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Color is important in helping users effectively process information like text and symbols when performing tasks on digital displays. Interface designers in safety- and mission-critical industries often utilize human factors design guidelines and standards to make important design decisions like the use of color for legibility and distinguishability. However, such guidance sometimes requires additional interpretation and calculation to readily apply to the design question at hand. This work describes a simple tool that can be used to evaluate the adequacy of color choices from a palette for being legible or distinguishable. The tool eliminates having to manually convert colors to a readable format while providing a specific set of colors that are acceptable from select human factors standards. This paper provides an exemplary case study applied to a digital modification at a nuclear power plant to highlight how the tool may be used in safety- and mission-critical industries.

INTRODUCTION

Color has a vital role in helping users effectively process information like alphanumeric text, numeric characters, and symbols when performing tasks on digital displays (Wickens, Gordon, Liu, & Lee, 2004). This is no exception for safety- and mission-critical industries. There are many factors that influence the readability of text, including font size, font type, word choice, and organization. Though, color is important in allowing the user to effectively identify the characters separated from the background.

For instance, using color to present important indications for safety and electricity generation on a digital display at a nuclear power plant must provide sufficient conspicuity for the user to read and process color codes that communicate the state of the plant. Figure 1, adapted from Boring et al. (2019), illustrates a turbine control system overview display for a conceptual nuclear power plant human-system interface. The color choices were carefully made so that critical information, like speed control, load control, pressures, and impacts to reactivity, is easily readable.

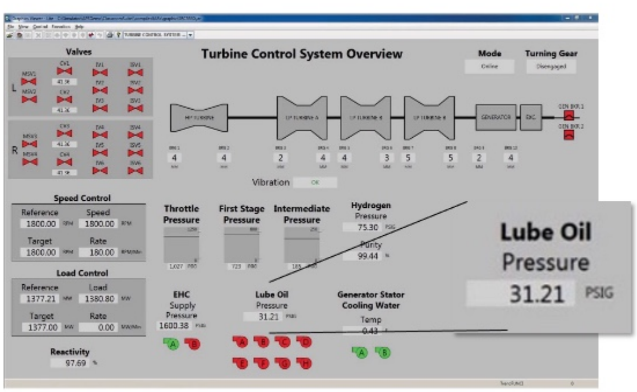

Figure 1. Example of the digital display of a turbine control system (adapted and expanded from Boring et al., 2019).

Color is commonly used to provide sufficient distinctiveness to allow a user to assimilate information from the content being provided, otherwise known as *legibility*. Labels, numeric readouts, and instructions all present alphanumeric and numeric information that must be legible particularly in the intended use environment.

Color is also used to present codes of information in a more abstract sense. For example, in Figure 1, valve indications at the top and pump indications at the bottom n use colors that are *distinguishable* from each other. Here, t indications change color from green to red, depending on i there is active flow (i.e., red to denote open valves and run pumps). The operator must discern the equipment state presented as icons through its color.

Interface designers in safety- and mission-critical industries like nuclear power generation often utilize huma factors design guidelines and standards such as NUREG-0 (2020) to make important design decisions like the use of color for legibility and distinguishability. However, such guidance sometimes requires additional interpretation and calculation to readily apply to the design question at hand. example, NUREG-0700 provides color guidance for an adequate color contrast of symbols to be legible as shown Figure 2.

1.3.8-8 Color Contrast
Symbols should be legible and readily distinguishable against the background colors under all expe ambient lighting conditions.
Additional Information: For adequate legibility, colored symbols should differ from their color background by an E distance (CIE Yu'v') of 100 units or more. The E distances (CIE Yu'v') are deri from the 1976 CIE UCS color diagram. As with the (CIE L*u*v) distances, caution should be used assessing legibility for characters in colors having small luminance differences. This caution applie only to characters in color but also to small luminance differences in background colors and for ver small luminance differences between characters in color and background in color. Unusually large small characters may lead to erroneous estimates of legibility. The elements required for the calcula are the luminance in cd/m² (Y) and the UCS coordinates (u',v') of the text and background. Equatio gives the metric.[5908]

Figure 2. Guideline 1.3.8-8 Color Contrast (adapted from NUREG-0 Revision 3, 2020).

