International Journal of Industrial Ergonomics 67 (2018) 180–191

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Effects of color codes used on marine supervision HMI on mental workload and information retrieval: Experimentations with novices and experts

Laurianne Boulhic[a,*], Alain Bignon[a], Fabien Silone[b,c], Thierry Morineau[b], Julien Rechard[d], Jean-Frédéric Bouillon[e]

[a] SEGULA Technologies, Rue de la Montagne du Salut, BP 50256, 56602, Lanester Cedex, France
[b] European University of Brittany, LP3C EA 1285, Campus de Tohannic, 56000, Vannes, France
[c] Isatech, rue Henri Becquerel, Parc innovation de Bretagne Sud, 56000, Vannes, France
[d] Airbus, 316 Route de Bayonne, 31300, Toulouse, France
[e] Ecole Nationale Supérieure Maritime, 38 rue Gabriel Péri, BP 90303, 44103, Nantes Cedex, 04, France

ARTICLE INFO

Keywords:
Supervision
Color code
Mental workload
Bicolor
Searching tasks
Expertise

ABSTRACT

Using a color code on human-machine interfaces could sensibly reduce the informational density. In this paper, we focused on the supervision interfaces used in engine room of Merchant Navy vessels. There is no regulation about color use on these interfaces, despite the color code playing an important role in showing information. The ISO Standard 14726-2008 regulates the color code printed on physical pipes and is used to represent the fluids flowing through it. The purpose of this study is to determine if we could use this standardized color code on the interfaces and create a connection between the physical pipes and their graphical representation. Two experimentations are presented, in which we compared the effects of two color codes on the performance at searching tasks carried out by novices and experts. One code is extracted from ISO Standard 14726-2008 (Normative Pipe Identification Color Code), and the other is created by taking into account general guidelines and common uses (Ergonomic Recommendations Color Code). The results showed that the NPICC, and its bicolor version in particular, increased the mental workload and the searching time required by novices. Experts had more difficulties to recognize the fluids represented by two colors and they used the two-colored fluid system less frequently than novices to retrieve an information.

1. Introduction

Supervision is an industrial technique for controlling and monitoring automated processes. Through data acquisition graphically displayed on a human-machine interface (HMI) (parameters such as measures, alarms, operating status feedback), supervision is a way for the operator to ensure that the system works properly without having to be physically present in front of the installation. Because there may be many variables to represent in a limited screen space, the color is a visual variable that could be used to represent or regroup information, or to draw attention to critical information (FAA, 2003; Friedman-Berg, 2008; Xing and Schroeder, 2005).

The use of a color code on a supervision HMI can have several advantages, but it can also have dramatic consequences if inappropriate. Indeed, color directly involves the operator's comprehension: if the perception of color is incorrect, the operator's understanding will be incorrect too (Tabart et al., 2007). According to Christ (1975), an incoherent or inappropriate color code will reduce the operator's ability to find a target among distractors. On the other hand, color could improve the recognition of objects at different levels of visual processing (for reviews see Bramão et al., 2011; Tanaka et al., 2001). For example, Ostergaard and Davidoff (1985) showed that colored objects (i.e. fruit and vegetables) were denominated faster than achromatic objects.

At the early stages of visual processing, color could improve the segmentation of visual scenes because it helps for the structural description of the object (Callaghan, 1984; Troscianko and Harris, 1988). Color improves both identification and time of searching for a target in comparison to achromatic coding dimensions (i.e. shapes, alphanumeric symbols, monochrome) and this advantage increases with the density of symbols in the display (Christ, 1975).

At later stages of the visual processing, color could help to make a semantic representation of the object (Bramão et al., 2011). According to the conclusions of Bramão et al. (2011), there is a strong relationship between visual perception of color and stored knowledge in the

* Corresponding author.
E-mail addresses: laurianne.boulhic@segula.fr (L. Boulhic), bignon.alain@neuf.fr (A. Bignon), fabien.silone@isatech.fr (F. Silone), thierry.morineau@univ-ubs.fr (T. Morineau), julien.rechard@airbus.com (J. Rechard), jean-frederic.bouillon@supmaritime.fr (J.-F. Bouillon).

https://doi.org/10.1016/j.ergon.2018.05.010
Received 5 January 2017; Received in revised form 16 March 2018; Accepted 17 May 2018
0169-8141/

memory. In fact, there is some evidence that color improves recognition of high diagnostic color objects more than low diagnostic color ones. High diagnostic color objects are objects strongly associated with a particular color (for example, a banana is strongly associated with yellow). Other studies showed that objects displayed with an appropriate color are recognized faster than objects displayed with an inappropriate color and monochromes objects (Humphrey et al., 1994; Price and Humphrey, 1989; Wurm et al., 1993). Consequently, the more we see an object in a particular color, the more we will associate it with this color in our memory, and the faster we will recognize it.

If there is a link between color perception and memory, it means that our past experiences will play a role in object recognition. Indeed, according to Eleanor J. Gibson's theory of perceptual learning (Gibson et al., 1932), perception is an active, dynamic process that depends on affordances (i.e. possibilities for action) provided by the environment and on the animal's capacities to perceive these affordances for action. Indeed, the animal and its surrounding environment form an interactive system (Gibson, 1997): the animal generates information about its environment, tailors its actions to this environment, and, reciprocally, the environment provides the animal with opportunities for action. Through experience, the animal learns how to generate and detect the appropriate perceptual information.

