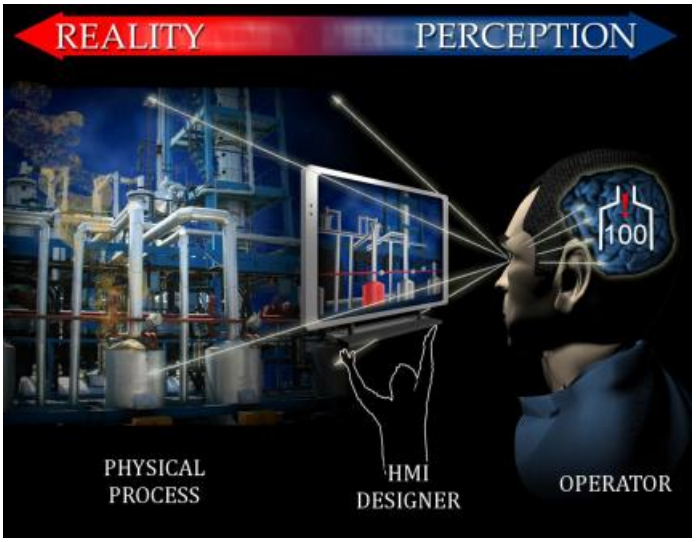
Applying Color Science to Design Effective Human-Machine Interfaces

A systematic, evidence-based color design process results in effective displays for color-blind and normal users.

by Dirk Beer, Harvey Smallman, Cindy Scott and Mark Nixon



Human operators are a key part of any process control system. As such, they constitute part of a complex, causal chain of overall system processing. Human machine interfaces (HMIs) form a key link in that chain by bridging the physical world where processes reside with the perceptual reconstruction and representation of those processes in the heads of human operators and supervisors.

If an HMI design gives rise to a flawed or inaccurate representation of a process, then error and suboptimal task performance may result. HMIs have become increasingly important links in this chain for two reasons. First, the arrival of distributed control systems (DCS) in the 1970s distanced operators from the physical entities they controlled, requiring all interaction be mediated by HMIs. Second, the ongoing introduction of complex automation into process control is increasingly changing human operators into supervisors. Supervision has complex decision-making requirements that must all be conveyed via HMIs.

It is no wonder that the process control industry is increasingly questioning how well its HMIs are conveying accurate task- and decision-relevant representations to its users. We are taking an evidence-based, human-factors approach to these questions. By leveraging a wealth of cognitive and perceptual science, we strive for HMIs that match the way humans process information. In this paper, we focus

on the role of color in HMI design and take a systematic approach to carefully realign its use to the requirements of human color vision to improve task performance.

Color HMIs have been available and enjoyed by users for decades. It has been observed in numerous work domains that color choices are driven first by preference and aesthetics and only second for function, for example, attracting attention to something with color. Both are important and need to be considered together to achieve a usable and effective HMI design. Color HMIs can offer significant advantages over monochrome displays, but only when carefully designed and aligned with color visionôs functions, capabilities and requirements. Typically, colors have been designed and picked in RGB, HSL or HSV ñcolor spacesò (3D representations of color), but these hardware-centric spaces donôt accurately predict how colors appear to the human visual system. Far superior color choices can be made by using available color spaces that are designed to be perceptually linear and perceptually uniform. Also, colors change appearance based on many factors, including spatial context, the size of objects, the lighting conditions and observer type (normal vs. several types of color anomaly or ñcolorblindnessò). Finally, while display manufacturers advertise millions of colors, only a very few basic color categories are consistently identified and named by users (see sidebar). Because colors are picked with lay knowledge largely oblivious of these perceptual subtleties, color HMIs suffer from a number of deficiencies, including:

- excessive color use misaligned to task needs,
- alerts that donôt attract attention,
- indiscriminable colors,
- illegible colored text,
- variable color appearance of elements possessing identical RGB values.

All of these issues can negatively impact operators performing tasks as they attempt to extract information from colored HMIs. Information may be harder to detect, interpret and relate; alarms may be harder to spot, etc. What science can be brought to bear to improve things?

