A Coherent Assessment of Visual Ergonomics in Flight Deck Impacted by Color and Luminance

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Abstract. This research proposed a coherent assessment method for evaluating visual ergonomics in simulated flight deck via evaluating psychological indices and performance during a series of experiments. A simulated flight deck environment was established according to the dimensions of a real commercial aircraft cockpit with back projection, and then a balanced sequence of pseudo random variates was generated with replicated Latin square design. After the experiment of 18 interior color levels and 2 luminance levels, a complex statistical analysis was conducted to examine the significance as well as correlations within different factors. The fluctuation of luminance can affects the results slightly, while the change of the interior color, both hue and saturation-intensity levels, can influence subjects' visual ergonomics significantly and interactively. This coherent assessment indicates that light blue was the best choice, whereas, vivid yellow was the last among the 18 colors.

Keywords: Visual ergonomics, psychological indices, performance, coherent assessment.

1 Introduction

According to the statistical results by Boeing Company, there were 1,085 fatal accidents involving commercial aircraft, world-wide, from 1950 through 2010 for which a specific cause was known [1]. Despite the continuing growth of worldwide commercial air traffic, accident rate persist nearly the same over the last 20 years. Therefore, the number of fatal accidents will increase. Mainly human factors, including weather related pilot errors, mechanical related pilot errors, air traffic controller errors, improper loading of aircraft, and other human errors, have been identified as the primary cause of air traffic accidents. Wrong decisions resting upon insufficient situation awareness are the main reason within that focus.

Flight deck environment, where pilots perform tasks, is the essential part, marking its safety of navigation. Thus, aircraft designers should transform their research focus into cognitive ergonomics related factors design of flight deck, which can affect interaction effectiveness subtly and remarkably, to guarantee pilots' adequate situation awareness (SA) and performance, rather than solely on the construction quality and morphological characteristics.

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This experiment being made by our research group aimed to investigate the influence of the ambient color and illumination of cockpit interior environment on pilots' psychological reactions and performance. The effects of colors of different hue, saturation and intensity levels and light or dark illuminance on visual ergonomics were examined.

1.1 Visual Ergonomic Assessment in Flight Deck

Numerous theories of ergonomic assessment of interior color and luminance have been developed [2], yet very little experimental research on the effects of interior color on pilots' visual ergonomics in the flight deck has been reported. In this special and small aircraft environment, ambient color plays an important role in enhancing pilots' psychological states, physiological status, performance, and even situation awareness by influencing pilots' visual ergonomics.

The constitution of SA is multifaceted and intricate, due to the most commonly used three-level model [3]. How the ambient environment affects pilots' SA is via fluctuating their anxiety, arousability, fatigue and laterality, which will further influence their attentiveness, memory, orientation, discrimination and capacity to withstand fatigue. Accordingly, visual ergonomics affecting SA should be assessed from different aspects simultaneously. Several ergonomics measurements for SA have been established [4], which highly suggests an integrated approach including human performance and subjective, physiological indices, self-report ratings or observer-rating techniques.

Two different ergonomics assessment tools were used coherently in this experiment to see if the different results converge into the same direction and how they can be integrated to evaluate the visual ergonomics in flight deck with different ambient environments.

1.2 Hypotheses

In terms of subjective rating and task performance, it was predicted that the interior color and ambient lighting conditions would affects the subjects main-effectively and interactively. In addition, the hue, saturation and intensity are predicted to have main effects on visual ergonomics.

Even though stimulus screening ability was considered as an individual differences which may interact with the interior environment significantly [5-8] and may affect experiment results, the aims of this experiment was to evaluate the visual ergonomics of a specific flight deck as well as the stability of the effects on subjects with different stimulus screening ability. Thus, the giant differences among pilots make the clarification of subjects unnecessary. The individual difference was assumed to be minor compared to the effects of ambient color and luminance in this within-subjects design.

2 Methods

2.1 Design and Subjects

This experiment employed a design with "ambient color" as a within-subject variable with 18 levels, "work plane illuminance" as a dichotomous within-subject variable.