Perceptual learning is the process whereby perceptual information becomes increasingly differentiated and specific to the things in the world and to what one can do with these things (Gibson, 1992). In fact, we never detect all the perceptual pieces of information, only those relevant to the current task. The more knowledge the perceivers have about what they are searching for, where and how to search for it, the less attention they will pay to information non-relevant to the current task. For example, studies in the maritime field showed that experts are more flexible than trainees are (Chauvin et al., 2009): they can choose better strategies for the situation, even in difficult contexts, because they have a large repertoire of patterns (Chauvin et al., 2009). According to this theory, past experiences and level of expertise should play a significant role in the perception of colored objects. Thus, we expect some differences between novices and experts concerning the effects of color codes used on interfaces (Boulhic et al., 2016).

In this study, we focused on supervision interfaces used in engine room of Merchant Navy vessels because there is currently no regulation about colors used for these, and there is a significant variability of color code choices from one vessel to another. In previous work, we proposed an automated approach for the design of this type of HMI (Bignon et al., 2013; Rechard et al., 2015) but didn't specifically address the problem of the color code. HMI are composed of synoptic representations of each sub-system of the vessel. Usually, color is used to represent the fluids that flow through the pipes and to highlight the operating status of the engine (i.e. on/off, warning). Furthermore, the ISO Standard 14726-2008 (Fig. 1) regulates the color code used to indicate fluids flowing through the physical pipes, using labels stuck on the vessels pipes. This color code is bicolor: a main color represents a category of fluids (e.g. fuel), and a second color identifies the specific fluid (e.g. heavy fuel oil).

It would be interesting to use this color code on the HMI because it would create a connection between the physical pipes and their graphical representations. It would also be logical because the interfaces act as intermediaries between the operator and the process to control. Unfortunately, we had some difficulties adapting the ISO Standard color code for HMI. In particular, the graphical representation would alternate the colors through the pipes, which can cause eyestrain and difficulties of legibility. Therefore, the distinction between the different pipes can be more difficult than with unique and distinct color for each fluid. It can also be difficult to implement in a software. Moreover, this color code is then excessively detailed – with approximately 70 combinations of colors – which can cause memorization difficulties. For these reasons, this color code may not be very reliable for the operators as they might not use it at all, for fear of being mistaken (potential risk for the safety of the vessel). We think that it may be necessary to create a more appropriate color code to avoid this. Thus, the principal objective of this study is to determine whether we could apply the ISO Standard color code on interfaces used for vessel monitoring or whether we have to create a color code specific to these interfaces. For this, we have to take into account existing general guidelines about the use of color in interfaces (Cardosi and Hannon, 1999; Department of the Army, 2006; FAA, 2003; NASA Color Usage Website, 2004). Reading these general guidelines, we noticed that there seems to be a contradiction between two of them, one concerning the distinction between colors, and one concerning the visual saliency of alarms.

On one hand, we have to choose very distinct colors to avoid confusion between colors used to represent different pieces of information. The colors associated with a meaning have to be easily identifiable and associated with a single meaning (Cardosi and Hannon, 1999; Xing, 2006). For this, the physical difference between the colors has to be as high as possible (Cardosi and Hannon, 1999; Department of the Army, 2006; FAA, 2003; Friedman-Berg, 2008; NASA Color Usage Website, 2004; Xing, 2006). This physical difference can be expressed as the Delta-E value which is a number corresponding to the distance between two colors placed in a given color space: the higher it is, the more distinct the colors will be perceived. Mokrzycki and Tatol (2012) gives a scale of perception of the difference between two colors by a standard observer depending on Delta-E (ΔE):

- $0 < \Delta E < 1$ The observer does not notice the difference.
- $1 < \Delta E < 2$ Only an experienced observer can notice the difference.
- $2 < \Delta E < 3.5$ An unexperienced observer also notices the difference.
- $3.5 < \Delta E < 5$ Clear difference in color is noticed.
- $5 < \Delta E$ An observer notices two different colors.

Different formulas were proposed for Delta-E calculation. We applied the formula approved by CIE (Luo et al., 2001): the Delta-E 2000 (ΔE_{2000}). According to International Maritime Organization (2000), the distance between two colors must be a minimum of $40\Delta E$ to ensure optimal differentiation of the colors on marine supervision interfaces. A high Delta-E value like this entails selecting colors from distinct hues and as pure as possible. Originally defined for the CIELAB color space, Delta-E 2000 formula can be transposed to other color spaces through converters.[1] Indeed, we choose to apply the HSL model as color space (Joblove and Greenberg, 1978). It defines color following three criteria: hue, saturation and luminosity. The hue of a color corresponds to its identity (red, green or yellow for example) and is coded according to its angle on the chromatic disc (0° or 360° correspond to red for example). The saturation is a numerical evaluation of the coloration of a color on a grey scale from 0 to 100%. The luminosity is a numerical evaluation of the brightness of a color on a scale from 0 (black) to 100% (white). Thus, a pure color is a chromatic color that has the highest saturation between the colors of the same hue, and is placed on the circumference of the chromatic disc. By changing these parameters, we can obtain an infinity of colors but their identity may be ambiguous.

On the other hand, to highlight important information like alarms, we have to create an attentional guidance by using bright and highly saturated color only for important pieces of information that need to draw attention (Cardosi and Hannon, 1999; Friedman-Berg, 2008; International Maritime Organization, 2000; Xing, 2006). Theeuwes (1992) showed that a change of color or shape could draw attention. According to Xing (2006), when we want to create a color saliency effect, the target color (like an alarm) needs to have a brightness level superior to $20\,cd/cm^2$ (candela per square centimeter) and a hue sufficiently different to that of the other colors present in the visual field. This means that we have to use color with low brightness and saturation

[1] http://colormine.org/.