Oftentimes, the designer uses a specific color palette apply the use of colors in presenting different display elements, like labels, readouts, tables, etc. With digital displays, these colors are likely presented as hexadecimal codes (i.e., hex codes) or red, green, blue (RGB) values. T designer must convert these common conventions into less frequently used formats, like the International Commissio Illumination (CIE) L*u*v color space, or luminance. This work describes a simple tool that can be used to evaluate t adequacy of color choices from a palette as being legible o distinguishable. The tool eliminates the need to manually convert colors to a readable format while providing a specific set of colors that are acceptable per guidance in select human factors standards.

The remainder of this work is structured into three sections. The first section summarizes common measures used to evaluate color for legibility and distinguishability. Next, this paper summarizes specific standards and guidelines across different industries that apply these measures. The final section provides a description of the tool, with a short case study of how it has been applied in digital modifications to a nuclear power plant main control room. It is assumed that the human factors analyst using this tool is interested in the specific guidelines and standards that apply to the domain in question. Hence, the tool provides the capability to select standards of interest.

MEASURES FOR EVALUATING COLOR

The evaluation of color for legibility or distinguishability is broadly performed based on comparing a foreground color (i.e., the color presenting the label, text, symbol) to a background color (Ware, 2019). As each color provides a unique signature of the amount of light emitted (i.e., luminance), one color can be compared to another in terms of their luminance. One such measure that is used is luminance contrast, which is a contrast ratio of luminance between a foreground and background color. There are also other measures that, while they are based on this concept of luminance, apply approximations of the human visual system. These types of measures are summarized next.

Luminance Contrast

Luminance contrast is a ratio of the difference between two luminance values (ISO 9241-303:2011). The formula can simply be described as: $LC = L_{max} / L_{min}$.

Here, L_{max} refers to the color with the greatest luminance while L_{min} refers to the color with the minimum luminance. The ratio ranges from 1:1 to 21:1. For example, a white foreground on a black background yields the greatest luminance contrast of 21:1. To illustrate how luminance contrast is used in display design, the reader is encouraged to visit the National Aeronautics and Space Administration Ames Researcher Center guidance for color usage: https://colorusage.arc.nasa.gov/luminance_cont.php.

International Commission on Illumination Color Difference

The CIE has developed several sophisticated color difference measures that are intended to approximate the human visual system (Luo et al., 2001). These measures holistically use the CIE chromaticity coordinate system that is based on a given color's relation to three primary color coordinates of red, green, and blue expressed as *x, y,* and *z*, respectively. The CIE color difference measures the Euclidean distance between two colors within the chromaticity coordinate system; the distance approximates the just noticeable difference from the human visual system (Daniel & Byrd, 2003).

A detailed discussion of the variants of the CIE color difference calculation is beyond the scope of this work. Though, it should be noted that there are three notable variants of the measure used throughout industry. The *CIE 1976*, or Delta E 1976, provides the base color difference measure from CIE and is still used in some modern standards like NUREG-0700 (2020). CIE 1976 has known limitations, such as having inaccuracies when comparing two highly saturated colors in which color differences can be overly inflated (Luo, Cui, & Rigg, 2001). The CIE 1994 calculation, Delta E 1994, extends from CIE 1976 to address these inaccuracies through several additions to the original 1976 formula. Delta E 1994 is referenced in known human factors standards like The American National Standards Institute (ANSI)/ Human Factors and Ergonomics Society (HFES) 100 (2007). Finally, an even more recent extension, CIE 2000 or Delta E 2000, provides even more corrections to account for inaccuracies in lightness found in the 1994 version (Luo et al., 2001). While Delta E 2000 is not widely used in the human factors community, the measure can be found in the International Organization for Standardization (ISO)/ CIE 11664-6:2014.