Independent Variables. After discussed in experimenter groups, 18 color variable levels, with 6 hue levels and 3 different saturation-intensity levels were chosen and detailed in Table 1. The illuminance levels were set as "light" from 120 to 240 lx, and "dark" from 0 to 120 lx.

Table 1. Variable levels of simulator interior color with Munsell notations

Hue	Saturation-Intensity		
	High S.-Medium I.	Low S.-High I.	Low S.-Low I.
Red	5R 5/18	5R 7/6	5R 2/6
Orange	2.5YR 6/18	2.5YR 8/6	2.5YR 2/6
Yellow	10Y 9/12	10Y 9/4	10Y 3/4
Green	10GY 7/16	10GY 8/6	10GY 2/6
Blue	10B 6/16	10B 8/6	10B 2/6
Gray	N 6/	N 8/	N 2/

Dependent Variables. During performing tasks in this experiment, participants' physical workload, mental workload and performance were analyzed using subjective, self-report rating scales together with performance via following methods:

Subjective Rating Scale. The simple rating technique called Instantaneous Self-Assessment (ISA) rating scale [9], which comprised several on-line ratings of the pilots, was administered in the current research to measure the pilots' overview of the situation on that particular moment in the scenario. While, the NASA-TLX [10] was a multi-dimensional rating scale and applied to assess pilots' workload comprehensively. According to this, VEISA (Visual Ergonomics Instantaneous Self-Assessment) was devised to evaluate subjects' anxiety, arousability and fatigue every 10 minutes to provide an overview assessment during the trial process (1 being very high and 5 being very low). Besides, subjects were asked to respond to the VERQ (Visual Ergonomics Rating Questionnaire) to give their assessment in terms of luminance, glare and spaciousness of the scenario they exposed to.

Performance. The accuracy and response time together were recorded by E-Prime program for assessing pilots' performance, and thus situation awareness during the landolt ring differentiation task and numerical verification task.

Subjects. A total of 36 graduate students (30 males and 6 females), whose visual acuity and color vision were qualified by Ishihara tests and Monoyer's chart, participated in this study as unpaid volunteers. Their mean age was 23.7 years (SD = 2.61).

Sequential Effects. Each participant spent about 3.5 hours in the scenario either in the morning, afternoon, or evening on three different time periods with one week in between. Each time, participants were firstly exposed to a controlled condition, and then exposed to the colorful rooms with different illuminance levels randomly in a balanced sequence determined by a replicated Latin square design.

2.2 Laboratory Setup

There is a prevailing perception that different colors arouse people's anxiety, arousal, fatigue as well as their performances to different extent. However, few scientifically conclusive results can be drawn about the impact of color on human performance [11], as many studies have lacked the necessary experimental control and appropriate design measures. Specifically, poor resemblance of the experimental conditions to the real contexts, unchangeable real world settings and the lack of long-term assessment have severe confused influence on the experiment outcomes.

Simulator Environment. This research proposed a simulator experimental method, applying back projection to change the ambient color, and several light emitting diodes (LEDs) to provide different illumination intensity levels. The simulated environment was constructed by four pieces of translucent screen, illustrated in Fig. 1, in accordance with the dimensions of a real commercial aircraft cockpit, and a projector for each surface.

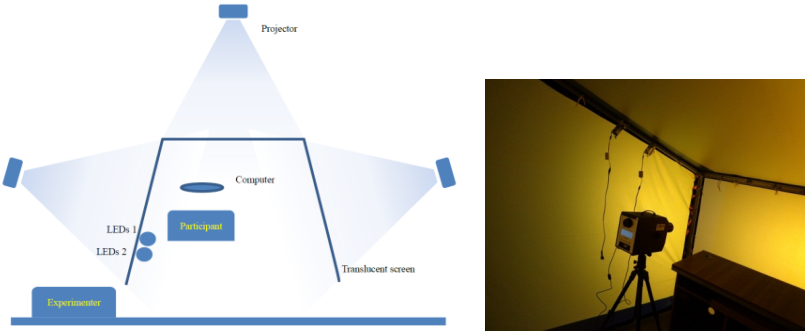

Fig. 1. Simulated experimental environment

Color and Illuminance Variable Levels Adjustment. The CIE (Y, x and y) equivalents of the color levels set in Munsell notations can be calculated assuming the standard Illuminant C as neutral origin, which approximates 6700°K. Therefore, the color variable levels were adjusted by Everfine CBM-8 color luminance meter, shown in table 2.