Color science is the ójewel in the crownôof our understanding of human vision. From photon to physiology, from molecule to mechanism, color has progressively surrendered its secrets. From Newtonôs famous initial observations with prisms three centuries ago, through the Neitzôs astonishing recent genetic curing of color blindness in monkeys three years ago, there have been enormous advances in our basic and clinical understanding of color. Our children will quite likely see color blindness eradicated in their lifetime.

For our application, there are now industry-standard, quantitative models of human color appearance and discrimination. This all begs a rather large question. If color science is so advanced, why is it routinely not applied to HMI design? There are several reasons.

The guidelines to apply color are written most often by researchers for researchers. Simple, actionable guidance for HMI developers is missing. Also missing from the guidelines is a clear **process** to apportion colors, tailored to domain needs. It requires sophistication in color science, paired with an applied human factors orientation (possessed by the first two authors), together with a domain understanding and

engineering expertise in process control HMIs (possessed by the third and fourth authors). Well-designed and consistent use of color results in consistent outcomes, improved production and efficiency, and reduced incidents. This paper reports our collaboration to apply color science to improve process control HMIs.

Color: a Precious Commodity to Use Sparingly

Given the past misuse of color and the advanced state of color science today, what attributes should be coded using color, and what colors should be used? Analysis of basic color research by FAA human factors experts (see Xing, 2007) and others indicate three specific functional roles of color when it is used to support tasks.

Functional Role of Color	Description
Directing Attention	Immediately direct users to important information, even in complex displays – for example using bright, saturated red alarms
Aiding Identification	Aid recognition or search for an item in a specific data category – for example blue-colored cold water pipes
Segmenting the Visual Scene	Organize information on the display into distinctive objects – for example a colored region that groups all information about a loop

Aesthetics aside, color should be used if, and only if, task performance can be improved by one of these functional roles. For example, when it is necessary to quickly and reliably alert an operator to an out-of-range process value, a bright, vivid color would direct attention to the alert and improve performance over a darker or dull-colored alert. However, use of vivid color when that functional role is not needed can decrease performance. For example, bright, vivid colors are not needed for good recognition and segregation of equipment shapes. Dimmer, desaturated colors are just as effective and more aesthetically pleasing. Use of excessively bright or vivid colors for equipment shapes would distract operator attention away from potential alerts by drawing attention to non-actionable shapes and increasing display clutter. This can increase alert response time or missed alerts.

The basis of our systematic color analysis and design procedure is **task-appropriate** selection of these three functional roles of color. Once the desired color role is known, basic perceptual research can provide quantitative criteria to achieve that function. For example, a color intended to direct attention must be brighter and more vivid than other colors in the display, and must have a large color difference from any other color in the display (measured as distance in a perceptually uniform 3D color space such as CIEDE2000, see sidebar).

In addition to consideration of the task-related functional roles of color, several basic perceptual and viewing condition requirements must also be met, such as sufficient contrast from the background. A set of simple, but comprehensive ñUniversal Color Requirementsò(see below) were recently developed and successfully applied to re-design U.S. Navy submarine displays by the first two authors. These are widely applicable to display interfaces in any domain and should be used to ensure all color-related requirements are met.

Universal Color Requirement	Description
UCR1: Discriminable	Colors must be identifiable and discriminable for different users, including colorblind users
UCR2: Sufficient contrast	Colors must have sufficient contrast for legibility and visibility
UCR3: Stable in appearance	Color must remain stable in appearance across HMI layouts and lighting conditions
UCR4: Sparse use of color	There should as few colors in the HMI as possible
UCR5: Consistent coding	A color should have the same meaning everywhere, so if red is chosen as an alarm color, it should not also be used to represent equipment that is not running
UCR6: Effective attribute mapping	Color mapping to data attributes should be cognitively appropriate, task-relevant, and culturally appropriate

Consideration of the three useful functional roles of color (directing attention, aiding identification, and segmenting display elements) and application of the Universal Color Requirements is needed for any display where complex data attributes are to be coded. Colors designed with these guidelines can provide important additional information to decision-makers, and support improved operator performance with less error.