It is worth noting that the results of Delta E 1976, 1994, and 2000 are qualitatively unique from each other. To illustrate, Figure 3 shows how a sampling of the ~16.7 million possible colors for a computerized display with distances between 100 and 101 per each Delta E measure (i.e., shown on a three-dimensional scale per red, green, and blue channels) compared to a reference gray (#D5D5D5) are notably different. Hence, the comparison between one version of Delta E and another should be done with caution.

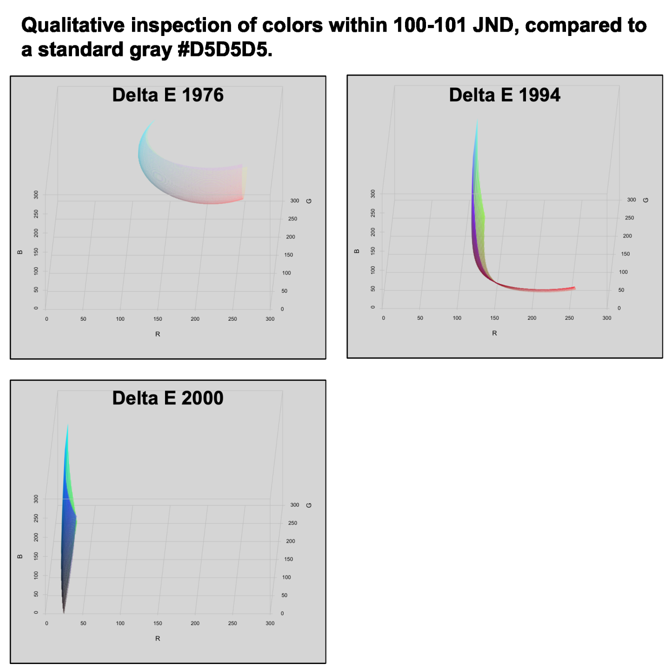

Figure 3. Comparison of Delta E 1976, Delta E 1994, and Delta E 2000.

APPLICABLE STANDARDS AND GUIDELINES

Guidance for the use of color as it supports legibility and distinguishability is provided across several safety- and mission-critical industries. Table 1 summarizes notable standards and guidelines and outlines the specific measure and criteria for evaluation used for legibility and distinguishability for digital displays across different representative industries.

Table 1. Applicable standards and guidelines.

Domain Applicable Standards	**Legibility Guidance**	**Distinguishability Guidance**
Aviation HF-STD-001B Department of Transportation (2003)	**Luminance Contrast** 3:1-5:1 for continuous reading ≥ 8:1 for dynamic text	**Luminance Contrast** > 7:1 to attract attention
Computer Workstations ANSI/HFES-100 (2007)	**Luminance Contrast** ≥ 3:1	**Luminance Contrast** ≥ 1.5:1 for codes on symbols **Color Difference** Delta E 1994 ≥ 20 for discriminating colors
Computer Workstations ISO 9241-303 (2011)	**Luminance Contrast** ≥ 3:1	**Luminance Contrast** ≥ 1.5:1
Web Content Accessibility Guidelines (WCAG) 2.1 (2018)	**Luminance Contrast** ≥ 4.5:1for normal text ≥ 3:1 for large text (14 point or larger)	-
Military MIL-STD-1472 (2020)	**Color Difference** Delta E 1976 ≥ 100 for symbols **Luminance Contrast** ≥ 4.5:1 for text 14 point or less ≥ 3:1 for text 14 point or larger	**Color Difference** Delta E 1976 ≥ 20
Nuclear Power NUREG-0700 (2020)	**Color Difference** Delta E 1976 ≥ 100	**Color Difference** Delta E 1976 ≥ 40
Space NASA-STD-3001 Vol. 2	**Luminance Contrast** Weber Contrast[1] ≥ 0.2 [1]WC = $(L_{max}-L_{min})/L_{max}$	-

A SIMPLE TOOL TO EVALUATE COLOR FOR LEGIBILITY AND DISTINGUISHABILITY

This section describes a simple tool, herein referred to as the Color Comparer for Usability (ColComp4U), that was developed to readily evaluate a proposed color palette for legibility and distinguishability. ColComp4U reads common color descriptors, like hex codes or RGB values, and calculates CIE color difference metrics, as well as the luminance contrast. It then assesses these metrics against guidance outlined in the common standards previously described. A notable advantage of ColComp4U is its ability to read a defined color palette for a given display and output specific colors that meet specified guidance and explicitly show what colors are "safe" to apply for legibility and distinguishability.