Table 2. Adjustment and measurement of color levels with CIE Yxy

Hue	High S.-Medium I.			Low S.-High I.			Low S.-Low I.		
	Y/cd/m^2	x	y	Y/cd/m^2	x	y	Y/cd/m^2	x	y
Red	55.6	0.49	0.25	220.7	0.34	0.36	30.8	0.43	0.32
Orange	117.4	0.50	0.43	188.9	0.37	0.38	30.2	0.43	0.38
Yellow	237.2	0.40	0.48	244.5	0.33	0.37	43.4	0.35	0.37
Green	171.7	0.30	0.54	194.2	0.31	0.36	32.7	0.27	0.47
Blue	147.6	0.21	0.28	216.3	0.27	0.32	44.0	0.22	0.26
Gray	101.4	0.30	0.33	166.5	0.30	0.33	36.3	0.30	0.33

Since lighting and color have a coherent impact on illuminance, the illuminance in each variable levels were measured by Everfine illuminance meter, shown in table 3. Most of them meet the setting value above.

Table 3. Measurement of illuminance levels in different color levels

Hue	High S.-Medium I.		Low S.-High I.		Low S.-Low I.	
	Light	Dark	Light	Dark	Light	Dark
Red	120.22	47.11	163.91	90	112.66	39
Orange	134.60	61.01	160.32	86.69	109.01	35.04
Yellow	215.13	142.45	218.08	145.41	115.75	41.75
Green	189.85	116.3	202.50	129.55	110.73	36.63
Blue	170.33	96.75	200.61	127.5	111.55	37.27
Gray	140.50	66.3	191.16	117.03	108.56	34.24

3 Results

3.1 Analysis of Variance of Color and Luminance

In terms of anxiety, a significant main effects of color, $F_{(17,1260)} = 95.20$, $p<0.01$, main effects of luminance, $F_{(1,1260)} = 14.73$, $p<0.01$, and interactive effects of color and luminance, $F_{(17,1260)} = 10.51$, $p<0.01$, were found. For the accuracy during landolt ring differentiation task, a significant main effects of color, $F_{(17,1260)} = 15.43$, $p<0.01$, and interactive effects $F_{(17,1260)} = 13.11$, $p<0.01$, as well as minor significant main effects of luminance, $F_{(1,1260)} = 4.15$, $p<0.05$, were detected. For other 8 indices, the main effects of color and interaction were significant, while, the main effects of luminance were non-significant.

As we predicted, the trivial fluctuation of luminance can only affects the results slightly. By contrast, the change of the 18 interior color levels can significantly influence subjects' psychological status and task performance. Luminance was mostly applied to examine the stability of a color's effect in this experiment.

3.2 Analysis of Variance of Hue, Saturation and Intensity

In terms of anxiety, a significant main effects of hue, $F_{(5,630)} = 60.95$, $p<0.01$, and interactive effects of hue and saturation-intensity, $F_{(10,630)} = 7.331$, $p<0.01$, were found. While, the main effects of saturation-intensity, $F_{(2,630)} = 2.001$, was non-significant. For anxiety and arousability, the main effects of both hue and saturation-intensity as well as their interactions were significant. The simple effects were detailed in Fig.2.

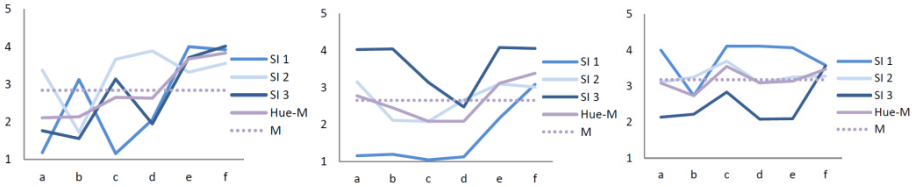

Fig. 2. Anxiety, arousability and fatigue by saturation-intensity levels over hue levels

In terms of luminance, glare and spaciousness, the main effects of both hue and saturation-intensity as well as their interactions were significant. The simple effects were detailed in Fig.3.

