squared
Hue Difference	411.620	2.271	181.268	46.446	.000	.710
Error term (Hue Difference)	168.385	43.145	3.903			
Vibration Environment	509.598	2.902	175.631	49.396	.000	.722
Error term (Vibration Environment)	196.014	55.129	3.556			
Background Hue	7.815	3	2.605	1.365	.263	.067
Error term (Background Hue)	108.813	57	1.909			
Hue Difference * Vibration Environment	71.049	7.728	9.194	2.998	.004	.136
Error term (Hue Difference * Vibration Environment)	450.211	146.829	3.067			
Hue Difference * Background Hue	189.987	7.108	26.730	7.816	.000	.291
Error term (Hue Difference * Background Hue)	461.813	135.043	3.420			
Error term * Background Hue	18.218	6.251	2.914	1.068	.386	.053

(Continued)

Table 1. Continued

Source	Type III Sum of Squares	df	Mean Square	F	Significance	Partial Eta Squared
Error (Vibration Environment * Background Hue)	323.969	118.776	2.728			
Hue Difference * Vibration Environment * Background Hue	86.637	12.557	6.899	1.531	.110	.075
Error term (Hue Difference * Vibration Environment * Background Hue)	1074.967	238.589	4.506			

In Vibration Environment 1(5Hz), the main effect of Hue Difference was significant ($F(3.747, 296.006) = 29.036$, $p < 0.01$, $\eta^2 = 0.269$). Post-hoc multiple comparisons revealed significant differences in reaction time between Hue Difference 30 and 45, 60, 75, and 90, as well as between Hue Difference 45 and 30, 60, and 75. Significant differences in reaction time were also found between Hue Difference 90 and 30, 60, with a marginal significance ($p = 0.061$) between Hue Difference 90 and 75.

In Vibration Environment 2(10Hz), the main effect of Hue Difference was significant ($F(4, 316) = 14.357$, $p < 0.01$, $\eta^2 = 0.154$). Post-hoc multiple comparisons indicated significant differences in reaction time between Hue Difference 30 and 45, 60, 75, and 90, and also between Hue Difference 75 and 90.

In Vibration Environment 3(15Hz), the main effect of Hue Difference was significant ($F(4, 316) = 20.234$, $p < 0.01$, $\eta^2 = 0.204$). Post-hoc analysis showed significant differences in reaction time between Hue Difference 30 and 45, 60, 75, and 90.

In Vibration Environment 4(20Hz), the main effect of Hue Difference was significant ($F(3.772, 298.002) = 8.442$, $p < 0.01$, $\eta^2 = 0.097$). Post-hoc multiple comparisons indicated significant differences in reaction time between Hue Difference 30 and 45, 60, 75, and 90. There were also significant differences between Hue Difference 45 and 60, 75, with a marginal significance ($p = 0.071$) between Hue Difference 45 and 90.

In Vibration Environment 5(no vibration), the main effect of Hue Difference was significant ($F(4, 316) = 4.191$, $p = 0.003 < 0.01$, $\eta^2 = 0.050$). Post-hoc analysis showed significant differences in reaction time between Hue Difference 30 and 45, 60, 75, and 90.

CONCLUSION

From the perspective of accuracy, the interaction between vibration environment and Hue Difference was found to be significant. In the absence of vibration, Hue Difference did not show a significant effect, and accuracy remained unchanged regardless of variations in Hue Difference. In contrast, under vibrating conditions, a Hue Difference of 30 consistently resulted in the lowest reaction times. Furthermore, the interaction between background Hue and Hue Difference was significant, with no further significant effect on the background Hue when Hue Difference reached 45 or higher. The green background exhibited the lowest average accuracy, and when the Hue Difference was 30, the accuracy dropped below 70%. Based on the data analysis and Figure 4, it can be observed that: Hue Difference had a direct effect on the efficiency of visual search and the fluency of information extraction. Based on the experimental data, the following gradient design for Hue Difference under different vibration environments was established: In the absence of vibration, the optimal foreground/background Hue Difference for the aircraft HUD interface color coding is 120; under low vibration conditions, the optimal Hue Difference is 90; and under high vibration conditions, the optimal Hue Difference is 60.

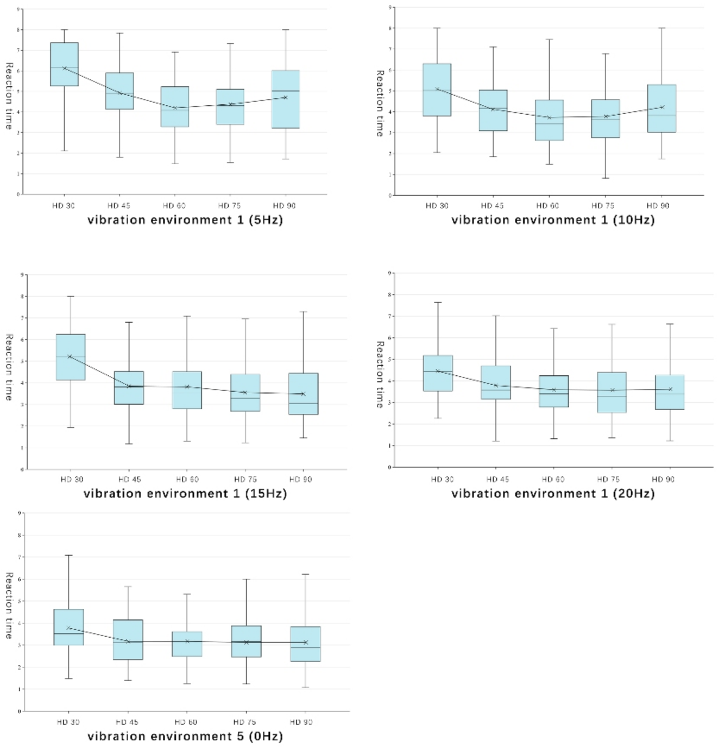

Figure 4: Hue difference and reaction time.

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