The following subsections describe the system dependencies necessary for installing ColComp4U, the input needs, a summary for using the tool, and the outputs the tool provides. There is then a brief case study of how ColComp4U was used to help inform the selection of colors for a digital interface (i.e., human-system interface [HSI]) being installed at a United States (U.S.) nuclear power plant. This brief case study highlights how ColComp4U may be used as one of many human factors approaches to display design.

Installing and Use

ColComp4U relies on both R and Microsoft Excel. A simple graphical user interface is provided using the *tcltk* (R Core Team, 2020) framework to allow the user to select the Excel file that contains a defined color palette. Figure 4 shows a snapshot of the Excel file that serves as a container for the color palette under analysis. The colors in the spreadsheet are reflective of the simplified digital HSI below; the *Name* variable corresponds to the colors used to design the HSI. The user can either enter the RGB values, as shown, or the hex code for each color. The *Condition* variable allows the user to enter descriptive text of what the color represents. Following this format, the user can enter many unique colors from the palette.

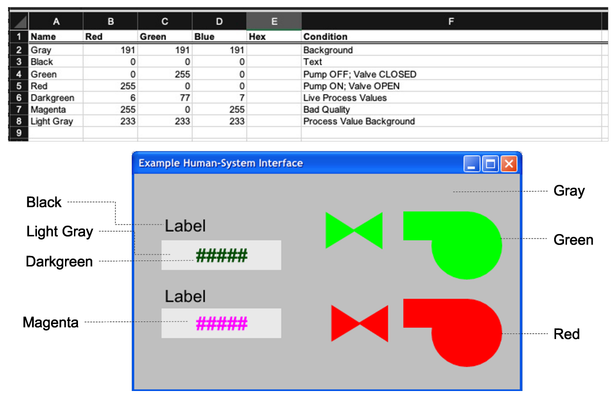

Figure 4. Example inputs needed for ColComp4U.

Once the color palette has been entered into the ColComp4U Excel spreadsheet (Figure 4), the tool is initiated by opening and running the R script. Calculations are done using *colorscience* (Gama & Davis, 2019). The entire workflow can be summarized in five main steps (Figure 5).

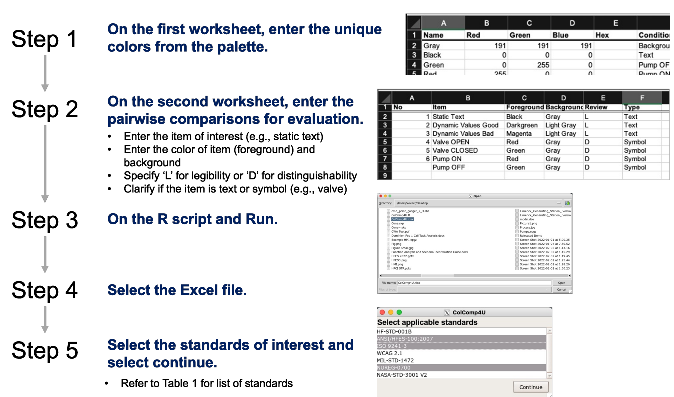

Figure 5. Steps for running ColComp4U.

Once the colors are defined in the palette, specific pairwise comparisons are defined in a second worksheet. Next, the R script can be opened and run, which presents a graphical user interface to select the Excel file and select the standards of interest.

Outputs and Interpretations

ColComp4U outputs a second Excel file that presents the results of the pairwise comparisons (Figure 6). By selecting the standards of interest, the output will present the corresponding results of each standard, which is outlined in Table 1 of this paper. As seen in Figure 6, the output file presents the results for legibility and distinguishability for each selected standard as an appended variable to the spreadsheet. The item in the pairwise comparison is also colored using the exact foreground and background color specified, as seen in Figure 6. The results allow the interface designer to quickly discern if the specified colors are acceptable or not, depending on the specific standard in review.