A Systematic, Evidence-Based Process to Apportion Color

We developed a systematic, evidence-based process to apportion color that applies these color considerations. The process consisted of a task analysis, color modeling, and HMI redesign. Our color modeling predicts color appearance and color differences for both normal and color-blind users and takes into account the effect of symbol size. The process is unique in that we define model-based, quantitative requirements for good performance to ensure that a chosen color will serve the intended function. These quantitative criteria are useful because they not only specify which color attributes are required, but also which are not required to achieve the function. Importantly, those attributes that are not required are then freed for other uses. This approach maximizes the utilization of color, while ensuring reliable color discrimination for all operators. In contrast, conventional approaches can throw away useful color codes and donôt guarantee optimal color task performance.

Modeling of discriminability for color-blind users is useful because it provides a principled method of design for color-blind users rather than the ad-hoc approach that is often taken. For example, a typical approach is to design for color-normals and then provide a so called ñredundantò non-color coding for color-blind users. This coding isnôt truly redundantð there is no fail-safe fallback code for color-blind users.

The approach described here can create a truly redundant code by designing colors to meet discriminability criteria for the most common types of color blindness. Some rare or severe forms of color blindness are not easily accommodated (tritanopiað a defect of vision in which the retina fails to respond to blue and yellowð and tritanomaly, where the sparsest blue cones are affected), and operators should be screened for these deficiencies.

Another unique feature of the process is consideration of the size of symbols and letters. One of color visionôs subtleties is that it degrades severely for small objects (as there are only two types of cones in the very center of gaze). Because complex process control HMIs may require numerous small symbols, operators may have more difficulty discriminating colors than is predicted by standard color metrics. We compensated for this by using a small-symbol modified CIEDE2000 color difference metric from the applied color vision literature (Carter & Silverstein, 2010).

The core steps of our process are described in sequence.

Step 1: Analyze Operator Task Requirements

Work began with a **task analysis** of the control system HMIs with subject matter experts. The purpose was to analyze the HMI designs to determine which tasks could be supported by color and to understand the intent of any existing color coding. During this step, it was essential to understand the relative importance of the tasks and the attributes to be coded by color. This is because there are a limited number of easily discriminable colors available, and tradeoffs must usually be made. For example, several types of alarms and notifications needed to be color coded, but only a few consistently named ñbasic colorò names are available (see sidebar).

An understanding of relative importance (in terms of safety, process impact, etc.) allowed us to allocate the basic color names to the most important alarms. In addition, subject matter experts can often reveal subtle, context-specific meaning of the display attributes in their domain that canô be gleaned from cursory inspections of the HMIs. A naïve color redesign without this basic domain understanding may apply color theory correctly, but in the end. it will not meet the needs of the process control system designer or operator.

For each task to be supported by color, the desired functional role for color (directing attention, aiding identification, or segmenting display elements) was specified. These specified roles, in combination with the Universal Color Requirements, led to a set of **quantitative criteria** for each color-supported task. Criteria were based on experimental human performance data to ensure that colors chosen would achieve the desired functional role (see the table below). For example, for a task requiring rapid identification, the chosen color must be more than 9 modified CIEDE2000 units different from any other color in the display.

		Quantitative color criteria			
Desired perceptual role	**Attention**	**Lightness:** Maximum available	**Saturation:** Maximum available	**Color difference:** > 18 ΔE	-
	Identification	**Hue:** Nameable basic hue	**Meaning:** Consistent with cultural norms	**Color difference:** > 9 ΔE	**Surround:** Similar for all instances
	Segregation	**Color difference:** > 9 ΔE (ideal) > 1 ΔE (minimum)	-	-	-
	Visibility/ Legibility	**Luminance contrast:** > 0.4	-	-	-

Note: ΔE in this table is a CIEDE2000 metric modified for small symbols.

Because we were assessing and re-designing color use in an existing process control HMI suite, we next documented colors of all task-relevant display elements. This included RGB values of these elements and of their surrounding pixels. This data served as input to the color modeling of Step 2.