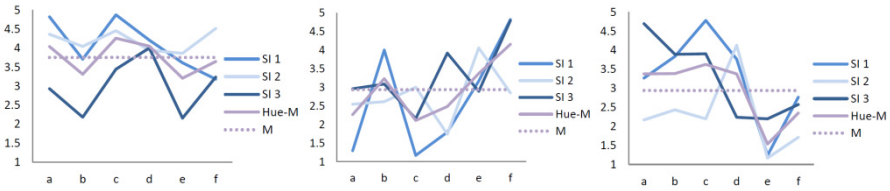

Fig. 3. Luminance, glare and spaciousness by saturation-intensity levels over hue levels

In terms of accuracy during numerical verification task, significant hue main effects, $F_{(5,630)} = 97.96$, $p<0.01$, saturation-intensity main effects, $F_{(2,630)} = 17.36$, $p<0.01$, and interactive effects of hue and saturation-intensity, $F_{(10,630)} = 7.331$, $p<0.01$, were found. While, in terms of response time, a minor significant interactive effects was found, $F_{(10,630)} = 2.098$, $p<0.05$, while, the hue main effects, $F_{(5,630)} = 1.378$, saturation-intensity main effects, $F_{(2,630)} = 0.8743$, were non-significant. The simple effects were detailed in Fig.4.

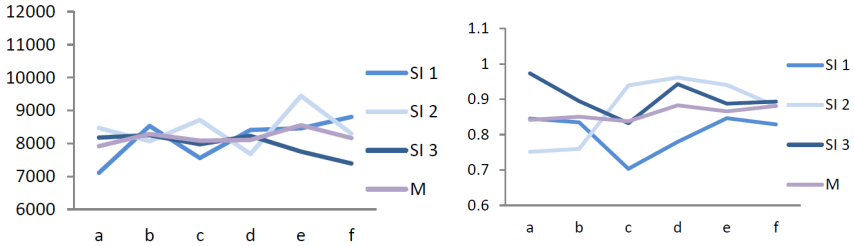

Fig. 4. Response time (ms) and accuracy (%) during numerical verification task by saturation-intensity levels over hue levels

In terms of accuracy during landolt ring differentiation task, significant hue main effects, $F_{(5,630)} = 2.359$, $p<0.01$, saturation-intensity main effects, $F_{(2,630)} = 16.65$, $p<0.01$, and interactive effects of hue and saturation-intensity, $F_{(10,630)} = 27.92$, $p<0.01$, were found. While, in terms of response time, a significant interactive effects was found, $F_{(10,630)} = 5.083$, $p<0.01$, whereas, the hue main effects, $F_{(5,630)} = 1.049$, saturation-intensity main effects, $F_{(2,630)} = 2.251$, were non-significant. The simple effects were detailed in Fig.5.

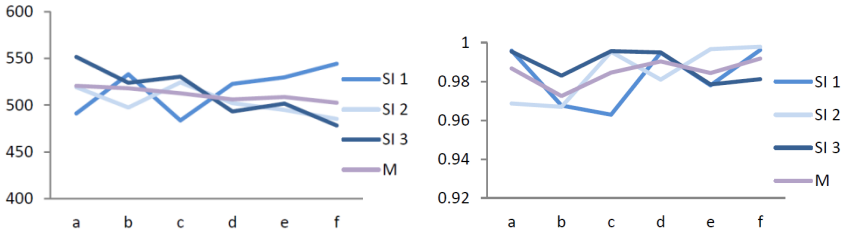

Fig. 5. Response time (ms) and accuracy (%) during the landolt ring differentiation task by saturation-intensity levels over hue levels

The obtained results of this experiment indicate significant main effects for flight deck ambient color on participants. Particularly, hue of ambient color significantly affected anxiety, arousability, luminance, glare and spaciousness; saturation-intensity variable significantly affected arousability, fatigue and luminance of subjects. The interactive effects of hue and saturation-intensity of ambient color is evidently significant in terms of task performance.