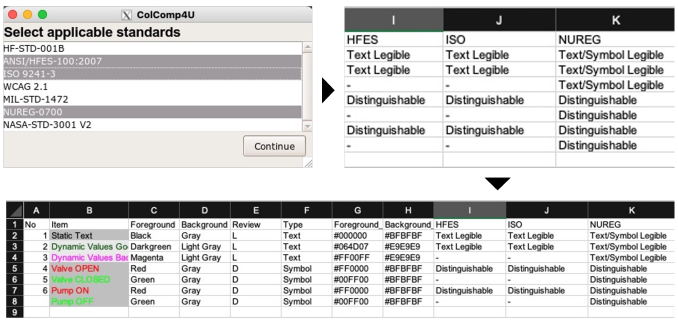

Figure 6. Output of ColComp4U

CASE STUDY: SUPPORTING NUCLEAR POWER PLANT DIGITAL INTERFACE DESIGN

ColComp4U was developed under the U.S. Department of Energy Light Water Reactor Sustainability Program and has been used to provide human factors design guidance for the use of color in several digital modifications at existing U.S. nuclear power plants. Several U.S. nuclear power plants have been planning or are currently undergoing significant modifications to their existing safety and non-safety control systems. That is, these plants, which are largely analog, are replacing legacy instrumentation and control systems with digital systems, which have significant economic benefits (e.g., Hunton et al., 2020).

Like other safety-critical industries, significant modifications to these systems require the application of human factors engineering to ensure the digital upgrades facilitate the safe, efficient, and reliable performance of operations, maintenance, tests, inspections, and surveillance tasks (NUREG-0711, 2012). The U.S. Nuclear Regulatory Commission provides detailed design (NUREG-0700, 2020) and process (NUREG-0711, 2012) guidance in reviewing applicant's human factors engineering program and products. Additionally, several complementary guidance documents have been developed to support industry in engaging in significant upgrades. One such guidance approach is shown in Figure 7, developed by the Light Water Reactor Sustainability Program (Kovesdi et al., 2021).

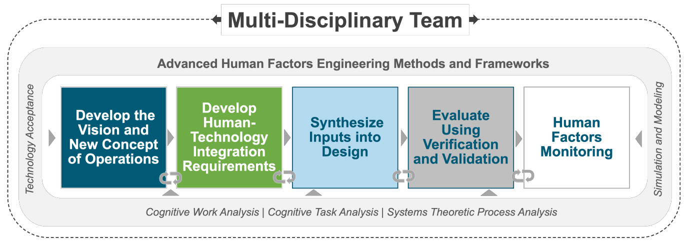

Figure 7. Human and technology integration methodology for nuclear power plant digital modifications (adapted from Kovesdi et al., 2021)

The methodology includes a variety of human factors engineering approaches that follow best practices in industry. Here, human factors design verification has an important role in the design synthesis and verification of these significant upgrades (i.e., light blue and gray sections of Figure 7). The use of ColComp4U is one such tool applied in design and verification to ensure state-of-the-art human factors engineering design principles are being considered, like NUREG-0700. ColComp4U enables the design team to identify colors that are compliant with NUREG-0700 to ensure important plant information is legible and distinguishable for plant personnel. The results provided by ColComp4U have been used early on to inform color selection when developing the HSI style guide. These results hence provide a technical basis for the design decisions made regarding the use of color.

CONCLUSIONS

This paper describes the development and use of a tool used to support human factors engineers perform color evaluations for legibility and distinguishability. The tool, ColComp4U, provides a simple workflow that enables the efficient analysis of a color palette based on select standards for various safety- and mission-critical industries. It should be emphasized that, while ColComp4U provides an analytical means of evaluating color, its interpretation and use should always be used with caution and preferably be followed by empirical approaches like usability testing. Collectively, the results from ColComp4U, when performing with other user-centered design approaches, offers a simple way to provide an additional technical basis from select standards that apply to the design problem at hand.

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