Step 2: Model Discriminability and Appearance

An initial, rough assessment of existing color codes was performed by processing screenshots of the displays to **simulate color appearance** for certain color-blind user types (deuteranopesð persons who canô respond to green and purplish-redð and protanopesð people for whom red appears as yellow). This simulation can suggest, but does not quantify, potential color issues such as indiscriminable colors or insufficient

contrast. However, it helps to ensure that obvious or critical color problems are not missed. Next, several **comprehensive analyses** were done, including assessment of

- **color differences** between all potentially confusable colors, calculated for color normal, deuteranopic and protanopic observers,
- **contrast** of symbols and text, calculated for color normal, deuteranopic and protanopic observers,
- appropriate use of hue, lightness and saturation (see sidebar),
- consistency of color use with cultural norms (e.g. red means bad).

The quantitative metrics used in this analysis (modified CIEDE2000, luminance contrast) can be based on physical color measurements of a display, but in many cases this is not necessary. Most modern displays conform to or exceed the Internet standard RGB color space (ñsRGBò), so colorimetric values can be estimated with sufficient accuracy from image RGB values. To ensure legibility and visibility, luminance contrast can be estimated with sufficient accuracy using a simple set of equations (shown in the sidebar). However, the CIE color difference equations are complex and are beyond what can be presented here.

Step 3: Revise HMI Design

Finally, the HMI color coding schemes were revised to maximize effective color task support, discriminability and stable color appearance. Results of the Step 2 analyses and modeling were compared to the criteria established previously, and a list of potential problem colors was made.

To ensure that relevant design trade-offs were taken into account, the problem colors were **prioritized** according to the importance of the task that they support, severity of the shortfall from color criteria and ease of design changes to the color. For example, an identified problem color supported an important task (e.g., directing attention to an alarm), but was difficult to redesign (e.g., because it is a widely accepted convention in the domain), and had a low severity color shortfall (e.g., a small shortfall from the required color difference to other colors). In that case, it was more effective to redesign a more-easily changed and less critical conflicting color. While this is a simple example, a systematic approach to prioritization helped to resolve the many design tradeoffs, and ensured a comprehensive color redesign that reliably supported critical process control tasks.

The specific redesign we implemented depended on the issues found. One type of redesign was a simple change in the color of a symbol or display region. In this case, new colors were first chosen in the perceptually uniform CIE color space, and then converted to the RGB values that specify color in software. Design changes also included revision of surround color to ensure stable appearance and revision of multiple symbol colors to achieve consistent color metaphors to better support a task. Once an initial redesign was complete, the color analyses described in Step 2 was repeated to ensure that the redesign solved the issues identified and did not create new problems. This validation step was more focused and less time-consuming than the initial analysis, but was comprehensive enough to ensure no unintended new problems were created.

In the three steps above, we have described our process in the context of a specific process control HMI analysis and redesign. However, based on our previous successful

application of the process in a very different domain, we believe it will effectively generalize for application to any complex control system.

Example Applications

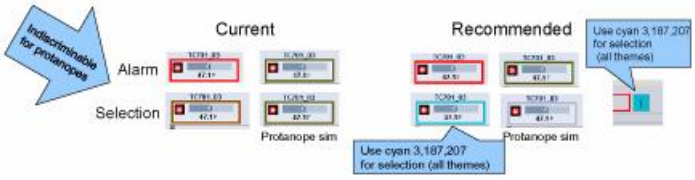
Below we illustrate examples from our application of the process described in this paper to a process control system HMI display suite. The examples show actionable design recommendations that were developed to improve HMI utility for color normal and color blind operators. Examples illustrate several common types of issues likely to be encountered and their solutions.

Application 1: Color Difference and Discriminability

A central consideration is to ensure that colors can be discriminated from each other. Color difference metrics based on perceptually uniform color spaces quantify that discriminability. A difference of 1 unit means that colors are discriminable under ideal conditionsð when large colored fields are directly juxtaposed. However, under more realistic conditions, for more reliable segregation or for non-abutting colors, a color difference of about 10 units is needed. For critical color functions, such as rapid direction of attention, or when a color needs to be found quickly in a complex display, a color difference of about 20 units is required.