3.3 Coherent Assessment of Visual Ergonomics

The score of each color on 10 sub-indices was marked (-1 being bad and unacceptable, 0 being acceptable, 1 being good) via analyzing the data and diagrams above. The weights of 6 subjective sub-indices were measured in evaluation of the overall psychological effects according to subjects' 5 rate scale after their third session, as shown in table 4.

Table 4. The weights of six subjective sub-indices

Anxiety	Arousability	Fatigue	Luminance	Glare	Spaciousness
0.2248	0.2171	0.1405	0.1826	0.1341	0.1009

The 4 sub-indices of performance could hardly be assumed to be more important or less important than any other, thus, were assumed to be of same important. The normalized overall psychological ratings, performance ratings as well as their mean values and differences were detailed in table 5. The mean values and differences of the two indices should be considered coherently to evaluate the comprehensive visual ergonomics. The vivid blue-SI1 and light blue-SI2 were considered as to

affect subjects' psychological ratings most positively, while vivid red-SI1, dark orange-SI3 and vivid yellow-SI1 were less positive; dark red-SI3 and light blue-SI2 facilitate task performance mostly, while vivid yellow-SI1 and dark gray-SI3 hampered subjects status from well performing tasks. Comprehensively, light blue-SI2 was the best choice among 18 flight deck interior colors in this experiment, followed by moderate gray-SI1, pale yellow-SI2 and light orange-SI2. By contrast, vivid yellow-SI1 was the last, followed by vivid red-SI1. Vivid blue-SI1and dark gray-SI3 were highly phrased subjectively, their effects on performance were relatively unacceptable, whereas dark red-SI3, dark orange- SI3 and light green-SI1 which were less preferred subjectively, stimulate subjects accuracy and response time when performing tasks.

In order to give a concise and coherent quantity to evaluate visual ergonomics, the equation 1 was proposed.

$$VE = \frac{c(w_1 Phy + w_1 Per)}{|Phy - Per| + c} \tag{1}$$

Where, w_1, w_2 and c are positive constants. Assuming the psychological effects and performance effects impacted by interior color were of the same importance, which means $w_1 = 0.5$, $w_2 = 0.5$, c was tested and set to 0.3, and thus the coherent value of visual ergonomics were calculated and detailed in table 5.

Table 5. Coherent assessment of visual ergonomics

	Phy.	Per.	Mean	|Phy.-Per.|	V.E.
Red-SI1	0.1910	0.25	0.2205	0.0592	0.1842
Red-SI2	0.7670	0.25	0.5085	0.5170	0.1867
Red-SI3	0.3167	0.875	0.59585	0.5583	0.2083
Orange-SI1	0.6820	0.375	0.5285	0.3070	0.2612
Orange-SI2	0.7248	0.5	0.6124	0.2248	0.3501
Orange-SI3	0.1341	0.625	0.3796	0.4909	0.1440
Yellow-SI1	0.1405	0	0.0703	0.1405	0.0478
Yellow-SI2	0.7670	0.625	0.6960	0.1420	0.4724
Yellow-SI3	0.7650	0.5	0.6325	0.2650	0.3358
Green-SI1	0.2746	0.75	0.5123	0.4754	0.1982
Green-SI2	0.7650	0.375	0.5700	0.3900	0.2478
Green-SI3	0.4502	0.625	0.5376	0.1749	0.3396
Blue-SI1	1	0.375	0.6875	0.6250	0.2230
Blue-SI2	1	0.875	0.9375	0.1250	0.6618
Blue-SI3	0.4094	0.5	0.4547	0.0907	0.3492
Gray-SI1	0.9496	0.75	0.8498	0.1996	0.5103
Gray-SI2	0.8174	0.5	0.6587	0.3174	0.3201
Gray-SI3	0.7325	0.125	0.4287	0.6075	0.1417

In conclusion, the result shows that two evaluation indices did not always converge into the same tendency, but can give an overview insight to subjects' physical and mental conditions and further indicate pilots' situation awareness. Participants' responses and evaluation of the simulations of real environments can be established to be adequately similar to people's responses to the actual environment, whereas color, light and other interior elements can be altered effortlessly and naturally. The experimental methods and ideas presented may have wider application in ergonomics analysis of interaction effectiveness for a specific scenario.

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