Our analysis of the process control HMIs determined that, as required, alarm colors were very different (greater than about 20 units) from other colors in the display for color-normal operators. However, modeling of protanopic color blind operators showed they would not be able to discriminate the red alarm color from an orange selection color. This problem is illustrated in the figure below using a colorblindness simulation. Note that the simulation illustrates the reduced discriminability (compare the two boxes above the word ñProtanope simò), however it is not possible to predict color appearance or color naming by color-blind observers.

The red alarm color and the conflicting orange selection color were both identified as ñproblem colorsòand prioritized as described previously. The orange selection color was identified as the higher priority for re-design since this is a severe color issue, affecting a high-priority task, and the selection color was relatively easy to redesign (compared to changing the red alarm color and violating the ñred means badòalarm color convention). Cyan was chosen to replace orange as the selection color, and this change was validated using the models and criteria (see the figure below, right side). This color was sufficiently discriminable for protanopic color blind operators and directs attention as required because of its lightness. In addition, this choice improved consistency of color use, since cyan was already used to indicate selection elsewhere in the HMIs.



Application 2: Size and Surround Effects on Color Appearance

Small regions appear less bright and less vividly colored than larger regions with the same RGB values. This can lead to difficulty identifying a color that is intended to code some process attribute. The appearance of thin colored lines is one example. In that case, one solution is to make the lines a few pixels wider.

Surrounding color also plays a large role in the appearance of a colored element. In fact, **color appearance** is determined primarily by color contrast at the edge of a display element. In the examples below, yellow, purple and red rectangles each code a type of alert. However, the alert colors occur in two different surrounds on the same display, which changes their appearance significantly, making identification by color more difficult. For example, in the figure below the yellow box on the dark surround (top, left) looks brighter and more vividly colored than the yellow box on the light surround (top, second from left). The operator may be confused by whether the vividness of the yellow alert is intended to code some variation of the coded attribute (for example, if yellow is used to indicate an advisory, the vividness could be interpreted as representing importance).

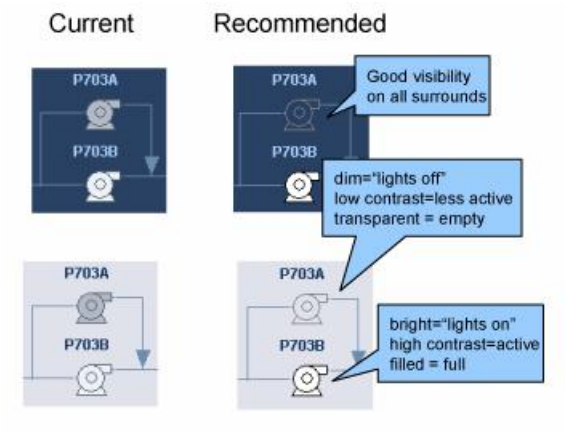
Since this was not the design intent, we redesigned the alert boxes to better maintain their color appearance across different display regions by include a one-pixel black line inside and around the colored boxes (top, third and fourth from left).

Application 3: Consistent Color Coding Metaphors

A more cognitive, rather than perceptual, potential color issue is consistency of color use with cultural and domain conventions. Red alarms indicating a serious condition is one example of coding consistent with the cultural convention that *"red means bad."* An operator would likely be baffled and confused if green, rather than red, alerts indicated danger.

In addition to strong cultural or domain conventions, less definite, but still common color-related metaphors such as *"bright is active"* can be used to create quickly understood and reliably remembered codes. An example is shown below for a pump symbol that codes on and off state. The original coding (figure below, left side) was initially identified as problematic because pump on and off colors were not discriminable for some color-blind users. In addition, the metaphor for on and off was confusing. For example, there are several possible interpretations of the light and dark colors used: Bright could indicate an active, and dark an inactive pump; or dark could indicate a filled, and light an empty pump. In addition, contrast of the pump colors varies with the background, leading to misinterpretation if one assumes that high contrast means active.

The redesigned on and off pump symbols use colors discriminable to all operators. Further, three common visual metaphors were combined to unambiguously indicate on and off. These included *“bright means lights on”, “high contrast means active”* and *“filled means full.”* These metaphors work consistently across display background colors and were judged effective by domain experts.



This systematic process and application of color science resulted in displays matched to the way the operatorsôvisual systems process color information. The colors chosen using this process directly support operator tasks. Where needed, large color differences and bright, vivid colors support rapid direction of attention; basic nameable hues allow unambiguous identification and communication of information categories; and less vivid, lower contrast, but still discriminable colors allow segmentation of equipment shapes and other static display features. When carefully and sparingly used, color becomes an asset, improving performance of selected tasks without overwhelming the operator with difficult-to-remember or indiscriminable color codes. Application of the universal color guidelines and quantitative color models ensures that information depicted in the displays will remain discriminable and identifiable under a wider range of conditions, and will work for all but the most severely color-blind (tritanopic) users. This systematic, domain-tailored application of color science is part of a wider, growing interest by Emerson in applying perceptual science to HMI design.

Conclusion

HMI colors configured and set by preference or with only lay knowledge of color vision, can result in several subtle issues that negatively impact visual task performance. In contrast, when colors are well-aligned with colorôs core three functions, these issues can be eradicated, and visual task performance improved. The color analysis and redesign process reported here showcases the wider benefits of taking a systematic, evidence-based approach to HMI design.

The major advances and subtleties of perceptual and cognitive science need to come off the shelves of a few academics and be translated into straightforward, actionable and quantitative guidance for HMI process control designers and developers, perhaps in the form of actionable style guides.

The impact achieved by Emersonôs Human Centered Design (HCD) design team is readily visible in many products. The initial focus of the HCD team resulted in completely

redesigned device displays and applications. Today device-level displays and applications are designed using a set of guidelines that are in use across all of Emerson's divisions.

This interest in applying human-centered design is now expanding and, as discussed in this paper, is now making its way into process control. In this paper, we described how color science can be applied to operator displays. We provided insight into how color science can be applied as a set of steps which could be documented as actionable guidelines.

Sidebar

Applied Color Science 101

Basic colors. First anthropologists, then psychologists have established that only 11 color names (red, green, yellow, blue, orange, pink, purple, brown, white, gray and black) are reliably and consistently used and communicated.

Color 'blindness' is a reduced or lost ability to discriminate between certain colors. It is caused by the loss (-anopia, causing inability to discriminate) or change in wavelength sensitivity (-anomaly, causing reduced ability to discriminate) of one of the three cone photoreceptors.

CIE is the International Commission on Illumination (Commission Internationale de l´Eclairage), an ISO-recognized international standardization authority on matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology.

CIEDE2000 color difference. An up-to-date, experimentally validated metric of color discriminability. In contrast, color differences in RGB or the RGB-derived HSL color space are grossly inaccurate estimates of discriminability.

Luminance contrast modulation (Michelson contrast) is the property of a colored display element most predictive of text legibility and symbol visibility. The following equations provide good estimates of luminance contrast based on RGB values of an element and its surrounding pixels:

$$L = 0.213 \cdot \left(\frac{R}{255}\right)^{2.2} + 0.715 \cdot \left(\frac{G}{255}\right)^{2.2} \; 0.072 \cdot \left(\frac{B}{255}\right)^{2.2}$$

$$C_M = \frac{(L - L_{surround})}{(L + L_{surround})}$$

Hue is generally described as color (e.g. red, blue), the property of a display element useful for identification and coding of categorical information.

Saturation is the vividness of a color, and is a property useful for controlling attention to a colored object. Saturation can be varied independently of hue, so that attention-grabbing and muted versions of the same hue are possible.

Lightness is useful for coding continuous data scales, such as temperature or signal strength, where higher values are usually coded as lighter. Lighter colors, like increased saturation, also attract attention.

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Cindy is the DeltaV product marketing operations team lead at Emerson Process Management, which includes marketing responsibility for operator interface products. She led the recent development of the DeltaV Operate themes, which incorporated colors and patterns to improve operator visual attention and recognition of important information in operator displays. She is active in the Center for Operator Performance.

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Mark is the director of applied research at Emerson Process Management. In the past he was the lead architect for DeltaV and played a key role in the design of WirelessHART. His current research includes control, data analytics, wireless, low power, virtualization, operator interfaces and advanced graphics. He is currently active in the Center for Operator Performance, WirelessHART, as well as several other forums.